IRRIGATION PERFORMANCE MEASURES: EFFICIENCY AND UNIFORMITY

Discussion by
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The discusser appreciates the tremendous amount of work that the task committee has done in presenting information concerning efficiency and uniformity terms; illustrations and diagrams; introduction of the terms irrigation sagacity and low quarter adequacy; and supporting arguments for use of low quarter minimum. However, he has a very serious concern about redefining the old long-used terms to have drastically new meanings, thereby superseding much previous information and accepted procedures. This leaves no terms to describe some of the previous concepts that have great utility.

The discusser is specifically concerned with (1) introduction of "plant elemental area" replacing "unit area" without introducing new names and symbols; (2) superseding in the concept of distribution uniformity and other terms of "depth infiltrated" (on a unit area) by the term "accumulated or distributed water"; (3) changes made in what is included as beneficial use with its effect on irrigation efficiency and other terms; (4) the apparent overemphasis on globalizing terms relative to measured single event evaluations to the extent in the companion paper (Clemmens et al. 1997) that it is stated "comparisons of reported uniformity values for various irrigation systems are meaningless unless they are global uniformities" (the writer discusses the companion paper separately); and (5) the conversion or change in usage of application efficiency. Some additional points are not included because of the word limitations.

The introduction of "plant elemental area" as a replacement for, not supplemental to, "unit area," with its long history of use, in the discusser’s opinion should not be done. Because the new concept is unique, it should use a new name and symbol, leaving the previous usage still available. In the case of distribution uniformity (DU) an additional term, plant distribution uniformity (PDU), should be introduced. In many cases where the plants are uniform the ratios are identical, but they measure different aspects and have different units.

In the presentation by the authors, DU (PDU) is defined as the uniformity with which irrigation water is distributed among the plants (i.e., volume/plant, a variable by plant size or plant area) in a field in contrast to the present usage of a measurable postirrigation infiltrated depth on constant unit areas, which are then distributed.

As noted, the "elemental area" (plant or unit area) must be small enough that it does not have significant variations within it. One must be able to compare methods and evaluations in common units. It is not adequately clear as to how "plant area" is to be used. In orchards, the output from four emitters per tree could be used to find a PDUq [a volume per day per tree (or a tree’s area?)]. Or the present technique for finding DUq could measure the flow from the four emitters and, regardless of the crop, determine a DUq for the irrigation system emitters.

The authors state that, where items are spaced non-uniformly, "the distribution from which to calculate DU consists of the volume per unit area for each element." This has the unit of depth, but the elemental unit area is a variable. They also properly note that the total area must be covered by the sum of all the elements. Potential inconsistencies in the presentation for plant area could have been overcome by some examples.

If the area allotted for each tree varies in a row, such as would happen in a contour planted orchard with uniform tree spacing along the row and the row spacing varying with the element area (varying along the row) would result in a different depth per tree area but not per tree and cause DUq and PDUq to vary, which is the apparent objective of the new term. DUq could be easily measured and represent the way the application system functioned. PDUq would be very difficult to obtain, though it would show that the plant areas were not uniformly supplied with water.

A partial-area-wetting furrow system, also wetting as do the emitters a constant part of the varying area (width), would provide comparable figures to the trickle system. However, if border strips were used, the volume infiltrated per tree would vary with the varying row spacing while the tree requirements did not. This is related to the adequacy of AEq which implicitly involves PDUq.

For the first several years after planting, when all the trees are growing equally to fill their root and leaf area, the furrow and trickle systems could nicely balance (AEq) the tree need. However, as the trees in their mature years continue to grow to fill their non-uniform areas, they would have non-uniform volume per day needs. The border-strip method would satisfy the larger but not the smaller than average areas, but the partial area wetting trickle and furrow systems would not. DUq could describe the system and operation. PDUq would relate to the plant needs but not as to whether under- or overirrigation occurred.

Similarly, assume there is an area in a field where salinity reduces plant size and ET. A sprinkler system could supply water reasonably uniformly to the field, DUq but imply overirrigating the saline area, PDUq. This implied condition would be adequately but not easily measured by application efficiency, AEq (which is omitted in the list of terms in the paper). Or presume a surface irrigation system is used and the salinity is sodium, so the water intake decreases happily to nearly match the crop needs, or is calcium, which increases the infiltrated depth to overirrigate the area.

