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A systematic and quantitative approach to improve water use efficiency in agriculture

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Abstract As the competition for the finite water resources on earth increases due to growth in population and affluence, agriculture is faced with intensifying pressure to improve the efficiency of water used for food production. The causes for the relatively low water use efficiency in agriculture are numerous and complex, including environmental, biological, engineering, management, social, and economic facets. The complexity of the problem, with its myriads of local variations, requires a comprehensive conceptual framework of the underlying physical and biological processes as the basis to analyze the existing situation and quantify the efficiencies, and to plan and execute improvements. This paper proposes such a framework, based on the simple fact that the overall efficiency of any process consisting of a chain of sequential step is the product of the efficiency (i.e., output/input ratio) of its individual component steps. In most cases of water use, a number of process chains, both branching and merging, are involved. Means to integrate the diverging and converging chains are developed and presented as equations. Upscaling from fields to regions and beyond are discussed. This chain of efficiencies approach is general and can be applied to any process composed of chains of sequential steps. Here the framework is used to analyze the systems of irrigated and dryland crop production, and animal production on rangeland. Range of plausible efficiencies of each step is presented as tables, with values separately for the poor and for the good situation of circumstances, management and technology. Causes of the differences in efficiency of each step, going from water delivery to soil water extraction, transpiration, photosynthesis, and conversion to crop biomass and yield, and to animal product are briefly discussed. Sample calculations are made to demonstrate how modest differences in the efficiencies of the component steps are manifested as large to huge differences in the overall efficiency. Based on an equation quantifying the impact of changes in efficiency of component steps on the overall efficiency, it is concluded that generally, it is more effective to made modest improvements in several or more steps than to concentrate efforts to improve one or two steps. Hence, improvement efforts should be systematic and not overly concentrated on one or two components. The potential use of the same equation as the point of departure to optimize the allocation of economic resource among the component steps to maximize the improvement in the overall water use efficiency is elaborated on. The chain of efficiencies framework provides the means to examine the current levels of efficiency along the pathways of agricultural water use, to analyze where inefficiencies lie by comparing with the range of known efficiency values in the tables presented, to assess the potential improvements that may be achieved in various parts and their impact on the overall efficiency, and to aid in the optimal allocation of resources for improvements.

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Introduction

The relentless growth of human population, coupled with the intensifying desire for higher living standard, including the continuous shifting to diets based more and more on meat and dairy products, are straining the water resources all over the world, especially in the more arid regions. Adding to the strain is the increased awareness of the need for water in the preservation of the environment and ecosystems (Falkenmark 2000). Since the fresh water resources are essentially finite on earth, and the development of additional supplies for human use is increasingly limited by economic and ecological reasons, making more efficient use of the water must be a major focus in coping with the growing water scarcity (Gleick 2003). This objective will be particularly relevant in food production systems for two reasons. One is that agricultural water use represents the lion's share of the water diverted by man for various uses worldwide (Seckler et al. 1998). The other is the intensifying competition for water with other sectors of our society, and the general perception that agricultural water use is often wasteful (Postel 2000) and has less value than other uses and should be reduced, even in the face of future increases in food demand (Jury and Vaux 2005). One issue that adds uncertainty to the future water supply for agriculture is that of climate change. Although assessing the impacts of global warming trend on crop production and water use is by no means an exact science, if the predictions of increased climatic variability materialize, the increased frequency and severity of droughts would decrease the reliability of irrigation water supply even beyond the uncertainties that are common today.

Past assessments of the efficiency of agricultural water use (e.g., Wallace 2000) have shown that for rain-fed crops, the fraction of rainfall used for crop transpiration is comparatively low, from 15 to 30%, and sometimes as low as 5% (Rockstrom and Falkenmark 2000). Similarly, low values have been proposed by Wallace and Gregory (2002) for irrigated agriculture (13–18% of irrigation water delivered). The production of crops and animals with water as a key input involves complicated processes with myriad of facets that are subjected to the impact of management decisions, institutional and cultural factors, and environmental influence. The challenge to improve the low efficiency is daunting, given the wide diversity of causes underlying water loss throughout the systems of water use and management evolved by man. Numerous ways have been devised or advocated, and much attention has been paid recently to improving the efficiency of water use in agriculture (Howell 2001; Kijne 2003). Nonetheless, progress has been slow due to a number of problems. One is that water supply and use for agricultural production span a range of disciplines, from hydrology, engineering and soil science, to ecophysiology, plant sciences and animal sciences. With the tendency of each discipline to focus on its own specialty, the approach is often fragmented and lacking in comprehensiveness. Another problem is the lack of a definitive means to relate the efficiency of the various parts of the water productivity system to the overall efficiency of the whole, especially when going from scales of farm fields to watersheds and regions. Complicating this scaling up process is the fact that apart from the water used consumptively, the same water may be used several times within the same watershed or river basin through the recycling of drainage or runoff water, or even the use of polluted wastewater. Still another problem is that determining the different components of the water balance represents a challenge in any agricultural system, but is a prerequisite for performance assessment prior to proposing improvements. Finally and importantly, most of the time there is insufficient practical incentive for farmers to improve their water use efficiency; either the cost of the water is kept artificially low by governmental subsidy, or the farmer has little motivation to conserve water given the common perception that the water he saves will go to other users without any benefit to him.

Although not the solution to all the problems described, a systematic approach to quantify and integrate the efficiency of water use of the various parts of the complex agricultural production process while also allowing the scaling up to the different scale levels is badly needed. It would provide the conceptual framework to examine the current levels of efficiency along the pathways of agricultural water use, to analyze where inefficiencies lie, and to assess the potential improvements that may be achieved in various parts and their impact on the overall efficiency. Most importantly, being quantitative, it should also provide the means to determine how to allocate limited resources available to maximize water productivity. This paper describes a relatively simple and yet comprehensive framework for all these purposes.

Concept of chain of efficiency steps and its significance

Generally and as commonly used in economics, efficiency (E) of any production process may be defined as the ratio of output to input for that process, both measured in quantitative units. That is

$$E = \frac{\text{Output}}{\text{Input}}. \tag{1}$$

The units to use vary depending on the nature of the output and input. If the same units define both, then the efficiency ratio is unitless. If the measure of input and output is expressed in different units, then the units for the efficiency must be given for the efficiency to be meaningful.

When the production of a product is complicated and the starting resource input goes through many processing steps sequentially ending in the product, a simple approach is available to quantify the overall efficiency of the whole process in terms of the efficiency of each of the component steps. Because the processing steps are in sequence and come one after another, the output of any step in the chain except the last one is the input of the following step, and the input of any step is the output of the preceding step. So generally

$$\text{Output}_i = \text{Input}_{i+1}, \text{ and } \text{Input}_i = \text{Output}_{i-1} \tag{2}$$

where the subscript i, a running number, designates the steps, step 1, 2, 3, etc.

As the consequence of the relationship expressed by Eq. (2), the overall efficiency for the whole sequence of steps (E_{all}) can be written in terms of the efficiency of individual steps

$$E_{\text{all}} = E_1 \times E_2 \times E_3 \cdot \cdots = \prod_i E_i \tag{3}$$

where Π is the multiplication operator (of all the i designated items). To see more easily why Eq. (3) holds, we will consider a simple example—an efficiency chain consisting of three steps

$$E_1 = \frac{\text{Output}_1}{\text{Input}_1}$$
$$E_2 = \frac{\text{Output}_2}{\text{Input}_2} = \frac{\text{Output}_2}{\text{Output}_1}$$
$$E_3 = \frac{\text{Output}_3}{\text{Input}_3} = \frac{\text{Output}_3}{\text{Output}_2}$$

and for the whole chain,

$$E_{\text{all}} = \frac{\text{Output}_3}{\text{Input}_1}.$$

As long as the steps are sequential, the output of the preceding step is the input of the following step. This gives rise, inevitably, to the following relationship between the efficiency of individual steps and the overall efficiency

$$E_{\text{all}} = \frac{\text{Output}_1}{\text{Input}_1} \times \frac{\text{Output}_2}{\text{Output}_1} \times \frac{\text{Output}_3}{\text{Output}_2} = \frac{\text{Output}_3}{\text{Input}_1}. \tag{4}$$

It is easily seen from Eq. (4) that the numerator of the first ratio or fraction cancels out the denominator of the second ratio, and the numerator of the second ratio cancels out the denominator of the third ratio, leaving only the ratio of the last output (output_3) to the first input, (input_1), which is E_{all}. So, the overall efficiency is the product of the individual efficiency steps as long as the steps for the whole process are sequential or in series. This simple mathematical outcome (Eq. 3) holds true regardless of the number of individual steps in the whole process.

When analyzing a production process, it is important not only to know the efficiencies of the different component steps, but also to know how improvements in the efficiency of the steps affect the overall efficiency. It turned out that by expressing the improvement as a fraction of the original efficiency, a simple equation to calculate the new overall efficiency is obtained. Denoting the fractional improvement by Δ, an expression for the improved efficiency of a step ($E_{i,\text{ new}}$) is

$$E_{i,\text{new}} = (1 + \Delta_i)\, E_{i,\text{original}}. \tag{5}$$

Applying Eq. (5) to all the steps in an efficiency chain and designating each step by the running number i, a general expression of the new overall efficiency ($E_{\text{all, new}}$) in terms of Δ_i and the original overall efficiency ($E_{\text{all, original}}$) is as follows:

$$E_{\text{all,new}} = E_{\text{all,original}} \times \prod_i (1 + \Delta_i). \tag{6}$$

Expressed in words, one plus the fractional improvement for each step, when multiplied together, and multiplied again by the original overall efficiency, is the new overall efficiency. Equation (6) is general, and can be applied to any sequential efficiency chain regardless of its nature. It also applies to cases where there is a reduction in efficiency of some or all the steps, simply by denoting the fractional change in efficiency (Δ_i) as negative.

There are some important features to note regarding Eqs. (3) and (6): (1) as long as the efficiency steps are sequential, the equations apply, regardless of the nature of the process, whether natural or man-made; (2) the treatment is quantitative, and by simple mathematics, demonstrates the fact that the overall efficiency is the product of the efficiencies of individual steps (and not the average of the efficiencies); (3) as made explicit by Eq. (3), the whole process can be divided into fine or coarse efficiency steps according to conditions and needs. That is, one can combine the sequential steps in any segment of the chain together as an integrated step by taking the ratio of the output of the last step in the segment to the input of the first step in the segment. Conversely, a given step can be divided into still finer steps as long as the latter are sequential; (4) even though the efficiency of each step may be high, the overall efficiency is considerably or much lower because of the multiplicative effect of individual efficiencies; (5) by the same token, the same multiplicative effect makes it possible to improve the overall efficiency substantially by making minor improvement in several of the individual efficiencies; (6) the impact of a change in the efficiency of one step on the overall efficiency is strictly according to the proportional change in the efficiency of that step (Δ_i in Eq. 6) regardless of where the step is located in the efficiency chain or how efficient the step is originally. Some of these features may not be intuitively obvious until a few examples are given, as will be done in the sections to follow, starting with applying the concept of chain of efficiency steps to irrigated crop production.

