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Identification and Quantification of Efficiency and Uniformity Components

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Abstract
Proper usage of irrigation performance indicators such as uniformity and efficiency require standardized definitions and equations, specification of vertical and horizontal boundaries, inclusion of all pertinent components, and accurate measurement and estimation of those components. The quantification of some critical components is a challenge, and errors always exist.

Introduction
Numerical values of irrigation performance indicators such as uniformity and efficiency provide convenient terms to express the overall effectiveness of the irrigation system and its management. The Task Committee on Describing Irrigation Efficiency and Uniformity; On-Farm Committee, WRE Division, ASCE has expanded earlier ASCE efforts (ASCE, 1978) in a draft statement which includes these key points:

1. Performance measures should adhere to a standardized definition and equation.
2. The boundaries of any efficiency study must be defined in terms of depth (root zone, potential root zone, aquifer, etc.) and area (field, irrigation district, hydrologic basin, etc.).
3. Computations must include all pertinent components. For efficiency estimations, this requires that a water balance must be satisfied for the defined boundaries. For computation of uniformity, the components will be different depending upon the irrigation method and system.
4. Once the appropriate definition/equation, boundaries, and components have been identified, there are errors associated with estimation and measurement. There can also be mathematical uncertainties about how one should combine components. The magnitude of error will always depend upon the particular case, but should be estimated.
5. Distribution Uniformity (DU) is applicable to a single event in a field, whereas efficiency terms can apply to a single event or longer period of time, and can pertain to a field or a larger unit such as water district or hydrologic basin.

Factors Affecting DU
The concept of Distribution Uniformity (DU) applies to all irrigation systems. Values of DU, if measured completely and properly, should be comparable between various irrigation systems. That is, a DU of 80% on a sprinkler system should have implications regarding the variation in application amounts similar to those of a border strip system with a DU of 80%. A complicating factor with traditional evaluations is that the reported DU values have rarely been ***global***; that is, they have not considered all of the factors

Although the concept of DU is the same for each method/system, the spatial distribution of the non-uniformity and ease of measurement will be different for various irrigation methods. Above-ground drip systems are the simplest to evaluate, because most of the non uniformity can be directly measured, i.e., by simply measuring the flow from individual emitters. Hand-move sprinklers are more difficult to evaluate, because in addition to flow rate differences at emission points, water is aerially distributed prior to arrival at individual plants. Center-pivot evaluations must weigh sprinkler-discharge measurements by the area served by each sprinkler. Evaluations must also account for spatial variation which occurs as end guns and towers are activated, and as system travel speeds unintentionally vary (e.g., wheel slip).

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Many times sprinkler application rates exceed the infiltration rate of the soil, resulting in runoff and surface redistribution of applied water. An example is on the outside of center-pivot circles, due to high application rates there. Such surface redistribution, which can also occur with other sprinkler methods, complicates determination of DU. There is an implicit assumption for sprinklers and drip systems that all water that reaches the ground infiltrates close to the point of initial contact. If that is not true, DU is mis-estimated with current evaluation procedures.

Surface-irrigation methods provide the greatest challenge, as can be evidenced by the numerous papers which have been published in attempts to describe infiltration equations. Once an evaluator has chosen an infiltration equation, there are numerous techniques available to estimate the constants in such equations; rarely do these evaluation techniques produce identical answers. In addition, questions of preferential flow through soils, and spatial variability of soil infiltration characteristics, have yet to be answered satisfactorily for evaluators.

