General irrigation efficiency for field water management

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Abstract

On-farm water management systems are traditionally evaluated using a set of performance indices which are inconvenient for evaluation and comparison. We propose a general efficiency (E_g) which is defined as the ratio of crop transpiration to the sum of the volume of applied water and the volume of deficit. E_g combines the characteristics of traditionally used irrigation efficiencies: application efficiency (E_a), storage efficiency (E_s) and the Christiansen's coefficient of uniformity (U_c). Thus, it is possible to compare the performance of different water application systems and/or design and management scenarios using a single index. The relationships of E_g vs. E_a, E_s and U_c are also presented using a transpiration fraction (α) which is defined as the ratio of transpiration to evapotranspiration.

Keywords: General efficiency; Irrigation efficiencies; Transpiration; Evaporation; Uniformity

1. Introduction

Many researchers proposed different criteria for the design and evaluation of on-farm water management systems (Israelsen and Hansen, 1962; On-farm Irrigation Committee of the Irrigation and Drainage Division, 1978; Merriam et al., 1983; Bos, 1985; Holzapfel et al., 1985), among which the most commonly used efficiency terms are application efficiency, E_a, storage efficiency, E_s, and the Christiansen's coefficient of

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uniformity, U_c. Nevertheless, none of these terms alone can fully characterize the effectiveness or performance of an irrigation event. For instances, the application efficiency, defined as

$$E_a = \frac{\text{water stored in the soil root zone}}{\text{water delivered to the field}} \tag{1}$$

describes only the fraction of applied water which could be used by plants. It is mainly concerned with the efficiency with which water is being utilized. However, it does not provide information regarding adequacy and uniformity of irrigation. The storage efficiency, defined as

$$E_s = \frac{\text{water stored in the soil root zone}}{\text{water needed in the crop root zone}} \tag{2}$$

is a measure of the adequacy of wetting in the crop root zone and is mainly concerned with the crop yield effectiveness. But, it does not account for the water losses beyond the root zone. The Christiansen's coefficient of uniformity was defined as

$$U_c = 1 - \frac{\sum_{i=1}^{N} |X_i - M|}{NM} \tag{3}$$

where M is the mean of N single observations of water depth infiltrated at X_i. Each X_i represents an equal area of the wetted field. U_c indicates only the uniformity of the final infiltration profile. It does not consider the efficiency and adequacy of the applied water. When E_s alone equals 100%, frequently too much irrigation or rainfall occurs, resulting in considerable deep percolation. When E_a equals 100%, the irrigation or the rainfalls, in most cases, are inadequate, resulting in complete under-irrigation. A fuller image of water-use effectiveness of an irrigation or rainfall event can be obtained by using the above-mentioned multiple terms simultaneously (Israelsen and Hansen, 1962, Holzapfel et al., 1985; Hart et al., 1980; Walker and Skogerboe, 1987; Keller and Bliesner, 1990, Hulsman, 1984; and Holzapfel et al., 1985). The use of multiple efficiency terms has the disadvantage that they hardly provide a clear and explicit picture of the level of performance for given irrigation events. Blair and Smerdon (1988) proposed a deficit/excess efficiency, $E_{d/e}$, defined as

$$E_{d/e} = \frac{\text{water stored in the soil root zone}}{\text{water delivered to the field} + \text{deficit}} \tag{4}$$

where, the "deficit" is defined as the difference between the volume of water needed in the crop root zone and the volume of water actually stored in the crop root zone following an irrigation. It can be used to evaluate irrigation performance with an unique efficiency term. This term, however, is still unable to distinguish the difference between post-irrigation/rainfall transpiration and evaporation, which can better quantify the crop yield response to the water applied.

The general efficiency, E_g, proposed in this paper, further considers the evaporation loss during an irrigation or rainfall interval. Only the finally used and unused waters are accounted for. The definition of the unified new efficiency term also enables one to give closer relationships between water management factors and crop production.

