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Improved indicators of water use performance and productivity for sustainable water conservation and saving

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ABSTRACT

Water use concepts and performance descriptors that may be useful in defining conservation and saving of water are discussed with the aim of improving the overall performance and productivity of water use. New indicators are proposed which include consideration of water reuse and aim to assist in identifying and providing clear distinctions between beneficial and non-beneficial water uses. An analysis of productivity concepts useful both in irrigation and elsewhere is provided together with suggestions for where commonly used terms, such as the broadly used "water use efficiency" among others, would be better avoided in irrigation engineering and given much more narrowly defined meanings in agronomy and biological sciences. Particular attention is given to economic issues in water productivity. The analysis is completed with various case study applications at irrigation farm and system scales. It is recommended that a set of terms (not necessarily those developed here) be widely adopted that will provide a basis for easy, certain communication and provide widespread common understanding of the issues which must be faced to develop approaches to achieve efficient water use.

1. Introduction

For millennia, civilizations developed in water scarce environments, however where scarcity was less stringent than that we know today. The respective cultural skills, particularly with respect to water use are an essential heritage of those nations and peoples, and of humanity generally. However, progress in the XXth century questioned traditional know-how, which has often been replaced by modern technologies and management imported from different environments and cultures. A culture of economising water is following the technical one, which was introduced when large irrigation schemes were built and water scarcity was not yet a challenge. Both technologies and management were generally imported from different cultural and institutional environments, and their adaptation to local conditions has not always been successfully adopted or accepted by farmers. Management therefore faces difficult challenges arising from the fact that irrigators perceive problems, practices and objectives different from those perceived by the non-farmer water and financial managers. Despite its great importance, a discussion on differences of perception of water management and efficiency objectives between farmers and policy- and decision-makers is out of the scope of this paper. For example, an analysis of UK farmers' perception of irrigation efficiency is addressed in this issue (Knox et al., 2011).

The last century has known an increased intervention of governmental and state institutions in water management following the enormous investments made. Traditional institutions lost importance and new centralized institutions were created to manage and operate the introduced investments and technologies. Even though in many places there is already 100% commitment of water resources there remains ongoing increasing demand. As a result of lack of success of existing institutional arrangements a number of variations of participatory irrigation management are now being considered to solve the resulting problems. Related challenges and successful issues for Asian irrigation communities are analysed in Shivakoti et al. (2005). Self-governing irrigation systems are advocated by many authors. The classical analysis on this subject by the 2009 Nobel Prize winner deserves attention (Ostrom, 1992). A reconsideration of traditional irrigation practices is starting and a new appreciation of the advantages of traditional know-how is beginning to appear. However, pressures on irrigating farmers are continuing to require them to increase irrigation efficiency, achieve higher water productivity and use less water. Yet there is often a lack of assistance for them to develop and adopt improved approaches and techniques appropriate to these changing farming objectives, however keeping farmers' objectives of financial and

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social nature. In addition, perceptions of an urban society that very highly prioritises environmental preservation for future water allocation are also challenging farmers' attitudes and requiring new approaches.

A new communication model has to be developed that could lead to a better understanding of water use in agriculture and demonstrate why performance improvement must occur within the context of the needs of the societies and the objectives of farming (Clemmens and Molden, 2007; Perry, 2007; Lankford, in this issue). New approaches are required to properly define and account for each item of water use and productivity with water conservation and saving being the primary drivers to achieve higher performance (Foster and Perry, 2010; Molden et al., 2010). From this perspective, the performance concepts need to be differently defined, understood and applied. In other words, we need a new model in terms of conceptualization of water use performance that can be understood by users, managers and decision-makers alike. This improved conceptualization can then provide a common framework around which actual water use (hopefully monitored water use – debate over words is not very useful if the actual volumes involved are only approximate) can become sustainable for large and small farmers or other users, in all climates and in societies with different degrees of development, utilising a wide range of technologies (see for example Rockström et al., 2010, calling for a paradigm shift to water management in rainfed agriculture).

The terms water conservation and water saving are generally associated with the management of water resources under scarcity. However, these terms are often used with different meanings within specific scientific and technical disciplines or in the water user sector considered. Often, both terms are used synonymously.

The term water conservation is used herein to refer to every policy, managerial measure, or user practice that aims to conserve or preserve the water resource, as well as to combat the degradation of the water resource, including its quality. Differently, the term water saving describes the avoidance of loss of water by limiting or controlling water demand and use for any specific purpose (cf. diversion and depletion savings proposed by Haie and Keller, 2008), including the avoidance of wastes and the misuse of water. In practice these terms or perspectives are complementary and inter-related. Water conservation plays a major role in rainfed agriculture and when irrigation is supplemental of rainfall (Unger and Howell, 1999; Oweis and Hachum, 2003, 2006; Rockström et al., 2010) but it is essential in all water use systems, often as a means to achieve water saving (Pereira et al., 2009). Water conservation can play a major role in agricultural and landscape irrigation considering that predictions for climate change indicate a concentration of rainfall and an increase of its intensity. A coupling of soil and water conservation is then essential to increase water infiltration and storage in the soil profile as well as to control soil evaporation. Water conservation increases the amount of consumptive use by crops and natural vegetation, sometimes called the green water fraction, and assists in preserving the quality of flows that are often called the blue water, the general good quality environmental water (Falkenmark and Lannerstad, 2005). Water savings usually refer to the blue water fraction. Despite it often not being easy to distinguish between "conservation" and "saving", these terms should not be used synonymously. For example questions relative to preservation and upgrading of water quality are essential in water conservation but are rarely relevant to the usual ideas of water saving. A comprehensive analysis on water conservation and saving for a variety of agricultural and non-agricultural uses is presented by Pereira et al. (2009).

It is arguably a modern tragedy that considerable volumes of the scarce resource can and are being lost or wasted due to lack of clarity of terms used and miscommunication between those involved. This is analysed in most papers in this issue, with the various authors adopting a variety of approaches. Yet communication must also apply to specific fields or scales: our main focus in this paper is water use at the farm scale, or a group of users served by the same system, not basin planning or water allocation. Therefore the aim of this paper is twofold: (1) to demonstrate the confusion of the terms used both between and within disciplines and groups of users, and the resulting potential for poor use of water, and (2) to suggest alternative terms that could gain wide acceptance and common usage. Some case study applications are used to illustrate the use of these terms and ideas.

2. Water use, consumptive use, water losses, and performance

2.1. Water systems, efficiency, and water use performance

The performance of water supply systems and water use activities are often expressed with terms relative to efficiency. However, there are no widely accepted definitions, and the efficiency terms are used with different meanings, mainly relative to the various water use sectors. In certain cases, both water conservation and water saving are used as synonymous with water use efficiency (e.g., Garduño and Arreguín-Cortés, 1994). For a better understanding of terminology utilized in relation to water use performance, a more consistent conceptual approach is required.

The term efficiency is often used in the case of irrigation systems and it is commonly applied to each irrigation sub-system: storage, conveyance, off- and on-farm distribution, and on-farm application sub-systems (Bos and Nugteren, 1982; Wolters, 1992). It can be defined by an output to input ratio, between the water depth beneficially used by the sub-system under consideration and the total water depth supplied to that sub-system, usually being expressed in percentage terms. In case of on-farm application efficiency, the numerator is replaced by the amount of water added to the root zone storage and the denominator is the total water applied to that field. However, we argue that an efficiency indicator refers to a single event and should not be applied to a full irrigation season without adopting an appropriate up-scaling approach. These indicators relate to individual processes and their use as a bulk term does not provide sufficient information on the processes involved. A schematic of processes involved in irrigation water use is given in Fig. 1. For non-irrigation water systems, the term efficiency is

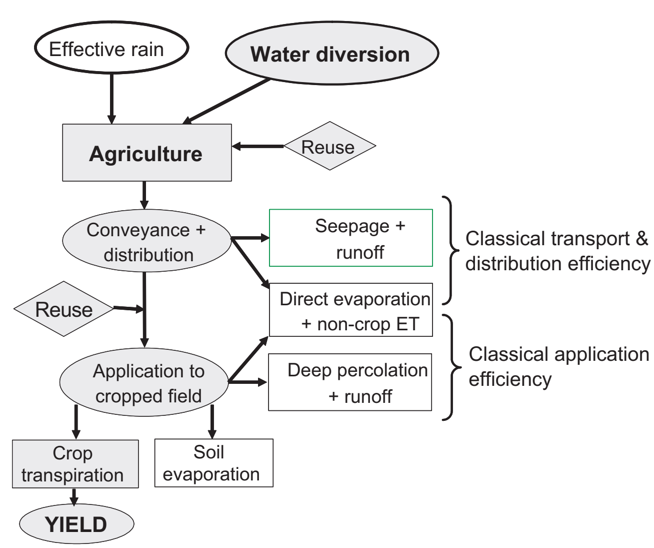

Fig. 1. Processes influencing irrigation efficiency off- and on-farm: grey boxes are the processes leading to the crop yield; white boxes are those leading to water wastes and losses.

less used but could be similarly applied referring to the various processes involved.

A good set of efficiency terms was developed in the 70s (Bos, 1979; Bos and Nugteren, 1982), which became the object of numerous discussions, applications and publications (e.g., Wolters, 1992; Bos, 1997). Later, the efficiency terms defined in those classical publications were considered less satisfactory, particularly relative to conveyance and distribution systems; hence, different irrigation system performance indicators were searched and progressively adopted (e.g., Molden and Gates, 1990; Murray-Rust and Snellen, 1993; Lamaddalena and Sagardoy, 2000; Bos et al., 2005; Molden et al., 2007). These changes in terminology were progressively adopted, with abandonment of the term efficiency including to describe farm irrigation processes (Bos et al., 2005).

