Geosyntec Consultants (Dan Haller) (Dan Haller)

Thanks for the opportunity to comment. I've attached a comment letter and 4 background files (5 files total). Dan Haller

Comments on Draft Water Resources Program Guidance – Determining Irrigation Efficiency and Consumptive Use Public Review Draft, September 2026, Publication 26-11-017

Provided by: Dan Haller, PE, CWRE

Date: October 22, 2026

Thank you for the opportunity to comment on the draft guidance and policy. This comment letter includes general observations, as well as specific recommendations in underline format for Ecology consideration.

General Comments

1. Ecology is commended for taking on an update to this guidance document and the role of the Washington Irrigation Guide (WIG) and other ET estimators in permitting. It's long overdue and inherently complicated.
2. I agree that Dr. Troy Peters is a recognized expert in this field, and close coordination with Dr. Peters and WSU in future updates to this policy will improve accuracy, consistency, and transparency in its implementation.
3. At the same time, one of the conflicts that resulted in the litigation (Superior Court Complaint 04-2-02345-6 *Benton County Water Conservancy Board and Franklin County Water Conservancy Board v. Ecology*) that created a need for GUID 1210 in the first place, was differing "expert" practitioner opinions around nuanced elements of the irrigation water budget.
    a. On November 9, 2024, I participated in a law conference panel on the origin of GUID 1210. I've uploaded a copy of that presentation which provides an overview of the events leading up to the creation of GUID 1210. Slide 22 of that presentation contains a list of peer-review scientists that Ecology convened on this topic in 2004. Ecology should consider whether some peer review of Dr. Peter's work, on which the GUID 1210 update is based, would be helpful to build consensus on the state of the science 20 years later.
    b. I presume that the new GUID 1210 authors have the benefit of the litigation and policy development file from 20 years ago. If you don't, I was able to resurrect much of this with the help of Assistant Attorney General Steve North, who was the lead attorney on the case at that time, in preparation for my 2024 law conference panel. I have uploaded select pieces of that record where I refer to it for context.
4. In addition to my comments, if any of the new GUID 1210 authors would like to talk more about this history, I would be happy to make myself available. As Ecology's

consumptive use expert in 2004 for that workshop, and the lead author of the original GUID 1210, I may be one of the few remaining practitioners in the state who still knows the entire history on this topic. My offer, and these comments are not made out of an idle desire to revisit the past, but rather it appears to me that some elements of the new guidance document, and statements made during the September 29th webinar Ecology hosted, appear to conflict with Ecology's previous positions and the state of the science outlined in the 2004 Workshop (discussed in more detail below).

5. One of the concerns raised previously, and is of potential concern now, is consistent application of consumptive use guidance across regions. Ecology proposed a two-fold solution to this issue in the past. First, the original Draft of GUID 1210 contains a three-page "Forward" that then was removed when the document was finalized (see upload). Page 2 of that Forward documents a proposed training schedule to help address this concern, which was implemented and helped raise the overall awareness of guidance implementation amongst permit writers. Additionally, Ecology created a statewide consumptive use expert position that had shared responsibility and availability across the regions to assist in permitting challenging or unique consumptive use cases. I occupied that position until I left Ecology in 2012. Given the large number of practitioners that will routinely use this guidance document for water right permitting (e.g. Ecology staff, conservancy board members, cost-reimbursement contractors), Ecology should implement an appropriate level of training and support.
    a. I've uploaded the February 2007 statewide training I gave to Ecology regions and conservancy board members at that time to help implement consistent application of the guidance.
6. Another concept that was a strong part of the agenda in the 2004 Workshop, and should receive some attention in this guidance, is direction to the user on the relative accuracy of the methods and the assumptions on which they are based. For example, in the 2004 Workshop Agenda (uploaded), the experts were asked to offer opinions on questions on accuracy and sensitivity in outcome to assumptions. Ecology should similarly include information on accuracy and sensitivity in its new guidance.
    a. For example, Ecology has good guidance on meter accuracy (e.g. 5% to 10%) in its metering rule, WAC 173-173.
    b. In contrast, Ecology and Dr. Peters last attempted significant updates to this guidance between 2008 and 2012 in what was known at that time as the "Provisional WIG". Ecology's FAQ on the Provisional WIG (uploaded) notes

that the relative accuracy of the ET method alone (e.g. Blaney-Criddle, ASCE Standardized Penman-Monteith) could affect results by ±25% (Page 2).

c. I worked with Dr. Peters on the Provisional WIG project before I left Ecology and recall we evaluated other sources of error that should be considered. These included weather station location and installation in conformance with NRCS standards, aerial photo interpretation, and accuracy around crop coefficient research. For example, I recall a presentation Dr. Peters likely still has, which graded the existing Washington stations, including many that do not conform to proper installation requirements.

d. My comments above are not intended to diminish this tool or guidance. Indeed, for many water right evaluations, this analysis will become the central investigatory tool. However, permit writers, conservancy board members, and cost-reimbursement consultants should have an appreciation for the relative accuracy of the method as the evaluate water rights.

e. For example, I've had discussions with permit writers about whether relinquishment or water code violations applys to a 100 acre-foot authorization, when metering data shows use within the 5% metering rule error (e.g. 97 acre-feet; is 3 acre-feet relinquished, or is the entire water right valid given the uncertainty in methodology?). Or in contrast, is a 103 acre-foot use a compliance violation relative to a 100 acre-foot authorization. For a method that introduces considerably greater error than metering, the guidance should consider how a permit writer approaches extent and validity other than just saying case-by-case. The latter will simply lead to permit inefficiency and litigation, while the former may help with more consistent application.

f. OpenET is a helpful tool, but should be used and viewed through the lens of its own published accuracy limitations, and I suggest you reference that: Accuracy & Known Issues | OpenET page on the OpenET site.

7. The draft guidance does not (but should) reflect other parts of the water budget noted in the Washington Irrigation Guide, and the draft GUID 1210 guidance from 2004, that may affect efficiency judgments. These include whether or not an irrigator uses water for frost protection, sunburn protection, leaching, pre-irrigation, post-irrigation, chemigation, fertigation, germination, wind erosion protection and other common additive uses. These uses will necessarily push one lower in, or out of, the typical efficiency range and may lead to questions about reasonable use and waste of water. These are all well-established beneficial uses and permit writers should at least be instructed to inquire about their applicability in making case-by-case judgements.

8. Indeed, the conceptual origin of the efficiency range noted in GUID 1210 may have been lost (for many) to time. Footnote 2 of the 2004 Draft GUID 1210 cites an important 2002 paper by Dr. Terry Howell as the basic foundation for the ranges ultimately adopted (but was not carried forward into the adopted guidance as it was part of the "Forward"). But even this paper was merely a compilation of research done by Howell, Hanson and many others as noted. The ranges are based on Distribution Uniformity research across hundreds of farms for each irrigation method. There were about two dozen papers compiled for the 2004 Workshop for the experts to review. I've retained many of these, and when I left Ecology in 2012, one of the senior managers in OCR likely inherited this "binder". Looking on-line, many of the references I've retained now appear to be behind journal paywalls. For example, the 1996 paper referenced by Howell called "Field assessment of irrigation system performance" is now behind a subscription paywall, but the Executive Summary notes it studied 385 irrigation systems relative to Distribution Uniformity. Slide 50 of the 2007 training presentation I uploaded includes excerpts of the 1000 systems evaluated by Hanson that informed Howell's table. I believe it is important to provide context for the ranges that appear in GUID 1210. The ranges agreed to in the 2004 Workshop generally reflected a standard deviation of farmers (e.g. 68% of those that were studied fall in that range around the mean of a normal distribution). Ecology should better explain the origin of the ranges, because it will help inform users on how to deal with circumstances where farms fall outside those ranges.
9. Ecology should consider improving language about the changing nature of this methodology relative to static water right authorizations and statutory tests. One of the concerns that stalled implementation of the Provisional WIG circa 2008-2012 was that water duties went down for some stations relative to the 1985 WIG. Some stations/locations also went up. Changes in water duty will occur over time as methodologies improve (e.g. Penman-Montieth replaces Blanney Criddle), research is updated (e.g. new crop coefficient values are published), weather stations are installed or relocated or removed, and climate itself changes. The WIG itself was actually the third ET guidance document co-published by NRCS and WSU, with Circular 512 and XB0925 both pre-dating it. These earlier publications contained some good information that the WIG did not, including how ET changes in response to drought, which eventually became part of the Yakima Water Transfer Workgroup consideration of drought transfers (e.g. colloquially, WIG +2 inches) to cover higher ET during drought years. The dynamic nature of changing ET can be challenging to interpret and apply to different static water code tests, including extent and validity, impairment, public interest, and relinquishment exemptions like "varying weather conditions" under RCW 90.14.140(1)(g). This guidance likely can't unpack every one

of these instances, but without some additional direction, confusion will result. Perhaps the examples could be strengthened with some of this in mind.