An evaluation using DUq and AEq would show the changing infiltration depths. What would PDUq show? Could its use really be trying to show the distribution to the plants of adequacy in application efficiency over elemental areas? This is the implication presented in the final paragraph about distribution uniformity, which discusses applying the concept to precision farming—precision irrigation: "A new definition of DU will be required to take into account non-uniform targets. Such a definition should be based on the relationship between the actual and target depth for each element area." (Distribution uniformities as ratios cannot have target depths.)

However PDUq is used, it should not be used as a standard, as proposed in the presented paper, to replace the 1987 DUq. It should have a separate name and symbol as well as a new meaning and units.

The discusser is also concerned that the old definition (ASCE 1978), DU = minimum depth infiltrated average depth infiltrated, which unambiguously measures the system’s capability, is superseded by a new concept which uses the same term distribution uniformity and symbol DU, but different wording. The authors, in (5b) (DU = minimum accumulated depth average depth of water accumulated) have replaced “infiltrated” by “accumulated,” with a different meaning, as fol-
The term accumulated water is used here to include the infiltration, canopy interception, and reduction of transpiration during irrigation. This is in addition to using the “plant area” concept rather than “unit area.”

This superseding wording is only pertinent with the use of sprinklers with the stated intent of improving the $DU_{\alpha}$ (and $AE_{\alpha}$) values of sprinkler systems. The use of “accumulated depth” as defined includes an unmeasurable value, plant evaporation minus plant transpiration, with its unnoted day-to-night variation as well as canopy interception. The argument is that during the daytime, the evaporation from the leaf surface essentially replaces transpiration, thereby leaving moisture unused in the soil. This is correct, but it does not occur at night. This logic implies that the soil moisture retained unused is equivalent to water that would be caught in the evaluation catch cans (or infiltrated). It is difficult to see how this affects $DU_{\alpha}$, where it is added to both the numerator and the denominator. However, it has an appreciable effect on $AE_{\alpha}$ and $IE$, where it is added to the soil moisture and beneficial use. Following this logic, the next irrigation at the daytime set location should apply one day less transpiration water, or be done a day later. This would not be applicable to a nighttime set. The daytime in-air evaporation would tend to have the same effect, but it is charged as a loss. The suggestion sometimes made to make day sets longer than night sets (12-1/2 versus 11-1/2 hours) is incorrect.

The inclusion of leaf evaporation as a beneficial use because of replacing transpiration, is not valid. Because the upward flow of nutrients with transpiration does not occur, plant growth—the qualifying condition for beneficial use—is reduced during the daytime set.

In the discusser’s opinion, accumulated is not an acceptable replacement for infiltrated and, if presented for use, should have a new distinguishing name and symbol.

The discusser further wishes to challenge the idea presented that water distribution within an element consisting of a root system of a vine or tree is immaterial, as is implied in the discussion of $DU$ and in Table 3, section (e). Nonuniformity in the root area is pertinent after the soil moisture depletion (SMD) is satisfied and deep percolation directly correlated to uniformity occurs. Tree branch or other plant interference, which is mentioned, should have appreciable effect on $DU_{\alpha}$ and $AE_{\alpha}$. The elemental area of a tree is questionable. The distribution of the retained (infiltrated and stored) is immaterial, but the infiltrated deep percolation is not.

The definition of irrigation efficiency ($IE = \text{average depth beneficially used/average depth applied}$) needs review as to what is beneficially used. The paper notes that “the most common misuse of $IE$ is the improper definition of beneficial uses.” In the early use of $IE$, beneficial use was just transpiration, the only water that grew a crop—just the basic, not the supporting uses. The 1978 ASCE Task Committee, with some reluctance, responded to pressure to include some of the supporting essential irrigation uses to present a more favorable front for agricultural water use to the public. “Salt leaching, frost protection, crop cooling, and pesticides and fertilizer application” were added to “satisfying the SMD” which included $ET$ rather than just the old $T$.