2. Fate of infiltrated water and traditional efficiency terms

At the end of an irrigation cycle, the water initially applied to the field is separated into four distinct portions: (1) Transpiration, which is the amount of water that was evaporated into the atmosphere via the plant tissues. Transpiration is directly related to the crop production (Howell, 1990). Several measurement methods and mathematical/computer models are available to estimate transpiration (Ritchie and Johnson, 1990); (2) Deep percolation, which is the portion of infiltrated water that has been drained below the crop rootzone. Deep percolation is generally considered as a loss in supplemental irrigation design and evaluation in the humid climates. It is directly associated with the leaching of fertilizers and the rise of water table, which are unfavorable for crop production. However, in dry regions where the soils are subject to potential salinization, a certain amount of deep percolation is necessary to maintain favorable salt balance in the root zone via the leaching requirement, LR, and, hence, permits sustainable irrigation. In this case, deep percolation should be the amount of water (drained out of the rootzone) in excess of the leaching requirement (LR); (3) Runoff, the portion of the total volume of irrigation or rainfall water that has left the field; and (4) Evaporation through soil surface. When the crop leaf area index is low, soil evaporation can be a large portion of evapotranspiration, especially if the soil surface is wetted frequently. Compared with transpiration (or plant evaporation), soil evaporation is not directly consumed by plants and has little effects on the formation of crop yield. Deep percolation, runoff and soil evaporation are considered here as the losses of initially applied water into the field.

Fig. 1 shows arbitrary infiltration profiles following a surface/sprinkler irrigation (or a rain) and a trickle irrigation, where the depth of infiltration, z, is expressed as a function of x, distance along the length direction of the field. V = volume; and Z_d = depth of water required to refill the root zone. L_t = the assumed total length of run if the field is longer; and e = the equivalent water depth of evaporation. The volume of deficit, V_0, represents the portion in the root zone that was not refilled by the infiltrated water. The best crop growth is assumed to be at the place $x = L_d$, where $z = Z_d$.
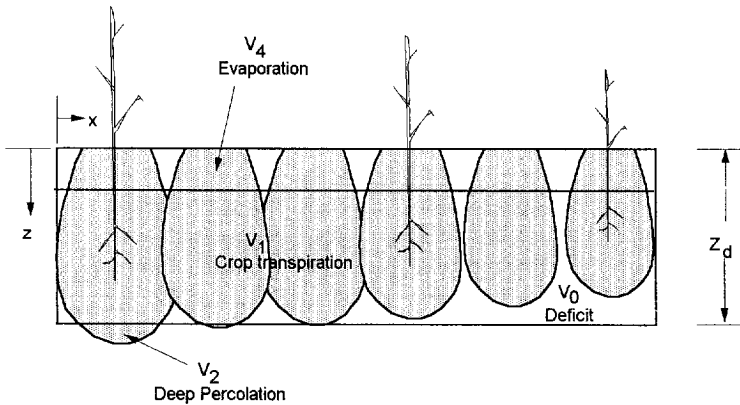
According to Fig. 1, the traditional definitions for E_a, E_s, U_c and $E_{d/e}$ can be expressed as:

$$E_a = \frac{V_1 + V_4}{V} = \frac{V_1 + V_4}{V_1 + V_2 + V_3 + V_4} \tag{5}$$

$$E_s = \frac{V_1 + V_4}{V_1 + V_4 + V_0} \tag{6}$$
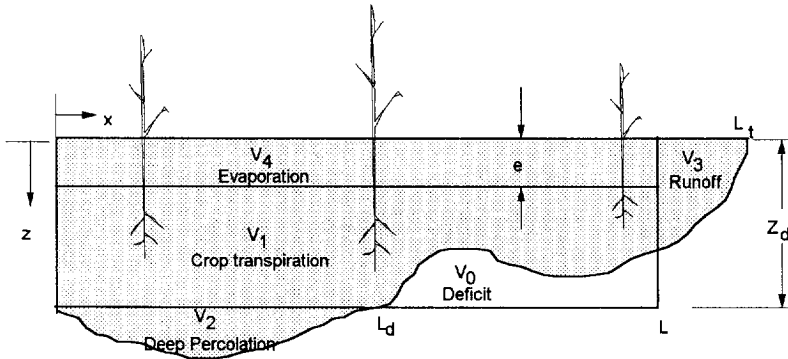
(a) Infiltration profile after a surface or sprinkler irrigation