10. In several locations in the draft guidance and in Dr. Peter's 2025 paper, there are references to "experts" and "irrigation professionals" and even a "Certified Agricultural Irrigation Specialist". The bulk of this guidance will most often be used by volunteer, unlicensed Conservancy Board members, cost-reimbursement staff (who may in some cases be licensed CWRE's, PE's, HG's), and Ecology review staff (typically in the Environmental Specialist series, but with no licensure). Where this guidance refers to experts and professionals, I recommend it clarify what is expected here.
11. A related concern is that some of the data sources underlying these on-line tools are not freely or consistently available to all users. For example, archived station records from programs such as WSU's AgWeatherNet appear to be subject to data-use restrictions or fee-based access, potentially limiting an applicant's or Board or Ecology reviewer's ability to independently verify results. Such limitations can make independent verification difficult and raise additional questions regarding reproducibility, consistency among reviewers, and reasonable access to the information needed to support regulatory decisions. We have already received comments from Ecology on this topic in response to specific changes saying it cannot independently verify such results because of cost. Is Ecology accepting at face value results that are behind subscriptions or paywalls, and for those that choose to follow this guidance (e.g. conservancy boards, cost-reimbursement contractors), what documentation burden does Ecology require? Alternatively, perhaps Ecology could maintain an annual ET spreadsheet on its website to assist with data access issues and help with repeatability and consistency.

Page-Specific Publication 26-11-017 (aka GUID 1210) Comments

1. Page 1. The bulleted list does not include a specific reference to evaluations of consumptive use under the public interest test. This is nested in part under some other cases (e.g. bullet 5, trust), but in my experience Ecology has applied a consumptive use increase/"recency" inquiry in other permitting situations. For example, groundwater changes trigger a public interest test that surface water changes do not. Does Ecology expect practitioners to consider consumptive use issues under the public interest test? If so, my understanding is that this is not a prohibition in increasing consumptive use in the same way ACQ works, but rather it would be a weighing of issues across the entire public interest spectrum.
2. Page 2. Consumptive Use Definition. Consider removing the fixed 10% value in the definition itself. It is the only numeric value provided in the examples, and (as I note

later), is better served in the context of examples rather than a definitional statement.

3. Page 2. Crop Irrigation Requirement (CIR) Definition. I don't believe this definition is correct, and it is inconsistent with the correct definition noted on Page 4, Page 6, and in the WIG. CIR does not include the other additive elements of the irrigation water budget like frost protection, leaching, and many others. Consider revising the definition here. This statement specifically conflicts with the original statement on Page 2 of GUID 1210 in the CIR definition, which is correct.
4. Page 2. ET Definition. When discussing / defining ETc, consider clarifying introducing crop coefficient (Kc), and that Etc is often calculated by multiplying reference ETr x Kc (e.g. National Irrigation Guide, Page 17-4). You introduce this fairly late in the paper in Section 5.2. Kc research is ever-changing which is another source of uncertainty in using the online models.
5. Page 2, TIR definition. While this definition is largely unchanged from its original form in the original GUID 1210, the statement on "miscellaneous water requirements" could be misconstrued if the CIR definition is left as is, and does not include the specific additive nature of elements of the water budget I've noted earlier. If the CIR definition is edited, no change here is needed.
6. Page 3, Background. If Ecology is interested in preserving the history of the development of this document here, it could condense my earlier comments into a simple bulleted list with relevant dates for Circular 512 (1969), XB0925 (1982), WIG (1985), WIG Supplement (1992), GUID 1210 (2004), Provisional WIG (2008-2012), New Ecology Consumptive Use Guidance Publication 26-11-017 (adoption date).
7. Page 3, Footnote 5. Unlike in the definition section, the reference to a 10% runoff evaporation rate is better suited here. Like other elements of the water budget, this too can be variable and at times Ecology has used vegetation surveys to better estimate this, but having an "order of magnitude" guidance value here is helpful.
8. Page 4. Practitioners often encounter situations where estimated TIR is greater than the duty in the water right. A footnote on this page and an example of this situation in Appendix B would be helpful guidance. The TIR (aka "Water Duty") itself is not a limitation of a water right, but is a tool in considering reasonable use as noted in *Ecology v. Grimes* (1993). When the estimated TIR > the original authorization, but reductions in acreage has occurred to compensate, that is typically just crop management. However, when the estimated TIR > the original authorization and acreage is the same as that authorized, then the practitioner should consider those implications. Either efficiency has to go up (i.e. reconsider whether original Ea assumptions are correct), or the ET has to go down (i.e. deficit irrigation may be occurring) to stay within the water right. Sometimes deficit irrigation is deliberate

(e.g. to meet other crop quality goals) and sometimes it results from not having enough water right authority or having a system that is low in the efficiency range and suffers from low distribution uniformity. An example on this topic will cost you little in page count and gain you greater consistency in the future.

9. Page 8. From a sequencing standpoint, consider moving the concluding sentence at the end of the second paragraph, "Selection of the average Ea, %Evap, %CU, and %RF from Table 1 is often reasonable", until after the bulleted list of reasons to consider something other than the mean value on Page 9. The practitioner should only select a value after the investigation—not default there. In addition to the bullets noted, here are additional situations that should help a practitioner think about whether their situation is similar to the mean, similar to a below-average application, or similar to an above-average application, and help select an Ea that is appropriate to it.
    a. What was the original authorization's assumed efficiency and has anything changed since that original Ecology judgement was made? Absent any changes in infrastructure, it may be appropriate to retain that judgment than supplant it with an average value.
    b. What is the size of the farm/water right? Of all criteria, size often matters. Small settings tend to have lower efficiency that are reasonable due to labor and capital constraints.
    c. Is the irrigation setting for commercial crops or self-use? Commercial ventures are better capitalized and have better labor control and are often at the higher end of the Ea range.
    d. Is the water right owner public or private? Public entities have access to public funding (also a waste consideration), have a rate base that allows for greater capitalization, and a fixed labor base. These can improve Ea in some situations.
    e. Is there a non-irrigation overlapping use? For example, if the land is also used for grazing / stock use, then that would tend to lower Ea. Similarly, if the land has a recreational component (e.g. irrigation of parks, golf courses), that can lead to compressed irrigation windows relative to typical farming and lower Ea.
10. Page 9. This page could use a greater explanation on the range of efficiencies and implications of each. Right now, it reads like we'll consider the average first as reasonable, we may increase Ea if the first set of bullets are true, and then if someone is below average, then pejorative words like "improper", "inadequate", and "error" should lead a practitioner to look at waste which has to be prevented to the

greatest extent possible. Instead, I would characterize 5 different groups of situations and recommend you include an example of each in Appendix B.