The current 1997 presentation uses a broad definition. “A beneficial use of water supports the production of crops.” It extends the previous list to include many more items, even including “$ET$ from plants beneficial to the crops (wind breaks or cover crops for orchards).” These somewhat ambiguous lists of items will not permit $IE$ to have a specific value without many specific qualifying statements. The soil evaporation can vary appreciably. The leaching requirement varies with crop tolerance, water quality, and whether the salt balance is maintained at each irrigation, once a season, or by rain.

$IE$ should not be a variable depending on the range of selected items of variable magnitude. It should not be used to evaluate a system or to place a water order, because it does not include nonbeneficial uses as $AE_{\alpha}$ does.

With the cogent inclusion in the list of definitions of irrigation sagacity ($IS = \text{depth of water beneficially and/or reasonably used/depth applied}$), it would appear desirable to redefine $IE$ in its original concept of just transpiration, the only truly beneficial use in growing a crop, and use $IS$ to cover the reasonable needs essential to sustainable irrigated agriculture. $IE$ would then have a definite value in the hierarchy of $IE$, $IS$, $ICUC$, and $AE_{\alpha}$ to describe water destinations.

$IE$ has often been incorrectly used to report on a system evaluation. Because $IE$ does not include the nonbeneficial uses of applied water, $AE_{\alpha}$ should be used. $AE_{\alpha}$ can more adequately be called actual, $AAE_{\alpha}$, to correlate with potential, $PAE_{\alpha}$, which describes conditions at 100% adequacy. $PAE_{\alpha}$ is the only term that can adequately be used for comparing systems. It can be used to compile water orders if a flexible supply is available to allow water to be turned off at 100% adequacy.

The use of (9) $PAE_{\alpha} = DU_{\alpha} (100 - \text{percent surface losses})$ is not correct.

The use of “surface losses” is inadequate, because all noninfiltrated losses must be included, and they are often only imprecisely estimated. Further $DU_{\alpha}$ for surface method changes materially with the adequacy $Ad_{\alpha}$ used. $DU_{\alpha}$ can be quite low when $Ad_{\alpha} < 1.0$, becomes larger as $Ad_{\alpha}$ reaches 1.0 (the correct value to use to measure a systems capability), and continues to slowly increase as $Ad_{\alpha} > 1.0$.

The discusser strongly objects to overriding the definitions of the 1987 terms $AE$ and $PAE_{\alpha}$ and to omitting $AE_{\alpha}$. These terms must be left for use in their original capacity. If new usage is desired, new terms and symbols should be presented.

The very old term $AE = \text{average depth stored/avg. depth applied}$ is replaced by $AE = \text{average depth contributing to target/average depth applied}$. The original use described the system efficiency by measured changes in the soil moisture condition. The replacement usage is to compare to a target value, possibly SMD. It can have a different value depending on the target chosen, which would have to be described before the resulting number has any use. It nearly negates any cross exchange of information.

The term $AE_{\alpha} = \text{average depth infiltrated and stored in the low quarter/average depth applied}$ should not be deleted. It is used in all other evaluations to determine how well the system is actually being used to replace a soil moisture deficiency. Because it utilizes the $IQ$ minimum, which $AE$ does not, it includes a concept of adequacy and uniformity.

**Closure by C. M. Burt, A. J. Clemmens, K. H. Solomon, T. A. Howell, and T. S. Strelkoff**

The writers thank the discusser for the opportunity to clarify a few items.

The 1997 paper does not eliminate definitions from 1978; rather, it refines them. Definitions and terminology should be
expected to evolve and change from time to time and yet remain sufficiently flexible and consistent for specific cases. A good case in point is the well-known Christiansen Coefficient of Uniformity (CU) which may still be used without question. However, the writers have attempted to advocate that the $DU_{eq}$ is a more universally applicable and descriptive statistic for all irrigation methods, not just sprinklers. Likewise, the writers have attempted to clarify and amplify that it is the crop root zone and not just infiltration that is important in efficiency and uniformity. These parameters must be assessed across a whole field or farm in a global viewpoint, not just at a few random spots. Admittedly, the crop root zone is more difficult to characterize than a unit soil area. But the goal of irrigation is to supply water to the crop, not to the soil.