The term efficiency often leads to misconceptions and misunderstandings (e.g., Jensen, 1996, 2007; Allen et al., 1997; Burt et al., 1997; Molden, 1997; Pereira, 1999; Perry, 1999, 2007; Pereira et al., 2002). Willardson et al. (1994) were the first to propose water use fractions as indicators and abandonment of efficiency terms. Keller et al. (1996) proposed the term 'effective efficiency' to take into consideration the reuse fraction of the applied water. Haie and Keller (2008) further analyse the usefulness of effective efficiency. Solomon and Burt (1999) adopted the term 'irrigation sagacity' to consider the irrigation water used beneficially or reasonably. Lankford (2006) introduced the term 'attainable efficiency' for a descriptor expressing the ratio between an irrigation dose when a farmer cares for the limited resource available and a dose that is applied less carefully (or in excess). All these approaches identify and qualify the insufficient information provided by the word efficiency. However, terms relative to application efficiency to measure the performance of irrigation events at farm scale are somewhat consensual (Heermann and Solomon, 2007).

A common misconception is that of considering that increasing irrigation efficiency is almost synonymous with creating more available water. In fact, increasing water availability requires the consideration of time and space scales of interventions, as well as other variables controlling the hydrologic processes. Earlier discussions on this subject include those by Seckler (1996), Keller et al. (1996) and Molden (1997). For the basin level, new concepts and terminology, on basin water accounting, were then introduced (Molden, 1997). Good reviews on this subject are presented in the book edited by Kijne et al. (2003), mainly that by Seckler et al. (2003). A good application and discussion is presented by Bluemling et al. (2007), who not only advanced ideas around adopting new water use indicators but related these ideas to water productivity. The available literature shows that there is the need to quantify the fraction of water used (diverted for a given use), that is beneficially consumed, and the fraction that is not consumptively used and is available for reuse or becomes degraded after use. For the later case, improving efficiencies would represent a reduction in water losses and contribute to the conservation of the available resource. In many cases, however, the non-consumed fraction is not degraded and is used by other systems downstream so that improving efficiencies would not necessarily be advantageous to the total system.

The present trend is to abandon the term efficiency for irrigation water conveyance and distribution and to adopt service performance indicators (Willardson et al., 1994; Burt and Styles, 2000; Bos et al., 2005; Merriam et al., 2007). In fact, it is recognized that impacts on agricultural yields, farmers' incomes, and farm water management largely result from the quality of the water delivery service (Clemmens, 2006; Calejo et al., 2008; Zaccaria et al., 2010). Indicators referring to the reliability, dependability, adequacy, or equity of deliveries may be used for that purpose (e.g., Hashimoto et al., 1982; Molden and Gates, 1990; Lamaddalena and Sagardoy, 2000; Pereira et al., 2003; Lamaddalena and Pereira, 2007). These and other indicators are measures of the capability of collective water systems for timely water delivery with appropriate discharges, pressure head, time intervals and duration to satisfy the farm requirements throughout the irrigation season and independently of the location of the gate or hydrant. It is well known to farmers in some systems (e.g., "warabandi" in the Indian subcontinent, Zardari and Cordery, 2009) that poor maintenance and disinterest among delivery system operators can devastate farm operations and ensure much of the delivered water is wasted, since lack of water for weeks at crucial parts of growing cycles means the death of the crop, and all subsequently delivered water produces very little or nothing. Similar water service indicators are also used for other non-irrigation networks. All irrigation systems need active, real time monitoring, with actual measurement of flows at a few key points to provide feedback on the directions and rates of flow at any time.

The term application efficiency is still used to characterize the management relative to a given event; meanwhile, Bos et al. (2005) already proposed its replacement by the term water application ratio. However, by themselves, neither of these terms is very meaningful. They need to be complemented by an indicator of the uniformity of water distribution within the field, such as the distribution uniformity or the uniformity coefficient (Burt et al., 1997; Pereira, 1999; Heermann and Solomon, 2007). In fact, if a system does not provide uniform water application, efficiency is necessarily low and percolation through the bottom of the root zone is high.

Another term commonly used is water use efficiency (WUE), but again no common definition has been adopted (Steduto, 1996; Pereira et al., 2002; Hsiao et al., 2007; Perry, 2007). Some authors refer to it as a non-dimensional output/input ratio as for the single term efficiency noted above, e.g., as used by Seckler (1996) when discussing issues on water use, particularly in relation to water saving and the basin scale. Others adopt it to express the productivity of the water, as a yield to water used ratio (e.g., Shideed et al., 2005). In crop production, the term WUE may be applied with precise meanings, such as the 'yield or biomass WUE', which is the ratio of the harvested biomass to the water consumed to achieve that yield, i.e., the season plant transpiration (e.g., Katerji et al., 2008). In plant physiology and eco-physiology the photosynthetic WUE expresses the ratio between assimilates or biomass produced during a certain period of time and the corresponding plant transpiration. WUE therefore expresses the performance of a given plant or variety in using water (Steduto, 1996). Various scales may be considered, from the leaf to the plant or the crop, and from the day to a growth period or the crop season as discussed by Steduto et al. (2007). Meanwhile, these authors abandoned the term WUE and replaced it by water productivity (WP) due to the misunderstandings behind the term efficiency, thus creating other misunderstandings with the term WP because they proposed to use the term WP down to the scale of the leaf (photosynthetic WP), which is typical of plants physiology, not irrigation engineering. Nevertheless, this approach was also adopted by Perry et al. (2009). In another paper, the same authors (Hsiao et al., 2007) adopted the term WUE with the same meaning of the classical term irrigation efficiency, thus not recognizing the many efforts to clarify water use communication and water accounting, but contributing to the confusion on the use of related terminology and concepts as analysed above.

To avoid misunderstandings, the term "water use efficiency" should only be used to measure the water performance of plants and crops, irrigated or non-irrigated, to produce assimilates, biomass and/or harvestable yield. The term "water productivity" (WP) should be adopted to express the quantity of product or service produced by a given amount of water used, i.e., consumptive and non-consumptive uses, both in irrigation and non-irrigation water uses, in contrast to the proposal by Perry et al. (2009) who

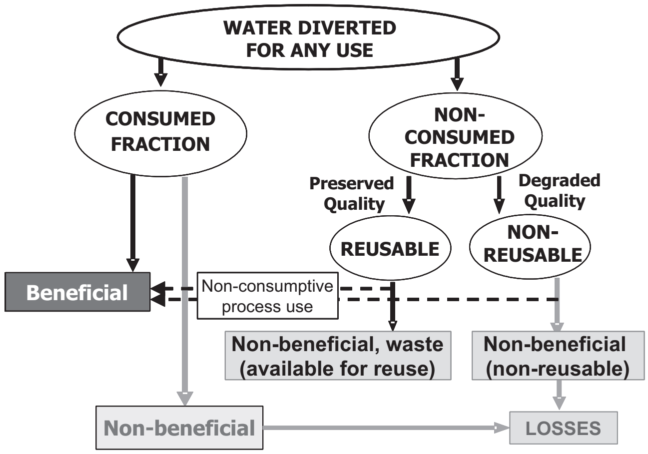

Fig. 2. Water use, consumptive and non-consumptive use, beneficial and non-beneficial uses, water wastes and losses.

adopted WP with physiological meanings such as photosynthetic and biomass WP, which are far from water uses in irrigation, industry or elsewhere. Hence, WP should be used with more precision with identification of the scales to which it refers, as discussed later in this paper relative to irrigation and non-irrigation water use.

2.2. Water use, consumption, wastes and losses

New concepts to clearly distinguish between consumptive and non-consumptive uses, and beneficial and non-beneficial uses are being developed. Similarly the differences between reusable and non-reusable fractions of the non-consumed water diverted into an irrigation system or subsystem are being clarified (Willardson et al., 1994; Allen et al., 1997; Pereira et al., 2002; Perry et al., 2009). Along this line, aimed at promoting sustainable groundwater use in irrigation, Foster and Perry (2010) also proposed a set of water use fractions. These descriptors consist of alternative performance indicators that are much more relevant than "irrigation efficiency" when adopted in regional water management for the formulation of water conservation and water saving policies and measures. An expected advantage of these indicators is that irrigating farmers understand them better than efficiencies. Moreover, these concepts and indicators are applicable to irrigation and non-irrigation water uses.

When water is diverted for any use only a fraction is consumptive use. The non-consumed fraction is returned after use with its quality preserved or degraded. Quality is preserved when the primary use does not degrade its quality to a level that does not allow reuse, or when water is treated after that primary use, or when water is not added to poor quality, saline water bodies. Otherwise, water quality is considered degraded and water is not reusable (Fig. 2). Alternatively, the terms recoverable and non-recoverable are adopted by Perry et al. (2009).

Both consumed and non-consumed fractions concern beneficial and non-beneficial water uses. These are beneficial when they are fully oriented to achieve the desirable yield, product, or service. Alternatively, when that use is inappropriate or unnecessary, it is called non-beneficial. Reusable water fractions are not lost because they return to the water cycle and may be reused later by the same or by other users. They are not losses, but are wastes since they correspond to water unnecessarily mobilized. Contrarily, the non-beneficial water consumed (perhaps evaporated) or returned to poor quality, saline water bodies, or that contributes to degradation of any water body, is effectively a water loss (Fig. 2).

Although a water use attempts to be purposeful, it is important to recognize, from the water economy perspective, both the

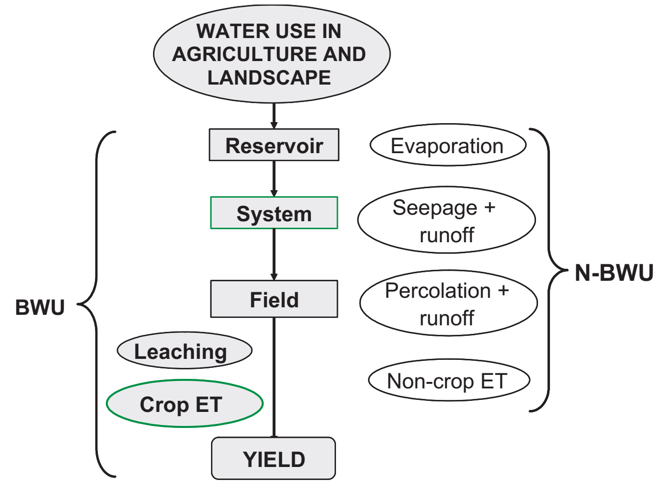

Fig. 3. Beneficial and non-beneficial water use (respectively BWU and N-BWU) in crop and landscape irrigation.

beneficial and non-beneficial water uses (Fig. 3). This has also been attempted by Solomon and Burt (1999) when they proposed the term irrigation sagacity. In crop and landscape irrigation, the beneficial uses are those directly contributing to an agricultural product or an agreeable garden, lawn or golf course where the desired product may be maintenance of certain characteristics in the biomass. Non-beneficial uses are those that result from excess irrigation, poor management of the supply system, or from misuse of the water.