a. Group 1 (peak Ea). Ea for their system is near 100%. These are groups who could be large, commercial private farmers (e.g. pivots, drip, soils moisture monitoring, irrigation scheduling). It could also include some that are deficit irrigating, so the practitioner should consider whether a full CIR is appropriate (e.g. deficit wine grapes example with drip irrigation, 100% Ea, but lower CIR than what may be published). Ecology's guidance in general doesn't not address deficit irrigation well, and it should as it is a common practice for farmers for many crops to produce appropriate quality over quantity.
b. Group 2 (above average Ea). Some/many of the higher Ea criteria in the bulleted list on Page 8 are present. This might direct a practitioner to select an Ea near the top of the range rather than the mean.
c. Group 3 (average Ea). This could include situations where elements of both higher and lower Ea criteria from the list on Page 8 and 9 are present, or situations where little is known (e.g. perhaps the farm is no longer operational and the water has been in a trust donation for some time).
d. Group 4 (below average Ea). This could include some/many criteria on the list on Page 9 and those I noted above. However, as I noted on how the ranges were developed, below average Ea is not waste. Words that have a negative connotation like "improper" and "inadequate" should not be used to describe this group. The 20-acre horse ranch and hayfarm I ran for 20 years was irrigated by wheelines, big gun sprinklers, and handlines. It would certainly be at the lower end of the efficiency range (e.g. 60%) as it had labor constraints (just me), was in a state of constant repair (grazing animals and irrigation infrastructure often collide (literally), was not a commercial venture, was small, did not employ automation or formal irrigation scheduling, but was not wasteful (according to the *Aquavella* Court that agreed on a reasonable, but low efficiency). Consider changing some of the adjectives you use to describe this case to differentiate it from Group 5.
e. Group 5 (wasteful). Ecology dips its toe in the waste arena here, and it is inevitable that you do so given the subject matter. However, citing Grimes and noting only that inefficient practices should make the practitioner consider waste does the topic a disservice. Ecology should also cite RCW 90.03.005 and the broader set of criteria for waste, as well as the seminal litigation on this subject (i.e. MVID I and MVID II): "*Further, based on the tenet of water law which precludes wasteful practices in the exercise of rights*

to the use of waters, the department of ecology shall reduce these practices to the maximum extent practicable, taking into account sound principles of water management, the benefits and costs of improved water use efficiency, and the most effective use of public and private funds, and, when appropriate, to work to that end in concert with the agencies of the United States and other public and private entities." Take for example the research by Hanson noted earlier (excerpted below). For periodic move sprinklers (i.e. handlines), draft GUID 1210 repeats the same range as the original GUID 1210: 60 to 85%. I agree with Dr. Peter that the state of this science has not likely changed much since 2004 when it was last considered. Hanson contains data that helped inform that. Certainly I would agree that the 1.8% of those surveyed with less than 10% DU are wasteful. But are the 14.6% of those surveyed in the 51% to 60% range wasteful just because they fell outside of one standard deviation relative to the mean? That may include windy farms, farms with poor soil, small farms and many other factors that are reasonable. Waste is a legal evaluation informed only in part by Ea, but has many other criteria that should be considered. In that latter example, if the farmer in question was a public irrigation district like MVID was, I might feel differently than if it was a 20-acre private hay farmer (e.g. public funding eligibility prong under RCW 90.03.005). I think you can expose a wider range of possibilities on Page 8-9 with minimal text additions. And having a better understanding of the GUID 1210 history and the genesis of the data that created the ranges below is critical to a permit writer making sound judgement, so preserving some sense of history in this guidance, even an abbreviate form, will lead to better results long-term.

DU Range	CM	SS	PM	MS	D	F	B
0-10	0	0	1.8	0	0	0	0
11-20	0	0	0.9	0	0	0	0
21-30	0	0	2.8	1.4	1.2	0	0
31-40	1.8	0	7.3	2.5	1.8	2.0	2.9
41-50	1.8	12.5	14.6	4.3	2.4	2.6	1.4
51-60	1.8	21.4	13.8	14.5	6.1	9.2	1.4
61-70	22.8	39.2	29.3	21.3	14.7	5.9	12.9
71-80	38.6	21.4	20.2	27.2	27.0	20.4	10.0
81-90	33.3	5.4	8.2	25	35.0	27.3	35.7
91-100	0	0	0.9	3.6	11.6	32.9	35.7

CM = continuous-move sprinklers, SS = solid-set sprinklers, PM = periodic-move sprinklers, MS = microsprinklers, D = drip emitters, F = furrow, B = border.

11. Page 9. The guidance mentions site constraints "soils" and "topography" but it may be helpful to provide more clarity on this topic. For example, cobbly or gravelly soils, or steeper topography, can result in lower efficiency. Referencing the NRCS Web Soil Survey Web Soil Survey - Home and USGS National Map Viewer tool for contours: (The National Map - 3D Viewer) could be helpful resources, or even the original Appendix A in the WIG as, unlike ET, static soil information in that publication is likely still relevant.
12. Page 10. Table 1. Most of the numbers in Table 1 changed slightly and largely conform with my understanding of the science. However, a central issue in the 2004 litigation was focused on a conservancy board change that allowed a very high %Evap value for a center pivot system with top of pipe sprinklers. Early literature suggested, as does the current Draft Ea, that 40%+ consumptive use can occur in those settings. The theory here is that the application level is on the order of 15 feet in the air, and has greater evaporation potential due to wind drift, low DU and spray evaporative loss. But later researchers found that the early literature overstated %Evap based on drop size research. Top of pipe sprinklers that have large drop sizes did not evaporate as greatly as previously theorized because the surface area to droplet volume ratio was small (as compared to small droplet mister type sprinklers, which have a high surface area to volume ratio). The collective experts decided on a range of %Evap from 5 to 15% largely based on height of application, stressing case-by-case judgement throughout (e.g. perhaps windier conditions could enjoy more than 15% evaporation). Ground level application (e.g. flood, furrow) didn't get a "zero" but rather 5% on the theory that there was greater evaporation from a free water surface than wet ground. Mid-elevation application methods (e.g. about 3 to 5 feet) got a 10% value for %Evap, while high elevation methods (e.g. top of pipe, overhead impact) got the highest value of 15%. The current draft Table 1 has values for %Evap that are much greater than the 2004 experts. Is this supported by the current literature and peer review? Please ask Dr. Peters to relook at the %Evap numbers for scenarios that have a "zero", and for sprinkler values > 15%, as these conflict with the earlier panel of experts' opinion.
13. Page 11. This could be a good place to discuss accuracy issues given you broach this topic in the first paragraph, or in Section 5.1 where you discuss meter accuracy.
14. Page 11. The discussion of when to use data from the Effective Water Use Model should be strengthened. I agree that annual consumptive use estimates are appropriate for ACQ. Averages, however, may not be the best choice for proposed water uses. With climate change and water use needs increasing, why would a historical average over any time period be the right choice. It may be better to consider the methodology outlined in XB0925 where you consider both the average

and the drought frequency of the individual locale. That pre-WIG guidance document contains table for 2, 5, 10, and 20 year drought additions to the water budget. An average-only outlook immediately sets the water right holder for failure on compliance if they follow crop need over water right authority, or on crop yield sacrifices (e.g. deficit irrigation) if they follow water right authority over crop need.

   a. The guidance provides no direction on the other criteria on page 1 (e.g. impairment, trust, and my recommended addition of public interest). It should. In fact, the original GUID 1210 contains this sentence on this topic: "*While an ACQ change requires averaging of the two highest years of consumptive use, consumptive increases that could lead to impairment may be evaluated using the highest year of consumptive use*". Ecology should not provide guidance on only a subset of the situations it instructs practitioners to use the guidance for.