Irrigated cropping and potential for improvements

The efficiency chain

The chain of efficiency steps approach, though not so called, is sometimes used in the literature to evaluate the delivery of water from a reservoir (e.g., Howell 2003) or other sources to the soil of the root zone of the crop. This covers the civil and irrigation engineering aspects but not the agronomic and crop aspects. On the other hand, Monteith (1972) used a very similar approach to analyze crop productivity in terms of the capture and use of solar radiation. The concept was also outlined for crop production in terms of the use of soil water (Azam-Ali and Squire 2002). In this paper, the concept is extended all the way from water diversion from the reservoir to crop yield, and to range animal production. Water, the input, is first conveyed from the reservoir outlet to the farm gate, and this constitutes the first efficiency step in the whole process. The efficiency of this step may be termed conveyance efficiency (E_{conv}) and is calculated as the ratio of the quantity of water (W) diverted out of the reservoir (W_{vo}) for that farm, to the quantity of water received at the farm gate (W_{fg}). The water loss along the way is by leakage and also commonly by evaporation. The efficiency of this step depends on the state of the delivery network, and its engineering and management practices, and can vary from very low to very high.

After the water arrives at the farm, it is temporarily stored or not stored depending on the farmer, and then is distributed to the fields for irrigation. For simplicity, we will combine the storage and on farm conveyance to the field into one step and call its efficiency farm efficiency (E_{farm}). The output is water at the field edge (W_{fd}) and the input is water at the farm gate (W_{fg}). Once the water is at the field edge, it is applied as irrigation to the crop in the field. The crop can only use the water retained in its root zone (W_{rz}), water that runs off the surface of the field or drains below the root zone represents losses. This step is well known in irrigation engineering and its efficiency is designated as application efficiency (E_{appl}). The output is W_{rz}, and the input W_{fd}. To arrive at crop yield, five more steps are needed. The first of these (fourth step of the chain) is consumptive efficiency ($E_{\mathrm{et}} = W_{\mathrm{et}}/W_{\mathrm{rz}}$), a measure of the proportion of water in the root zone removed by evapotranspiration (W_{et}). The loss of efficiency in this step is due to water left in the soil at harvest time. The next step is transpiration efficiency ($E_{\mathrm{tr}} = W_{\mathrm{tr}}/W_{\mathrm{et}}$), a measure of the proportion of water taken up by the crop and transpired (W_{tr}), as distinguished from water evaporated from the soil. The next step is assimilation efficiency ($E_{\mathrm{as}} = m_{\mathrm{as}}/W_{\mathrm{tr}}$), a measure of the mass of carbon dioxide assimilated by photosynthesis (m_{as}) relative to the volume of water transpired. The measurements here now are in terms of the mass of assimilated carbon dioxide as well as the volume of water. The next step is biomass conversion efficiency (E_{bm}), a measure of the plant biomass produced (m_{bm}) relative to the mass of carbon dioxide assimilated. This efficiency is primarily determined by the chemical composition of the crop and is not easily changed, except for possible changes of respiration as affected by thermal regimes. The last step is yield efficiency (E_{yld}), a measure of the proportion of plant biomass that ends up in the harvested yield (m_{yld}), and is equivalent to harvest index (HI), a well-known parameter in the crop and agronomic literature.

Applying Eq. (3) to link all the efficiency steps described, the whole efficiency chain and the overall efficiency are

$$\frac{W_{\mathrm{fg}}}{W_{\mathrm{vo}}} \times \frac{W_{\mathrm{fd}}}{W_{\mathrm{fg}}} \times \frac{W_{\mathrm{rz}}}{W_{\mathrm{fd}}} \times \frac{W_{\mathrm{et}}}{W_{\mathrm{rz}}} \times \frac{W_{\mathrm{tr}}}{W_{\mathrm{et}}} \times \frac{m_{\mathrm{as}}}{W_{tr}} \times \frac{m_{\mathrm{bm}}}{m_{\mathrm{as}}} \times \frac{m_{\mathrm{yld}}}{m_{\mathrm{bm}}} = \frac{m_{\mathrm{yld}}}{W_{\mathrm{vo}}} = E_{\mathrm{all}}. \quad (7)$$

Again, because the output of the preceding step is the input of the following step, all the terms on the left side of Eq. (7) cancel out except for the denominator of the first and numerator of the last efficiency.

Note that the efficiency steps do not have to be all in the same units and can involve quantities of different nature. In this case the first five steps are all concerned with quantity of water (W), and the last two steps are concerned with mass of materials of different nature.

For each of the efficiency steps of Eq. (7), the efficiency ratio can vary widely depending on the circumstances and practices. The plausible range of efficiency is given for each of the steps in Table 1, separately for situations of poor conditions and practices, and for situations of good conditions and practices. Undoubtedly, the ranges could be widened by including more extreme examples, especially for the poor category. Nonetheless, overall the ranges are consistent with the literature, general understanding, and the authors' own experience, and should reflect reality. Due to space limitation, it is not possible to provide the details on how the rang of efficiency values for the steps were arrived at and all the relevant references, but a number of the references are given later when the efficiency of each step is discussed. Table 1 also gives the overall efficiency (E_{all}) for the poor and good situations, calculated according to Eq. (7) from the mid-value (average of the two limits of the range) of each step efficiency. The numerator and denominator of the efficiency ratio for each step are also given in the table, as well as the efficiency units.

For the purpose of this paper, carbon dioxide assimilated, biomass and yield produced are given in kilograms and the amount of water given in cubic meter (=1,000 kg) in Table 1. Hence, the efficiency of all but two of the efficiency steps are unitless in Eq. (7). The exceptions are assimilation efficiency (E_{as}) and overall efficiency, which are in units of kilogram (of carbon dioxide or plant dry matter) per cubic meter (of water). This is equivalent to 10 kg (carbon dioxide or dry matter) ha^{-1} mm (water)$^{-1}$.

In the effort to present a unified approach, we chose to use the term ''efficiency'' to denote the ratio of output to input (Eq. 1). This grosses over certain complexities in the agricultural production systems, in that a lower output to input ratio automatically indicates lower efficiency, which may not be true in some cases in a strict sense. For example, oil and legume crops have low E_{bm} values (Steduto et al. 2007). That is dictated by the chemical composition of their final products (which require more assimilates to make), and is not a reflection of poor efficiency of utilization of the photosynthetic assimilates. A much better way to compare E_{bm} among species with very different chemical compositions of final product is to express biomass in glucose equivalent. Unfortunately, that is not practical presently because almost all the literature data are in terms of mass of dry matter or fresh material. Similarly, E_{yld} is also lower for oil and legume grain crops because the yield products with their different chemical composition compared to that of the crop residue require more assimilates to make. This tends to place these crops in the ''poor'' category of Table 1. Generally then, the ''efficiency'' term as used here should be viewed keeping such possible complexity in mind. A more accurate term would be ''output/input ratio'', but it is too cumbersome for convenient use.

Table 1 Range of efficiencies of the steps in the efficiency chain from water diverted out of the reservoir to yield of annual grain (or fruit) crops, for poor and good situations, and the overall efficiency for the two situations, calculated from mid-values of the individual efficiency steps

Efficiency step	Efficiency ratio	Unit	Efficiency	
			Poor circumstances and practices	Good circumstances and practices
E_{conv}	W_{fg}/W_{vo}	Unitless	0.5–0.7	0.8–0.96
E_{farm}	W_{fd}/W_{fg}	Unitless	0.4–0.6	0.75–0.95
E_{appl}	W_{rz}/W_{fd}	Unitless	0.3–0.5	0.7–0.95
E_{et}	W_{et}/W_{rz}	Unitless	0.85–0.92	0.97–0.99
E_{tr}	W_{tr}/W_{et}	Unitless	0.25–0.5	0.7–0.92
E_{as}	m_{as}/W_{tr}	$kg_{CO_2}\ m_{water}^{-3}$	6.0–8.0	9–14
E_{bm}	m_{bm}/m_{as}	$kg_{biomass}\ kg_{CO_2}^{-1}$	0.22–0.36	0.4–0.5
E_{yld}*	m_{yld}/m_{bm}	Unitless	0.24–0.36	0.44–0.52
E_{all}	m_{yld}/W_{vo}	Kg m^{-3}	0.0243	1.22

See text for the basis of the ranges of efficiency values. Symbols and abbreviations are defined in Appendix

* For main cereal grain crops; for other crops it may vary between 0.1 and 1.0, with forage crops being the latter

Factors affecting the efficiency of the steps and potential for improvement

Most of the more important factors that impact the various efficiency steps are now discussed, along with potential improvements that can be made.

Conveyance efficiency and farm efficiency

Starting with the first step of the chain of efficiencies, a poor E_{conv} implies leaky conduits or substantial evaporation of the water en route. Evaporative loss is normally a minor portion even for open conveyance and storage, unless there is a long time lag before the water arrives at the farm. For example, a very long and slow conveyance in a shallow and broad stream will lead to high evaporative losses under warm weather. Evaporative loss can also be indirect, through transpiration by riparian vegetation adjacent to unlined canal or stream. Improvements in E_{conv} could be very costly (e.g., converting open channel to closed conduits) or at least more than nominal (e.g., repairing cracks and sprung joints widely spread along the conduit length). The state of many networks around the world is such, that many programs of modernization in irrigation are focused on reducing losses at this step (Playán and Mateos 2005).

The next step efficiency E_{farm}, is more amenable to improvement. A common cause for low E_{farm} is water leakage from conveyance ditches and from unlined or poorly lined on-farm reservoirs, where they exist. Lining with plastic sheeting could be relatively inexpensive, as would be dispersing clay in ponds to reduce leakage, and could raise E_{farm} from poor to the good level in Table 1. The longer lasting solution, requiring substantial capital, would be to line the storage reservoir and ditches with concrete, or use closed pipes in place of ditches. Another improvement requiring capital investment is to deepen on-farm reservoirs to minimize the evaporative water surface. Although the efficiency expressions for conveyance and storage do not explicitly differentiate between leakage and evaporation loss, it is important to do so if the leaked water can be recovered for use. This will be discussed in a subsequent section.

Application efficiency

After the arrival of the water at the edge of the field, the next efficiency step is application efficiency. E_{appl} is closely linked to uniformity of water distribution by the chosen water application system. For surface irrigation, if the rate of application is not correctly matched to the infiltration rate of the soil and slope of the land, water would be unevenly distributed from the head to the tail of the field and E_{appl} would be low. An extreme poor situation may be represented by furrow irrigation on a coarse sand (extremely high infiltration rate) in a field of very little slope such as on some newly developed desert lands in north Africa. When surface irrigation is practiced well under the right conditions, however, E_{appl} would fall in the good situation range, and can be as high as 0.8 (Howell 2003). Level basin surface irrigation with very high flow rates, as designed and practiced in Arizona, USA, and elsewhere, achieves E_{app} values higher than 0.8 (Erie and Dedrick 1979). Nevertheless, there is a fundamental difference between surface and pressurized irrigation methods, in that for the former, the soil with its inherent spatial variability determines partly the uniformity of water distribution, while for the latter the system itself determines the uniformity.