Irrigation methods and understanding have advanced considerably since the work on the excellent 1978 report was published. The 1997 paper was written and published specifically to address omissions in the 1978 and other reports and the confusion that has frequently arisen with matters of efficiency and uniformity.

Many of the discussion points are related to two key concepts in the 1997 paper: (1) global $DU$; and (2) unit area. The discussion focuses on the $DU$ around a single plant or tree or down a row—not across the whole field. Global $DU$ values are important because, quite simply, farmers grow plants throughout a whole field. A $DU$ term should be capable of quantifying how evenly those plants receive water, not just down a single row or between four sprinklers, but throughout a whole field. The topic of global $DU$ is treated in more detail in the closure of the global $DU$ paper.

The discussion takes us back to 1978 and earlier, when $DU_{eq}$ was calculated in a manner such that if two fields had different irrigation methods, the calculated $DU_{eq}$ would be different even though the evenness with which plants throughout a field received water was the same. Furthermore, the old understanding frequently required the same evaluation procedure for a given irrigation method, even if the crop was different—a serious error when one considers a rectangular grid of sprinklers on almonds versus the same sprinklers on the same rectangular grid on wheat. Obviously, with almonds it is not important that every spot in the field be wet (drip would have an incredibly poor $DU_{eq}$ if such was the case). For wheat, that wetting requirement is important.

The previous example indicates the importance of using the elemental area approach to $DU_{eq}$. This is not a totally unrelated, new concept, but rather a more specific definition of unit area. Some of the writers have encountered instances in which standards have required, for example, that Christiansen’s Coefficient of Uniformity (related to overlap uniformity of sprinklers only) be high on undertree sprinklers, even though those CU values would be fairly meaningless in certain cases. Without some sort of a plant-root-zone criterion, it is impossible to interpret what a given $DU_{eq}$ means. The discussion’s argument in favor of a pure $DU_{eq}$ concept, which is devoid of the practical content given by the new elemental area approach, assumes that it would simplify things. In fact, history shows that it actually complicates things.

The discusser’s statement that “the present technique for finding $DU_{eq}$ could measure the flow from the four emitters and, regardless of the crop, determine a $DU_{eq}$ for the irrigation system emitters” is classical and points out the need for a clearer understanding of $DU_{eq}$. First, the flow from four emitters cannot possibly characterize an entire system. Second, a group of emitters in one part of the field may have exactly the same flow rate as a group in another part of the field; yet, if they are operated twice as long in one place as in another, there would be a 100% difference in the volume of water applied per tree. Finally, even if the volumes/plant are the same in two parts of the field, if one portion of the field has vines on a 2 m × 3 m spacing, and another portion of the field has vines on a 2.5 m × 3 m spacing, the depths of water accumulated per plant are not the same—an important point with many drip-irrigated fields. Simplistic treatments of $DU$ are inappropriate for design, management, or evaluation.

The question of water distribution within an element is one with which the authors of the 1997 paper wrestled. As mentioned in the beginning of the paper, no one definition is satisfactory for all purposes. It is true that spatial variability of water infiltration within an element can potentially impact how much of the water can actually be stored within the root zone. The writers selected the elemental area because of its vast superiority to the older “depth-infiltrated” approach, while recognizing that there are unknowns about how non-uniform infiltration within the unit area is redistributed within the root zone. Certainly, this depends on the soil type, soil layering, depth of root zone, and application depth relative to the soil moisture depletion. Though some studies have been done on this subject, the conclusions have been varied and the authors of the 1997 paper felt it would be best left for a year 2017 task committee report.

The points in the discussion about day and night sets are difficult to interpret. The 1997 paper points out that setting boundaries for efficiency measurements includes a three-dimensional spatial boundary (horizontal and vertical) as well as a temporal boundary. Only for time intervals shorter than one day is the day-to-night variation relevant. For longer time intervals, these may “average out.”

The use of accumulated water allows $DU_{eq}$ to be comparable among systems. It does not preclude one from using infiltrated water for surface systems, nor does it preclude one from using catch-can (overlap) $DU_{eq}$. But it does say that these $DU_{eq}$ estimates represent only components of the true field $DU_{eq}$. Knowledge of the values of the $DU_{eq}$ components is essential when making recommendations for improvement, but it is incorrect to substitute components for the true or global $DU_{eq}$.