15. Page 13. Section 5.2. We have had recent firsthand experience in using these models, only to find that the data change months later when we go back to them without any explanation. The WIG is outdated, but was repeatable and immutable. The point about recording the date and information at time of retrieval is important. However, how will Ecology evaluate this if the information changes mid-processing? For example, if an analysis is completed by a conservancy board or cost-reimbursement contractor, and then Ecology reviews and finds it different, does that prompt a modification of the decision or not? Or what if that data is behind a paywall and Ecology can't independently verify that a third party has erred or promoted an unreasonable interpretation? Does it matter if the change is within the margins of error noted previously? And if we're to use these on-line techniques, can those keepers be instructed to maintain a log of changes when data sets are updated so the causation is not left in doubt? One can imagine a situation where data gives you a 10% higher or lower number and we don't know how or why to discuss the change (e.g. did a new crop coefficient get published, was another two years added to the data set, did a station calibration change?).
16. Appendix A: Yellow boxes. This has the danger of short-circuiting all of the judgement discussion that came before, because %CU noted here is based on Average % Evap, rather than a calculated or estimated %Evap given Ecology's bulleted lists on Page 8 and 9. This same challenge exists throughout this flowchart whenever %CU is used, because %CU in Table 1 really means Average %CU. I suggest you add a footnote to %CU throughout this graphic that say: "Table 1 provides both %CU based on Average %Evap, and a means to modify %CU based on criteria described on Pages 8 and 9 of this guidance. Users should bias towards calculating %CU based on site specific conditions rather than assuming it".

17. Appendix B. The three examples provided here are mildly helpful, but are the equivalent of "vanilla" and "chocolate" in an ice cream parlor of "rocky road" and "spumoni". Having examples that only outline situations where average and above average results occur, and calling them "reasonable and non-wasteful" does not explore the harder elements that are all too common, and reinforces the undercurrent in this policy that anything that is below average is wasteful. Contrast this to Ecology's Terms of Use Policy that has many more examples, across a larger range of situations, and is therefore more instructive. Or contrast it with the six examples in the 2007 Ecology training that includes harder topics like deficit irrigation and Ecology calculations that differ only slightly from that of a Conservancy Board's and within the margin of error. Please include a wider range of examples dealing with the subjects I've raised herein to provide greater guidance on the diversity of experiences that are commonplace. The guidance document is already 32 pages—a couple more for clarity is worth it.

Technical Workshop on
Water Use Efficiency of Irrigation Practices

Date: November 29-30, 2004 (Monday and Tuesday)

Location: Red Lion Inn, Pasco, Washington

Participants: Dan Haller, P.E., Washington Department of Ecology, Central Regional Office
Dennis Kincaid, PhD, USDA-Agricultural Research Station (ARS), Idaho
Darryll Olsen, PhD, Benton County Water Conservancy Board (BCCB)
Leigh Nelson, P.E., United States Department of Agriculture (USDA)
Mark Nielson, Franklin Conservation District (FCD)
Robert Montgomery, P.E., Montgomery Water Group
Tom Spofford, P.E., USDA, Washington, DC (invited)
Robert Stevens, PhD, Washington State University
Allen Thompson, PhD, University of Missouri
Paul Wattenburger, PhD, P.E., IRZ Consulting
Fred Ziari, P.E., IRZ Consulting (FACILITATOR)

DRAFT AGENDA

Monday, November 29th, 2004

8:30 – 8:45 a.m. Introductions, Agenda Review, Group Process. (Fred Ziari, Workshop Facilitator and Participant)

8:45 – 9:10 a.m. Context for the Technical Workshop (20 min. presentations; 5 min. discussion)

1. Welcome; Washington Water Law (Keith Phillips)
2. Implications for Water Right Changes (Dan Haller)
3. Statutory context for return flows (Darryll Olsen)

9:10 – 9:30 a.m. Irrigation Requirements: Evapotranspiration, Frost Protection, Cooling, Salt Leaching, Germination, Return Period. (Leigh Nelson/15 min. presentation; 5 min. discussion)

9:30 – 9:45 a.m. Defining Key Water Use Components of the On-Farm Irrigation Water Budget: Evaporation (spray, canopy, soil), Transpiration, Wind Drift, Soil Reservoir, Leaks, Runoff, Deep Percolation. (Allen Thompson/10 min. presentation; 5 min. discussion)

9:45 – 10:15 a.m. Plant Evapotranspiration. (Paul Wattenburger/10 min. presentation, Allen Thompson/5 min. opening comments; 15 min. discussion)

10:15 – 10:30 a.m. Break

10:30 – 11:00 a.m. Spray Evaporative Loss and Wind Drift. (Dennis Kincaid/10 min. presentation; 20 min. discussion)

11:00 – 11:30 a.m. Canopy Loss. (Allen Thompson, 10 min. presentation; 20 min. discussion)

11:30 – 12:00 p.m. Irrigation Scheduling and the Soil Reservoir. (Bob Stevens, 10 min. presentation; 20 min. discussion)

12:00 – 1:00 p.m. Lunch

1:00 – 1:45 p.m. Irrigation Uniformity, Measurements and Estimates. (Mark Nielson, 15 min. presentation; 30 min. discussion)

1:45 – 2:30 p.m. Return Flows -- Deep Percolation and Runoff. (Bob Stevens, 15 min. presentation, Mark Nielson/5 min. opening comments; 25 min. discussion)

2:30 – 3:30 p.m. Sources of Irrigation Information in Washington – Benefits and Limitations, ET and Efficiency Assumptions. (Tom Spofford or his designee, 30 min. presentation, 30 min. discussion)

1. Washington Irrigation Guide, USDA/SCS/WSU (1985)
2. Irrigation Requirements for Washington, WSU, XB0925 (1982)
3. National Engineering Guide (USDA)
4. PAWS (WSU Cooperative Extension)
5. AGRIMET (Bureau of Reclamation)

3:30 – 3:45 a.m. Break

3:45 – 4:45 p.m. Irrigation Efficiencies: How are they calculated, what are the published ranges for different irrigation systems, how is it defined in Washington? (Tom Spofford or Leigh Nelson, 30 min. presentation, 30 min. discussion)

4:45 – 5:00 p.m. Summary of Monday's discussion; Preview of topics for Tuesday (Facilitator)

Tuesday, November 30th, 2004

8:30 – 10:30 a.m. From current understanding and information, which factors should be considered when determining irrigation efficiency, and how are those factors defined and bounded? (Facilitated Discussion for All)

1. What ET values should be used?
2. What efficiency values should be used?
3. What are the consumptive and nonconsumptive portions of irrigation efficiency for different irrigation systems?
4. What is the accuracy of our estimation methods?
5. How sensitive is the outcome to different assumptions?

10:30 – 10:45 a.m. Break

10:45 – 12:00 p.m. Recommendations on a Practical Approach. (Facilitated Discussion for All)

For the task of estimating the consumptive use of water in a given irrigation water rights case, how can irrigation efficiency be determined in a practical manner?

Updating the Washington Irrigation Guide

In 2008, the Department of Ecology (Ecology), Washington State University (WSU), and the United States Department of Agriculture's Natural Resource Conservation Service (NRCS) funded a project to update the Washington Irrigation Guide (WIG). This publication is the standard in Washington State for estimating crop water needs.

Q: Has the WIG ever been updated before?

A: Yes. The current WIG was published in 1985, with supplemental data added in 1992. Prior to the current WIG, similar publications were developed in 1982 (*Irrigation Requirements for Washington—Estimates and Methodology, or "Bulletin XB0925"*) and 1969 (*Circular 512*).

Q: Why update the WIG now?

A: There are 3 reasons that Ecology, WSU and NRCS decided to collaborate on an update to the WIG. First, it is an important guidance document used today by farmers, irrigation design professionals, and state agencies in their daily work. Having the most accurate and up-to-date information is important to those that use the WIG. Second, several decades worth of new climate data are available. The WIG uses climate data to estimate crop water needs. And third, better scientific formulas are now available to estimate crop water needs.

Q: Are there different methods to estimate crop water needs?

