Systematic approach to the improvement of agricultural water use efficiency

Hsiao T.C.

in

Lamaddalena N. (ed.), Shatanawi M. (ed.), Todorovic M. (ed.), Bogliotti C. (ed.), Albrizio R. (ed.).
Water use efficiency and water productivity: WASAMED project

Bari : CIHEAM
Options Méditerranéennes : Série B. Etudes et Recherches; n. 57

2007
pages 51-57

SYSTEMATIC APPROACH TO THE IMPROVEMENT OF AGRICULTURAL WATER USE EFFICIENCY

T.C. Hsiao
Professor Emeritus, Dept. of Land, Air, and Water Resources, University of California, Davis.
1 Shields Ave., Davis, California, 95616, U. S. A. Email: tchsiao@ucdavis.edu

SUMMARY - Effective management of scarce water resources requires a systems approach. Starting at the source of water, a cascade of events leads to the final production of crops or animal products at the expense of water. These events are mostly sequential, with each process step in the sequence having its own efficiency of output per unit of input. Using a simple sequence of three hypothetical steps, it is shown that the overall efficiency of a process is the product of the efficiencies of each sequential step. That is, efficiencies of individual process steps are multiplicative in determining the overall efficiency. Thus, improvement in any one of the efficiency steps has equal effect in improving the overall efficiency, and the overall improvement is more than the sum of the individual improvements. This principle provides a simple and quantitative means to optimize the allocation of limited resources in improving water use efficiency.

Crop production in relation to water use are considered in terms of the pertinent sequence of efficiency steps for irrigated conditions. Rainfed conditions will be considered in another presentation in the Rainfed and Drought session. Efficiency steps and the sequences are outlined and discussed and the likely improvements assessed quantitatively for some scenarios. The universal applicability of this approach to different cropping as well as animal production systems when water is limiting is emphasized.

Key words*:* Irrigation, crop productivity, water saving, management, resource allocation, optimization.

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 regimes. Adding to the problem is the increased awareness of the need for water in the preservation of the environment and ecosystems. Since the fresh water resources are essentially finite on earth, making more efficient use of the water must be a major focal point in coping with water shortage. Numerous ways have been devised or advocated and major efforts have been made to improve the efficiency of water use in agriculture. 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 and environmental influence. A systematic and quantitative approach is needed to analyze where the inefficiency lies, to assess the potential improvements, and most importantly, to determine how to allocate limited available resource to maximize the improvement in water productivity. This paper describes briefly a relatively simple and yet quantitative and comprehensive framework for these purposes. A more complete treatment is given in a paper in the forthcoming special issue of *Irrigation Science* (Hsiao *et al.*, 2005).

THE CONCEPT OF CHAIN OF EFFICIENCY STEPS AND ITS SIGNIFICANCE

Generally and as commonly used in economics, efficiency of any production process may be defined as the ratio of input to output for that process, both measured in quantitative units. The units to use vary depending on the situation; if the same units define both, then the efficiency ratio is unitless. For example, if the resource input as well as the production output is measured in monetary units such as dollars or euros, the efficiency ratio (or simply efficiency) would be in fractions or percentage. If the measure of input and output are in different units, then the units for the efficiency must be given for the efficiency to be meaningful. For example, fuel efficiency of a car may be expressed in km per liter, the ratio of the distance traveled to the volume of gasoline consumed.

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 in terms of the efficiency of each of the component steps. Because the processing steps are in sequence and comes one after another, the output of the first step is the input of the second step, and the output of the second step is the input of the third step, etc. In equation form:

$$\text{Output}_i = \text{Input}_{1+1}\,, \qquad \text{and}$$

$$E_1 = \frac{\text{Output}_1}{\text{Input}_1} \qquad (1a)$$

$$E_2 = \frac{\text{Output}_2}{\text{Input}_2} = \frac{\text{Output}_2}{\text{Output}_1} \qquad (1b)$$

$$E_3 = \frac{\text{Output}_3}{\text{Input}_3} = \frac{\text{Output}_3}{\text{Output}_2} \qquad (1c)$$

where E designates efficiency of a step in the efficiency chain, and the subscripts i, a running number, designates the steps; 1, 2, and 3 refer to the specific steps, 1 being the first step and 3 being the last (third).