These concepts may also be applied to the use of water in industry, urban regions, energy production and other activities. Then beneficial uses include all the activities and processes leading to achievement of some production or service which results in some good or benefit, such as drinking, cooking, washing, heating, cooling, or generating energy. The uses are not beneficial when water is used in non-necessary processes, is misused or is used in excess of the requirements for productivity (Fig. 4).

It is important to recognize that the approach referred to above, which is based upon the water use fractions proposed by Willardson et al. (1994) and Allen et al. (1997), as well as the water accounting developed by Molden (1997), essentially aims at assessing the pathways for improving water uses in agricultural and

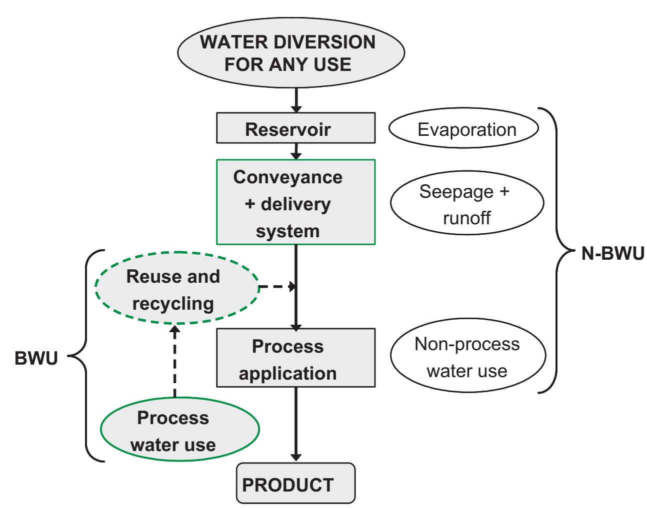

Fig. 4. Beneficial and non-beneficial water use (respectively BWU and N-BWU) in agriculture, industry, urban processes, energy production and landscape development, with reference to reuse or recycling.

non-agricultural processes. They apply to single users or to grouped users practicing a common activity that leads to the same type of product or service, e.g., a farm, a group of farmers within an irrigation sector, an industry or a urban sector. This paper's approach differs from the water accounting approach developed by IWMI (Molden, 1997; Molden et al., 2003) where the water balance is mainly focused on the (basin) water allocation and its assessment.

Assuming the concepts above, it is therefore important to recognize what is meant by "efficient water use". To support this concept, a few important ideas are developed in Fig. 5. First, it is necessary to identify the water pathways in any water use, then to distinguish what is consumptive and non-consumptive water use, what is a beneficial or a non-beneficial water use, and which fractions are really losses or wastes; the latter can be recovered later by some means and used for other uses. This requires that productive and non-productive processes, i.e., those oriented to achieve the water use goal, be recognized. Then, a water use is more efficient when beneficial water uses are maximized, water productivity is increased, and water losses and wastes are minimized. However, it does not mean that less water is consumed when making water use more efficient because maximizing beneficial water uses and water and land productivities through the use of improved technologies may give the opportunity for higher crop evapotranspiration with reduced water wastes and losses (e.g., Ahmad et al., 2007). The term efficient water use may therefore be thought of as a synonymous with sustainable or rational water use.

3. Water use performance indicators

3.1. Consumptive use and beneficial use

Assuming the concepts above, it is possible to define water use indicators adapted to any process or system involving water, for irrigation or non-irrigation uses, and to ensure measures are put in place to make more efficient use of the water, i.e., aimed at improving performances from the perspective of water resources conservation. These indicators may be useful for water resources planning and management under scarcity. They may be combined with process indicators, including those which relate to the quality of service of water systems. It needs to be emphasized that it is necessary to actually measure water flows at various points in the system so that real values can be attributed to the performance and productivity of each part of the system. For example, most urban water delivery systems suffer large leakage losses (from buried pipes) which remain undetected for years because insufficient measurements are routinely made to allow the location of major leaks to be determined.

The indicators refer to the three water use fractions (Fig. 2) and to the respective beneficial and non-beneficial water use components. These indicators can be characterized in equations such as those show below:

(a) *The consumptive use fraction* (CF), consisting of the fraction of diverted water which is evaporated, transpired or incorporated in the product, or consumed in drinking and food, which is no longer available after the end use:

$$\mathrm{CF} = \frac{E + \mathrm{ET}_{\mathrm{process}} + \mathrm{ET}_{\mathrm{weeds}} + \mathrm{IN}_{\mathrm{food}} + \mathrm{IN}_{\mathrm{product}}}{\mathrm{TWU}} \tag{1}$$

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

The CF beneficial and non-beneficial components are:

$$\mathrm{BCF} = \frac{E_{\mathrm{process}} + \mathrm{ET}_{\mathrm{process}} + \mathrm{IN}_{\mathrm{food}} + \mathrm{IN}_{\mathrm{product}}}{\mathrm{TWU}} \tag{2}$$

and

$$\mathrm{N\text{-}BCF} = \frac{E_{\mathrm{non\text{-}process}} + \mathrm{ET}_{\mathrm{weeds}}}{\mathrm{TWU}} \tag{3}$$

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

$$\mathrm{RF} = \frac{(\mathrm{Seep} + \mathrm{Perc} + \mathrm{Run})_{\mathrm{non\text{-}degraded}} + (\mathrm{Ret\ flow} + \mathrm{Effl})_{\mathrm{treated}}}{\mathrm{TWU}} \tag{4}$$

where the numerator consists of non-consumptive use processes – seepage (Seep), deep percolation (Perc) and runoff (Run) – that did not degrade the water quality, thus allowing further uses, including when the return flows (Ret flow) and effluents (Effl) are treated to avoid degradation of water bodies where effluents are disposed. The RF components are the beneficial and non-beneficial reusable fractions. The beneficial reusable fraction (BRF) is:

$$\mathrm{BRF} = \frac{(\mathrm{LF} + \mathrm{Runoff}_{\mathrm{process}})_{\mathrm{non\text{-}degraded}} + \mathrm{Effl}_{\mathrm{treated}}}{\mathrm{TWU}} \tag{5}$$

which includes water used for salt leaching (LF), runoff necessary to the processes such as tail end runoff in open furrow and border irrigation, or channel filling (though developments in pipe networks and sprinkler and micro irrigation methods can reduce the need for this water use), and controlled effluents (Effl) required by non-agricultural uses, as for many domestic uses. The non-beneficial reusable fraction (N-BRF) is then

$$\mathrm{N\text{-}BRF} = \frac{(\mathrm{Seep} + \mathrm{Perc} + \mathrm{Exc\ Runoff})_{\mathrm{non\text{-}degraded}} + \mathrm{Exc\ Effl}_{\mathrm{treated}}}{\mathrm{TWU}} \tag{6}$$

and refers to excess (Exc) water use in the processes involved such as seepage and leaks from canals and conduits, spills from canals, excess percolation in irrigation uses or excess runoff that is non-degraded, and effluents produced by water wastage when they are captured and treated.

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

$$\mathrm{NRF} = \frac{(\mathrm{Seep} + \mathrm{Perc} + \mathrm{Run})_{\mathrm{degraded}} + (\mathrm{Ret\ flow} + \mathit{Effl})_{\mathrm{non\text{-}treated}}}{\mathrm{TWU}} \tag{7}$$

which refers to the same process as the RF but where the water has lost quality and is not treated or is added to water bodies which are not usable for normal processes. The NRF shall also be divided into a beneficial (BNRF) and a non-beneficial component (N-BNRF):

$$\mathrm{BNRF} = \frac{(\mathrm{LF} + \mathrm{Runoff}_{\mathrm{process}})_{\mathrm{degraded}} + \mathrm{Effl}_{\mathrm{non\text{-}treated}}}{\mathrm{TWU}} \tag{8}$$

and

$$\mathrm{N\text{-}BNRF} = \frac{(\mathrm{Seep} + \mathrm{Perc} + \mathrm{ExcRunoff})_{\mathrm{degraded}} + \mathrm{ExcEff}_{\mathrm{non\text{-}treated}}}{\mathrm{TWU}} \tag{9}$$

In addition to the indicators defined above, it is also worthwhile defining the beneficial and the non-beneficial water use fractions (BWUF and N-BWUF), which are obtained from the various components defined above, respectively through Eqs. (2), (5) and (8) for the first, and (3), (6) and (9) for the second. Examples of application of indicators defined above are described in Section 4.

Illustrations of the main processes of water use for the fractions described above are presented in Tables 1 and 2 for agricultural and non-agricultural uses, respectively.

