IRRIGATION EFFICIENCY AT FIELD LEVEL

The Context

The water balance of an irrigated field (Figure 1) should be viewed from three perspectives: (1) a crop growth perspective, (2) a sustainability perspective, and (3) form the view that scarce water resources should be used efficiently. Hence, a match needs to be found between the following, partly conflicting, rules:

1. To facilitate crop growth, water stress should be limited especially during the first growth stages. This means that during the initial stage and development stages of the crop the relative evapotranspiration ET_a / ET_p should be greater than about 0.67 within the irrigated fields.
2. For sustainable agriculture, the accumulation of chemicals (salt, pesticides, etc.) in the root zone must be avoided. Since all chemicals are transported by water, this means that the annual downward seepage from the root zone must exceed the annual capillary rise into the root zone by some 10 to 20 percent. The accumulation of chemicals can be tolerated during dry months provided that they will be leached during the following wet months.
3. Thirdly, the efficient use of irrigation water demands that the volume of applied irrgation water is as practically low as possible. Precipitation on the area should be used as effectively as practical.

The interaction between the ratio ET_a / ET_p in the fields, the stability of the groundwater table under the command area, and the use of irrigation water are discussed in detail by Bos et al (2009). Here, we further elaborate on irrigation water application.

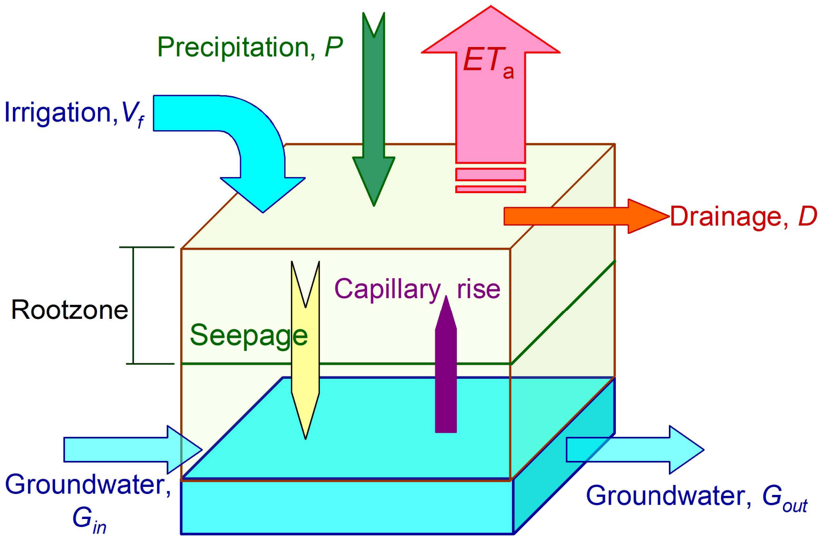

Figure 1. Schematic water balance in an irrigated field (Bos 1984)

Field Application Ratio

Looking back over several thousand years, irrigators have developed a wide variety of methods in order to apply water to a field. All methods were designed to apply water as uniformly as possible to all plants so that water stress is limited. Depending on the used level of technology, each method has the ability to apply water with a related uniformity. However, all methods apply more water to some plants in a field and less to others. Because farmers tend to apply sufficient water to the driest part of the field, most of the field gets more water than required.

Water need and water delivery are related to each other through the field application ratio , R_a. The ICID (1978) standard definition for the field application ratio (efficiency equals $100R_a$) is:

$$R_a = \frac{V_m}{V_f} \qquad 1$$

Where,

V_m = volume of irrigation water needed, and made available, to avoid undesirable stress in the crops throughout the growing cycle (m^3/period).

V_f = volume of irrigation water delivered to the fields during the period under consideration (m^3/period).