(b) Infiltration profile after a trickle irrigation

Fig. 1. Infiltration profiles.

$$E_{d/e} = \frac{V_1 + V_4}{V_1 + V_2 + V_3 + V_4 + V_0} \tag{7}$$

$$U_c = 1 - \frac{\Delta z_{avg}}{M} = 1 - \frac{V_2' + V_0'}{V_1' + V_2'} = \frac{V_1' - V_0'}{V_1 + V_2 + V_4} \tag{8}$$

where V = total volume of water delivered to the field; V_1 = transpiration during the irrigation cycle; V_2 = deep percolation; V_3 = runoff; V_4 = evaporation; V_0 = water deficit in the rootzone; z_{avg} = the average depth of infiltration in the field; Δz_{avg} = the average deviation from z_{avg}; V_1' = volume of water stored in the soil above z_{avg}; V_2' = the volume stored below z_{avg}; V_0' = the volume of deficit above z_{avg}. The sum of V_1' and V_2' equal to the sum of V_1, V_2 and V_4. If $Z_d = z_{avg}$, then V_1', V_2' and V_0' are equal to $V_1 + V_4$, V_2 and V_0, respectively, as shown in Fig. 1. The drawbacks of these definitions are outlined before.

3. General efficiency, E_g

The general efficiency, E_g, is defined here as the ratio of crop transpiration to the sum of the volume of water applied to the field and the volume of deficit. Using the notations in Fig. 1, the equation for E_g is

$$E_g = \frac{V_1}{V_1 + V_2 + V_3 + V_4 + V_0} \tag{9}$$

A schematic view of the different components into which the total applied water is broken down is shown in Fig. 1. The advantage of Eq. (9) over Eq. (8) is that only the volume of water transpired by the crop during an irrigation or rainfall interval is taken as the used water by crops.

Transpiration accounts for a fraction of the evapotranspiration (sum of evaporation and transpiration)

$$V_1 = \alpha(V_1 + V_4) \tag{10}$$

where α = transpiration fraction of the evapotranspiration. This factor will be discussed later.

Substituting Eq. (10) into Eq. (9), one can obtain another expression of E_g

$$E_g = \frac{\alpha(V_1 + V_4)}{V_1 + V_2 + V_3 + V_4 + V_0} \tag{11}$$

E_g can be used as a criterion for comparing and evaluating the performance of different types of on-farm irrigation or other water conservation systems. For a perfect (but unrealistic) irrigation where there is no deep percolation, runoff and deficit E_g is unity. Conversely, E_g has a minimum value of zero when no water is used by the crop to meet its transpiration demand.

4. Relationships between E_g, E_a, E_s and U_c

Using Eqs. (5), (6) and (11), the relationship between E_a, E_s and E_g can be found as

$$\frac{\alpha}{E_g} = \frac{1}{E_a} + \frac{1}{E_s} - 1 \tag{12}$$

Simplifying Eq. (12) results in

$$E_g = \frac{\alpha E_a E_s}{E_a + E_s - E_a E_s} \tag{13}$$

Eqs. (12) and (13) show the following results:
- if no deficit occurs ($V_0 = 0$ and $E_s = 1$), which is typical of large applications with a significant amount of runoff and deep percolation, then $E_g = \alpha E_a$; furthermore, when $\alpha = 1$ (means no evaporation loss), $E_g = E_a$;
- If the application of water is small and the runoff (V_3) and deep percolation (V_2) are zero ($E_a = 1$), then $E_g = \alpha E_s$;

- if no water is used for transpiration ($\alpha = 0$), then $E_g = 0$; and
- if $E_a = E_s = 1$ and $\alpha = 1$ (perfect irrigation), then $E_g = 1$.