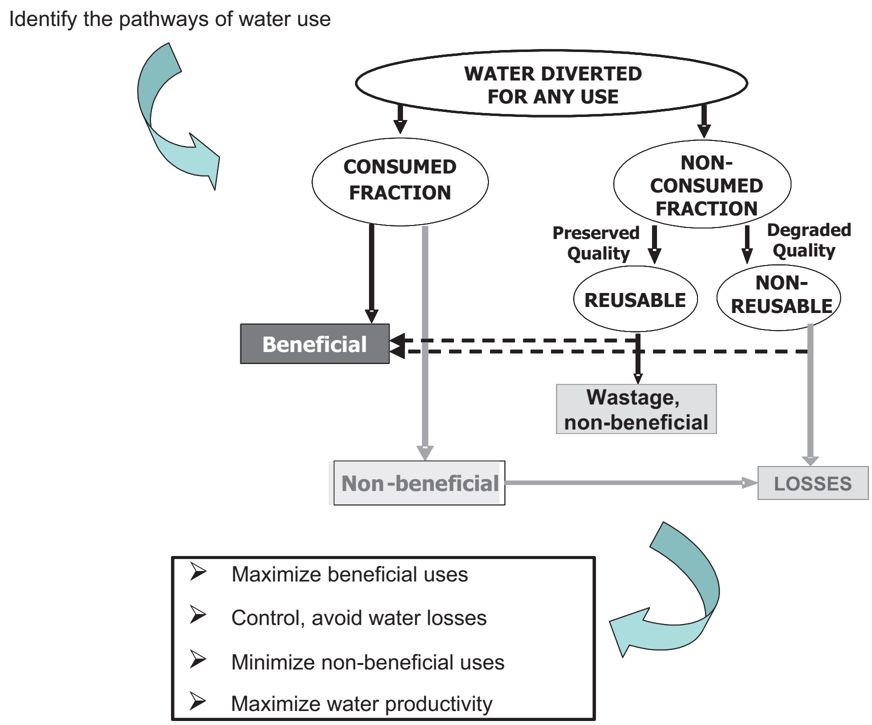

Fig. 5. Pathways of water use identifying main locations or processes influencing the efficient use of water.

Table 1
Beneficial and non-beneficial water use and its relation to consumptive and non-consumptive uses in irrigation.

	Consumptive	Non-consumptive but reusable	Non-consumptive and non-reusable
Beneficial uses	• ET from irrigated crops • Evaporation for climate control • Water incorporated in product	• Leaching water added to reusable water	• Leaching added to saline water
Non-beneficial uses	• Excess soil water evaporation • ET from weeds and phreatophytes • Sprinkler evaporation • Canal and reservoir evaporation	• Deep percolation added to good quality aquifers • Reusable runoff • Reusable canal seepage and spills	• Deep percolation added to saline groundwater • Drainage water added to saline water bodies
	Consumed fraction	Reusable fraction	Non-reusable fraction

Table 2
Beneficial and non-beneficial water use and its relation to consumptive and non-consumptive uses in non-irrigation user sectors.

	Consumptive	Non-consumptive but reusable	Non-consumptive and non-reusable
Beneficial uses	• Human and animal drinking water • Water in food and process drinks • Water incorporated in industrial products • Evaporation for temperature control	• Treated effluents from households and urban uses • Treated effluents from industry • Return flows from power generators • Return flows from temperature control	• Degraded effluents from households and urban uses • Degraded effluents from industry • Degraded effluents from washing and process waters • Every non-degraded effluent added to saline and low quality water bodies
	• ET from vegetation in recreational and leisure areas • Evaporation from recreational lakes	• Non-degraded effluents from washing and industrial processes	
Non-beneficial uses	• ET from non-beneficial vegetation	• Non-degraded deep percolation from recreational and urban areas added to good quality aquifers	• Deep percolation from recreational and urban areas added to saline aquifers
	• Evaporation from water wastes	• Leakage of non-degraded water from urban, industrial and domestic systems added to good quality waters	• Leakage from urban, industrial and domestic systems added to low quality waters and saline water bodies
	• Evaporation from reservoirs		
	Consumed fraction	Reusable fraction	Non-reusable fraction

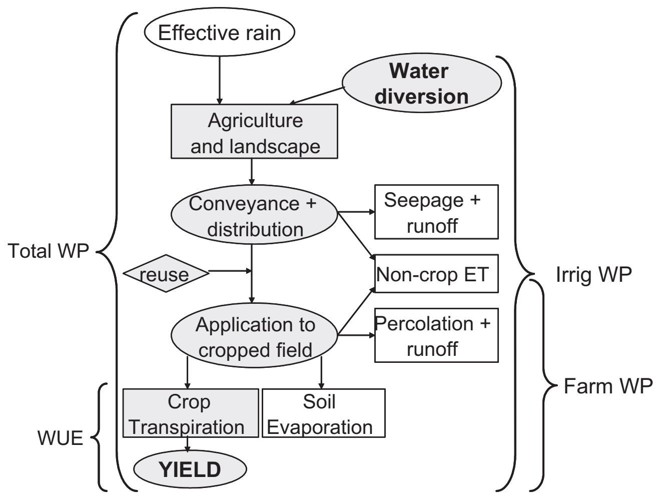

Fig. 6. Water productivity in agriculture at various scales: (a) the plant, through the water use efficiency WUE; (b) the irrigated crop at farm scale (Farm WP); (c) the irrigated crop, at system level (Irrig WP); and the crop including rainfall and irrigation water (Total WP).

3.2. *Water productivity: irrigation water uses*

Nowadays, there is a trend to call for increasing water productivity (WP) as an important issue in irrigation (Molden et al., 2003, 2010; Oweis and Hachum, 2003; Clemmens and Molden, 2007). The attention formerly given to irrigation efficiency is now transferred to water productivity. However, this term is used with different meanings in relation to various scales (Fig. 6) as discussed by Molden et al. (2003, 2010) and, relative to biomass WP, by Steduto et al. (2007). The analysis herein is oriented only to the WP of irrigated crops. WUE was discussed in Section 2.1.

Water productivity in agriculture and landscape irrigation may be generically defined as the ratio between the actual crop yield achieved (Y_a) and the water use, expressed in kg/m^3. For a given landscape, a convenient definition of Y_a has to be selected by observers/users of a particular landscape because irrigating gardens, lawns or golf courses produces qualitative yields. The denominator may refer to the total water use (TWU), including rainfall, or just to the irrigation water use (IWU). This results in two different indicators:

$$\mathrm{WP} = \frac{Y_a}{\mathrm{TWU}} \tag{10}$$

and

$$\mathrm{WP}_{\mathrm{Irrig}} = \frac{Y_a}{\mathrm{IWU}} \tag{11}$$

The meaning of these indicators is necessarily different. The same amount of grain yield depends not only on the amount of irrigation water used but also on the amount of rainfall water that the crop could use, which depends on the rainfall distribution during the crop season. Moreover, we believe pathways to improve crop yields are often not so much related to water management as to agronomic practices and the adaptation of the crop variety to the cropping environment. However, a crop variety with a higher WUE than another variety has the potential for using less water than the second when achieving the same yield. Therefore, discussing how improving WP could lead to water saving in irrigation requires the consideration of various different factors: (a) the contribution of rainfall to satisfy crop water requirements, (b) the management and technologies of irrigation, (c) the agronomic practices, (d) the adaptability of the crop variety to the environment, and (e) the water use efficiency of the crop and variety under consideration.

Eq. (10) may take a different form:

$$\mathrm{WP} = \frac{Y_a}{P + \mathrm{CR} + \Delta\mathrm{SW} + I} \tag{12}$$

where Y_a is the actual harvestable yield (kg), P is the season amount of rainfall, CR is the amount of water obtained from capillary rise, ΔSW is the difference in soil water storage between planting and harvesting, and I is the season total amount of irrigation, all expressed in m^3. When appropriate soil water conservation practices are adopted, the proportion of total P that is available to the crop is increased and soil water storage at planting may also be increased. When irrigation practices are oriented for water conservation, crop roots may be better developed and the amount of water from CR and ΔSW may become higher. The result may then be a lower demand for irrigation water.

The same Eq. (10) may be written in another form:

$$\mathrm{WP} = \frac{Y_a}{\mathrm{ET}_a + \mathrm{LF} + \text{N-BWU}} \tag{13}$$

where Y_a is the actual harvestable yield (kg), $\mathrm{ET_a}$ is the actual season evapotranspiration, LF is the leaching fraction, the water used for leaching when control of soil salinity is required, and N-BWU is the non-beneficial water use, i.e., the water in excess to the beneficial $\mathrm{ET_a}$ and LF water needs. N-BWU consists of percolation through the bottom of the root zone, runoff out of the irrigated fields, and losses by evaporation, and wind drift in sprinkling, as shown in Fig. 3. WP may be increased by minimizing the N-BWU components. The relationship between WP and the potential seasonal irrigation efficiency referring to these N-BWU components is discussed by Rodrigues and Pereira (2009). For sprinkler systems it is also of interest to analyse the energy performance of the irrigation system and crop production (e.g., energy output to input ratio, i.e., crop energy produced per unit of energy used in production, or crop energy produced per unit water used, MJ m^{-3}) in addition to irrigation performance (Rodrigues et al., 2010a).

A higher WP could also be attained through higher yields. Achieving this may require an increase in $\mathrm{ET_a}$ to its optimum level, $\mathrm{ET_c}$. It could be that attaining the maximal value for WP in irrigation requires that yields are maximized, ET and LF are optimized and N-BWU is minimized:

$$\max(\mathrm{WP}) = \frac{Y_{\max}}{\mathrm{ET}_c + \mathrm{LF} + \min(\text{N-BWU})} \tag{14}$$

A high WP may also be obtained when a crop is water stressed, but then the yield is reduced. It is the case for deficit irrigation, where crops are deliberately allowed to sustain some degree of water deficit in such a way that crop production is economically viable. It is also observed that the resulting increases in WP are often small (e.g., Zairi et al., 2003). Under these conditions the economic results of production may not be good, particularly for small farms where perfect management may not be possible or economically feasible. This implies that in addition to WP economic water productivity should also be considered as shown in the analysis by Rodrigues and Pereira (2009) on the economic water productivity of various scenarios of deficit irrigation as influenced by the water price. An interesting review on water value issues was recently presented by Hussain et al. (2007).