A: Yes. There are over 50 scientific formulae to estimate evapotranspiration (ET). ET is a term used to describe the sum of evaporation and plant transpiration from the Earth's land surface to atmosphere. ET, combined with how much water is available from rainfall, determines how much irrigation water is needed to grow a crop. *Circular 512* (1969) used the modified Blaney-Criddle method to estimate ET, while *Bulletin XB0925* relied on the Doorenbos and Pruitt Blaney-Criddle method. The WIG (1985/1992) relied on both the FAO 24 Modified Blaney-Criddle and SCS Modified Blaney-Criddle methods. The current method for the new WIG will rely on the ASCE Standardized Penman-Monteith method.

FOR MORE INFORMATION

Information on this topic can be accessed through Ecology's website. The address is:
http://www.ecy.wa.gov/programs/wr/wig/wig.html

Ecology contact

Melissa Downes
Central Regional Office
Washington State
Department of Ecology
1250 W Alder St
Union Gap WA 98903-0009
Phone: 509-454-4259
Email: wig@ecy.wa.gov

Special accommodations

To ask about the availability of this document in a version for the visually impaired, call the Water Resources Program at 360-407-6872. Persons with hearing loss can call 711 for Washington Relay Service. Persons with a speech disability can call 877-833-6341.

The Penman-Monteith method predicts ET based on actual data and assumptions about local area temperatures, wind speed, solar radiation, and precipitation.

Q: How does the method of estimating ET affect how much water the crop needs?

A: Depending on what method is used, the estimate of crop water need can vary by ± 25%. For this reason, the American Society of Civil Engineers did a study of the most appropriate ET method to use when estimating crop water needs and determined that the Penman-Monteith method was preferable.

Q: How does the data in the Penman-Monteith equation affect crop water needs?

A: The current WIG (1985/1992) is based on average climate conditions from 1951 to 1980 over a limited number of weather stations. We now have access to many more stations around the state, and more recent data on rainfall, temperature, wind, relative humidity, solar radiation and other data. By updating the WIG to include newer data, the crop water needs will be more accurately predicted. WSU & NRCS applied standardized data cleaning methods to ensure that the data being used in the new WIG were based on best available science.

Q: How are peak water needs estimated?

A: The current WIG (1985/1992) included a method to translate average daily use to peak daily use to help in sizing irrigation infrastructure. However, the peak day estimate was still based on average rainfall and temperature conditions (as opposed to a drought year). *Bulletin XB0925* provided tables that showed the variation between average years and drought conditions on a 1:5, 1:10, and 1:20 year frequency. The new WIG will incorporate both of these tools allowing the user to specify the data set that best meets their need.

Q: Are peak water needs due to drought significantly different than average water needs?

A: Crops require more water in droughts because temperatures are hotter and rainfall is lower. Crops cannot always get the water they need during drought because water may not be physically available from the source, or legally available under the water right. If water is available, then crops may consume on the order of 10 to 15% more water depending on the severity of the drought. For example, *Bulletin XB0925* published crop water needs for average and drought years. Pasture in Ellensburg in an average year requires 32 inches, while in a 20-year drought it would need 36 inches. A particular water user's reaction to drought varies, from diverting more water if available, to diverting the same amount of water and becoming 10% more efficient that year, to diverting the same amount of water and deficit irrigating the crop that year which reduces crop yield.

Please reuse and recycle

Q: How well documented was the old WIG?

A: Unfortunately, much of our understanding of how the old WIG was developed has been lost to time. We know the method of calculation and the data set used to develop the tables estimating crop water use. However, over the last 25 years, much of the actual data have been lost and the institutional memory of how it was developed is no longer available from the original authors. For example, the actual data sets and computations are not available, a bibliography of sources that provided the data are not available, data cleaning methods were not described, and sources of crop coefficients used to translate reference ET (e.g. grass) to a specific crop (e.g. apples) cannot be replicated. So while the WIG remains the standard ET guidance in Washington today, the underlying data are not well-documented. By contrast, all of the data in the new WIG will be documented, peer-reviewed and available, with both a written-published document and a web application.



Q: What is different in the results between the old WIG and the new WIG?

A: There are many differences that will be interesting to users of the WIG:

- The number of stations for which results are available increased from 90 to 232.
- The number of crops for which results are available increased from 40 to 76.
- Depending on specific locations, some crop irrigation requirements increase and some decrease.

Q: Does Ecology use the WIG when evaluating water rights?

A: Yes. Ecology routinely uses the current WIG when evaluating applications for new water right permits and applications for water right changes and transfers. In some cases this is required by statute because some water right transfer applications trigger a "consumptive use analysis," which requires Ecology to determine how much water is lost to ET from an irrigation water right. The WIG is the best source of information available to Ecology to comply with this statutory requirement. In other cases, Ecology uses information from the WIG, along with aerial photographs, to estimate historical water use when metered water or power data are not available to ascertain the extent that water was put to beneficial use in the past. When Ecology tentatively determines the extent and validity of a water right for the purpose of evaluating a water right transfer application, it tries to use multiple data sources to come up with the most accurate answer possible.

Please reuse and recycle

Q: Until the new WIG is completed, what data will Ecology use when evaluating water rights?

A: Until the new WIG has been peer-reviewed and gone through a robust public review process, Ecology will continue using the old WIG. Ecology wants to make sure it and the public have confidence in the new numbers before adopting them and training staff in their use.

Q: Once the new WIG is finalized, will Ecology allow applicants to use the old WIG or an ET estimate other than the Penman-Monteith method?

A: Not unless there is a compelling scientific basis to do so. The new WIG is based on the best method available for estimating ET in Washington State, the most comprehensive data set available, and a peer-reviewed work product. Other methods and data sets may yield higher (or lower) numbers, but they won't necessarily be more accurate. Ecology will consider such requests on a case-by-case basis.

Q: What data set will Ecology use when evaluating water rights?

A: It depends on the type of analysis Ecology is required to do by statute. Generally, Ecology will try and match the data set to the statutory test prescribed.

- For extent and validity determinations, Ecology will use the WIG long-term average which is based on the most recent 30 year data set from 1980 to 2010. WSU and NRCS considered whether longer data sets would affect results, and generally the correlation was within an inch, so a standardized 30 year data set was selected for all of the stations.
- For new water right application, Ecology will use the WIG long-term average as a starting point for a reasonable water duty. However, it will also consider drought frequency in the local area and the ability of the proposed irrigation system to adapt to changing crop water demands. Ultimately, a certificate will only issue for the quantity of water put to beneficial use.
- For annual consumptive quantity (ACQ) evaluations triggered when someone seeks to add acres or purposes of use to a water right, or for trust water donations, Ecology will use the most recent 5-year period of water use directed in the statute.
- For impairment evaluations based on a consumptive use evaluation, Ecology will consider the highest consumptive use over the life history of the water right.
- For drought transfers, Ecology will consider using the climate data that best correspond to the frequency of the drought being experienced.

Q: What if I recently got a water right transfer approved under the old WIG and the new WIG would have given me a higher number?

A: Because Ecology typically uses multiple data sources to estimate historical beneficial use, it does not expect that the WIG update will dramatically affect recent decisions. However, Ecology's change authorizations are permissive and its extent and validity determinations are tentative in nature. An applicant may cancel a change authorization which remains in a valid development schedule, and may re-file a change application and seek a new tentative determination. Ecology will consider such applications on a case-by-case basis. In addition to the new WIG data, Ecology may require corroborating evidence

such as power or meter records, irrigation scheduling, or production records to confirm historical water use under the water right.

Q: What if the old WIG numbers were used in adjudicating my water right?

A: An adjudication court's determination of the extent and validity of a water right is final. If the court relied on the old WIG as part of the evidence of the total annual quantity confirmed, then changes in the new WIG cannot change the total annual quantity authorized (unlike for changes where Ecology's decisions are only tentative). However, adjudication courts typically do not assign a consumptive use value as an express limit of an adjudicated water right. Therefore, future transfers on adjudicated water rights can rely on the new WIG as one of several data sources in evaluating historical beneficial use.