With pressurized systems, one of the causes of non uniformity is pressure differences. The effect of known differences can be evaluated if one knows the pressure/flow rate relationship of the emission devices. The following equation is often used for sprinklers and emitters:

$$Q = C P^x$$

P = pressure at the discharge point
Q = flow rate
C = a constant which depends upon the emitter or nozzle geometry and the units for Q and P
x = a discharge exponent, usually between 0 and 1.0 for drip and 0.5 for sprinklers and microsprayers

Likewise, a major factor in non uniformity with surface irrigation methods is differences in infiltration opportunity time. The following equation is often used to describe the relationship between infiltration opportunity time and the depth infiltrated:

$$D = k (t_o)^a$$

where: D = infiltrated depth
t_o = infiltration opportunity time
k = a constant which depends upon the soil and the units for D and t_o
a = an infiltration exponent, usually between 0 and 1.0

One might consider a variation in opportunity time with surface irrigation to be somewhat analogous to a variation in pressure with sprinkler systems. Similarly, a difference in sprinkler nozzle sizes is similar to having different soil types in a field (i.e., as represented by differences in k).

Components of Uniformity

As shown in Table 1, consideration of global uniformity for different irrigation systems implies consideration of many components of uniformity. The particular components depend on the particular irrigation method. Unless all the factors are considered, the estimate of uniformity will be inflated. In field evaluations, it is often convenient to make measurements relating to each component individually, and then to combine these results to determine the global uniformity (Burt et al, 1992). By measuring individual uniformity components, an evaluator is able to identify specific problem areas and quantify their importance.

Defining Boundaries for Efficiency Estimates

Proper quantification of water uses requires careful definition of boundaries. Vertical boundaries are much more difficult to define than horizontal boundaries. For an individual field, the bottom of the root zone is commonly taken as the lower vertical boundary. It is difficult to measure vertical flow below the root zone, and in many cases this is taken as the only unknown or remainder in the water balance. With shallow water tables, this is not an appropriate boundary, since neither deep percolation nor groundwater uptake can be easily estimated. However, including shallow groundwater in the water balance is also problematic, unless groundwater flow into and out of the system can be defined. Finally, for large hydrologic basins (one or more irrigation districts) with restricted inflows and outflows, the lower boundary can include the entire groundwater basin.

Quantifying Water Sources for Efficiency Estimates

Water sources for irrigation are subject to considerable inaccuracy. Some typical problems are:

- Inaccurate or no water measurement device at source of supply.
- No continuous recording of flows which vary with time.
- Undocumented or poorly documented splitting of flows in irrigation canals.
- Poor record keeping.
- Inadequate rainfall records.
- Separating rainfall from irrigation use.

Quantifying Water Uses

Water uses may be classified as:

- Consumptive-Beneficial: e.g., Crop *ET*.
- Nonconsumptive-Beneficial: e.g., Deep percolation for salt removal.
- Consumptive-Non beneficial: e.g., Sprinkler and bare soil *E* and weed *ET*.
- Non consumptive-Non beneficial: e.g., Runoff and deep percolation in excess of leaching requirement.

These are not the only components to consider in assessing reasonable and beneficial use, but they are generally the pertinent ones. Due to the limited nature of this paper, only one technique regarding one of these four items will be discussed - that is, using soil moisture measurements to estimate Crop ET (ET_c). The final report of the Task Committee will provide much more detail; the purpose of the discussion below is to indicate that while we can make reasonable estimates of performance indicators, indeed they are only estimates and not exact values.

Evapotranspiration estimates can vary substantially in different efficiency studies of the same areas. Of course, there is only one actual ET_c value. There are four main methods for estimating ET_c:

- Direct measurement of soil moisture depletion,
- Energy balance calculations based on weather data and crop coefficients,
- Crop yield based on relationship between yield and ET_c,
- Water-balance approach, in which total ET is the remainder after all other components have been measured or estimated. This approach may be done on a field, water district, or hydrologic basin scale.

Table 1. Components and factors of DU for three irrigation systems.