The value of V_m in Equation 1 is difficult to establish on a real-time basis because many complicated field measurements would be needed. However, the method that is used to quantify V_m is not very important, provided that the same (realistic) method is used for all command areas (lateral or tertiary units) within the irrigated area. For practical purposes, we can assume that V_m equals the evapotranspiration by the irrigated crop, minus the effective part of the precipitation (i.e. the $ET_p - P_e$ as calculated by CRIWAR). The ratio then can be rewritten as:

$$R_a = \frac{ET_p - P_e}{V_f} \qquad 2$$

Following a closer look at Figure 1, we note that neither ET_p nor P_e are components of the water balance. The value of the ET_p is estimated from meteorological data and from crop data. Most of the time, the actual evapotranspiration (ET_a) is less than the potential value. The effective part of the precipitation is estimated using a variety of factors such as intensity of precipitation, infiltration rate, etc. The effective precipitation (always) is less than the actual precipitation. Therefore, the ratio (efficiency) is not recommended to be used for water balance evaluations. For that purpose it is recommended to use the depleted fraction: DF = $ET_a /(V_f + P)$ as presented in Bos (2004).

Some Background	The field application ratio R_a (efficiency equals 100 x R_a) was developed some 50 years ago as an performance indicator downstream of the conveyance- and distribution ratios (Bos and Nugteren 1974). At that time, they formulated the following four serious drawbacks due to the lack of knowledge on water utilization efficiencies: 1. In the planning and design of irrigation systems a large safety margin is applied, as a consequence of which irrigation facilities like canals, structures, and reservoirs are constructed with capacities that are too large. 2. Investments are considerably higher than otherwise be necessary. 3. The limited water resources are not optimally distributed and used, as a result of which much water goes to waste and less land can be irrigated. 4. Last, but not least, the low overall irrigation efficiency creates harmful side effects such as rising groundwater tables and soil salinization. To control the groundwater table a costly subsurface drainage system may be necessary and this will seriously affect the economy of the project. By now, the focus is on part of the third drawback while the others are neglected.

One of the main purposes of using the ratio of Equatio 2 is to calculate the volume of irrigation water that needs to be delivered to (a group of) fields during the period under consideration. This target irrigation water requirement at the field inlet then equals:

$$V_f = \frac{ET_p - P_e}{R_{a,target}} \qquad 3$$

The target value of the field application ratio, $R_{a,target}$, depends on the level of technology used to apply water, on the level of aridity of the climate, on the availability of irrigation water, and on crop characteristics (dry-foot crop or paddy rice). How they can be determined is shown below.

Dry-foot crops

The ability of an irrigation technology to apply water uniformly to a field is an important criterion in swlwcting the level of technology to be used. At the same time, this uniformity influences the volume of water (per irrigation turn) that needs to be applied to the field, in addition to the crop irrigation water requirements. As an example, let us consider a level basin to which V_m = 100 mm needs to be applied for the considered turn (Figure 3). If the actually applied water depths, $V_{a,i}$, (applied volume or depth per irrigation turn) to parts of an irrigated field are measured, we can assume:

$$V_f = \sum V_{a,i} \qquad 3$$

If the irrigator would decide to apply a volume V_f to the field being exactly equal to V_m, the field application ratio is 1.0 (100% efficiency). Nevertheless, 50% of the field has then been given more water than V_m; the other 50% has received less. In the part of the field that has received less, the ET_a will be less than ET_p and as a result, salt may accumulate in the root zone. This would not cause a problem if sufficient off-season precipitation is available to leach these salts. Hence, the fraction, F, of the field that is allowed to receive less water than $V_m = ET_p - P_e$ depends on the climate.

Till and Bos (1985) assumed a normal distribution of $V_{a,i}$ and recommended that the summed target flow to avoid water stress and salt accumulation to a field (or volume of flow over a considered period) equals

$$V_{f,target} = (\sum V_{a,i})_{target} = (1 + sT_p) \times \sum V_{m,intended} \qquad 4$$

Where, the standard deviation, s, of the ratio, $V_{a,i}/V_f$, should be measured for an applied volume (or depth) of water that approximates $V_{m,intended}$. The latter depends on the depth of water applied due to the uniformity of the water application. For the example of Figure 3, the value of s equals 0.11.

T_p is a statistical value that is exceeded by a random variable, normally distributed, with zero mean, and with standard deviation units. Values of T_p versus F are listed in statistical handbooks. An extract is given in Table 1.

Table 1, Values of T_p versus F.