Sprinkler irrigation generally provides more uniform water distribution than surface application methods, but can also result in poor E_{appl} under some conditions even when the nozzles are correctly sized and spaced on paper. Common poor situations include inadequate line pressure, especially in developing countries, and sprinkling under windy conditions (Playán et al. 2005). When properly carried out under good conditions, sprinkler irrigation can achieve very high distribution uniformity, and application efficiency can be 0.9 or higher (Howell 2003). Trickle irrigation has the potential to achieve the highest uniformity in water applied to each plant. However, poor uniformity and E_{appl} can result from a variety of causes, particularly emitter clogging and inadequate system design. This is why the range of on-farm efficiencies of this method varies from 0.7 to 0.95 (Howell 2003).

Even with high uniformity of water distribution, however, E_{appl} can be low if soil storage capacity or crop rooting depth is overestimated, and hence, more water is applied than the root zone soil can hold and substantial drainage occurs. Even with the correct assessment of soil water holding capacity and rooting depth, E_{appl} can still be low if consumptive water use (ET) is overestimated and each irrigation exceeds the soil water depletion for that irrigation cycle. In addition, soil of most fields is spatially heterogeneous and substantial variation in water holding capacity with location may exist. Applying water in adequate amount to refill the root zone for much of the field may lead to excessive drainage for a minor portion of the field where water holding capacity is lower. Generally speaking, deficit irrigation, by applying less water than the full ET need of the crop, would improve E_{appl} by minimizing or even eliminating drainage (Fereres and Soriano 2007). E_{appl} will also be reduced if runoff occurs. Well-designed and managed irrigation systems either do not have runoff or captures it for reuse on-farm (see later sections).

Summarizing the discussion on E_{appl}, it is clear that an efficiency value in the poor situation range can be improved to fall within the good situation range by a wide variety of means. The more obvious path—changing to application methods of high distribution uniformity—is capital intensive, not always justified. Improving the design and management of existing systems has much potential. Use of technical irrigation scheduling procedures based on rooting depth, soil water holding capacity, and ET is still another means to improve E_{appl}, and can be done at low cost, if information is available. The potential for improvement, however, is often hampered by the constraints and rigidity of the water delivery schedules. In general, solutions based on improving water management are more cost effective than those based on investing on new physical infrastructures (Playán and Mateos 2005).

Comsumptive efficiency and transpiration efficiency

Following application efficiency is consumptive efficiency (E_{et}), the ratio of amount of water evapotranspired to that stored in the root zone. This step is usually not explicitly recognized, but is dealt with in terms of the residual soil moisture in the analysis of water balance of crop fields. For the initial wetting–drying cycle, E_{et} could be relatively low, especially for crops that are very sensitive to water stress and require irrigation at relatively high soil water status. On the other hand, when considered over a crop's life span, E_{et} is almost always very high and can approach 100%. That is due to the fact that after the initial wetting–drying cycle, the next irrigation adds considerably less water to the still relatively moist soil in the root zone. Hence, summed over the season, the water placed in the root zone often matches closely the cumulative ET, with the denominator in the efficiency ratio exceeding the numerator by only the amount of water left in the root zone at harvest time. In Table 1, the difference between E_{et} for the poor and good situations is small because the values are for a season. One reason for identifying consumptive use efficiency separately in this paper instead of combining it with transpiration efficiency (E_{tr}) is to allow a more clear discussion of the latter. Another reason is that for dryland cropping where soil water is exhaustively extracted by the crop, E_{et} could be significantly different for different species and even for different cultivars (see Dryland cropping).

The next efficiency step, transpiration efficiency[1], indicates how much of the total ET is actually the water taken up by the crop and transpired. It has long been recognized that transpiration represents beneficial use because it is in exchange for carbon dioxide assimilation, whereas evaporation from the soil is largely a waste of the water (Fischer and Turner 1978). Depending on conditions and crop growth stage, E_{tr} can vary widely and usually highly dynamically, from virtually zero to close to 100%. The variability is rooted in the fundamentals of the soil evaporation process. Basically, evaporation from the soil is determined by two factors—how wet is the soil surface and how much energy does the soil surface receive to sustain the evaporation process. When the soil surface is fully wet, evaporation is determined by the energy supply to the soil surface (energy limiting stage). When the soil surface starts drying, water vapor pressure at the surface decreases with time and evaporation decreases (water limiting stage). The transition from energy limiting to water limiting stage may be as short as a few hours, when the soil surface starts at field capacity or slightly wetter, to as long as several days, when the soil at and below the surface is water saturated at the start. For a soil supporting a crop, the part of the soil shaded by the crop foliage receives very little net radiation and its energy supply to evaporate water is minimal, as is its rate of evaporation. For a crop field with full foliage canopy cover (e.g., 95% shading at midday), soil evaporation is usually less than 10% of the total ET even when the soil surface remains quite wet (Villalobos and Fereres 1990; Jara et al. 1998). Obviously, soil E can constitute a major part of ET only if the soil surface is wet and not shaded (Ritchie and Burnett 1971). Soil E makes up a smaller and smaller part of the ET as crop canopy develops and as the soil surface dries. Canopy coverage can be accelerated by increasing the planting density and the crop growth rate. Other things being equal, the faster the canopy covers the soil, the lower is the soil evaporation and the higher is E_{tr}. On the other hand, the more frequent is the wetting of the soil surface by irrigation or rain, the lower is E_{tr} if the canopy does not cover the soil fully. Thus, manipulation of canopy growth rates and of irrigation frequency constitutes effective management tools to reduce the E fraction of ET and to increase E_{tr}.

[1] It is necessary to define transpiration efficiency (E_{tr}) as the ratio of transpiration to ET here. In the literature transpiration efficiency is often also used to designate the ratio of assimilation to transpiration, equivalent to assimilation efficiency (E_{as}) of this paper

Increasing plant density within practical limits, though minimizing soil *E*, will cause a moderate increase in cumulative transpiration and cumulative ET because the faster development of a full canopy (Hsiao and Xu 2005). This, however, is in exchange for more biomass production (Steduto et al. 2007). Reducing irrigation frequency is associated with the risk of water stressing the crop and excessive drainage, and must be done with care. Another important management tool is localized irrigation; by wetting only parts of the soil surface, *E* is reduced relative to that of full wetting irrgation under the same frequency. Because trickle systems are operated under high-frequency, their *E* losses for row crops with relatively fast canopy development are similar to those of conventional furrow irrigation (Pruitt et al. 1984). In tree crops, however, the *E* reductions by localized irrigation can be substantial (Bonachela et al. 2001), especially when the canopy cover is sparse. Subsurface trickle systems eliminate most if not all of the *E* loss. The savings potential of this method of irrigation varies with degree of ground cover (Bonachela et al. 2001). Generally speaking, the elimination of *E* may not justify the investment by itself, except in very water-short situations (Orgaz and Fereres 2004).

Assimilation efficiency

The water transpired by the crop is in exchange for the carbon dioxide assimilated photosynthetically by the crop and this exchange determines E_{as}. E_{as} is commonly referred to as transpiration efficiency in the literature, and also as photosynthetic water productivity (Steduto et al. 2007). Here, we termed it assimilation efficiency to be consistent with the naming of all the steps in the efficiency chain. Over the diurnal cycle E_{as} varies dynamically because the evaporation demand (and to a much lesser degree, the carbon dioxide concentration in the air) varies diurnally (Asseng and Hsiao 2000; Xu and Hsiao 2004). It turned out, however, that for a given species, climate and atmospheric carbon dioxide concentration, E_{as} is actually nearly constant when integrated over daily cycles for a number of days and cannot be easily altered (Steduto and Albrizio 2005). The reason for this is discussed extensively in another paper (Steduto et al. 2007) of this issue. Regardless, there is some room for improvement in E_{as}; namely, by changing crop species, improving mineral nutrition, or changing location or planting date to grow the crop under lower evaporative demand.

Species differ in E_{as}; particularly well known is the difference between C_3 and C_4 species, and between CAM (Crassulacean acid metabolism, e.g., pineapple) and non-CAM (i.e., C_3 and C_4) species. E_{as} for C_4 is considerably higher than that for C_3 because the initial carboxylation in C_4 is carried out by an enzyme (PEP carboxylase) that has much stronger affinity for CO_2 than the carboxylating enzyme (RuBP carboxylase) in C_3 plants. Consequently, the intercellular CO_2 concentration (c_i) of leaves of C_4 is considerably lower than that of C_3 leaves, and the driving force for CO_2 transport into leaves in C_4 species is correspondingly larger. In addition, stomata of C_4 species tend to be less open than those in C_3 species (except when air humidity is very low and temperature high), leading to slightly lower canopy transpiration. E_{as} for CAM plants are still much higher, mainly because of their peculiar stomata operation, closing mostly during the day, and opening at night when the evaporative demand is much lower. More detailed discussion regarding the photosynthetic syndromes in relation to water use efficiency can be found in Steduto (1996). The range of E_{as} in Table 1, for simplicity, does not include values for CAM species, most of which are minor specialty crops. Although changing species may improve E_{as} markedly, it is often not economically viable because of marketing and other institutional constraints.

For the same species, limited data indicate that when nitrogen as a nutrient is limiting, E_{as} is likely lower (Ritchie 1983; Steduto and Albrizio 2005). This may be expected because intercellular CO_2 concentration (c_i) in leaves tends to remain the same for different levels of nitrogen supply, but stomata are less open under low nitrogen (Wong et al. 1979). According to the analysis of Hsiao (1993b), E_{as} will be lower in that case because leaves with less open stomata will be warmer and the driving force for transpiration will be greater, whereas the driving force for CO_2 transport remains the same (See Eq. 3, Steduto et al. 2007). If N is limiting, adding N fertilizer will increase yield, in addition to enhancing E_{as}. Nitrogen fertilization must be carried out with care, however, since excessive N will lead to water pollution and a possible reduction in E_{yld} in some crops due to excessive vegetative growth, as discussed below.

Other ways to improve E_{as} requires changing the environment of the crop. As discussed in Steduto et al. (2007), two key factors affecting E_{as} are evaporative demand of the atmosphere and CO_2 concentration in the air. Growing the crop at a location lower in evaporative demand (mainly lower temperature and higher humidity) will improve its E_{as} (Tanner and Sinclair 1983; Fereres et al. 1993; Hsiao 1993b; Asseng and Hsiao 2000; Xu and Hsiao 2004). Although changing location is not normally an option, it is possible to lower the evaporative demand of a cropping season in temperate environments by either planting earlier in the spring, or if a winter crop, earlier in the fall to avoid the high evaporative demand of the summer. Gimeno et al. (1989) showed winter planted sunflower to be more efficient in water use for biomass production than late plantings in a Mediterranean environment, due to differences in evaporative demand (Soriano et al. 2004). It is fair to infer that E_{as} was higher for the winter planting. Fall plantings of grain legumes have also been successful along the same lines (Singh et al. 1997).