The discusser points out that “these somewhat ambiguous lists of items will not permit $IE$ to have a specific value without many specific qualifying statements.” The writers applaud this thought and certainly believe we made that point in the 1997 paper. The qualifying statements are the boundary conditions—three spatial intervals and one temporal interval. Without those qualifying statements, $IE$ is meaningless, anyway. The windbreak objection, for example, is merely a problem of boundary setting. If there is a reason to include the windbreaks in the boundaries, then they have to be included (similar to a cover crop on orchards), and $IE$ must be calculated to reflect this. If the appropriate boundaries exclude the windbreaks, then $IE$ must be calculated to reflect that. And in neither case can one interpret $IE$ without knowing what boundaries go with the $IE$ value. Just as there is no pure $DU_{eq}$ without qualifications, there can be no pure $IE$ without qualifications. Rather than being an unnecessary complication, boundaries are a necessary recognition of the real world that cannot be ignored. An understanding of the boundary issue allows us to use the same $IE$ definition for a field, a farm, and an irrigation project—a point which clearly has been inadequately recognized in historical irrigation discussions.

The idea that transpiration is the only real-world beneficial use of water for growing plants goes against common sense and several decades of legislation regarding water rights. The agricultural community would certainly be done a disservice if important beneficial uses such as salinity management and climate control were not included. Numerous papers and legal decisions have included these as beneficial uses.

Evaporation from wetted plant foliage and the soil surface presents some challenges when partitioning it into components.
of beneficial and nonbeneficial uses. Some of the evaporation will increase the relative humidity of the air and decrease the transpiration in that field. Certainly that component of evaporation is beneficial. The more problematic issue is with the remainder of the evaporation. From one point of view, one could say that all other evaporation is nonbeneficial.

But it can be argued that evaporation that is unavoidable with a particular irrigation method should be considered beneficial. The second argument might be buttressed when one recognizes certain cases, such as seed germination irrigations, which virtually always have very high percentages of evaporation. Even basal crop coefficients ($K_{cb}$) include some component of evaporation from soil although the surface is dry. ET from a crop having a dry soil surface is typically considered to be beneficial, but even that includes some component of evaporation from soil cracks and vapor, so where does one draw the line on exactly what portion of evaporation is beneficial versus nonbeneficial? Hence, the importance of the new term “irrigation sagacity,” which places this evaporation in either the “beneficial” or “nonbeneficial but reasonable” category, both of which are “sagacious uses” of water.

The application efficiency ($AE$) term needs a more flexible definition than that provided in the 1978 paper. Reducing the soil moisture deficit (to zero) is only one possible objective of irrigating. The insistence on using “depth stored” for “the very old term” $AE$ is unwarranted; with that limited definition, an irrigation for frost control following a rain would yield a 0% $AE$—a meaningless value. Other, similar cases include the application of water for seed germination, cooling, incorporation of herbicides, softening heavy clay soils prior to tillage, and leaching salts from the soil. As pointed out in the discussion, $AE$ can also include nonbeneficial uses in the numerator “target,” making $AE$ and $IE$ distinctly different.

As the 1997 paper defines $AE$, if the adequacy of the low quarter is less than 1.0, then $AE$ is redefined as $AE_{q}$. By doing this, one does not need to define a separate term. This is actually less ambiguous than the 1978 definitions.

Eq. (9) is indeed correct. This is precisely how $PAE_{q}$ irrigation scheduling is done when one assumes that the target depth will be just met in the low quarter. If there is such “perfect scheduling,” the gross applied must account for just three components of water: (1) target depth; (2) extra water needed to compensate for nonuniformity; and (3) water which is lost on the surface and which therefore does not contribute to the target depth or non-uniformity. Eq. (9) shows that the relationship is approximate; there are slight differences depending upon the non-uniformity of the losses. However, these are more theoretical than practical considerations. With surface irrigation methods, the selection of the $DU_{q}$ value must recognize that it varies as the depth infiltrated varies.