Q: Will the WIG be updated in the future?

A: Yes. This is the fourth time the State has updated this guidance document and updates will occur in the future. It is likely that future updates will occur more often (e.g. every 5 years) rather than 25+ years apart since the last update to the WIG.

Please reuse and recycle

GUID-1210 WATER RESOURCES PROGRAM GUIDANCE

DETERMINING IRRIGATION EFFICIENCY AND CONSUMPTIVE USE

Forward

In 2002, Ecology's Water Resources Program "Internal Policy Team" (IPT) began working on internal guidance for implementation of the "annual consumptive quantity" (ACQ) test required under RCW 90.03.380. The two-year effort culminated in the adoption of POL 1210 and PRO 1210, a policy and procedure to assist permit writers in administering this test. The need for further guidance was discussed in early 2004 around irrigation efficiency and determining consumptive use for ACQ-related changes. Because the need to understand and quantify consumptive use spanned multiple purposes of use (e.g. irrigation, dairy, stockwatering, domestic, industrial, etc.), IPT determined that revision and adoption of the internal Water Allocation Guidelines (PRO 1070, unsigned) would be necessary. Based on IPT's current workplan, this effort is slated for 2005.

In October 2004, the Benton County and Franklin County Water Conservancy Boards filed a lawsuit in Benton County Superior Court objecting to Ecology's selection of irrigation efficiencies and quantification of consumptive use associated with irrigation water right changes. Ecology and the Board's settled this lawsuit by agreeing to hold an irrigation efficiencies technical workshop to address this topic.

On November 29-30, 2004, Ecology held the workshop in Pasco, Washington. The conference was attended by irrigation experts from academia, government, and the private sector[1]. Dan Haller participated in the workshop on behalf of Ecology and Darryll Olsen participated on the behalf of the conservancy boards. The experts were asked to assist Ecology to 1) understand and quantify the terms and factors that affect irrigation system efficiency, and 2) within each irrigation efficiency term, understand and quantify the consumptive/non-consumptive balance. As the two-day workshop progressed, it was clear that this was an ambitious goal, with many variables, room for debate on issues of science and on-farm application, and challenges in measurement. Despite these challenges, Ecology did come away with a number of sound recommendations to address its core goals, including the following:

1. USDA-NRCS has prepared a National Irrigation Guide and is working on a new Washington State supplement to the National Guide. By January 2005, USDA-NRCS plans to submit a draft supplement for stakeholder review.

   Ecology plans to participate in this review and provide USDA-NRCS with a better understanding of how our permit writers use irrigation guides.

[1] Tom Spofford, USDA, Washington, D.C.; Leigh Nelson, USDA-NRCS, Ephrata; Allen Thompson, University of Missouri; Dennis Kincaid, USDA-ARS, Idaho; Robert Stevens, WSU, Prosser; Mark Nielson, Franklin County Conservation District, Pasco; Robert Montgomery, Montgomery Water Group, Kirkland; Fred Ziari and Paul Wattenburger, IRZ Consulting, Hermiston, Oregon.

DRAFT

2. Within 2 years, USDA expects to update the crop irrigation requirement portion of the Washington Irrigation Guide. The new standard methodology is expected to be based on the Penman-Monteith ET equation, which was recently adopted by ASCE, after a prolonged study of more than 50 ET equations, as being the most accurate and easy to use. USDA has a simplified computer program to assist its staff in calculating ET that is currently based on the Blanney-Criddle formula. Part of the 2-year effort is expected to be updating this program to the new methodology. The software allows the user to specify the data set to calculate ET, which can include a long-term average (e.g. 30 years as in the case of the WIG), or year-by-year (which may be useful in ACQ calculations which require an average of the highest 2-years within the most recent five year period).

   Ecology plans to adopt USDA methodologies in quantifying ET and will consider use of the free USDA software internally for use with its permit writers.

   In the interim, Ecology will continue to use the Washington Irrigation Guide (WIG) as the definitive irrigation guidance document for the State, and will also use WSU PAWS, and the Bureau of Reclamation's AgriMet sites for supplemental information depending on the proximity of monitoring stations to proposed project sites, availability of data and the type of change requested. While Ecology is coordinating with USDA on adoption of new methodologies for the State, Ecology agrees that the use of WIG by water conservancy boards is appropriate. Following Ecology's adoption of a new State standard, Ecology will provide updated information and training to water conservancy boards.

3. USDA-NRCS is willing to assist with training of Ecology staff on irrigation efficiency, and calculation of ET and consumptive use.

   Ecology will work with USDA over the next 2 years to determine an appropriate training level.

4. The experts determined that there is no one irrigation efficiency number that can be applied to all irrigation systems of a particular type (e.g. center pivot or wheel line). System management is as important as the type of irrigation system in determining efficiency and each farm needs to be looked at on a case-by-case basis. The experts recommended ranges for the different types of irrigation systems and identified a 2002 journal article[2] by Terry Howell, USDA as a good foundation for these ranges.

   Ecology has included a table of irrigation efficiency ranges within this guidance document, including directions for permit writers to use in assessing irrigation

[2] *Irrigation System Efficiencies*, Terry A. Howell, PhD, PE, USDA-Agricultural Research Station, Bushland, Texas, 2002 Proceedings of the Central Plains Irrigation Short Course and Exposition.

DRAFT

management practices and determining how to select an appropriate irrigation efficiency from the range[3].

5. The workshop included a prolonged discussion of the component elements of irrigation efficiency, including spray evaporative loss, canopy loss, wind drift, deep percolation, and runoff. These components vary based on numerous other variables, and were all dependent on irrigation scheduling and management. The experts recommended against individual quantification of these elements and focused instead on grouping and quantifying the consumptive (e.g. spray loss, canopy loss, and wind drift) and non-consumptive terms (e.g. deep percolation and runoff).

   Ecology has included a table of the consumptive/non-consumptive balance of irrigation efficiency within this guidance document.

The following guidance document only provides information on consumptive use associated with irrigation use. Consistent with the IPT's workplan, development of consumptive use guidance on other irrigation issues (e.g. frost protection and cooling) and on non-irrigation issues (e.g. domestic, industrial, stockwatering, etc.) will be forthcoming.

DRAFT

[3] Table 1 in the guidance document attached is contains a few modifications made by Ecology following the workshop. Notably, this includes the addition of common irrigation systems not discussed at the workshop (e.g. flood, lateral-move, handline), modification to the solid-set/wheelline sprinkler efficiencies, and additional description for the consumptive/non-consumptive portions of the irrigation efficiency.

DETERMINING IRRIGATION EFFICIENCY AND CONSUMPTIVE USE

Resource Contact:	Policy and Planning Section	Effective Date:	DRAFT
		Revised:	NEW

References: RCW 90.03.290, RCW 90.03.380(1), RCW 90.44.100, POL 1120, POL 1210, PRO 1210

Purpose: The purpose of this document is to provide guidance to water resources permitting staff for:

1. Determining irrigation efficiency; and
2. Determining consumptive use associated with irrigation.

Application:

1. When issuing new water rights for irrigation purpose of use, and when conducting tentative determinations of existing irrigation water rights, Ecology frequently must estimate or determine irrigation efficiency.
2. Ecology must determine the consumptive use of an irrigation right when:
   a. A change in purpose is proposed that could increase the consumptive use of a water right and such increase could result in impairment of existing water rights; and
   b. A change to enable irrigation of additional acres or an additional purpose of use is proposed, requiring application of the Annual Consumptive Quantity test.