Biomass efficiency

Following E_{as} is the conversion efficiency to biomass (E_{bm}), a measure of the biomass produced for the amount of carbon dioxide assimilated. As discussed in another paper (Steduto et al. 2007) in this issue, E_{bm} is largely a function of the chemical composition of the crop biomass. E_{bm} is also influenced by conditions that affect plant respiration, particularly temperature (Amthor 1989). Although generally there is a tight correlation between cumulative respiration at night and cumulative CO_2 assimilation during the day (Albrizio and Steduto 2003), presumably more of the assimilated carbon would be lost by respiration in high temperature environments, leading to lower E_{bm}. Possible improvement would involve changing either to a location of lower temperature, or planting dates to avoid the hotter part of the year, as in the improvement of E_{as}. If genotypic variation in respiration exists, it may be exploited to improve $E_{bm.}$ Notice that in the literature, most of the long-term data on water use efficiency are reported in terms of biomass produced, relative to water transpired (e.g., Hanks 1983). Hence, the data are for the ratio of biomass to transpiration, here $E_{as} \times E_{bm}$.

Yield efficiency

The final step is yield efficiency E_{yld}. It represents the proportion of the biomass produced that actually ends in the harvested product, termed harvest index in the literature (Donald 1962). Most studies of crop production report only aboveground biomass because of the extreme difficulties in accurately assessing non-storage root biomass in field experiments. Thus, the common practice is to consider only aboveground (shoot) biomass in the determination of the E_{yld} of non-root crops. Fortunately, indications are that for non-root crops root biomass constitutes a small portion (perhaps in the 10–15% range) of the total biomass at the maturation and ripening stages (Loomis and Connor 1992), and that the ratio of root to shoot tends to be constant (Brouwer 1983). Unless specified otherwise, we will follow the common practice of considering only aboveground biomass in this discussion.

In this context, E_{yld} is taken to be close to 1.0 for forage crops. For grain crops, E_{yld} can be 0.50 or even slightly higher for modern high yielding cultivars. Over the last century plant breeders have inadvertently selected for higher water use efficiency by selecting for higher yielding ability (Hsiao 1993a, b). The higher yields turned out to be mostly the result of partitioning more biomass to the grain or fruit and less to vegetative parts (Evans 1993). For example, E_{yld} for wheat and rice were in the range of 0.33 at the beginning of the twentieth century and rose to as high as 0.53 in the 1980s (Evans 1993). At the same time, efficiency for biomass production from transpired water (i.e., $E_{as} \times E_{bm}$) appears to remain almost unchanged (Steduto et al. 2007). As can be seen by applying Eq. (6), this increase in E_{yld} of 60% translates into an increase in overall water use efficiency of 60%, other things being equal.

Since the 1980s there have been only marginal improvements in E_{yld} of the major crops (Evans and Fischer 1999). The reason for this is not clear. However, there should be a theoretical limit to HI for grain crops because the stem must be strong enough to support the grain weight and avoid lodging and because there must be sufficient leaves to provide the assimilates; and perhaps that limit is being approached now. Based on experimental data, a substantially higher theoretical limit (0.62) has been calculated for HI of winter wheat by Austin et al. (1980). A part of the experimental data, however, were obtained by providing artificial support to prevent lodging; and the physics of stems as load bearing beams was not considered. Lodging may be the critical factor limiting the achievement of such high HI. Consistent with this is the fact that for root crops such as potato and sweet potato with no need of mechanical support for the harvested organs, E_{yld} is in the range of 0.7–0.8 (Evans 1993), and can reach as high as 0.86 (Shahnazari et al. 2006).

It is well established that, depending on the crop species, E_{yld} can be altered by water regimes, adding another efficiency step to the suite that can be manipulated through irrigation management. Although E_{yld} frequently decreases under water deficit (Evans 1993), it can also increase under some mild water deficit regimes with certain crops because excessive vegetative growth is restricted. Leaf growth is sensitive to even very mild water deficit, and can be inhibited while photosynthesis is unaffected (Hsiao 1973; Hsiao and Xu 2000). Mild water deficit imposed after the development of full canopy would increase E_{yld} in species with a tendency to excessive vegetative growth (Hsiao et al. 1976). Moderate water stress during the maturation phase frequently reduces E_{yld} by accelerating senescence of older leaves (Sionit and Kramer 1977; Bradford and Hsiao 1982; Hsiao 1993a, b). Earlier senescence of the canopy leads to lower assimilation rate (Wolfe et al. 1988b) and less assimilates available for the growing organs, which at that stage are the harvestable organs. Consequently, yield is reduced comparatively more than biomass and E_{yld} is lower (Fischer 1983, for wheat; Wolfe et al. 1988a, for maize).

E_{yld} can be reduced even more if sufficient water stress occurs at the time of pollination. The inhibition of pollination and fruit set, however, requires severe water stress (Hsiao 1982; Westgate and Boyer 1986) and the impact is limited to a narrow time window, affecting only the fraction of flowers whose pollination time coincides with the period of severe stress. The effect of stress on E_{yld} is only marked if the stress is severe and lasts over a major portion of the pollination period of the crop. For example, if a short but severe stress develops during pollination and lasted only 2 or 3 days but the crop pollinates over a 20-day period, the impact on E_{yld} should be only slight or minor.

Overall regarding E_{yld}, it may be concluded that strategically better-timed irrigation provides a means to improve yield efficiency at a minimum or no additional cost. For that improvement, irrigation should be scheduled: (1) to avoid severe water stress any time, especially during pollination; (2) in moderation to restrict excessive leaf growth after the canopy is closed; and (3) to provide sufficient water during maturation to avoid early senescence.

Overall efficiency of irrigated cropping and sample computations of improvements

Any effort to improve water use efficiency needs to start with the assessment of the actual and attainable efficiencies for the given situation, as quantitatively as possible. This information is fundamental for making rational improvements aiming at raising the overall efficiency to the attainable level. With the information in Table 1 and taking the chain of efficiencies approach, hypothetical situations of improvements can be analyzed. The most striking results (Table 1) of applying Eq. (3) or (7) to irrigated cropping is that the difference in overall water use efficiency (last line, Table 1) between the poor situation and the good situation is huge, in spite of the fact that for each efficiency step the difference between the two situations is not that large or even minor. Nonetheless, E_{all} for the poor situations is only 2% of E_{all} for the good situations. The reason for this huge difference lies in the multiplicative nature of the efficiency chain, as already noted. This 50-fold difference in water use efficiency to produce yield (grain or fruits of herbaceous crops) indicate that there is much room for improvement in many situations. It should also be noted that the comparison is not between the extremely poor and the extremely good situations, but between the mid-values of the efficiency steps for the two situations. Even when the comparison is based on the upper limit values of the poor and on the mid-values of the good, the difference is still 12-folds.

This large difference may come as a surprise to some in view of the difficulties encountered when attempting to make large improvement in the individual efficiency steps. The point to make is that because of the multiplicative nature of these steps in determining the overall efficiency, the overall difference between the poor and good situation is very large and should provide many opportunities for improving the poor situation with only limited investment in people and material resources.

One of the potential improvements—recycling of drainage and runoff water for reuse (see later section for more quantitative treatment)—is well known and indirect, and addresses the inefficiencies in the engineering segment of the chain. For the poor situation, if 50% of the water lost in each of the first three steps in Table 1 is recovered and used consumptively, E_{all} based on mid-values would be markedly better, raising it from 0.0243 to 0.113 kg (yield) m^{-3} (water), a 4.7-fold improvement, but still only 9% of the mid-value based E_{all} for the good situation. This again highlights the need to take the multi-step approach in efforts to improve the overall water use efficiency.

In what steps in the chain may improvements be made at reasonable cost? In the conveyance and storage segments of the chain, the shift from unlined to lined ditches and reservoirs can lead to large efficiency increases, often at a low costs if plastic sheeting is used as lining. For example, if the fractional improvement in E_{farm} is in the range of 0.6–0.7 (Δ = 0.6–0.7), E_{farm} would be raised from the poor to the good category (see Eq. 5). To increase E_{appl} the irrigation system or its management must be improved. There is a general trend worldwide to promote a shift from surface to pressurized systems. The main reason that is being advocated is the higher attainable E_{appl} of pressurized methods. Nonetheless, with precise land grading it is possible on many soils to achieve very high E_{appl} by surface irrigation (Erie and Dedrick 1979). In addition to good maintenance, pressurized methods require appropriate design and accurate assessment of effective rooting depth and soil water holding capacity to achieve high E_{appl}. Their inherently higher E_{appl} is often not realized for not meeting those requirements. An extensive survey (Hanson 1996) found E_{appl} values of pressurized systems substantially below those expected. Meeting the requirements should entail little or modest cost.

Good agronomy and management can influence the rest of the efficiency steps. E_{tr} can be improved substantially, by developing the crop canopy quickly (optimizing planting density and arrangement), by reducing the frequency of irrigation, and by reducing the soil surface area wetted (via trickle or alternate-furrow irrigation). Appropriate nutrient fertilization, particularly nitrogen, enhances both E_{tr} (Cooper et al. 1987) and E_{as} (Steduto et al. 2007) when nutrients are deficient. This also leads to higher yields so it should be very cost effective. E_{as} may also be improved at almost no cost by adjusting the planting time to grow the crop under weather generally lower in evaporative demand (Soriano et al. 2004; Steduto et al. 2007). Finally, there may also be some room for improvement in E_{yld} of the crop by careful irrigation scheduling as discussed earlier, at a minimal or no additional cost.

If the original efficiencies for each of the irrigated cropping steps are the mid-values of the poor situation listed in Table 1, and improvements are made as discussed above, as one scenario, the fractional changes in efficiency, Δ_i (Eq. 6), for E_{farm}, E_{appl}, E_{tr}, E_{as}, and E_{yld} that one can reasonably expected could be 0.5, 0.35, 0.4, 0.2 and 0.2, respectively. The overall improvement in efficiency according to Eq. (6) is then slightly more than fourfold, raising E_{all} from 0.0243 to 0.099 kg (yield) m^{-3} (water). Note that this hypothetical improvement is effected with minimal or low costs, and the efficiency of each step in the chain are still at relatively low levels.

Reuse of drainage or runoff water

Much of the water lost along the efficiency cascade from the reservoir to the root zone is due to drainage or deep percolation, and some may be due to runoff. In theory and practice, much of this water can be recovered by either pumping the groundwater or channeling runoff for use in the lower fields. Some of the losses, however, are consumed by evaporation, or by drainage into saline sinks and are not economically recoverable (Wallace and Gregory 2002; Jensen 2007 this issue).