F (in %)	T_p (dimensionless)
50	0
25	0.67
10	1.28
5	1.64
2.5	1.96
1.0	2.33

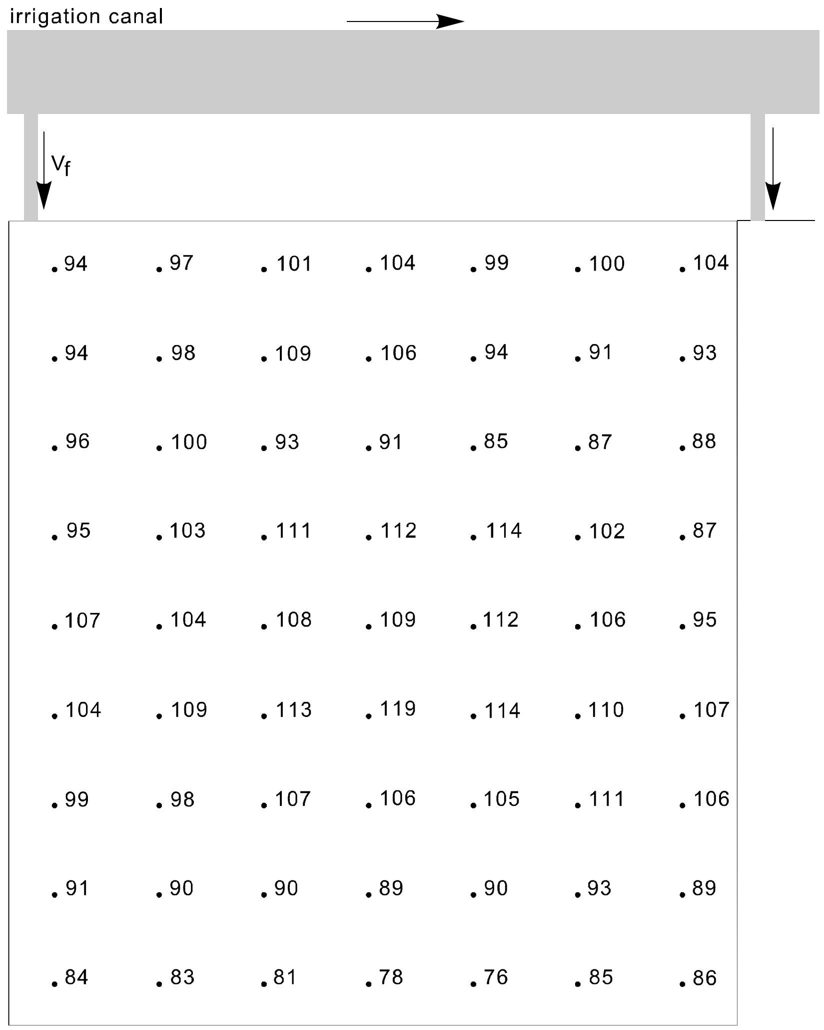

Figure 3 Measured depths (V_{aiI} in mm/turn) of irrigation water applied to a level basin (Till and Bos 1985).

As shown above, the target value of V_f depends on the standard deviation, *s*, of the 'irrigation water application' and on the fraction of the field where a water shortage is acceptable (*F* in %). The standard deviation depends on the level of technology available to apply water uniformly and on the 'quality of management and on operation by the farmer'. As mentioned earlier, the percentage of the area where a water shortage is acceptable depends on the climate. Till and Bos (1985) recommend a T_p-value of 0.67 (*F* is about 25%) if off-season precipitation is available to leach the accumulated salts. In arid and semi-arid climates, this precipitation may not be available. Then a value of T_p = 2.0 (*F* is about 2.5%) is recommended. The target value of the field application ratio for dry-foot (non-rice) crops is then,

$$R_{a,target} = \frac{V_m}{(1+sT_p)\times V_m} \qquad 5$$

Figure 4 shows values of $R_{a,target}$ as a function of the level of technology (the standard deviation of water application) and the part of the field that may receive less than the intended water need (*F* in percent of field).