For irrigation of small application amount with no runoff and deep percolation ($V_2 = 0$ and $V_3 = 0$), E_g can also be expressed as

$$E_g = \frac{\alpha(V_1 + V_4)}{V_1 + V_4 + V_0} = \alpha\left(1 - \frac{V_0}{V_1 + V_4 + V_0}\right) = \alpha\left(1 - \frac{\Delta Z_d}{Z_d}\right) \tag{14}$$

where ΔZ_d = the average deviation in infiltrated depth from Z_d. Eq. (14) shows that when no runoff and deep percolation occurs, E_g has similar characteristics with that of U_c as shown in Eq. (3). This conclusion is also true for applications where V_2 and V_0 are not zero, because both U_c and E_g as shown in Eqs. (8) and (11), respectively, increase with the decrease of V_2 and V_0, and vice versa. Moreover, when an irrigation event results in complete over infiltration ($V_0 = 0$) E_g will not be able to indicate the uniformity. In this case, it may be necessary to use both E_g and U_c to identify possible causes and consequences of poor performance.
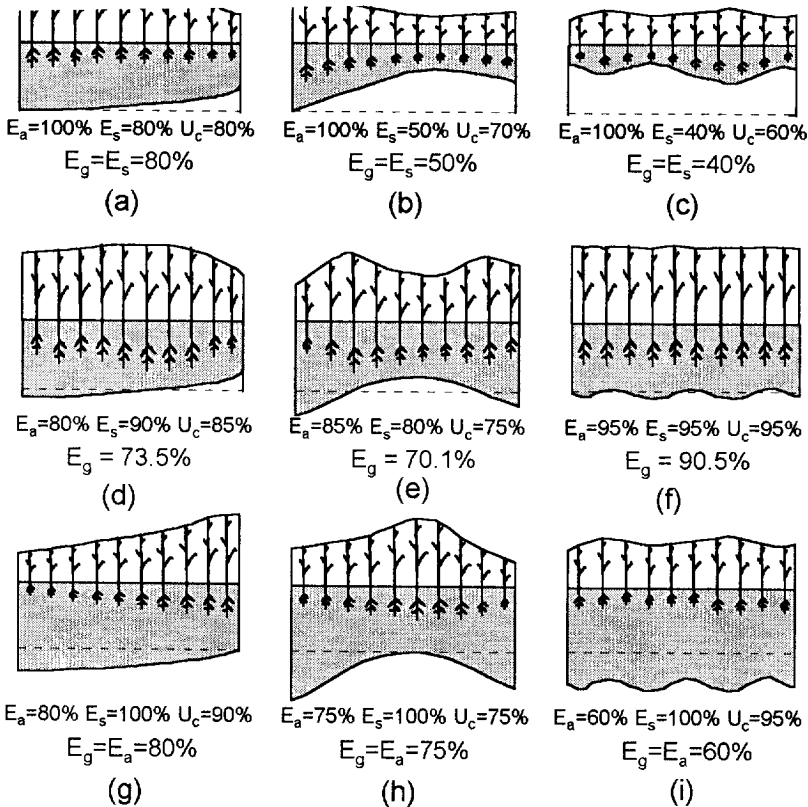

$E_a=100\%$ $E_s=80\%$ $U_c=80\%$
$E_g=E_s=80\%$
(a)

$E_a=100\%$ $E_s=50\%$ $U_c=70\%$
$E_g=E_s=50\%$
(b)

$E_a=100\%$ $E_s=40\%$ $U_c=60\%$
$E_g=E_s=40\%$
(c)

$E_a=80\%$ $E_s=90\%$ $U_c=85\%$
$E_g = 73.5\%$
(d)

$E_a=85\%$ $E_s=80\%$ $U_c=75\%$
$E_g = 70.1\%$
(e)

$E_a=95\%$ $E_s=95\%$ $U_c=95\%$
$E_g = 90.5\%$
(f)

$E_a=80\%$ $E_s=100\%$ $U_c=90\%$
$E_g=E_a=80\%$
(g)

$E_a=75\%$ $E_s=100\%$ $U_c=75\%$
$E_g=E_a=75\%$
(h)