In many areas, runoff water is recovered on the same farm, and the recovered amount can be simply added to the farm water delivered as a part of the input for the efficiency calculation. The recoverable water estimation is complicated by the fact that each reuse of the recovered water leads to yet another loss (a fraction of the reapplied water) to be recovered again. So the recovery calculation has to be iterated for at least a couple of times to be realistic. In some trial runs, we found that four iterations of the recovery calculations account for most (within a few percent) of all the water that could be recovered and placed in the root zone, unless the recovery efficiency is very high. The equation to use for this is

$$W_{rz,re} = W_{ar} \times E_{fm} \times E_{appl} \times E_{re}\left[1 + E_{re}(1 - E_{fm} \times E_{appl}) + E_{re}^2(1 - E_{fm} \times E_{appl})^2 + E_{re}^3(1 - E_{fm} \times E_{appl})^3\right] \quad (8)$$

where $W_{rz,re}$ is the total amount of recovered water placed in the root zone after four cycles of iteration, W_{ar} is the initial (or starting) amount of water available and subjected to recovery, and E_{re} is recovery efficiency. The term ($1–E_{fm} \times E_{appl}$) is the fractional loss of water for each recovery cycle, the result of inefficiency in conveyance and storage on the farm, and inefficiency in irrigation water application. This equation is simplified in that the evaporative loss of water (as distinguished from crop ET) for each recovery cycle is assumed to be negligible. For the case of fewer recovery cycles (fewer iterations), Eq. (8) with fewer terms within the bracket is used. For one, two and three iterations, respectively, the first term within the bracket (namely 1), the first two terms (up to power of 1), and the first three terms (up to power of 2), are needed. Note that in situations where E_{re} is quite low, increasing the number of recovery cycles beyond one or two does not increase the amount of water recovered very much because of the small contributions from the last two terms of Eq. (8) due to squaring and cubing of E_{re}. These results support the conclusions of Wallace and Gregory (2002). They did not give the procedure used, although it was likely the same as Eq. (8).

Deficit and supplemental irrigation

In many areas around the world, irrigation is practiced even though water is scarce and available water is insufficient to meet the full ET needs of the crop. In those situations, deficit irrigation (DI), defined as the application of irrigation below the full crop ET, is an important tool to increase the efficiency of water use (English et al. 2002). Deficit irrigation is practiced when farmers have less water than the maximum ET needs, and have to irrigate their fields at levels below full ET. Deficit irrigation almost always increases water use efficiency for a number of reasons. Firstly, as the applied water is less than the depletion by ET, E_{appl} increases because most or all of the applied water remains in the root zone (Fereres and Soriano 2007). In addition, E_{et} may be somewhat higher because the crops are forced to extract more water from the soil. Further, HI and hence E_{yld} may be enhanced because full irrigation can lead to excessive vegetative growth of some crop species. A well-known example among herbaceous crops is cotton (Hearn 1980), which grows excessive foliage while dropping most of its early flowers and fruits (bolls) and set bolls late when kept well irrigated. To obtain high E_{yld}, cotton in locations with limited growing season needs to be well irrigated early in the season to develop a good canopy, then subjected to moderate water stress to restrict vegetative development and facilitate boll retention, growth and maturation (Grimes and El-Zik 1982). Another example, familiar to home gardeners, is tomato, which also develops a large leaf area and fails to set early fruits if kept at very high water status, especially when supplied amply with nitrogen (Hsiao 1993). Other horticultural crops grown for fruits, such as pepper and eggplant, appear to exhibit similar behavior, but less markedly. For monocots, some small grains tiller profusely when kept at very high water status. Many of these tillers are heavily shaded in dense plantings, do not produce grain, but add to the total biomass and hence, lead to a lower E_{yld}. One major conclusion that can be extracted from many studies on DI of annual crops is that optimal levels of water supply under DI should be relatively high, one that permits achieving at least 50–60% of potential yields and ET, as can be inferred from the data of Musick et al. (1994) for wheat.

Deficit irrigation is more common in tree crops and vines than in field crops because economic returns in tree crops are generally higher than field crops and less directly related to biomass production, but more to the quality of fruits and yield (Fereres et al. 2003). Water deficits can be imposed at times when yield is not or minimally affected, a practice termed regulated deficit irrigation (RDI; Chalmers et al. 1981) that requires close control of the timing and level of water deficit. The higher economic return affords high-frequency, microirrigation systems that are ideally suited for RDI (Fereres and Goldhamer 1990). At present, RDI has been tested in many tree crops and grapes with generally good results (Fereres and Soriano 2007), particularly with respect to product quality (citrus Goldhamer and Salinas 2000; wine grapes McCarthy et al. 2000). There are risks associated with using RDI over the long run, mostly related to the control of soil salinity and to the longevity of plantations. Nevertheless, it is now evident that irrigating below the full ET requirements leads to higher E_{all} in many tree crops and vines (Fereres and Evans 2006). One crop where RDI has been adopted extensively is winegrapes (Girona et al. 2006). Among the techniques used for imposing RDI on this crop, one is to drip irrigate about every 2 weeks alternatively on either side of the vine row, defined as partial root drying (PRD; Dry and Loveys 1998). This technique should increase both E_{et} and E_{yld}, and possibly E_{tr}, relative to full irrigation, but has not shown any specific advantage in the few comparisons conducted against other forms of RDI, when the amount of applied water and the soil surface area wetted by the emitters were the same (Fereres and Soriano 2007).

Supplemental irrigation is used in some humid to temperate areas as a tactical measure to complement reasonably ample rainfall and stabilize production. In the drier zones, supplemental irrigation is used as a form of DI, with only one or two applications per season because water supply is very limited (Oweis et al. 1998). In this case, the impact of DI on water use efficiency relative to the rain fed situation is very positive. For example, in situations where rainfall is not reliable at planting time, one irrigation just before or after planting would ensure the establishment of a good crop stand. With a better crop stand, there would be fewer bare spots and more of the soil surface is protected by the crop canopy; hence, E_{infil} would be higher. E_{rzstor} (see following section and Table 2 for E_{infil} and E_{rzstor}) and E_{et} would also be higher because a more extensive canopy also means a denser root system and more of the infiltrated water would be in the root zone and extraction by roots would be more effective. With a more complete canopy cover, there would be less soil evaporation and more crop transpiration; so E_{tr} is also higher. Overall then, a single irrigation raises those four efficiencies in the chain, while also adding some water for crop use, leading to dramatic improvement in E_{all} and yield. Other times when a supplemental irrigation may also be highly beneficial is at pollination time, to ameliorate severe water deficit which inhibits pollination and reduces HI and hence E_{yld} (Hsiao 1993a), or at grain filling to minimize early foliage senescence (Wolfe et al. 1988a, 1988b), which also leads to lower E_{yld}. Examples of some marked increase in water use efficiency effected by supplemental irrigation are given by Oweis et al. (2000) and Xue et al. (2006).

Dryland cropping

Much of the agriculture in the world is not irrigated and has to rely on rainfall. In the drier areas, the capture of rainfall for crop use is critical in determining crop productivity and E_{all}. In rain fed situations, the first three steps of the efficiency chain described in Table 1 are reduced to only two steps. The first step is infiltration (of rainfall into the soil, W_{infil}) efficiency; and the second step is rhizostorage (of infiltrated water in the root zone) efficiency, as given in Table 2. Also given in the table are the ranges of efficiencies for poor and good situations.

The first of the efficiency step, infiltration, is jointly determined by the slope and roughness of the soil surface, rainfall intensity, and infiltration rate of the soil (Rockstrom and Barron 2007 this volume). If rainfall rate exceeds infiltration rate, runoff will occur unless there is surface storage through ponding and subsequent infiltration. The built-up in water depth associated with ponding raises the hydraulic gradient and therefore increases infiltration rate. Infiltration rate is determined largely by this gradient and soil hydraulic conductivity and exhibits substantial spatial and temporal variations across agricultural fields. Soil hydraulic conductivity, being a function of soil pore size distribution, is sensitive to the degree of aggregation of the primary particles (Unger and Stewart 1983). Management practices can affect E_{infil} significantly. Tillage increases infiltration rate by creating more voids in the soil for water to infiltrate, but its effects are temporary. Conservation tillage that leaves sufficient residue on the surface can enhance E_{infil} due to better soil aggregation because of long term increase in soil organic matter, and because the surface residue detains runoff and shields the surface soil aggregates from the dispersive impact of rain drops (Unger and Stewart 1983). In the case of rain-fed tree crops, there are spatial variations in infiltration rate (Gomez et al. 2001), with infiltration rate normally being higher under the tree canopy, because of lack of compaction due to traffic and the higher organic matter originated from leaf fall (Gomez et al. 2001), and because of the shielding of soil aggregates from impact of the rain by the canopy. This spatial pattern of infiltration rate enhances E_{infil} of the area as a whole, since areas under the tree capture the runoff from the more compacted areas subjected to traffic (Castro et al. 2006).

After infiltrating the soil, the water needs to be stored in the root zone for the crop to use. This efficiency step, named rhizostorage efficiency (E_{rzstor}) here, is determined jointly by the water holding capacity of the soil and the effective rooting depth of the crop. Of course, high water holding capacity and deeper rooting usually result in higher E_{rzstor}.

The foregoing discussion makes clear that plants play a role in determining both efficiency steps in Table 2. Infiltration efficiency would be enhanced if there is a plant canopy, of either trees or herbs, covering the soil so that momentum of the falling rain is dissipated by the foliage first, thus reducing disintegration of the soil aggregates at the surface and minimizing soil surface sealing (Thurow 1991). More canopy cover also means more biomass produced, leading to more organic matter in the soil and better aggregation. The other important plant influence is effective rooting depth, which varies with growth stages, and also substantially among vegetation types (Canadell et al. 1996) and annual crop species (Taylor 1983). Equally important in determining rooting depth is the presence or absence of compacted or cemented layers, or highly acidic subsoil, at some soil depth. In addition to rooting depth, variations in E_{rzstor} may result from the dynamics of root system expansion relative to the temporal distribution of rain. Non-coincidence of rainfall and crop root development and transpiration

Table 2 Range of efficiencies for the steps in the efficiency chain from rainfall (W_{ppt}) to water in the root zone, for poor and good situations, and the overall efficiency for the two situations, calculated from mid-values of the efficiency steps

Efficiency step	Efficiency ratio	Units	Range of efficiency	
			Poor circumstances and/or practices	Good circumstances and/or practices
E_{infil}	W_{infil}/W_{ppt}	Unitless	0.25–0.55	0.75–1.0
E_{rzstor}	W_{rz}/W_{infil}	Unitless	0.35–0.55	0.75–1.0
E_{all}	W_{rz}/W_{ppt}	Unitless	0.18	0.77

The basis for choosing the efficiency ranges is given in the text associated with Table 1. Symbols and abbreviations are defined in Appendix needs may result in more percolation below the root zone, thus reducing E_{rzstor}.