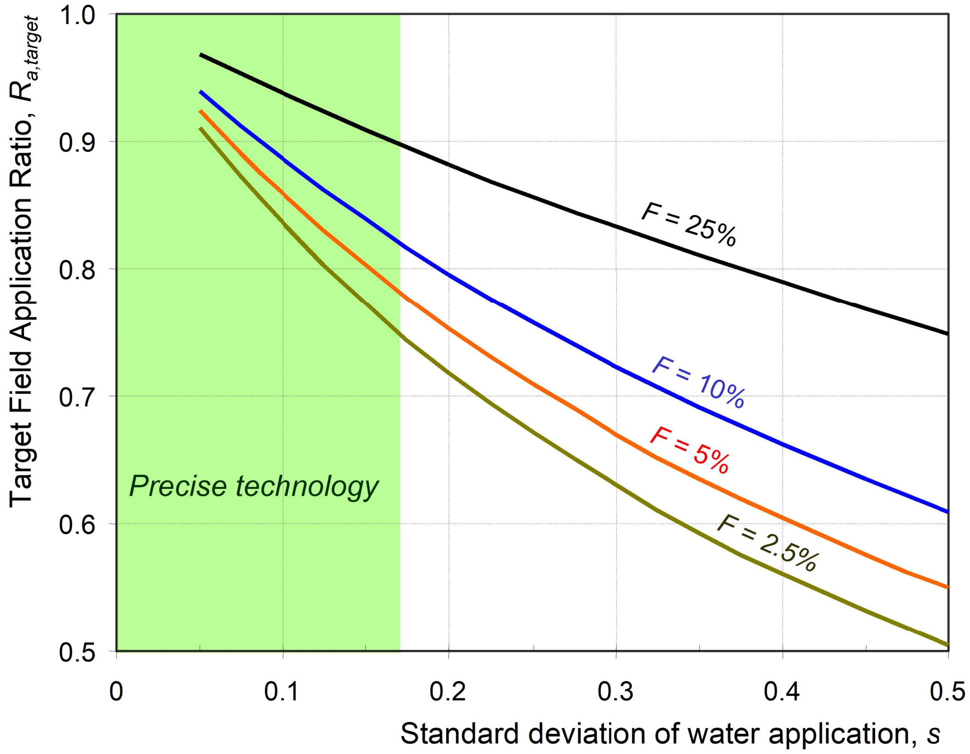

Figure 4, Values of $R_{a,target}$ as a function of the level of technology (the standard deviation of water application) and the part of the field that may receive less than the intended water need (F in percent of field).

If the field of Figure 3 is in a climate with sufficient rain to leach accumulated salts (*F* = 25%), Equation 5 gives:

$$R_{a,target,humid} = \frac{100}{(1+0.11\times 0.67)\times 100} = 0.93$$

In arid climates, the fraction *F* should be as low as 2.5%. Hence,

$$R_{a,target,arid} = \frac{100}{(1+0.11\times 2.00)\times 100} = 0.82$$

Substitution of the latter two target values into Equation 2 shows that, under arid conditions, the required volume of irrigation water, V_f, is 0.93/0.82 = 1.13 times greater than under more humid conditions. This extra water is needed for sustainable agriculture. Since water is a scarce resource in arid zones, its efficient use would require a higher level of technology and related management (smaller value of *s*). As shown in Figure 4, the standard deviation of water application needs to be better than 0.17 in order to enable an acceptable target value of R_a.

Paddy rice

For paddy rice, the ICID (Senga and Mistry 1989) recommended that the seepage from the field, $V_{f,seepage}$, be added to the target volume of water application. Hence,

$$R_{a,target,paddy} = \frac{V_m}{(1 + sT_p) \times V_m + V_{f,seepage}} \qquad 6$$

For well-levelled fields with ponded water, the values of both s and T_p approach zero. Equation 6 shows that the target ratio for paddy rice decreases with increasing seepage from the field. A lower limit should be set to the target field application ratio; if there is too much seepage, the paddy should not be grown.

Common Pitfalls	• Misuse and mixed use of the terminology on "used water" and "consumed (evapo-transpirated) water". Used water that is not consumed can be reused if its quality remains acceptable. • Assume that the non-consumed part of the used water is lost. In reality this "lost" water either recharges the aquifer or becomes surface drainage. This water, however, becomes available for further use. Always think water balance! • Assume that the irrigation efficiency should approach 100%. This implies, however, that all salts in the applied water will be stored in the root zone until leached by infiltrated (off-season) rain. With insufficient rain agriculture will be unsustainable. • Believe that so-called "modern techniques" like sprinkler and drip are more efficient than the properly levelled surface irrigation methods. This believe is greatly stimulated by advertising. In reality, laser levelled surface irrigation often is superior to the above "modern techniques". • Believe that raising the efficiency of water use will "create more water". In reality it means that ET_a will increase, resulting to less recharge and drainage. Considering the water balance, however, Figure 1 shows that this results to a reduction of available water to the next downstream user.