If there are only three steps in the whole efficiency chain, the overall efficiency (E_{all}) would be the ratio of the final output (output3) to the initial input (input1), i. e.,

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

Because the steps are sequential, the output of the preceding step is the input of the following step, as can be seen by a close examination of Eq. 1a, 1b, and 1c. This gives rise, inevitably, the following relationship between the efficiency of individual steps and the overall efficiency:

$$E_{all} = \frac{\text{Output}_1}{\text{Input}_1} \times \frac{\text{Output}_2}{\text{Output}_1} \times \frac{\text{Output}_3}{\text{Output}_2} \qquad (2)$$

It is easily seen from the right side of the equation that the numerator of the first fraction cancels out the denominator of the second fraction, and the numerator of the second fraction cancels out the denominator of the third fraction, leaving only the ratio of the last output (output3) to the first input, (input1), 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. This simple mathematical outcome holds true regardless of the number of individual steps in the whole process, although Eq 2 is written for an efficiency chain consisting only of three steps.

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 can be obtained. Denoting the fractional improvement by □, an expression for the improved efficiency of a step (E_{new}) is:

$$E_{new} = (1 + \Delta)\, E_{original} \qquad (3)$$

Applying Eq. 3 to all the steps in an efficiency chain and designating each step by the running number j (j = 1, 2, 3, etc. depending on the position of the step in the chain), a general expression of the new overall efficiency (E_{all},new) in terms of □ and the original overall efficiency (E_{all}, original) is as follows:

$$E_{all,\,new} = E_{all,\,original} \times \prod_j \left(1 + \Delta_j\right) \quad (4)$$

where Π is the multiplication operator over items j. 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. Eq. 4 is general, and can be applied to any efficiency chain. 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) as negative.

There are some important features to note regarding Eq. 2 and 4: (1) The treatment is quantitative, and by simple mathematics, demonstrates the fact that the overall efficiency is the products of the efficiencies of individual steps (and not the average of the efficiencies). (2) 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. (3) 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. (4) 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, 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 some examples are given. Befitting the objectives of this conference and as an example, the chain of efficiency steps concept is applied in the next section to irrigated crop production to quantify water productivity or water use efficiency.

EFFICIENCY OF IRRIGATED CROPPING AND POTENTIAL FOR IMPROVEMENT

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 or other sources to the soil of the root zone of the crop. This covers the water and irrigation engineering aspects but not the agronomic and crop aspects. In this paper the concept is extended all the way to crop yield, starting from water diversion from the reservoir. Beginning with the engineering aspects, one may divide up the processes into some obvious sequential steps. 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 of course on the circumstances and engineering and management practices, and can vary from very low to very high. In Table 1 the range of efficiency for this first and each following step are given, one for poor situations when the efficiencies are low, and one for good situations when the efficiencies are high. These ranges are based on literature and our general understanding and do not include the more extreme values, especially those in the poor situation category. Also given in Table 1 are the overall efficiency (E_{all}) for the poor and good situations, calculated according to Eq. 2 from the mid-value (average of the two limits of the range) of each step efficiency. In addition, the numerator and denominator of the efficiency ratio for each step are also given, as well as the efficiency units.

After the water arrives at the farm, it is stored or not stored depending on the farmer, and 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}). The ranges of efficiency for the poor and good situations are also given in Table 1. 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}. Applying Eq. 2 to link the three efficiency steps described, as well as the subsequent five steps leading to crop yield to be described later, the whole efficiency chain and the overall efficiency are:

$$\frac{W_{fg}}{W_{vo}} \times \frac{W_{fd}}{W_{fg}} \times \frac{W_{rz}}{W_{fd}} \times \frac{W_{et}}{W_{rz}} \times \frac{W_{tr}}{W_{et}} \times \frac{m_{as}}{W_{tr}} \times \frac{m_{bm}}{m_{as}} \times \frac{m_{yld}}{m_{bm}} = \frac{m_{yld}}{W_{vo}} = E_{all} \quad (5)$$

Again, because the output of the preceding step is the input of the following step, all the terms on the left side of Eq. 5 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. Efficiency of the sixth step is the mass (m) of carbon dioxide assimilated per unit of water transpired by the crop. Units of each efficiency as used in this paper are given in Table 1.

Table 1. Range of efficiencies for the steps in the efficiency chain from water diverted out of the reservoir to yield of annual grain (or fruit) crops. Two ranges are given, one for poor circumstances and practices, and the other for good circumstances and practices. Also given are the overall efficiency for the two situations, calculated from mid-values of the efficiency steps. The denominator of the efficiency ratio is the input, and the numerator, the output, for each efficiency step.

			Efficiency	
Efficiency step	Efficiency ratio	Units	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
$\mathbf{E_{all}}$	m_{yld}/W_{rz}	kg m^{-3}	**0.0242**	**1.22**

With the chain of efficiency steps fully written out in Eq. 5, we now return to describe the remaining steps (from the fourth step onward), which concern the plant and agronomic aspects. The fourth step is consumptive efficiency ($E_{et} = W_{et}/W_{rz}$), 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 ($E_{tr} = W_{tr}/W_{et}$), 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 ($E_{as} = m_{as}/W_{tr}$), a measure of the mass of carbon dioxide assimilated by photosynthesis (m_{as}) relative to the volume of water transpired. The measurements here now include 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. 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.