Matching crop phenology to rainfall distribution with time has ramifications for dryland cropping much beyond the two efficiency steps in Table 2. A number of subsequent steps (from the 4th step onward in Table 1) may also be altered as the result. Much of the rain falling before there is significant canopy will mean more soil evaporation and lower E_{tr}. Within a given species, there is variation in the extent of subsoil water use, and hence in E_{et}, which is normally related to differences in maturity date among cultivars (Gimenez and Fereres 1986). On the other hand, too long a life cycle would mean maturing at the time after the soil water is exhausted and HI and E_{yld} would be reduced. This is why matching the crop developmental pattern to the anticipated rainfall is so critical in achieving high efficiency of water use in dryland agriculture (Gimenez et al. 1997). Even for similar maturity dates, there could be differences related to the degree of osmotic adjustment. A cultivar with stronger osmotic adjustment capability would be able to lower its solute potential and extract soil water down to a lower soil water potential, resulting in higher E_{et} (Wright and Smith 1983; Wright et al. 1983).

In dry areas, there is often the opportunity to improve the water available for the crops by rainwater harvesting (Oweis and Hachum 2006). The soil slope is reshaped or low bounds are built to funnel runoff to where the crop is instead of infiltrating where crop roots do not reach. Sometimes, the surface of parts of the catchment is treated (mechanically or chemically) to increase runoff that is funneled to the cropped areas. In terms of the efficiency steps, this can be treated as an increase in E_{rzstor}. To do so, the rainfall over the crop as well as the water harvesting area is taken as the input (W_{ppt}). A higher proportion of this water would be in the root zone as the result of water harvesting. E_{infil} may also be increased if runoff is reduced from the whole area. In addition, the improved water supply to the crop would enhance E_{tr}, and likely also E_{yld}.

Range vegetation for animal production

In areas not suited for crop production, the land is often used as range for the production of animal products. This is particularly true in the arid zones where, even though the land could be physically cultivated, the very limited rainfall does not allow for sustainable cropping. In analyzing the production system from the water limitation standpoint, and in seeking improvements, the efficiency steps involved in producing plant material for animal consumption are the same as those for dryland crop production, with the exception that the chain stops at biomass efficiency (E_{bm}) and does not involve E_{yld}. The animals consume a part of the biomass and produce the animal product in return. So at least two other steps need to be added to the chain after the biomass step, grazing efficiency (E_{graz}) and conversion efficiency of the animal ($E_{convert}$). E_{graz}, the ratio of biomass consumed by the animal to the biomass produced (standing biomass), is strongly dependent on the edibility and palatability of the biomass, and the stocking rate for the grazed area. $E_{convert}$ is dependent on the digestibility and nutritional content of the consumed biomass, the chemical composition of the animal product(s), and the energy requirement of the animal for maintenance and grazing and other activities. For simplicity, in this paper $E_{convert}$ is the ratio of live mass of the animal to dry biomass of the herbage consumed.

A substantial amount of food is required just to maintain the existing body mass of an animal. For goat and sheep, metabolizable energy (ME) for maintenance (ME_m) per day is about 420 kJ/kg live body mass raised to the power of 0.75 (Aguilera et al. 1990; Ørskov and Ryle 1990), times the efficiency of utilization of the ME in the feed, provided that the activity of the animal is at a minimal level. Similar values are also applicable to cattle. According to the widely used booklet of U. S. National Research Council (NRC 1981a), an animal weighing 30 kg requires about 0.54 kg of food of high quality (10 MJ ME per kg of biomass) per day to maintain existing weight. If the food is lower in quality, 8.4 MJ ME per kg, the required food consumption to maintain weight would be about 0.65 kg per day. If the animal walks long distances to obtain the food because edible biomass is sparse and widely dispersed on the range, NRC recommended the ME_m be increased by 50%. For arid range with hilly terrain, the recommendation is to increase ME_m by 75%. There is indication that these recommended increases may be overly generous for animals well adapted to the local conditions (e.g., Lachica et al. 1997). If a more conservative estimate of the increase needed for hilly arid range of 35% is used, the intake of the lower quality food would have to be 0.88 kg per day for a 30 kg animal. It turned out that the forage available on rangeland may be even poorer in quality. ME content of forage selected and ingested by cattle on fairly good rangeland in Colorado with 420 mm rainfall, determined by feeding cattle-ingested but not digested forage to sheep in metabolism trials, was 10.5, 9.5, 7.4 and 6.2 MJ ME per kg of biomass, respectively, for the month of June, July, September, and December (Wallace 1969). For degraded and overgrazed rangeland of dry areas, the likely ME content of forage for much of the year is probably similar to those eaten by the cattle in September and December on the Colorado range. The efficiency of utilizing ME for maintenance decreases as ME content of the forage decreases. Extrapolating this decrease from the numbers given by NRC (1981b), one can estimate that about 1.5 kg per day of biomass intake is necessary just for maintenance in such situations. Consumption of 1.5 kg of biomass per day is substantially higher than the normal rate for sheep or goat weighing 30 kg, and may not be possible due to constraints imposed by size of their rumen (Ørskov and Ryle 1990). In any event, the poorer is the forage quality, the higher is the proportion of the consumed forage used for maintenance and the smaller is the proportion used for growth or production. It turned out that overstocking and overgrazing tend to be the norm for much of the dry area (e.g., Mencke and Bradford 1992). Overgrazing leaves mostly only the unedible plant species growing. So E_{graz} as well as $E_{convert}$ would be extremely low. In fact, the latter can be negative (the animal loses weight daily). Furthermore, overgrazing would leave the soil largely exposed without canopy cover. Consequently E_{infil} would also be very low. In addition, overgrazed plants have a very limited root system and as the result E_{rzstor} may also be low. Perhaps the most important is the fact that with very sparse canopy, most of the water is consumptively used by soil evaporation and not by transpiration, leading to very low E_{tr}. Consequently, E_{all} for animal production on overgrazed range in dry areas can be extremely low, or even negative, and supplementary feeding with feed of high nutrient content is necessary to achieve reasonable production.

Since overgrazing and overstocking are the main cause of the markedly low water use efficiency for the poor situation, controlled grazing, particularly rotational grazing at the appropriate stocking rate, offers a tremendous potential for improvement. By rotating the animals to different parts of the range periodically, the desirable herbage species at each location are given the time to develop more of a canopy before being eaten. The most direct and obvious benefit is that this raises the amount of edible biomass produced because there is more photosynthetic surface area to capture more of the radiation for photosynthesis. The less obvious benefits, though no less important, is the fact that the efficiency of at least five steps in the efficiency chain—E_{infil}, E_{rzstor}, E_{tr}, E_{graz}, and $E_{convert}$—are raised by this one change in management practice, leading to huge improvements in overall water use efficiency. This is best illustrated by a sample calculation using Eq. (3). Starting with the mid-values of efficiency steps for the poor situation in Table 2 and linking them with those for the poor situation in Table 1, but with the exception that the mid-value of E_{tr} is adjusted downward to 0.13, the efficiency for biomass production from rainfall is calculated accordingly to be 42 g m^{-3}. The adjustment of E_{tr} is in recognition of the fact that canopy cover for degraded and overgrazed dryland ranges are normally very low compared to that for crop fields, making a range of 0.06–0.2 as a reasonable estimate of E_{tr} for the poor situation. Linking the biomass produced to the animal production for the poor situation (Table 3), the E_{all} from rainfall to animal produced is then calculated to be 0.32 g live body mass per m^3 of rainwater. With this efficiency, the animal live body mass produced per year for an annual rainfall of 180 mm would be only 0.58 kg ha^{-1}. If rotational grazing with appropriate stocking rate is practiced, the fractional improvement (Δ) in E_{infil}, E_{rzstor}, E_{tr}, E_{graz}, and $E_{convert}$ may reasonably be expected to be, 0.3, 0.5, 1.6, 2.2, and 1.8, respectively. These hypothetical values for Δ are based on limited data in the literature (e.g., Hsiao and Xu 2005; Le Houérou et al. 1988; Thurow 1991) and judgment on the part of the authors, and are obviously situation dependent. Anyway, according to Eq. (6), these fractional improvements in the five efficiencies would culminate in a new E_{all} of 14.6 g live body mass per m^3 of water, or a 45-fold improvement in water use efficiency. Animal live body mass produced per year for 180 mm of rainfall would be 26.3 kg ha^{-1}. It is doubtful that any other management improvement at a minimal or modest cost can have such a dramatic impact on productivity. Needless to say, the improvement upon switching to rotational grazing is not instantaneous and will take several years to achieve, and may require seeding of desired forage species, as well as community action and change in governmental policy.

It is well known that rangeland can be improved by various means other than rotational grazing. Increasing the desirable plant species by seeding or transplanting is one, and fertilizing with the limiting mineral nutrients (e.g., phosphorus) is another. These improvements would also raise the same efficiency steps raised by rotational grazing because more plant cover and biomass would result, provided that the increase in canopy cover/duration lasts and is not cut short by increased grazing activity.

Scaling up beyond the field level

Branching along the chain

Scaling up from a single field to a farm and beyond increases the complexity of the analysis because the

Table 3 Range of efficiencies for the additional steps needed to link range animal production ($m_{\text{live ani}}$ in kg of live weight) to plant biomass (kg of dry matter) production for poor and good situations, and the overall efficiency for the two situations, calculated from mid-values of the efficiency steps

Efficiency step	Efficiency ratio	Units	Range of efficiency	
			Poor circumstances and/or practices	Good circumstances and/or practices
E_{graz}	$m_{\text{bm eaten}}/m_{\text{bm}}$	Unitless	0.04– 0.3	0.6– 0.86
E_{convert}	$m_{\text{live ani}}/m_{\text{bm eaten}}$	Unitless	0.01–0.08	0.18–0.28
E_{all}	$m_{\text{live ani}}/m_{\text{bm}}$	Unitless	0.0077	0.168

The basis for choosing the efficiency ranges is stated in the text associated with Table 1. Symbols and abbreviations are defined in Appendix

water stream divides and distributes along the way and each branch may have different efficiency ratios for its own steps. Take the simple case of a canal conveying water from a reservoir to four farms located along the canal (Fig. 1). Assuming the water for each farm forms a separate stream within the canal flow as depicted in Fig. 1, the efficiency steps from the reservoir to the root zone can then be described as follows:

Farm 1 $\frac{W_{\text{fg},1}}{W_{\text{vo},1}} \times \frac{W_{\text{fd},1}}{W_{\text{fg},1}} \times \frac{W_{\text{rz},1}}{W_{\text{fd},1}} = \frac{W_{\text{rz},1}}{W_{\text{vo},1}}$

Farm 2 $\frac{W_{\text{a},2}}{W_{\text{vo},2}} \times \frac{W_{\text{fg},2}}{W_{\text{a},2}} \times \frac{W_{\text{fd},2}}{W_{\text{fg},2}} \times \frac{W_{\text{rz},2}}{W_{\text{fd},2}} = \frac{W_{\text{rz},2}}{W_{\text{vo},2}}$

Farm 3 $\frac{W_{\text{a},3}}{W_{\text{vo},3}} \times \frac{W_{\text{b},3}}{W_{\text{a},3}} \times \frac{W_{\text{fg},3}}{W_{\text{b},3}} \times \frac{W_{\text{fd},3}}{W_{\text{fg},3}} \times \frac{W_{\text{rz},3}}{W_{\text{fd},3}} = \frac{W_{\text{rz},3}}{W_{\text{vo},3}}$

Farm 4 $\frac{W_{\text{a},4}}{W_{\text{vo},4}} \times \frac{W_{\text{b},4}}{W_{\text{a},4}} \times \frac{W_{\text{c},4}}{W_{\text{b},4}} \times \frac{W_{\text{fg},4}}{W_{\text{c},4}} \times \frac{W_{\text{fd},4}}{W_{\text{fg},4}} \times \frac{W_{\text{rz},4}}{W_{\text{fd},4}} = \frac{W_{\text{rz},4}}{W_{\text{vo},4}}$

where the subscript a, b, and c stand for either the canal segment so designated in Fig. 1 or the end of the canal segment, and subscript 1, 2, 3, and 4 stand for the particular farm. The other subscripts are as defined earlier.