Resources:

1. State of Washington Irrigation Guide (WIG), 1985 (amended 1990, amended 1992 for select western Washington crops)
2. Irrigation Requirements for Washington—Estimates and Methodology, 1982 (XB0925, reprinted 2001 EB1513)
3. National Irrigation Guide, 1997[4]
4. National Engineering Handbook, 1993[5]
5. WSU Public Agricultural Weather System (PAWS)[6]
6. Bureau of Reclamation AgriMet[7]

[4] http://www.wcc.nrcs.usda.gov/nrcsirrig/irrig-handbooks-part652.html
[5] http://www.info.usda.gov/CED/
[6] http://index.prosser.wsu.edu/
[7] http://www.usbr.gov/pn/agrimet/

DRAFT

Definitions

The following definitions are intended within this policy:

- "**Application Efficiency (Ea)**". The ratio of the average depth of water infiltrated and stored in the root zone to the average depth of water applied, expressed as a percentage.

- "**Available Water Capacity (AWC)**". The portion of water in a soil that can be readily absorbed by plant roots of most crops. It is the amount of water stored in the soil between field capacity and permanent wilting point. Also called the Water Holding Capacity

- "**Deep Percolation**". Water that infiltrates below the root zone, including water used for leaching and water resulting from non-uniform application of water for irrigation.

- "**Distribution Uniformity (DU)**". A measure of how evenly water infiltrates into the ground across a field during irrigation. DU is expressed as a percentage between 0 and 100. It is defined as the ratio of the average low-quarter depth of infiltration to the average depth of infiltration.

- "**Evapotranspiration (ET)**". The sum total of plant transpiration, evaporation off of the plant foliage and the soil surface, and water used for plant growth.

- "**Field Capacity**". The water content at which drainage becomes negligible in a free-draining soil.

- "**Irrigation Scheduling**". All farmers schedule their irrigation to some degree. Irrigation scheduling as defined in the literature consists of 1) understanding how much *available water capacity* the farm has in its *root zone* for the crop being grown; 2) estimating crop *ET* to predict the interval between watering; and 3) field-truthing ET predictions with some kind of soil-moisture measurement.

- "**Management Allowed Depletion (MAD)**". This value, expressed in percent, is the percentage of the AWC in the root zone that plants can utilize before experiencing stress.

- "**Permanent Wilting Point**". The minimum soil-water content when plants permanently wilt.

- "**Return Flow**". The sum of deep percolation and runoff that returns to waters of the State.

- "**Root Zone**". The effective depth of crop roots in the soil from which water is extracted.

DRAFT

Irrigation 101, The Water Budget

Crops need water to grow (photosynthesis), to transport nutrients from the soil and for cooling (transpiration). During the course of irrigation, some water that is intended for the root zone ends up in other places. Some water lands on the soil and evaporates before it can infiltrate. Collectively, these components of the water budget are called *evapotranspiration* or ET.

In addition to ET, applied water can evaporate in the air (*spray evaporative loss*), it can evaporate off the plant canopy (*canopy loss*), it can blow off the irrigated property (*wind drift*), it can *runoff* the land if the application rate is greater than the soil infiltration rate, it can *leak* out of the conveyance or distribution system, and it can *deep percolate* past the root zone due to over-application or non-uniform application. The irrigation water budget is shown in Figure 1 below[8].

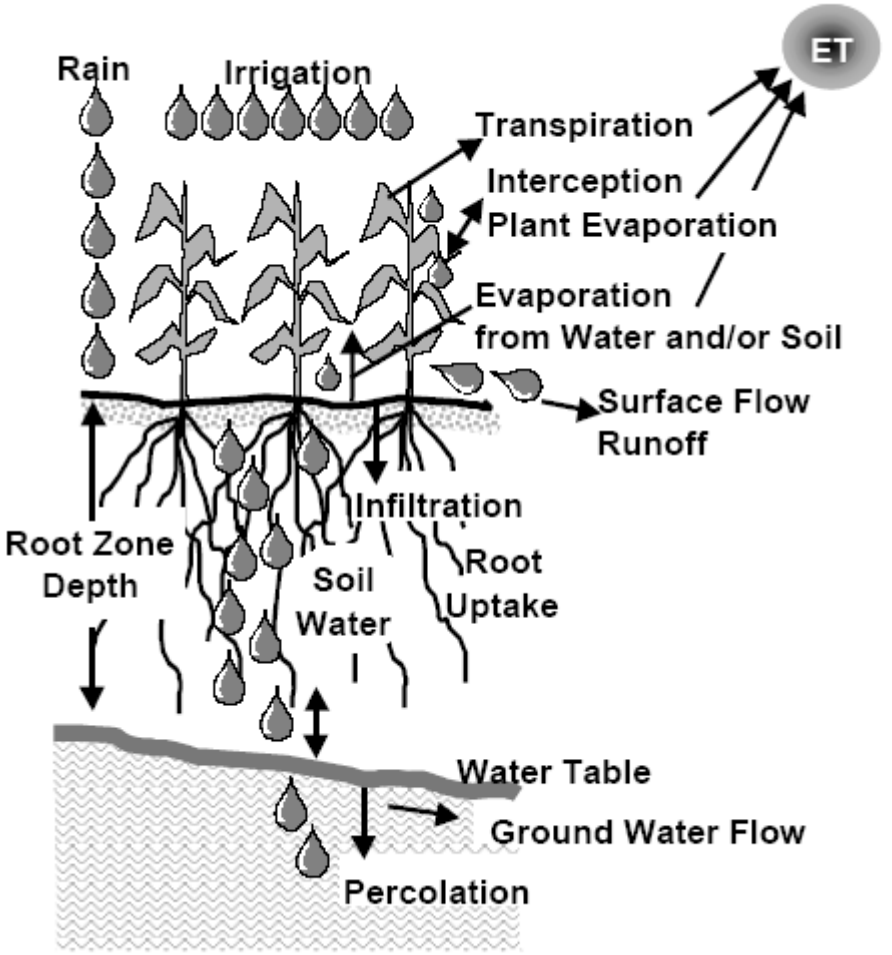


Figure 1: The Irrigation Water Budget

[8] Figure from *Irrigation Efficiency, Encyclopedia of Water Science*, Dr. Terry Howell, USDA, 2003.

Magnitude of Components of the Irrigation Water Budget

The magnitude of the components of the irrigation water budget vary according to numerous variables, the most important of which is how the irrigation system is actually managed (e.g. irrigation set times, maintenance practices, matching supply to demand, and other local conditions). The following provides a summary of each of the components and magnitude ranges. Table 1 on the following page summarizes this information for use in estimating irrigation efficiency and consumptive use.

- *Evapotranspiration*. There are over 50 different methods for calculating ET, including simple temperature methods (e.g. Blanney-Criddle) to more accurate energy methods (e.g. Penman-Monteith). The Washington Irrigation Guide utilized the SCS Blanney-Criddle Modified method and work done by WSU using the FAO 24 Blanney-Criddle method in XB 0925 to derive crop consumptive use estimates (WIG, page WA683.11(a)(2)). PAWS and AgriMet both site the use of a Kimberly-Penman ET model. Depending on the monitoring station and the years selected, values among these data sources within Washington can vary by as much as 20%, but for most stations, the variance is on the order of 1-2 inches.

- *Irrigation Efficiency*. Irrigation efficiency represents the amount of water that needs to be applied in addition to the crop requirement for a particular type of irrigation system to meet the demands described below.

    - *Spray Evaporative Loss*. When water travels through the air during sprinkling, some water evaporates. The magnitude of evaporation depends on drop size (smaller drops evaporate quicker), drop travel time (e.g. sprinkler height off the ground, sprinkler angle, and wind), and environmental conditions (temperature, humidity, etc.). For sprinkler systems within low heights and low wind conditions (5 feet or less off the ground and 5 mph or lower average conditions), spray evaporative loss tends to be on the order of 2% or less. For higher elevations and wind conditions, evaporative losses can be > 10%.