The most striking results (Table 1) of applying Eq. 2 or 5 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 annual 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.

DETERMINANTS OF EFFICIENCY OF THE STEPS AND IMPROVEMENTS OF EFFICIENCY

Some of the more important factors that impact the various efficiency steps are now discussed briefly, along with potential improvements that can be made at relatively low costs, and a sample improvement in the overall efficiency is calculated to illustrate the potentials. Starting with the first step of the chain of efficiencies, a poor E_{conv} implies leaky conduits or open conveyance over long distance with much loss by evaporation. Improvement could be very costly (e.g., converting open channel to closed conduits) or at least more than nominal (e.g., repairing cracks widely spread along the conduit length). The next step efficiency, E_{farm}, is more amenable to improvement. A common cause for low E_{farm} is water leakage from unlined or poorly lined storage pond and conveyance ditches. Lining with plastic sheeting could be relatively inexpensive and could raise E_{farm} from poor to the good level in Table 1. The next step, E_{appl}, may also be improved at nominal cost. One common cause of low E_{appl} for surface irrigation is applying the water too fast or too slow relative to the infiltration rate of the soil and slope of the land, resulting, respectively, either in too much deep drainage at the head, or too much drainage at the tail end, of the field. Better control of the application rate to match the infiltration rate and slope should entail only minimum cost. For sprinkler irrigation, E_{appl} may be improved by avoiding irrigating under strong wind, and by pressurizing the sprinkle line adequately to ensure even water distribution. The next step, E_{et}, is already relatively high for the poor situation; improvement is more readily made in E_{tr}. Low E_{tr} is the result of too much soil evaporation relative to crop transpiration. Since soil evaporation is high when coverage of the ground by foliage canopy of the crop is low and when the soil surface is frequently wetted (Ritchie and Burnett, 1971), E_{tr} is raised if the crop is planted more densely and more uniformly distributed over the soil to provide better canopy cover, and the soil is not irrigated frequently to minimizing wetting of the soil surface. The water transpired by the crop is in exchange for the cabon dioxide assimilated photosynthetically by the crop. E_{as} is generally higher for C_4 species than C_3 species, and higher if mineral nutrients, especially nitrogen (Steduto et al. 2005), are not deficient. E_{as} is also affected by evaporative demand of the atmosphere, being higher under cooler temperature and higher humidly (Hsiao, 1993b; Xu and Hsiao, 2004). If switching from a C_3 to a C_4 crop is not an option, It may be possible to change the planting time so growth of the crop takes place under the lower evaporative demand of the cooler part of the season. Better fertilization would improve E_{as} as well and the extra cost of the fertilizer may pay for itself by increasing yield in addition to enhancing E_{as}. Next step is biomass efficiency, E_{bm}. Because it is largely a function of the chemical composition of the crop, it is not easily changed except for the possibility of reducing respiratory loss of assimilates by growing the crop under a cooler temperature regime. The last step is E_{yld}, the ratio of harvested yield to the total crop biomass. E_{yld} has been improved considerably during the last century as the result of breeding for crops with higher yield. The higher yields turned out to be largely the result of partitioning more biomass to fruit or grain and less to vegetative parts (Evans, 1993). For a number of crops, the partitioning can be modulated by water status of the plant, and hence by irrigation scheduling. Unusually high water status induces more vegetative growth in many species and can reduce E_{yld}. Mild water deficit after the crop canopy is fully grown may improve E_{yld}, but very severe water deficit at pollination time would reduce it markedly. Moderate water stress also reduces E_{yld} during grain filling because of accelerated leaf senescence, especially if the crop is relatively low in nitrogen. These effects are more thoroughly discussed elsewhere (Hsiao, 1993a; Hsiao et al., 2005). It suffices to say that strategically better timed irrigation provides a means to improve yield efficiency (equivalent to harvest index) at a minimum or no additional cost.