Note that the first term of each equation above, though designated for different farms, are the same in value since they all represent the conveyance efficiency to the point at the farm gate of Farm 1 (the same as to the end of canal segment a). Similarly, the second term is the same for Farms 2, 3, and 4; and the third term is the same for Farms 3 and 4.

In general then

$$\frac{W_{\text{rz},j}}{W_{\text{vo},j}} = \prod_i E_i$$

where j designates the particular farm, and i the efficiency step in the efficiency chain for farm j. To know the overall efficiency for the canal-farm system, it is necessary to know what portion of the reservoir-out water is allocated to which farm. The water allocation to each farm (A_j), as a fraction of the total allocation, can be used as a weighting factor. The overall efficiency for the canal farm system ($W_{\text{rz}}/W_{\text{vo}}$) is then the sum of the weighted efficiency of each farm drawing water from the reservoir. In equation form

$$\frac{W_{\text{rz}}}{W_{\text{vo}}} = \sum_j A_j \left(\frac{W_{\text{rz},j}}{W_{\text{vo},j}}\right) \tag{9}$$

Eq. (9) is written with the example of farms along a canal in mind, and with water in the root zone as the final output and water out of the reservoir as the initial input. Extending to different situations in general, the equation would take the form of

$$\frac{\text{Output}_{\text{final}}}{\text{Input}_{\text{initial}}} = \sum_j A_j \left(\frac{\text{Output}_{\text{final},j}}{\text{Input}_{\text{initial},j}}\right) = E_{\text{all,diverge}} \tag{10}$$

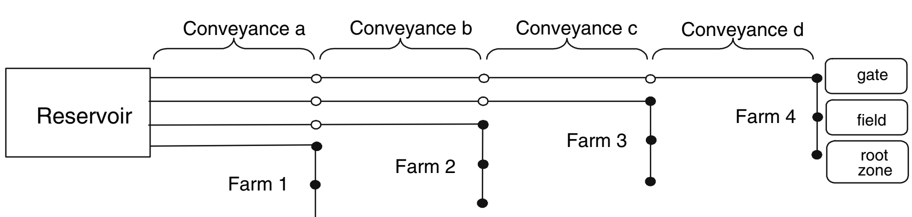

Fig. 1 Schematic diagram of a reservoir supply water to four farms along a canal. The diagram is drawn to make the connections among the various efficiency steps explicit, with (*filled circle*) indicating the beginning and end of each efficiency step, and (*open circle*) indicating the imaginary divisions in the conveyance step

Here the overall efficiency is for any branching chain that diverges downstream from the source of the water (e.g., a reservoir).

Convergence of chains

Instead of starting from one chain and branching into a number of chains as discussed above, in other cases the chains converge and merge along the way. This typically happens upstream from the reservoir. Runoff from the land merges to form a small stream, small streams merge to form a large stream, and large streams merge to form the river feeding the reservoir. These converging chains have losses due to seepage and evaporation, and transpiration by riparian vegetation. The efficiency steps of each chain can be assessed using Eq. (3). After they merge, the overall efficiency for the converging chains at the point of the merger can be calculated with the appropriate weighting of the contribution from the chains, as follows:

$$\sum_k \mathrm{I}_k\left(\frac{\mathrm{Output}_{\mathrm{final},k}}{\mathrm{Input}_{\mathrm{initial},k}}\right)=\frac{\mathrm{Output}_{\mathrm{final}}}{\mathrm{Input}_{\mathrm{initial}}}=E_{\mathrm{all,converge}}. \quad (11)$$

To differentiate from the downstream and branching case, the upstream converging chains are identified by the subscript k, instead of the subscript j. The efficiency of each of the merging chains is weighted by I_k, the amount of water that chain starts with as a fraction of the total amount of starting water for all the upstream chains. If the starting amounts are not known but the amounts contributed by each chain at the mingling point are, and there are reasonable estimates of the upstream efficiencies of each, I_k can be calculated as the input from the output and efficiency of each chain. Note that Eqs. (10) and (11) are identical in form. The key difference between them is that the weighting factor represents the portion of water allocated from the single source (A_j) for the former, and the initial water input of each source (I_k) for the latter.

In many cases the water comes from several sources. That is true even for a single field, where the water stored in the soil at the start of the season is substantial, or where rainfall supplies a significant amount in addition to irrigation. Soil water stored in the root zone merges with water from the rain at the point of root zone water (W_{rz}). Applying Eq. (11) (efficiency of converging chain), E_{k} for soil-stored water would be 1.0, and the weighting factor (I_k) would be the stored soil water divided by the sum of rainfall and stored soil water. E_k for rain water would be the product of rainfall, E_{infil}, and E_{rzstor}, and would be less than 1.0 for most cases; and the weighting factor would be the rainfall divided by the sum of rainfall and stored soil water.

For the case of rainfall adding water to irrigation, and to scale up to the point of the gate of the farm, both Eqs. (10) and (11) would be needed. For each field, Eq. (11) would be used to merge the efficiency of rainwater and irrigation water at the root zone, with the weighting factors calculated using the sum of rainfall and irrigation water delivered to the field. Efficiency of the rainwater would be calculated as indicated in the previous paragraph, and efficiency of irrigation water would be the application efficiency. To aggregate to the farm gate level, Eq. (10) would be used, with E_j calculated for each field being weighted by its own A_j, and the calculated overall efficiency of individual fields. An example of the calculations for a hypothetical small farm consisting of three fields is given in Table 4, with footnotes specifying the various calculation steps. In the table, W_{irrig} (instead of W_{fd}) is used to designate the volume of water supplied to each field by irrigation, to clearly differentiate it from water coming from rainfall (W_{ppt}). That is, W_{irrig} in the table is synonymous with W_{fd} in the previous text.

Up through hierarchical levels

Reservoirs have generally more than one canal, each with its own laterals. In that case, Eq. (10) would be applied successively, starting with the lowest scale (each lateral) and going upward, until the full system is integrated. For the more complicated situations where there are more than one water source, Eq. (10) is still crucial for scaling up, but with due consideration of the multiple sources of water.

If there are several sources of water in a geographic area and there is no interaction among them, the scaling up process would be straight forward, treating each source separately first, then sum up the weighted overall efficiency of each source, as described by Eq. (10). A_j in this case is the fraction of total water in the area accounted for by source j. When there is mingling among the water sources, however, the downstream distribution and use of the water would be assessed as usual by taking the mingled water source as a single source. To combine the downstream efficiency with the efficiency upstream from the point of mingling, the overall efficiency for the converging upstream chains leading to the point of mingling is assessed by applying Eq. (11). Then the overall efficiency including both the converging and diverging

Table 4 Sample calculation of integrated efficiency ($E_{\mathrm{all,fg + ppt\ to\ rz}}$ = 0.553), with rainfall and water delivered to the farm gate as input and water in the root zone as output, for a hypothetical farm consisting of three fields

	Field a	Field b	Field c
Area (m^2)	9,200	5,450	7,650
Rainfall (mm)	110	110	110
W_{ppt} (m^3)	1,012	600	842
E_{infil}	1	0.86	0.9
E_{rzstor}	1	1	1
[a]I_{ppt}	0.191	0.167	0.208
Irrigation (mm)	465	550	420
W_{irrig} (m^3)	4,278	2,998	3,213
E_{appl}	0.7	0.65	0.85
[b]I_{irrig}	0.809	0.833	0.792
[c]$E_{\mathrm{all,converge}}$	0.757	0.685	0.860
E_{farm}	0.8	0.7	0.65
[d]$W_{\mathrm{fm,j}}$ (m^3)	5,348	4,282	4,943
[e]A_{j}	0.367	0.294	0.339
[f]$E_{\mathrm{all,fg + ppt\ to\ rz}}$			0.553

The efficiency of the various steps are assumed, as are the amount of rainfall and irrigation. Water stored in the soil at planting is taken to be negligible. Equation 11 was used to calculate $E_{\mathrm{all,converge}}$ for each field, and Eq. 10 was used to integrated the efficiencies of the fields with E_{farm} to obtain the overall efficiency. Calculations are as specified in the footnotes

[a] $I_{\mathrm{ppt}} = W_{\mathrm{ppt}}/(W_{\mathrm{ppt}} + W_{\mathrm{irrig}})$ Each field is treated separately in this and the following four calculations

[b] $I_{\mathrm{irrig}} = W_{\mathrm{irrig}}/(W_{\mathrm{ppt}} + W_{\mathrm{irrig}})$

[c] $E_{\mathrm{all,converge}} = (I_{\mathrm{ppt}} \times E_{\mathrm{infil}} \times E_{\mathrm{rzstor}}) + (I_{\mathrm{irrig}} \times E_{\mathrm{appl}})$

[d] $W_{\mathrm{fm},j} = W_{\mathrm{irrig}}/E_{\mathrm{farm}}$

[e] $A_j = W_{\mathrm{fm},j}/(W_{\mathrm{fm,a}} + W_{\mathrm{fm,b}} + W_{\mathrm{fm,c}})$ where j stands for Field a, or Field b, or Field c

[f] $E_{\mathrm{all,fg + ppt\ to\ rz}} = (A_{\mathrm{a}} \times E_{\mathrm{all,converge,a}} \times E_{\mathrm{farm,a}}) + (A_{\mathrm{b}} \times E_{\mathrm{all,converge,b}} \times E_{\mathrm{farm,b}}) + (A_{\mathrm{c}} \times E_{\mathrm{all,converge,c}} \times E_{\mathrm{farm,c}})$

portion are calculated as the product of $E_{\mathrm{all,diverge}}$ and $E_{\mathrm{all,converge}}$.

In theory then, by applying Eqs. (3), (10) and (11) carefully, according to the connections between the steps in the efficiency chain and among the chains, the water use efficiency of complex systems at the landscape and watershed level can be integrated and quantified. With some simplifying assumptions this scaling up can be carried to even higher scales, to cover large land areas and even nations.