$E_a=60\%$ $E_s=100\%$ $U_c=95\%$
$E_g=E_a=60\%$
(i)

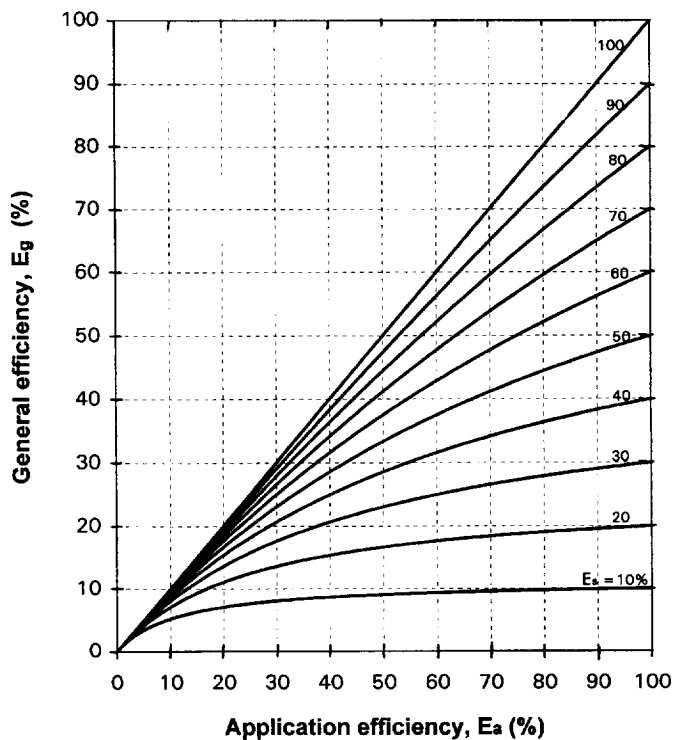Fig. 2. General efficiency, E_g, for typical infiltration profiles (assuming $\alpha = 1$).

Fig. 3. Relationship between E_g, E_a and E_s (assuming $\alpha = 1$).

Fig. 2 shows typical infiltration profiles of surface and/or sprinkler irrigation. The corresponding crop growth status and values of E_a, E_s, U_c and E_g are also indicated in the graphs (assuming $\alpha = 1$). Fig. 2(a), 2(b) and 2(c) show profiles of complete under (or deficit) irrigation; Fig. 2(d), 2(e) and 2(f) show profiles of "dose" irrigation where the volume of water applied is exactly equal to the required amount of water in the root zone; and Fig. 2(g), 2(h) and 2(i) show profiles of complete over irrigation. With complete under irrigation with no runoff $E_a = 100\%$, therefore, $E_g = E_s$. On the other hand, when the "dose" irrigation is applied E_g is calculated using Eq. (13). When the complete over irrigation happens $E_s = 100\%$, hence, $E_g = E_a$. It can be seen that E_g is a good indicator of the general levels of both water use effectiveness and crop growth status while the other indices alone are not.

The graphical relationship between E_a, E_s and E_g (assuming $\alpha = 1$) is shown in Fig. 3, from which it is clear that any reduction in values of either E_a or E_s from 100% results in a less than 100 percent value of E_g.

5. Transpiration fraction, α

Basically, transpiration fraction, α, is the ratio of the actual transpiration to the actual evapotranspiration during an irrigation/rainfall interval. It is affected mainly by climate
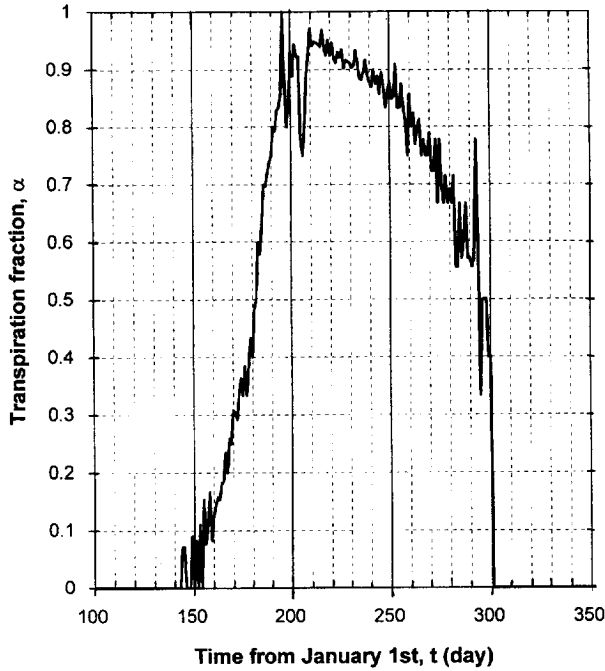
Fig. 4. Transpiration fraction of corn in Belgium (1988).