3.3. *Economic water productivity: irrigation water use*

The productivity of water needs to be considered not only in physical terms but also in economic terms. The economic value of water is of great importance but so is the economic return that results for the farmer when using water in irrigation. A good discussion on the need to consider the social or public value of water was presented by Perry et al. (1997). An appropriate consideration

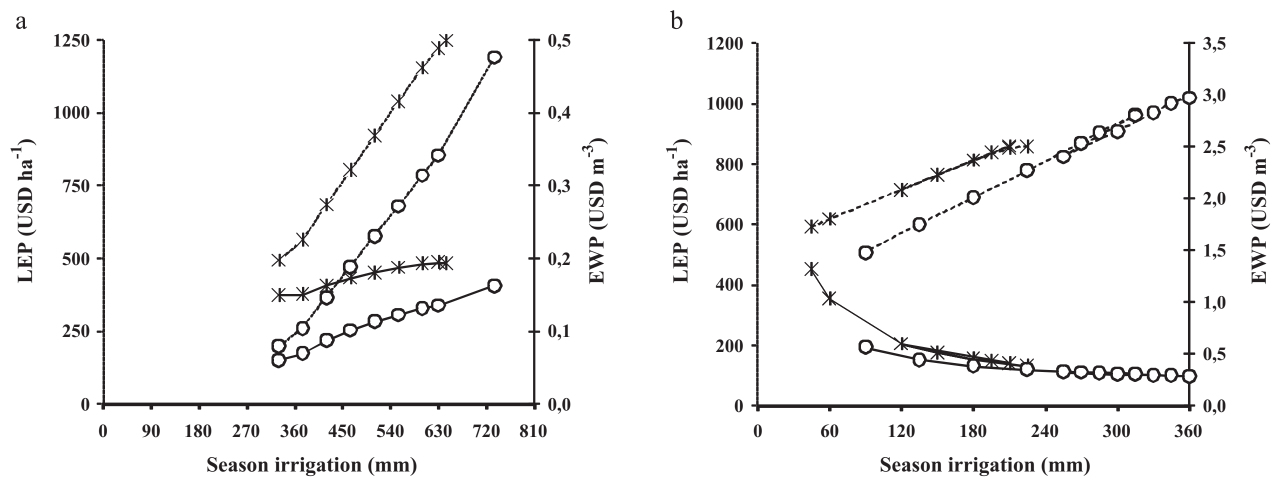

Fig. 7. EWP (—) and LEP (– –) curves relative to various water stress irrigation strategies for maize (a) and wheat (b) under center-pivot irrigation and the average (*) and very high climatic demand (○) in southern Portugal.
Source: Rodrigues et al. (2003).

of the problem is possible when WP is observed under an economic perspective (Barker et al., 2003; Rodrigues and Pereira, 2009).

Replacing the numerator of the equations above by the monetary value (€) of the achieved yield Y_a, the economic water productivity (EWP) is expressed as €/m^3 and can be defined by:

$$\mathrm{EWP} = \frac{\mathrm{Value}(Y_a)}{\mathrm{TWU}} \tag{15}$$

However, the economics of production are less visible in this form. An alternative when focusing at farm level is to use in the numerator the gross margin corresponding to the achieved yield Y_a; then EWP describes the farmer' gross return, particularly when considering deficit irrigation (Rodrigues et al., 2003; Zairi et al., 2003). It is interesting to note the difference in behaviour of both EWP and land economic productivity (LEP) as a function of the consumptive use of the crops, also depending upon the climatic evapotranspiration demand. EWP and LEP curves for maize and wheat relative to various water deficit irrigation strategies are compared in Fig. 7 for the average and very high climatic demand (drought). Both EWP and LEP were obtained from the gross margins of both crops (Rodrigues et al., 2003).

Because maize yields strongly depend upon irrigation water in climates having a dry spring-summer period, both EWP and LEP decrease when the season's irrigation dosage also decreases (Fig. 7a); that decrease is greater when the climatic demand for water is higher under drought conditions. Alternatively for a winter cereal such as wheat (Fig. 7b), where irrigation is supplemental of rainfall, LEP decreases when the season irrigation application dose is lesser but EWP increases when less water is applied. These differences between a full irrigated and a supplemental irrigated crop explain why it is relatively easy to adopt deficit irrigation for winter wheat in contrast with maize.

To understand the economics of water productivity, it may be better to express both the numerator and the denominator in monetary (€) terms, respectively the yield value and the TWU cost, thus yielding the economic water productivity ratio (EWPR):

$$\mathrm{EWPR} = \frac{\mathrm{Value}(Y_a)}{\mathrm{Cost(TWU)}} \tag{16}$$

which shows to be very useful to analyse impacts of water prices on the economic return of irrigation (Rodrigues and Pereira, 2009). Alternatively, considering Eq. (12), we have:

$$\mathrm{EWPR} = \frac{\mathrm{Value}(Y_a)}{\mathrm{Cost(soil\ water\ conservation)} + \mathrm{Cost}(I)} \tag{17}$$

Eq. (17) shows the costs for capturing more rainfall in the soil and encouraging capillary rise, and the costs of irrigation. Improving this ratio implies finding a balance between production and yield costs, as well as appropriate soil and water conservation and irrigation practices. This is not easy to achieve and explains why farmers may retain low irrigation performance and poor conservation practices if related costs for improvement are beyond their economic capacity.

Alternatively, considering Eq. (13), the following ratio is obtained:

$$\mathrm{EWPR} = \frac{\mathrm{Value}(Y_a)}{\mathrm{Costs}(\mathrm{ET_a} + \mathrm{LF} + \mathrm{N\text{-}BWU})} \tag{18}$$

This suggests that the costs for reducing the N-BWU may be the bottleneck in improving water productivity. To reduce N-BWU implies investment in improving the irrigation system and this may be beyond the farmers' capacity, particularly for small farmers. Attention can then be directed to the need for support and incentives for farmers when a society requires they decrease the demand for water and increase the water productivity. In collective and cooperative irrigation systems part of the difficulty results from poor system management and inadequate delivery services, which are often outside the control of the farmers, as mentioned earlier (Section 2.1) for the warabandi water sharing system (Zardari and Cordery, 2009).

Maximizing EWPR, when all costs other than for water use are kept constant, means finding the limit to the ratio between the yield value and the water use costs, which corresponds to maximizing crop revenue in the form:

$$\max(\mathrm{EWPR}) = \max \frac{\mathrm{Value}(Y_{\mathrm{opt}})}{\mathrm{Water\ Costs\ for}\ Y_{\mathrm{opt}}} \approx \max(\mathrm{Income}) \tag{19}$$

This maximal EWPR generally relates to the maximal farm income. The optimal yield, Y_{opt}, is often different from the maximum yield, depending upon the structure of the production costs.

An alternative to EWPR (Eq. (16)) is to compute the ratio yield value to full production costs ($\mathrm{EWPR_{full\text{-}cost}}$). It allows assessing the feasibility of a different irrigation strategy, e.g., a deficit irrigation strategy. An application is given in Section 4.

3.4. Water productivity for any water use sector

The concept of water productivity is also applied in other water user sectors. It must be adapted to the specificities of each sector

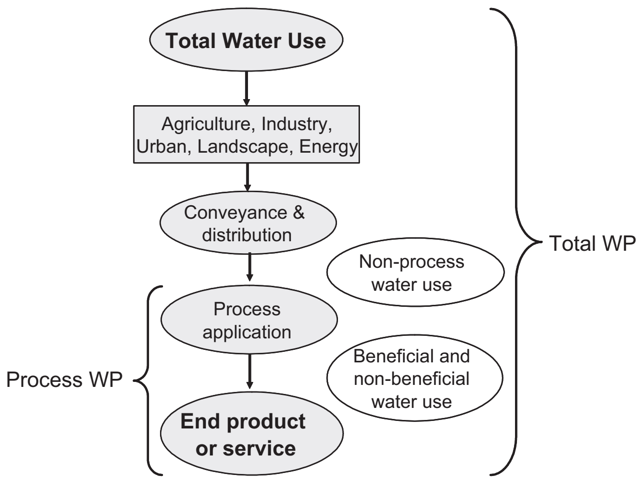

Fig. 8. Water productivity in any user sector considering the full water use (Total WP) and a single process.

and activity. The term 'water productivity' probably needs to be used or defined separately for each production or service process (Fig. 8). Similar to WP being expressed in kg of grain per m^3 of water used in the case of irrigation, it is also possible to express WP in meters of fabric per m^3 of water in the textile industry; kWh produced per m^3 of water in energy generation; m^2 of lawns irrigated per m^3 of water in recreational areas; or m^2 of area washed per m^3 of water in commercial areas, or even as value of sales per m^3.

Extending the water productivity concepts used in agriculture to other user sectors yields:

$$\mathrm{WP} = \frac{\text{End Product or Service}}{\mathrm{TWU}} \tag{20}$$

where the numerator is expressed in units appropriate to the activity under consideration, and the denominator consists of the total water used to yield that product or service.

Eq. (20) may take a different form to distinguish the beneficial and non-beneficial water uses contributing to yield of product or service

$$\mathrm{WP} = \frac{\text{End Product or Service}}{\mathrm{BWU} + \text{N-BWU}} \tag{21}$$

This equation shows that WP may be increased through improved production processes that may require less BWU or when N-BWU (non-process water uses) is minimized. In the industrial applications, BWU is commonly reduced by recycling and reuse for less stringent processes and applications. In urban and domestic uses, BWU may also be decreased when treated wastewater is used for processes not requiring the highest water quality.

Replacing the numerator of equations above by the monetary value (€) of the achieved product or service produces the economic water productivity (EWP) expressed as €/m^3

$$\mathrm{EWP} = \frac{\text{Value(Product or Service)}}{\mathrm{TWU}} \tag{22}$$

and the economic water productivity ratio

$$\mathrm{EWPR} = \frac{\text{Value(Product or Service)}}{\text{Cost(TWU)}} \tag{23}$$

Eq. (23) shows that when this ratio is very large, which is common to most non-agricultural water uses there is no incentive to reduce TWU unless water policies relative to the quality of effluents and respective treatment induce a reduction of the amounts to be treated and, therefore, used. Water scarcity may be a significant reason for reducing TWU, mainly when competition among users is high or the available supply is very limited. Simple monetary cost may not be a possible disincentive since high water cost may cause elimination of processes or services considered essential – for example irrigation water to provide food but also local employment.