Water application methods

In order to illustrate the above relationship (Figure 4) between crop production, uniformity of water application (and the related field application ratios), several irrigation methods are discussed below.

Furrows, laser graded. This is the highest level of technology available with furrow irrigation. In combination with skilled flow control a reasonably high uniformity of water application is possible ($s \cong 0.25$).

Furrows, other quality grading. Low quality grading makes it difficult for the operator (farmer) to apply sufficient water to all parts of the field. Together with poor flow control this often leads to low uniformity of water application ($s >> 0.5$). The field application ratio often is less than 40%. A poorly graded furrow is difficult to operate and is the least efficient water application method.

Border strips, laser graded. From a hydraulic and water management point of view, border strips are ’wide furrows’. Because of this width, the flow rate per strip is proportionally greater. The operator (farmer) needs to be careful that the bund at the downstream end of the strip does not break. In combination with skilled flow control a reasonably high uniformity of water application is possible ($s \cong 0.25$).

Border strips, other quality grading. Because of its width, flow in a border strip is sensitive to cross-slope (perpendicular to the flow direction. Bunds are used to direct water over the full width of the strip. However, because of the cross-slope, uniformity will be lower than above (here about $s \cong 0.3$).

Level basin. Laser levelling allows a variation in land surface of about 1 cm. In this basin ridges were made to grow a row-crop (cotton). Water enters in between the ridges simultaneously and from both sides. With the proper matching of basin size, soil type and measured flow very high uniformities can be reached ($s \leq 0.1$). Thus, laser levelled basins allow very efficient water use (90%).

Level basin, Traditional levelling of basins often results in a wide variety of water depth on the field. If the flow rate into the basin is low (often the case with traditional basins) this results to a major difference between the ’opportunity time’ for water to infiltrate in the lowest and highest part of the basin. Values of $s >> 0.5$ are common, resulting in inefficient water use.

Level basin, paddy rice. With well-levelled basins the value of $s \approx 0$. Thus, the only part of the applied water that is not consumed (ET_a) is the seepage (and drainage) from the field. This ’drainage water’ may cause downstream water-logging or pollution. In that case, it is recommended to set a limit on the percentage of applied water that is drained (e.g. 20%).

Sprinkler, hand-move system. Following water application, the ’first generation’ sprinkler systems were moved to the next location for irrigation of the next strip of land. Because of problems with the nozzle alignment the spray pattern was fairly often non-circular. Variation in nozzle spacing also caused non-uniform water application. The value of s is rather high (> 0.4) resulting to efficiencies of 60% or less.

Sprinkler, overhead rain drops. Irrigation machines (e.g. centre pivots and lateral move) were developed in order to save labour and water. Because of improved nozzle alignment, nozzle spacing and timing of water application, the uniformity improved considerably ($s \approx 0.25$). Target field application ratios of 70 to 75% are common for overhead 'rain drops'.

Sprinkler, downward fine spray. Multiple downward spraying nozzles reduce evaporation from 'rain drops' and increase uniformity ($s < 0.1$). These irrigation machines thus should (and can) operate at field application ratios (efficiencies) between 0.90 and 0.95%.

Drip irrigation differs from all other application methods because it applies water to the part of the field where a crop grows. As a result, salts accumulate at the wetting front. Provided that emitter clogging can be prevented (clean and filtered water is used) a value of $s \approx 0.10$ can be reached. Field application ratios as high as 90% can be targeted provided that off-season (winter) rain is available to leach accumulated salts.

Micro sprinkler partly uses the same technology as drip, except that the emitter is replaced by a small sprinkler. Because of the relative size of the hole through which water is applied, the sprinkler is less vulnerable to clogging. Also the wetted area is larger so that this method can be used to leach accumulated salts. The uniformity is slightly better than with drip ($s < 0.10$) so that water can be used efficiently (better than 90%).

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