and crop factors. Fig. 4 shows typically the daily changes of α of corn in Belgium (year 1988). The simulated results were obtained by applying a software package called WAVE (Vanclooster et al., 1995). Similar results can also be obtained for other crops from both experiment and simulation.

Transpiration fraction, α, is useful for proper management, evaluation and optimiza-tion of on-farm water application systems. As typically shown in Fig. 4, α value during earlier stages of crop growth is low ($\alpha < 0.5$, t < 182 days), irrigation and rainfall water is lost predominately through evaporation. Even if high values of E_a and E_s are achieved, the general efficiency E_g is low. Frequent irrigation will result in greater loss of water. From $t \approx 185$ days on, α increased quickly and kept above $\alpha = 0.6$ until $t \approx 295$ days, during which time the crop leaves cover large portions of soil surface. Irrigation or rainfall during this period will achieve high value of E_g, provided that E_a and E_s are simultaneously high. α decreased rapidly to zero after $t = 300$ days when the crop ripened and became dry. In arid and semi-arid regions, agronomic water-con-servation measures such as surface mulching and soil loosing are useful in preventing the evaporation loss and thus increasing the transpiration use. These management measures automatically increase α value (especially during the earlier growing stages), resulting in higher value of E_g and longer intervals between irrigations.

Annual or seasonal evaluation of water effectiveness using E_g can be obtained through Eq. (9), where V_0 through V_4 should be the measured or calculated average quantities during the corresponding periods. Leaf interception of precipitation water

should be added to the amount of V_1 because approximately the same amount of water would have been transpired if without the interception. Better relationship between crop production and E_g is likely to be found because the yield reducing factors, such as deep percolation (V_2) and deficit (V_0), are considered simultaneously in E_g, and the evaporation loss (V_4) is excluded from the criteria used to measure the yield effectiveness of the applied water. Penalty factors may also be assigned to deep percolation, deficit and runoff according to their specific influences on crop production. The weighted general efficiency has the potential for use as a unimodal objective function for optimization purposes in the design and management of on-farm water application systems.

6. Conclusions

This paper presents a unified efficiency term for design, evaluation and optimization of on-farm water application systems. The new efficiency, termed as general efficiency, E_g, combines the characteristics of traditional efficiency terms: E_a, E_s and U_c. Only the transpiration is considered as the used water by crop during irrigation/rainfall intervals. A transpiration fraction, α, which is defined as the ratio of transpiration to evapotranspiration, is introduced to indicate the utility of evapotranspiration and to derive the relationships between the general efficiency and traditional efficiencies.

For small irrigation applications with no deep percolation and runoff, the general efficiency is expressed as $E_g = \alpha E_s$. For large applications in which complete over infiltration happens $E_g = \alpha E_a$. While with the simultaneous occurrence of deep percolation and deficit in the crop root zone $E_g = \alpha E_a E_s / (E_a + E_s - E_a E_s)$. Moreover, E_g has similar characteristics with that of U_c if the deficit is not zero. Raising the α value through better management practices will increase crop productivity in dry climates and/or prolong irrigation intervals, which consequently reduces the require amount of water application.

The proposed general efficiency is expected to be of help for irrigation evaluation and optimization. Closer relationship between yield and E_g is likely to be found especially if penalty factors are assigned to deep percolation, runoff and deficit.

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