Different products and multiple use of a product

Commonly, farms and fields in the same area may differ in the kinds of crops grown. In addition, often more than one product are produced from a field. For example, animals may produce eggs, wool, or milk in addition to meat, and vegetative residue from a grain crop may be used to feed animals. For the analysis of the individual efficiency steps and chains into an overall efficiency, the various final products must be expressed in a common unit for output (usually in monetary or relative values, but can be in terms of energy content). When more than one product are produced by a crop or animal species, it is simply a matter of adding the values of each together in the efficiency quantification process. When different fields or farms have different product mixes, Eq. (10) will be used, once they are expressed in common units. For cases where different crops growing on different fields are fed to the same animals, Eq. (11) would be applied since it represents a convergent situation.

Use in economic analysis and optimization

The ability to quantify the contribution of improvement in any efficiency step to the improvement in overall efficiency makes this approach extremely useful. Different steps have different efficiencies and the cost of their improvement also differ. Often the cost of raising a step efficiency to a top level is very high, but raising it to a modest level is low or moderate. Equation (6) indicates that generally it is better to allocate resources to improve the steps with the lowest efficiencies, because the overall improvement is proportional to the fractional improvement of a step. So a given percentage improvement (e.g., 10%) in a low efficiency step (e.g., from 0.3 to 0.33) has exactly the same effect on the overall efficiency as the same percentage improvement in a high efficiency step (e.g., from 0.9 to 0.99). In most situations it would be easier and cheaper to raise the efficiency of a step from 0.3 to 0.33 as compared to raising it from 0.9 to 0.99. When many step efficiencies are less than the good situation, however, how to allocate the limited resources for improvement among the steps is not simple and requires optimization. The chain of efficiency steps approach provides the quantitative means to do this.

The starting point is Eq. (6), which expresses the new overall efficiency as the product of the original overall efficiency times the products of the fractional improvements at each step of the chain. To optimize resource allocation so to obtain the maximal benefit, we need first to identify the cost (C_i) that is required to achieve each fractional improvement (Δ_i). That is, we need to know the unit marginal cost as defined by the $\delta C_i/\delta \Delta_i$ of the cost function $C_i = f(\Delta_i)$. For instance, what is the cost of improving canal maintenance to raise the efficiency of the conveyance step (E_{conv}) by one tenth of its existing efficiency? What is the cost of a new irrigation system, new equipment to improve the irrigation management, or the training of irrigators to improve the application efficiency step (E_{appl}) by one tenth of its existing value? In all cases, it is necessary to identify or make reasonable estimations of C_i for different levels of Δ_i. Of course it would be even better to have the actual function of $C_i = f(\Delta_i)$, or a reasonable approximation thereof. With C_i per Δ_i known or estimated, the total cost of all the improvements in the chain to move from the original overall efficiency to the new overall efficiency would be

$$C_{\text{total}} = \sum_{i=1}^{i} C_i \, \Delta_i. \tag{12}$$

The next step of the optimization process consists of setting the boundary conditions and constraints. In most cases, the total amount of fund available is one constraint. With fund limitations, one may decide not to spend more than some given amount on any or all of the efficiency steps. In addition, some physical or other limitations may restrict the extent an efficiency step may be improved. For example, due to poor soil characteristics and a lack of power to operate a pressurized irrigation system, the fractional improvement in application efficiency step (E_{appl}) can be set not to exceed a certain value. Similarly, fractional improvements in other steps may also be confined to given ranges. These conditions need to be specified as the boundary functions in the optimization processes

$$C_{\text{total}} = \sum_{i=1}^{i} C_i \, \Delta_i$$
$$C_{\text{total}} \le \$_{\text{total}}$$
$$C_1 \le \$_1$$
$$C_2 \le \$_2$$
$$C_3 \le \$_3$$
....
$$C_i \le \$_i$$

and/or

$$v_1 \ge \Delta_1 \ge \omega_1$$
$$v_2 \ge \Delta_2 \ge \omega_2$$
$$v_3 \ge \Delta_3 \ge \omega_3$$
....
$$v_i \ge \Delta_i \ge \omega_i$$

where \$ denotes the amount of fund, v the lower limit of fractional improvement in efficiency, and ω the upper limit of fractional improvement in efficiency. The subscripts refer to the specific efficiency steps (1, 2, 3,.....,i).

Once the boundaries conditions are set, the optimization is formalized with the objective function

$$\text{Maximize } E_{\text{all, new}} = E_{\text{all, original}} \times \prod_i (1 + \Delta_i).$$

The optimization problem is then solved with suitable methods available in operational research practices (e.g., Mitchell 1993), easily implemented in computer software that searches for the optimal solutions through numerical iterations. Although our discussion is on optimizing a single efficiency chain, the treatment can be extended to the cases of branching or convergence chains and scaled up to higher levels of aggregation by inserting into the optimization process the new overall efficiency to maximize (through application of Eqs. 10 and 11) and the pertinent boundaries functions.

Concluding discussion

Use of water in agriculture is perceived by wide segments of society as a very inefficient process. In particular, irrigated agriculture is under intense scrutiny because it competes with other sectors for water and because of its negative impact on the environment. The pressures to become more efficient in the use of water in agriculture can only increase in the future. This paper, by considering the use of water to produce food as interlinked chains of sequential efficiency steps, proposes a relatively simple way to quantify the overall water use efficiency in terms of the efficiency of each of the steps, which can be divided finely or coarsely according to needs. Particularly important is the fact that the impact on the overall efficiency of any change (increase or decrease) in the efficiency of one or more of the steps can be readily quantified. Using this chain of efficiencies approach as the framework, we have analyzed the key underlying engineering, agronomical, and physiological processes and identified many opportunities for improving water use efficiency in agriculture. Depending on the geographical location, some or many of the improvements might have already been made, many others might have been ignored, or the potential for improvement in those steps might not be even recognized. What are the requisites for advancing this process? Obviously, successful adoption of new water technologies has socio-economic and institutional requirements that are discussed in detail by others in this issue (Hussain et al. 2007). On economics, the price that farmers pay for water in many world areas is much less that the value of that water. While water pricing may be a useful instrument to promote new technologies that lead to more efficient water use, it has many shortcomings if applied rigidly, especially in poor rural areas (Hussain et al. 2007 this issue). Water markets or market-like arrangements (Jury and Vaux 2005) also offer advantages in the quest for higher efficiency. Though having limitations, they work best in situations of water scarcity where agriculture and water rights are well developed. A very important social requisite is the need for farmers' participation in the management of local water resources. In fact, the combination of self-reliance and solid water rights are two critical ingredients always found in areas of high water productivity. To the extent that water management institutions are fully participatory and having resources for infrastructure maintenance and long-term investments, the adoption of measures to increase water use efficiency will become much more likely.

In looking at the future, water scarcity is considered the single biggest water problem worldwide (Jury and Vaux 2005). Global food production may soon be limited by water availability, as it already is now in many geographical areas, but it will be increasingly difficult to generate additional water supplies for agriculture without impacting the environment and other users of water. It is obvious then that the solution to this conflict lies mostly on improving the efficiency of water use for food production. The chain of efficiency approach delineated above serves this purpose in three important ways. First, it provides a comprehensive framework, cutting across a number of disciplines, to diagnose the actual efficiency level and its components of a given situation, and to compare them to what would be reasonable or the attainable levels of that situation. Second, by offering a mechanism to scale up quantitatively from individual processes to water use efficiency on large scales, it provides the means to analyze and assess the extend of overall improvement in water use efficiency in terms of potential improvements in the component steps. Especially useful in this regard is the fact that the effects of changes in efficiency of component steps on overall efficiency is multiplicative, and that the same fractional improvement in any of the sequential steps has identical effect on the improvement in overall efficiency. This culminates in the conclusion that generally it is better to make improvements in at least several of the steps low in efficiency, instead of concentrating efforts in improving one or two of the steps. Practically, this provides a simple means, by trial and error with a calculator or spreadsheet, to aid in the decisions on which specific steps should be given more attention in improvements. Finally, the quantitative relations developed make it possible to use optimization techniques to decide on the best allocation of limited economic resources to maximize water use efficiency of a system.

Although throughout our analysis emphasis has been placed on the quantitative aspects, it is clear that the primary factor that determines the differences between good and poor situations is mostly tied to management. Water management is a human undertaking and therefore has to deal with social and cultural issues that can often dominate over the agronomic, physiological and engineering considerations discussed. A key social and environmental consideration is sustainability of the agroecosystem. There are many facets to the sustainability, including dependability of water supplies, land degradation and salt leaching, the quality and fate of irrigation return flows, health hazards carried by the flows, economic viability and markets, and the existence of reliable water institutions and policies. To achieve higher water use efficiency in an area, advances in the dissemination of new technologies must be coupled with the development of new institutions that are capable of managing water effectively. All these make water management extremely complex, demanding attention from professionals of many different disciplines.

One approach that is now being used to deal with the complexity of managing the scarce water resources is that of adaptive management (Walters 1986). Rather than undertake an elaborate analysis a priori and base all subsequent decisions on predictions from that analysis, the adaptive approach emphasizes the updating of knowledge that is acquired through observations that feed back to the decision makers. Management actions would change, or adapt, to the changing behavior of a system that is too complex to be easily predictable. This adaptive approach is particularly appealing in the case of managing water for the multiple functions and the variety of stakeholders in human society. Managing water resources in a basin has to deal with population growth, land use change, climate variability and climate change, all processes where available information and experience are insufficient for predictive purposes. This is because such systems involve complex and often highly nonlinear relationships among their various elements; even with the use of simulation models, prediction can be difficult in the short term and nearly useless in the long term. The process of 'learning by doing' based on monitoring programs that include periodic observation, evaluation, and revision of decisions and projections seems a promising approach to sustain continuous improvement of water use efficiency in agricultural systems. The chain of efficiencies concept would provide a clear and fundamentally based framework to carry out these efforts.

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Appendix

Table 5 Table of abbreviation for the subscripts designating efficiency, and water or mass

Subscript for *E* (efficiency)		Subscript for *W* (water) or *m* (mass)	
Abbreviation	Meaning	Abbreviation	Meaning
All	Overall	ar	Available for recovery
appl	Application	bm	Biomass produced
as	CO_2 assimilation	bm eaten	Biomass consumed by animal
bm	Plant biomass	et	Consumptive
conv	Conveyance	fg	Farm gate
convert	Animal conversion	as	Assimilated CO_2
et	Consumptive	fd	Field
farm	On farm	infil	Infiltrated into soil
graz	Grazing	irrig	Irrigation (same as field)
infil	Infiltration	Live ani	Live body of animal
n	New	ppt	Precipitation (rain)
o	Original	rz	Root zone
rec	Recovery	tr	Transpired
rzstor	Root zone storage	vo	Reservoir outlet
tr	Transpiration	yld	Yield of crop
yld	Yield	letters a, b, c, etc.	Designating individual farms along a canal

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