Maximizing EWPR is a question of minimizing the costs of water used to yield the desired product or service:

$$\max(\mathrm{EWPR}) = \max \frac{\text{Value(Product or Service)}}{\text{Water Costs}} \tag{24}$$

Differently from agriculture, where water use and related costs (including equipment, labour, and energy) may constitute a large percentage of production costs, water costs in other user sectors are often thought to be a small fraction of the production costs, but often include wastewater treatment and water recycling. Therefore, the rationale behind water productivity for most sectors and activities is very different from that in agriculture. In urban supply systems consumption data are usually available in terms of litres/person/day; considering water saving objectives, there needs to be an operational aim to have these quantities continually falling. In all the above cases, for farms, factories and domestic supply operations there need to be policies and incentives aimed at bringing water consumption to the lowest possible level for each unit of production or activity, i.e., increasing the water productivity in all uses.

Table 3
Assessing deficit irrigation strategies for sprinkler irrigated potato and tomato and respective alternatives in terms of surface allocated to each crop under drought conditions.

Water deficit irrigation strategies	Season net irrigation water available (mm)	Land economic productivity, LEP (USD ha^{-1})	Economic water productivity, EWP (USD m^{-3})	Percent surface allocated to given irrigation strategy as alternative to a more severe water deficit
Potato				
SC	320	3209	0.802	100% SC
LDI	280	3032	0.866	100% LDI
DI	240	2537	0.845	85% LDI
LID	200	2159	0.863	71% LDI
VLID	160	1612	0.806	57% LDI
EID	120	976	0.650	42% LDI
Tomato				
SC	840	4206	0.400	100% SC
LDI	680	3600	0.423	100% LDI
DI	560	2700	0.385	82% LDI
LID	560	2700	0.385	82% LDI
VLID	480	2207	0.367	71% LDI
EID	400	1734	0.346	59% LDI

Source: Zairi et al. (2003).
Note: SC: satisfaction of crop need; LDI: low deficit irrigation; DI: (moderate) deficit irrigation; LID large irrigation deficit; VLDI: very large irrigation deficit; EID: extreme irrigation deficit.

It can be difficult to achieve water savings in industrial and commercial activities unless there are significant incentives because changes in processes usually require capital investment. It is not difficult to justify increasing the price of water for large users, but to make the incentives large enough to ensure changes in behaviour, industries need to be charged for their effluent releases as well as for their intake of water as it currently happens in Europe and elsewhere. Tariffs for disposal can easily be related to the quality of the effluent and made large enough to encourage recycling. Introduction of recycling usually leads to the double benefit of a reduction of pollutants passing to the environment and a reduction in volumes of water taken from the local supply system (Asano, 2005; Tangsubkul et al., 2005; Memon et al., 2007; Radcliffe, 2010).

4. Case study applications

4.1. Selection of deficit irrigation strategies and crop land allocation under drought

Under drought water scarcity, when water is not available to fully satisfy crop irrigation requirements, farmers may have to adopt deficit irrigation and/or reduce the area cropped. To provide the farmer with a sound economic basis for deciding on his strategy an analysis was performed to compute the economic water productivity (EWP) and land economic productivity (LEP) from the crop gross margins obtained from potatoes and tomatoes for various water deficit irrigation strategies (DI). Analysis of both the EWP and LEP for various DIs allows selection of the DI that gives the best performance considering the available amount of water, or alternatively shows how the best result can be obtained by cropping a smaller area and adopting a less stringent DI. A study for potato and tomato was developed for the Siliana area, Tunisia, and main results are shown in Table 3. Description of methods applied and results obtained for other crops, irrigation methods and climatic conditions are given by Zairi et al. (2003) and Rodrigues et al. (2003).

It can be observed in Table 3 that LEP steadily decreases when the season irrigation water decreases while the EWP for this case study has a maximum when a low deficit irrigation (LDI) strategy is applied. The best solutions when less season irrigation water is available are not to apply a larger deficit but to reduce the cropped area and to allocate 100% of LDI to that area to produce the highest EWP.

4.2. Assessing impacts of deficit irrigation, water pricing and irrigation system performance using the economic water productivity ratio

The economic water productivity ratio (EWPR) was used to assess the impact of water price combined with farm irrigation system performance in southern Portugal under average and drought climatic conditions. Both deficit and full irrigation were considered for selected center-pivot maize irrigation farms (Rodrigues et al., 2010b, 2010c). EWPR was computed taking the yield value in the numerator and the irrigation cost (water and application costs) in the denominator as for Eq. (16) (Fig. 9a) or the irrigation production full cost in the denominator (Fig. 9b and c), herein $EWPR_{full\text{-}cost}$.

Adopting EWPR (Eq. (16)) results shows the impact of water prices (Fig. 9a). EWPR falls hugely from present conditions, with subsidized water costs, to foreseen conditions when the European water framework policies are applied to fully cover the operation, maintenance and management (OM&M) costs, or to cover OM&M and investment costs. Results in Fig. 9a also show the impacts

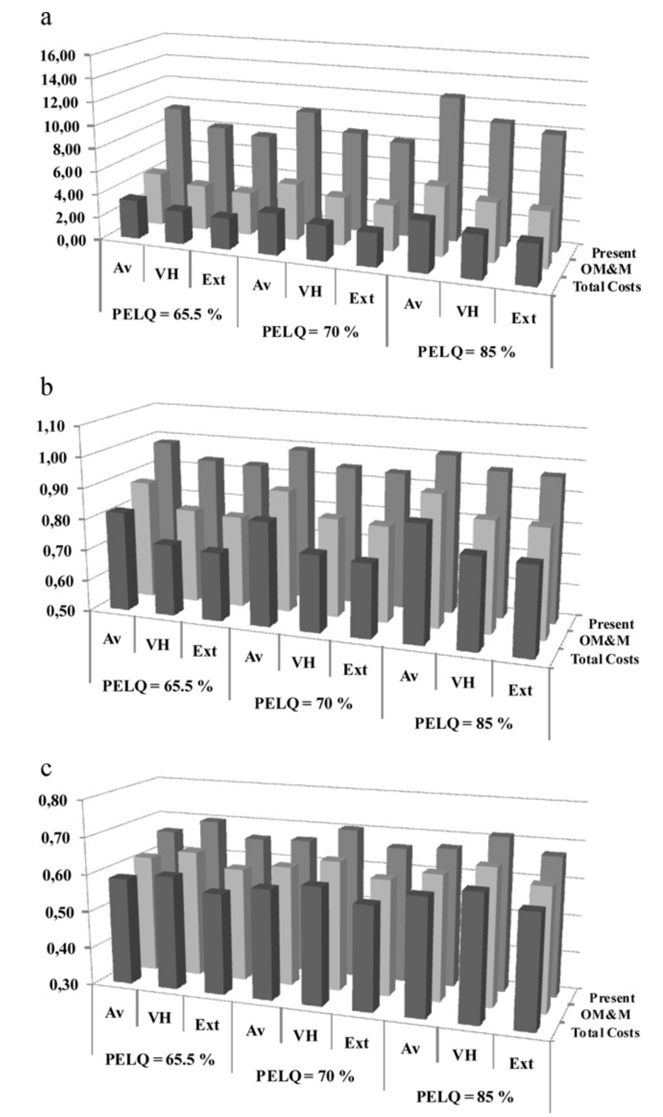

Fig. 9. Economic water productivity ratios applied to a center-pivot maize irrigation farm to assess impacts of water prices (present and covering OM&M or total costs) for various seasonal PELQ and average (Av), very high (VH) and extreme climatic demand (Ext): (a) EWPR for deficit irrigation, (b) $EWPR_{full\text{-}cost}$ for full irrigation, and (c) $EWPR_{full\text{-}cost}$ for deficit irrigation (Vigia, Portugal).
Source: Rodrigues et al. (2010b, 2010c).

of irrigation performance, when the season 'potential low quarter application efficiency' (PELQ), as defined by Pereira (1999), is taken into account. When $EWPR_{full\text{-}cost}$ is considered, the results show that adopting full or deficit (water stress) irrigation (respectively Fig. 9b and c) leads to farm economic losses when OM&M or full water price recovery are practiced. Results also show the influence of climatic demand and operational management (PELQ) on the economic results. Despite the brevity of the summary presented here, this case study shows the potential benefits of using economic water productivity indicators when analysing irrigation management options and the impacts of policies at farm level.

4.3. EWP for assessing impacts of irrigation improvements at farm and system scales

The assessment of impacts of improvements in farm irrigation and in distribution and conveyance systems requires some integrative approach, which may be provided by EWP computed for the water use at farm and system level. A case study of farm and

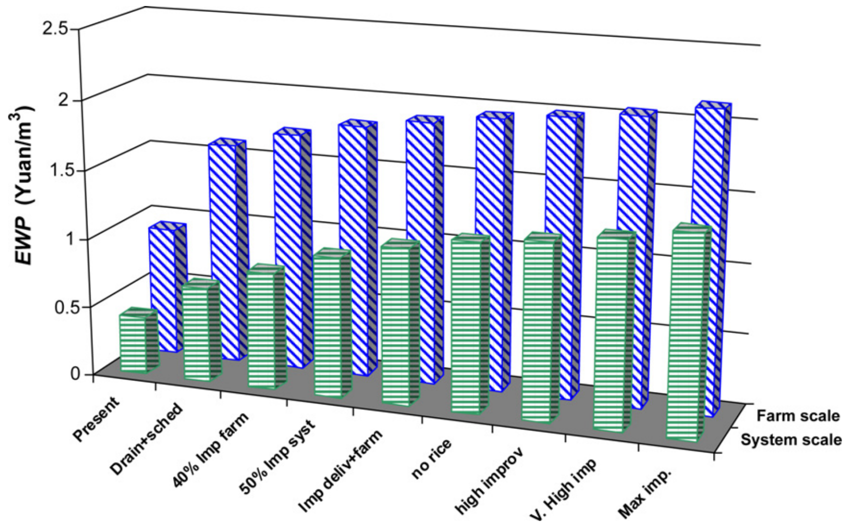

Fig. 10. EWP for various levels of farm and system improvements for water saving in the Huinong system, Yellow River basin, China.
Source: Gonçalves et al. (2007).

system modernization was analysed through a decision support system (DSS) applied to the Huinong canal system in the upper reaches of the Yellow River, China (Gonçalves et al., 2007). Results of this application were analysed using the EWP corresponding to each step of the improvement (Fig. 10).