Just how much increase in E_{all} of the poor situation in Table 1 can be expected if some of the nominal or low cost improvements in the individual efficiency steps discussed above are carried out? Eq. 4 shows that if the improvement is only in one step, say a 55% increase in the efficiency of that step (Δ = 0.55), then the improvement in E_{all} is also 55%. This holds regardless which step is being improved. On the other hand, if improvements are made in a number of the steps and none of them are major, there would be marked improvement in E_{all}. To illustrate, the improved E_{all} is evaluated by applying Eq. 4 assuming the following: the original E_{all} is that for the poor situation in Table 1; E_{farm} is increased 40% (Δ = 0.40) by lining the ditches but not the storage pond with plastic sheeting; E_{appl} is increased 37% by taking more care to regulate water application for the furrow irrigated field; E_{tr} is increased 25% by reducing irrigation frequency somewhat while increasing the water applied per irrigation to ensure good water supply to the crop; and the other efficiency steps in the chain remain unchanged. The $(1 + \Delta)$ values for the improvements in the order given are: 1.4, 1.37, and 1.25, and their product is 2.4. That is, the new overall efficiency is now 2.4 times the original overall efficiency, and calculates out to be 0.058 compared to the original 0.0242 kg of yield per m^3 of water. If some additional but still not costly improvements are made in the steps, E_{all} could be raised still much higher. For example, if the storage pond is spread with clay to reduce the porosity of the soil bottom and E_{farm} is increased by 78% as the result instead of only 40%, E_{as} is increased 19% by improved nitrogen fertilization, and E_{yld} is increased 24% by better control of irrigation to restrict leaf growth after canopy closure. The overall efficiency would be increased 4.5 fold in this case, to 0.109 kg of yield per m^3 of water. Note that the overall improvement is marked although still much lower than that for the good situation in Table 1. The point is that a systematic and integrated approach must be taken to produce more crop per unit of water, by examining all the individual steps for potential improvements at nominal cost, and not just focus the attention on one or two of the step. That way limited resources can go a long way in improving water use efficiency.

APPLICATION TO OTHER PRODUCTION SYSTEMS AND ON LARGER SCALES

Because the principle and equations are general, the chain of efficiency steps is application to any production systems as long as the steps in the production process are largely sequential. Water is of paramount concern in rainfed cropping systems in less humid areas. To apply this approach, the engineering aspects, from conveyance from the reservoir to placing water in the root zone, are replaced by a couple of efficiency steps involving infiltration of rain water into the soil and retention of the water in the root zone. From that point onward the steps are the same as those starting on line 4 (E_{et}) of Table 1. The concept is also valid for animal production. By adding animal production steps following the biomass step (for forage fed animal) or yield step (for grain fed animal), the final outcome is animal product instead of crops. These interesting applications are discussed elsewhere (in a presentation in the Rainfed and Drought session of this conference, and in Hsiao et al, 2005).

The treatment here is confined implicitly to the local scale. In fact, the unit considered is a single field. For practical use, it is necessary to account for more complex situations such as a farm with a number of fields of different crops, or an irrigation district comprised of many farms and several distribution canals. These situations certainly make the calculations more complicated, but the principle and basic equations still apply. A way to integrate the basic equations for application at large scale has been worked out and is discussed in Hsiao et al. (2005). Another complication is the need to account for the use of recycled runoff and drainage water, also discussed in Hsiao et al.

USE IN ECONOMICAL ANALYSIS

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 difference 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. Eq. 4 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., 20%) in a low efficiency step (e.g., from 0.4 to 0.48) has exactly the same effect on the overall efficiency as the same percentage improvement in a relatively high efficiency step (e.g., from 0.8 to 0.98). When many step efficiencies are less than the good situation, how to allocate the limited resources for improvement among the steps is not simple and requires optimization. The approach here provides the quantitative fundaments for that process.

Acknowledgement

The intellectual development of the approach described here owns much to discussions with and suggestions from Dr. Pasquale Steduto. I also thank Prof. Elias Fereres for valuable input, criticism and encouragement.

REFERENCES

Evans, L. T. (1993). *Crop evolution, adaptation, and yield*. Cambridge University Press, Cambridge.

Hsiao, T. C. (1993a). Growth and productivity of crops in relation to water status. *Acta Hortuculturae* 335:137-148.

Hsiao, T. C. (1993b). Effects of drought and elevated CO_2 on plant water use efficiency and productivity. In: M. B. Jackson and C. R. Black (eds.) *Interacting Stresses on Plants in a Changing Climate*, NATO ASI series. Vol. I 16. Springer-Verlag, Berlin. pp. 435-465.

Hsiao, T. C., Steduto, P, and Fereres, E. (2005) A Systematic approach to the improvement of water use efficiency. *Irrigation Sci.*, in preparation.

Ritchie, J. T. and Burnett, E. (1971). Dryland evaporative flux in a subhumid climate: II. Plant Influences. *Agronomy J*. 63:56-62.

Steduto, P, Hsiao, T. C., and Fereres, E. (2005) On the conservative behavior of biomass water productivity. *Irrigation Sci*., in preparation.

Xu, L.-K. and Hsiao, T. C. (2004). Predicted vs. measured photosynthetic water use efficiency of crops stands under dynamically changing field environments. *J. Expt. Bot*. 55:2395-2411.