Irrigation system	Uniformity component	Factors causing non-uniformity

Hand-move sprinklers	Flow rate differences between sprinklers	- Pressure differences Friction Elevation change Pressure regulator differences - Different nozzle sizes - Nozzle wear - Nozzle plugging
	Catch can uniformity	- Spacing - Sprinkler design (angle of trajectory, characteristics of impact arm interception) - Nozzle size and pressure - Wind - Plant interference around the sprinkler
	Unequal application during startup and shutdown	- Pipe diameter and length - Set duration - Practices of running water down the lateral during pipe moving
	Edge effects	- Lack of overlap
Furrows	Opportunity-time differences down a furrow	- Extent of ponding - Flow rate and duration - Slope - Roughness - Furrow geometry - Furrow length
	Opportunity-time differences between furrows and within a field	- Different day/night set times - Wheel row/non-wheel row differences - Different furrow flow rates - Non-uniform land grading
	Different infiltration characteristics	- Different degrees of compaction due to tillage and tractor tires - Soil differences - Preferential flow - Chemical differences - Different viscosities between day and night irrigations - Differences in wetted perimeter due to slope changes or flow restrictions along the furrow.
Drip/ microirrigation	Differences in discharge between emitters due to pressure differences	- Pressure regulator variations - Differences in outlet pressure for buried emitters in different soils - Friction - Elevation changes
	Differences in discharge between emitters due to other causes	- Manufacturing variation - Clogging - Different emitter types in the same field - Emitter wear and aging
	Volumes applied not proportionate to plant area	- Variations in plant spacing are not matched by emitter spacing or scheduling
	Unequal discharge during startup and drainage	- Fill time - Elevation differences

By economic necessity, ET_c estimation from soil moisture depletion must be based on measurements throughout the year for only a few "representative" sites within the field. The values for those sites are then extrapolated for the whole field. Typical problems are:

- The data for the "representative" sites do not agree with each other for any explainable reason.
- Non uniform irrigation applications may cause deficits in some parts of the field not included in the "representative" sites.
- During the soil moisture sampling, the site can be disturbed so that it is no longer representative. An example would be the trampling of vegetation around a neutron probe access tube, or channeling of water along a buried tube.

- If two soil-moisture measurement techniques, say a neutron probe and a time-domain reflectrometry device, are used on exactly the same site, different numbers can result.
- The soil-moisture measurement device may be incorrectly calibrated. It is difficult to have accurate calibrations for every 15 cm or so, of soil depth on every site.
- Parts of the field may have weak plant growth, resulting in low ET in those areas.
- The existence of a high water table makes soil-moisture measurements meaningless once the roots reach the capillary fringe area. The contribution to ET by the water table cannot be measured at the field scale.
- Most soil moisture measurement devices do not adequately measure soil moisture conditions near the soil surface, where there may be very large changes in moisture content. This is especially important for frequent, small irrigations.
- Estimates of changes in surface soil-moisture content may be in error (*e.g.*, it could be assumed that soil-moisture content just before irrigation is at the wilting point, whereas in fact it is actually drier).
- The effective root-zone depth may be under-estimated. An example would be an estimate of a 1.5 *m* root zone depth for cotton, which ignores deep moisture withdrawal late in the season when the cotton is deliberately stressed prior to harvest.
- The timing of the soil-moisture measurements may be such that slow drainage (deep percolation) is missed. Since field capacity is not a static concept, some "stored" water may eventually percolate down below the root zone. This is especially common on heavy-textured soils after pre-irrigations.
- There may be no "representative" spot to measure soil-moisture depletions. This is the case for micro-irrigation, where only portions of the soil are wet, and plant water-uptake rates in various parts of the wetted root zone are quite different. Soil-moisture measurements in fields with micro-irrigation systems can be valuable for indicating trends, but they are inadequate to define ET rates.
- The annual water balance may ignore the effect of "carry-over" moisture from one season to another. For example, deep percolation beyond the root zone of a shallow-rooted plant such as lettuce is not a loss if it remains in the potential root zone of a subsequent, more deeply rooted crop.

Summary

The examples of DU components, and the difficulties with estimating only one parameter in an efficiency calculation, demonstrate that an accurate assessment of uniformity or efficiency can be a challenge.

References

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