Fig. 10 shows that improvements in drainage and the delivery system bring the largest improvements overall. Results comparing EWP computed at the farm and system scales show that following those improvements leading to higher water productivity, the EWP increases more at the system scale than at the farm scale, suggesting there are difficulties in involving farmers in a large and long lasting process of modernization when they do not perceive a reasonable and continuous gain at their level.

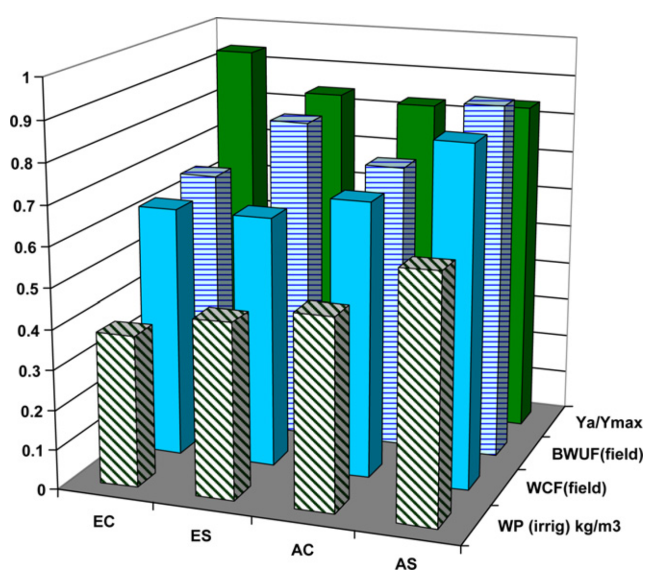

Fig. 11. Comparing water productivity (WP), water consumed fractions (WCF), beneficial water use fractions (BWUF) and relative yields (Y_a/Y_{max}) for furrow irrigated cotton at Fergana, Uzbekistan, for various farm systems. Farm system symbols are: EC – irrigation in every furrow with continuous flow; ES – irrigation in every furrow with surge flow; AC – irrigation in alternate furrows with continuous flow; and AS – irrigation in alternate furrows with surge flow.
Source: Horst et al. (2007).

4.4. *Relating yields and the beneficial water use fraction for various farm furrow irrigation improvements*

Water saving in cotton irrigation in the Aral Basin, Central Asia, is generally considered a must. However it is necessary to assess the economic feasibility of adopting improvements in presently used furrow irrigation systems. Experimental results obtained for Fergana, Uzbekistan, from comparing various techniques – continuous and surge flow, and irrigation in every furrow or in alternate furrows – are summarized in Fig. 11 (Horst et al., 2007).

Results show the potential for water saving when adopting alternate furrow irrigation and surge flow since these systems produce the highest WP, consumed fraction and beneficial water use fraction (BWUF). However, the actual yield is less than the maximum because these practices are difficult to apply by the local farmers, thus causing a decrease in yields. Since the farmers income directly relates to the actual yield and not to WP, the farmers are reluctant to adopt water saving. These results were confirmed in a study on furrow irrigation design applied to the same area using multicriteria analysis. Environmental and economic criteria were shown to be contradictory: when water saving criteria prevail more advanced solutions are selected, but when economic criteria are prevalent then the water saving techniques are rejected (Gonçalves et al., 2011). It is likely that when economic factors change and all farmer subsidies are removed the adopted managerial and technical options may change and real water conservation and saving may occur.

Examples above may be extended to analyse water use and productivity for non-irrigation uses. Similarly, the extension of economic water productivity concepts to industry may show that paying the real value for releasing effluents (which is not exactly the same as the principle that the polluter pays) can have a huge impact on water saving and conservation – but few agencies or governments appear willing to confront this issue, presumably because they fear it may have unexpected effects in the wider economy.

5. Conclusion

There are some difficulties in discussing water productivity and efficiency because there are many terms which are used rather loosely and even synonymously. Opportunities for increases in water productivity and efficient application of water are being missed or hidden by the use of a number of similar, but actually quite different terms. Unfortunately the imprecise use of these terms can prevent managers seeing or understanding some of the issues (such as hidden subsidies) which can influence the best use of water or opportunities for saving of water. In our water deficient world of the 21st century this is unfortunate. A new communication model has been proposed here with emphasis on clearly defining terms, proposing some new terms and better integrating operations to make most effective use of all available water, including providing water for environmental uses. Some of the subtle differences between terms used for management of both irrigation and non-irrigation water uses have been discussed with a plea for more careful and thoughtful use of the terms. For example, instead of discussing "wastes" and "losses", both of which have broad meanings but are seen by some irrigators to only apply to other water users (never their own operations) there is perhaps a need to use "beneficial" and "non-beneficial" uses, with which irrigators and other water users are more likely to identify. Adopting water use fractions relative to consumptive and non-consumptive use of the water, to beneficial and non-beneficial water uses and to reusable and non-reusable non-consumptive uses may encourage better understanding by water users than the flawed and misleading concept of irrigation efficiency. Then it is likely more easy to develop programs that lead to improved and sustainable water uses.

The consideration of economic water productivity indicators shows to be of relevance when analysing improvements in irrigation systems and management at farm and project scales. Case studies are shown to illustrate the use of these economic water productivity indicators in practice. It may be expected that their adoption will provide for a better understanding of water conservation and saving. Similar concepts of water productivity may be adapted to non-irrigation uses, including with consideration of the costs for releasing effluents and for their treatment, which are main issues in water conservation and saving.

It is expected that adoption of a new openness in considering all costs and benefits, and more precise use of terms could lead to much improved communications between disciplines and aid in achieving large improvements in management of scarce resources. Inevitably this could lead to better understanding of water performance and productivity by farmers and the public and by government and water agency decision makers.

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References

Ahmad, M.D., Turral, H., Masih, I., Giordano, M., Masood, Z., 2007. Water saving technologies: Myths and realities revealed in Pakistan's rice-wheat systems. Research Report 108, IWMI, Colombo, Sri Lanka, 44 pp.

Allen, R.G., Willardson, L.S., Frederiksen, H.D., 1997. Water use definitions and their use for assessing the impacts of water conservation. In: de Jager, J.M., Vermes, L.P., Ragab, R. (Eds.), Sustainable Irrigation in Areas of Water Scarcity and Drought (Proc. ICID Workshop, Oxford). British Nat. Com. ICID, Oxford, pp. 72–81.

Asano, T., 2005. Urban water recycling. Water Sci. Technol. 51 (8), 83–89.

Barker, R., Dawe, D., Inocencio, A., 2003. Economics of water productivity in managing water for agriculture. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. IWMI and CABI Publ., Wallingford, pp. 19–35.

Bluemling, B., Yang, H., Pahl-Wostl, C., 2007. Making water productivity operational—a concept of agricultural water productivity exemplified at a wheat–maize cropping pattern in the North China plain. Agric. Water Manage. 91, 11–23.

Bos, M.G., 1979. Standards for irrigation efficiencies of ICID. J. Irrig. Drain. Div. ASCE 105 (IRI), 37–43.

Bos, M.G., 1997. Performance indicators for irrigation and drainage. Irrig. Drain. Syst. 11 (2), 119–137.

Bos, M.G., Nugteren, J., 1982. On Irrigation Efficiencies. Int'l Inst. for Land Reclamation and Improvement, ILRI Publ. 19, Wageningen, 138 pp.

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

Burt, C.M., Styles, S.W., 2000. Irrigation district service in the Western United States. J. Irrig. Drain. Eng. 126 (5), 279–282.

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

Calejo, M.J., Lamaddalena, N., Teixeira, J.L., Pereira, L.S., 2008. Performance analysis of pressurized irrigation systems operating on-demand using flow driven simulation models. Agric. Water Manage. 95 (2), 154–162.

Clemmens, A.J., 2006. Improving irrigated agriculture performance through an understanding of the water delivery process. Irrig. Drain. 55 (3), 223–234.

Clemmens, A.J., Molden, D.J., 2007. Water uses and productivity of irrigation systems. Irrig. Sci. 25, 247–261.

Falkenmark, M., Lannerstad, M., 2005. Consumptive water use to feed humanity – curing a blind spot. Hydrol. Earth Syst. Sci. 9, 15–28.

Foster, S.S.D., Perry, C.J., 2010. Improving groundwater resource accounting in irrigated areas: a prerequisite for promoting sustainable use. Hydrogeol. J. 18, 291–294.

Garduño, H., Arreguín-Cortés, F. (Eds.), 1994. Efficient Water Use. UNESCO Regional Office ROSTLAC, Montevideo, Uruguay.

Gonçalves, J.M., Pereira, L.S., Fang, S.X., Dong, B., 2007. Modelling and multicriteria analysis of water saving scenarios for an irrigation district in the Upper Yellow River Basin. Agric. Water Manage. 94, 93–108.

Gonçalves, J.M., Muga, A.P., Horst, M.G., Pereira, L.S., 2011. Furrow irrigation design with multicriteria analysis. Biosyst. Eng. 109, 266–275.

Haie, N., Keller, A.A., 2008. Effective efficiency as a tool for sustainable water resources management. J. Am. Water Resour. Assoc. 44 (4), 961–968.

Hashimoto, T., Sredomger, J.R., Loucks, D.P., 1982. Reliability, resilience and vulnerability criteria for water resources system performance evaluation. Water Resour. Res. 18 (1), 14–20.

Heermann, D.F., Solomon, K.H., 2007. Efficiency and uniformity. In: Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L. (Eds.), Design and Operation of Farm Irrigation Systems. , 2nd ed. ASABE, St. Joseph, MI, pp. 108–119.

Hsiao, T.C., Steduto, P., Fereres, E., 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. Irrig. Sci. 25, 209–231.

Horst, M.G., Shamutalov, Sh.Sh., Gonçalves, J.M., Pereira, L.S., 2007. Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. Agric. Water Manage. 87, 115–127.

Hussain, I., Turral, H., Molden, D., Ahmad, M., 2007. Measuring and enhancing the value of agricultural water in irrigated river basins. Irrig. Sci. 25, 263–282.

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

Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245.

Katerji, N., Mastrorilli, M., Rana, G., 2008. Water use efficiency of crops cultivated in the Mediterranean region: review and analysis. Eur. J. Agron. 28, 493–507.

Keller, A., Keller, J., Seckler, D., 1996. Integrated Water Resource Systems: Theory and Policy Implications. Research Report 3, International Irrigation Management Institute, Colombo, Sri Lanka, 1996.

Kijne, J.W., Barker, R., Molden, D. (Eds.), 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement. IWMI and CABI Publ., Wallingford.

Knox, J.W., Kay, M.G., Weatherhead, E.K., 2011. Water regulation, crop production and agricultural water management – understanding farmer perspectives on irrigation efficiency. Agric. Water Manage., doi:10.1016/j.agwat.2011.06.007.

Lamaddalena, N., Sagardoy, J.A., 2000. Performance Analysis of On-Demand Pressurized Irrigation Systems. Irrigation and Drainage Paper No. 59, FAO, Roma.

Lamaddalena, N., Pereira, L.S., 2007. Pressure-driven modeling for performance analysis of irrigation systems operating on demand. Agric. Water Manage. 90, 36–44.

Lankford, B., 2006. Localising irrigation efficiency. Irrig. Drain. 55 (4), 345–362.

Lankford, B., Fictions, fractions, factorials, fractures and fractals; on the framing of irrigation efficiency. Agric. Water Manage., in this issue.

Memon, F.A., Zheng, Z., Butler, D., Shirley-Smith, C., Lui, S., Makropoulos, C., Avery, L., 2007. Life cycle impact assessment of greywater recycling technologies for new developments. Environ. Monit. Assess. 129, 27–35.

Merriam, J.L., Styles, S.W., Freeman, B.J., 2007. Flexible irrigation systems: concept, design, and application. J. Irrig. Drain. Eng. 133 (1), 2–11.

Molden, D., 1997. Accounting for water use and productivity. SWIM Paper 1. International Irrigation Management Institute, Colombo, Sri Lanka.

Molden, D.J., Gates, T.K., 1990. Performance measures for evaluation of irrigation–water delivery systems. J. Irrig. Drain. Eng. 116 (6), 804–823.

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

Molden, D., Burton, M., Bos, M.G., 2007. Performance assessment, irrigation service delivery and poverty reduction: benefits of improved system management. Irrig. Drain. 56 (2–3), 307–320.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: between optimism and caution. Agric. Water Manage. 97, 528–535.

Murray-Rust, D.H., Snellen, W., 1993. Irrigation System Performance: Assessment and Diagnosis. International Irrigation Management Institute, Colombo, Sri Lanka, 141 pp.

Ostrom, E., 1992. Crafting Institutions for Self-Governing Irrigation Systems. ICS Press, S. Francisco.
Oweis, T.Y., Hachum, A.Y., 2003. Improving water productivity in the dry areas of West Asia and North Africa. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. IWMI and CABI Publ., Wallingford, pp. 179–198.
Oweis, T., Hachum, A., 2006. Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agric. Water Manage. 80, 57–73.
Pereira, L.S., 1999. Higher performances through combined improvements in irrigation methods and scheduling: a discussion. Agric. Water Manage. 40, 153–169.
Pereira, L.S., Oweis, T., Zairi, A., 2002. Irrigation management under water scarcity. Agric. Water Manage. 57, 175–206.
Pereira, L.S., Calejo, M.J., Lamaddalena, N., Douieb, A., Bounoua, R., 2003. Design and performance analysis of low pressure irrigation distribution systems. Irrig. Drain. Syst. 17, 305–324.
Pereira, L.S., Cordery, I., Iacovides, I., 2009. Coping with Water Scarcity. Addressing the Challenges. Springer, Dordrecht, 382 pp.
Perry, C.J., 1999. The IWMI water resources paradigm – definitions and implications. Agric. Water Manage. 40, 45–50.
Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrig. Drain. 56, 357–378.
Perry, C.J., Rock, M., Seckler, D., 1997. Water as an economic good: a solution, or a problem? Research Report 14. International Irrigation Management Institute, Colombo, Sri Lanka, 16 pp.
Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. Agric. Water Manage. 96 (11), 1517–1524.
Radcliffe, J.C., 2010. Evolution of water recycling in Australian cities since 2003. Water Sci. Technol. 62 (4), 792–802.
Rodrigues, G.C., Pereira, L.S., 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. Biosyst. Eng. 103, 536–551.
Rodrigues, G.C., Carvalho, S., Paredes, P., Silva, F.G., Pereira, L.S., 2010a. Relating energy performance and water productivity of sprinkler irrigated maize, wheat and sunflower under limited water availability. Biosyst. Eng. 106, 195–204.
Rodrigues, G.C., Silva, F.G., Pereira, L.S., 2010b. Análise económica e da produtividade da água em rega em condições de seca: aplicção às culturas de milho e trigo no regadio da Vigia. In: Pereira, L.S., Mexia, J.T., Pires, C.A.L. (Eds.), Gestão do Risco em Secas. Métodos, tecnologias e desafios. Edições Colibri e CEER, Lisboa, pp. 321–344.
Rodrigues, G.C., Silva, F.G., Pereira, L.S., 2010c. Assessing the feasibility of deficit irrigation under drought conditions. In: López-Francos, A. (Ed.), Options Méditerranéennes Séries A 95, pp. 285–291.
Rodrigues, P.N., Machado, T., Pereira, L.S., Teixeira, J.L., El Amami, H., Zairi, A., 2003. Feasibility of deficit irrigation with center-pivot to cope with limited water supplies in Alentejo, Portugal. In: Rossi, G., Cancelliere, A., Pereira, L.S., Oweis, T., Shatanawi, M., Zairi, A. (Eds.), Tools for Drought Mitigation in Mediterranean Regions. Kluwer, Dordrecht, pp. 203–222.
Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., Qiang, Z., 2010. Managing water in rainfed agriculture—the need for a paradigm shift. Agric. Water Manage. 97 (4), 543–550.
Seckler, D., 1996. The new era of water resources management. Research Report 1. International Irrigation Management Institute (IIMI). Colombo, Sri Lanka, 17 pp.
Seckler, D., Molden, D., Sakthivadivel, R., 2003. The concept of efficiency in water resources management and policy. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. IWMI and CABI Publ., Wallingford, pp. 37–51.
Shideed, K., Oweis, T.Y., Gabr, M., Osman, M., 2005. Assessing On-Farm Water-Use Efficiency: A New Approach. ICARDA, Aleppo, 86 pp.
Shivakoti, G.P., Vermillion, D.L., Lam, W.-F., Ostrom, E., Pradhan, U., Yoder, R. (Eds.), 2005. Asian Irrigation in Transition. Responding to Challenges. IWMI and AIT, Sage Publications, India, New Delhi, 528 pp.
Solomon, K.H., Burt, C.M., 1999. Irrigation sagacity: a measure of prudent water use. Irrig. Sci. 18, 135–140.
Steduto, P., 1996. Water use efficiency. In: Pereira, L.S., Feddes, R., Gilley, J.R., Lesaffre, B. (Eds.), Sustainability of Irrigated Agriculture. Kluwer, Dordrecht, pp. 193–209.
Steduto, P., Hsiao, T.C., Fereres, E., 2007. On the conservative behavior of biomass water productivity. Irrig. Sci. 25, 189–207.
Tangsubkul, N., Beavis, P., Moore, S.J., Lundie, S., Waite, T.D., 2005. Life cycle assessment of water recycling technology. Water Res. Manage. 19, 521–537.
Unger, P.W., Howell, T.A., 1999. Agricultural water conservation – a global perspective. In: Kirkham, M.B. (Ed.), Water Use in Crop Production. The Haworth Press, New York, pp. 1–36.
Willardson, L.S., Allen, R.G., Frederiksen, H.D., 1994. Universal fractions and the elimination of irrigation efficiencies. In: Proceedings 13th Technical Conference, US Commission on Irrigation and Drainage, Denver, CO, 19–22 October 1994.
Wolters, W., 1992. Influences on the Efficiency of Irrigation Water Use. ILRI Publ. 51, Wageningen.
Zaccaria, D., Oueslati, I., ·Neale, C.M.U., Lamaddalena, N., Vurro, M., Pereira, L.S., 2010. Flexible delivery schedules to improve farm irrigation and reduce pressure on groundwater: a case study in southern Italy. Irrig. Sci. 28, 257–270.
Zairi, A., El Amami, H., Slatni, A., Pereira, L.S., Rodrigues, P.N., Machado, T., 2003. Coping with drought: deficit irrigation strategies for cereals and field horticultural crops in Central Tunisia. In: Rossi, G., Cancelliere, A., Pereira, L.S., Oweis, T., Shatanawi, M., Zairi, A. (Eds.), Tools for Drought Mitigation in Mediterranean Regions. Kluwer, Dordrecht, pp. 181–201.
Zardari, N.u.H., Cordery, I., 2009. Water productivity in a rigid irrigation delivery system. Water Resour. Manage. 23, 1025–1040.