    - *Canopy Loss*. When water travels from the sprinkler to the ground, some water lands on the plant canopy[9]. The amount of water held on the canopy depends on crop leaf area, crop type, and growing season. Water that is retained on the canopy will evaporate fairly quickly once irrigation stops (e.g. 1 hr or less during the day). Water evaporating off the plant canopy cools the plant, which reduces the amount of transpiration for the day. However, because evaporation from a free water surface occurs at a faster rate than transpiration through the plant leaves, the ET on the day of irrigation is greater than the ET on the day before or the day after irrigation. The net increase in evaporative loss associated with canopy losses (after subtracting out the transpiration that would have occurred that day) is typically on the order of 3 – 5%. Net canopy losses can be greater (10% or more) when application rates are low (e.g. center-pivots at high rotation speeds).

[9] Although XB0925 indicates that the crop irrigation requirements in Appendix B of the WIG include evaporation off the plant foliage, this does not include canopy losses. The WIG derives its ET estimates based on an assumption of a surface application (e.g. rill), applying a 2-inch application depth for a silt loam soil.

DRAFT

- *Wind Drift*. Wind can cause sprinkled water to drift out of the application area. If it drifts off the irrigated property, it is typically considered to be consumed (e.g. edge effects). If it drifts to the crop in another part of the field (more common), then subsequent evaporation of these droplets off the plant canopy or the soil cools the crop and reduces transpiration. The net consumptive magnitude of wind drift under most conditions is on the order of a few percent. However, under high average wind conditions, 10% or more, wind losses can be higher and can lead to decreased application uniformity.

- *Runoff*. When water is applied at a rate greater than the soil can infiltrate, it can lead to runoff. Runoff within a field may still be used by the crop, although areas of low elevation may be areas of deep percolation if runoff typically collects there. If runoff returns to waters of the State, it is considered to be return flow. Runoff is more prevalent in surface irrigation systems (10 – 40%) than in sprinkler systems, although some irrigation systems (e.g. center-pivot LEPA) can have runoff due to high application rates (2 – 20%).

- *Deep Percolation*. Deep percolation is common in both surface and sprinkler irrigation systems, the magnitude of which is heavily influenced by irrigation scheduling and soil type. Leaks, over-application and non-uniform application can all lead to deep percolation. If deep percolation returns to waters of the State, it is considered return flow.

    - *Leaks*. Leaks are a function of system age and system maintenance. Leaks can occur underground at joints and from cracks in the pipe due to age or improper bedding, and can occur above ground at sprinklers, valves and plugs. The National Engineering Handbook identifies the magnitude of leaks as 1 – 10%, with the lower end of the range indicative of a well-maintained system.

    - *Over-Application (Spring/Fall, Irrigation Scheduling)*. Over-application occurs when irrigation water is supplied in excess of the water storage capacity of the soil. Over-application most commonly occurs when irrigation demand is low (spring and fall), due to labor constraints (fixed irrigation times associated with hand-move systems), and due to non-uniformity of soils within a field (e.g. areas of sandy soil in a predominantly silt-loam field). Over-application can be estimated by comparing the sprinkler capacity and run time (e.g. gpm x irrigation hours) to the available water capacity of the soil (Appendix A in the WIG).

    - *Non-Uniform Application (DU)*. Sprinklers overlap in order to provide uniform application of water on the field. However, all sprinklers designs result in some areas of the field getting too much water and some areas not getting enough. Environmental conditions (e.g. wind) and system conditions (e.g. pressure and wear-and-tear on sprinklers) also affect uniformity. The DU is a measure of uniformity and indicates how much water the lowest ¼ of the field gets compared to the average. DU's are typically derived from catch-can tests.

DRAFT

Table 1: Summary of Application Efficiency Ranges, Consumptive Use, and Return Flows [1]

Method		Application Efficiency, Ea (%)[2]		Consumptive Use		Return Flow [5]
		Range	Average	%Ea Consumed [3]	CU Eff. [4]	Average
Surface:	Graded Furrow	50 – 80	65	5	95	30
	w/ tailwater reuse	60 – 90	75	5	95	20
	Level Furrow	65 – 95	80	5	95	15
	Graded Border	50 – 80	65	5	95	30
	Level Basins	80 – 95	85	5	95	10
	Flood	35 – 60	50	5	95	45
Sprinkler:	Periodic Move (Handline)	60 – 85	75	10	90	15
	Side Roll (Wheelline)	60 – 85	75	10	90	15
	Moving Big Gun	55 – 75	65	10	90	25
	Solid-Set—Overtree	55 – 80	70	15	85	15
	Solid Set--Undertree	60 – 85	75	10	90	15
Center-Pivot	Impact heads w/end gun	75 – 90	80	15	85	5
	Spray heads w/o end gun	75 – 95	90	10	90	0
	LEPA w/o end gun	80 – 98	92	5	95	3
Lateral-Move	Spray heads w/hose feed	75 – 95	90	10	90	0
	Spray heads w/canal feed	70 – 95	85	10	90	5
Microirrigation:	Trickle/Drip	70 – 95	88	5	95	7
	Subsurface Drip	75 – 95	90	0	100	10
	Microspray	70 – 95	85	10	90	5

1. The data presented herein should be used in conjunction with data gathered during the site investigation on a case-by-case basis. Historic irrigation practices for the individual farm will affect where in the efficiency range a particular water right applicant falls.
2. Ea = ET / Total Use. Total use can be obtained from water meter readings, estimated from power readings, or estimated from system capacity x run time.
3. %Ea Consumed reflects the portion of the irrigation efficiency that is consumptively used through evaporation (spray, wind, canopy) in addition to the ET.
4. CU Eff is the efficiency term to be used in the ACQ calculation and is equal to 100% - % Ea Consumed. For example, for a given year and crop, the Consumptive Use = ET / CU Eff. For a surface irrigation system, only an additional 5% above the ET is consumed, while in a center-pivot with impact heads, 15% above the ET is consumed. CU Eff values are based on the average Ea. If actual efficiency is less than the average, CU Eff does not typically increase; rather, additional return flow is present and can be a part of the tentative determination as long as the magnitude of the return flow does not constitute waste as defined in RCW 90.03.005. If actual efficiency is higher than the average, than the permit writer needs to determine how to reduce CU Eff and return flow quantities on a case-by-case basis. Systems more efficient than the average may reflect deficit irrigation or well-managed irrigation scheduling which would serve to reduce the return flow quantities before reducing CU Eff.
5. Average Return Flow = CU Eff – Ea Average. For systems with lower than average efficiency, return flows will be proportionately larger.

DRAFT

How Do I Use Table 1 When Making a Tentative Determination of the Extent and Validity of an Existing Water Right?[10]

When making a tentative determination of the extent and validity of an existing water right, the permit writer should attempt first to calculate actual efficiency rather than assume an efficiency from Table 1. Actual efficiency (Ea) can be determined by dividing ET for the crop(s) grown by total water use. Total water use can be calculated:

- From water meter data.
- By converting dedicated power meter data (kW-hr) to flow (see WAC 173-173-160).
- From system capacity (e.g. average pump rate x average hours/day run x irrigation season).

If actual efficiency is less than the ranges shown, the permit writer should consider whether such use is reasonable or whether it is waste of water as defined in RCW 90.03.005. If efficiency is higher than the range shown, this can inform the permit writer that the full ET may not have been satisfied (e.g. deficit irrigation).

If actual efficiency cannot be calculated due to unavailability of data, then the tentative determination is often made by selecting an ET for the crop(s) grown, selecting efficiency, and estimating or measuring the irrigated acres.

- Selection of an ET will typically be based on the Washington Irrigation Guide, although depending on the location of the project to agricultural/weather stations, use of PAWS or AgriMet may be appropriate. Because the difference in ET predicted from these sources is typically small, permit writers may use any of these sources[11].
- Selection of an average efficiency from Table 1 is reasonable. The permit writer may also consider local custom in determining an assumed efficiency.
- Estimation of irrigated acres is typically determined by GIS calculation from one or more state-wide aerial photo coverages, from parcel information, or by direct measurement using a professional survey or GPS.

How Do I Use Table 1 When Making Permitting Decisions Involving ACQ or Consumptive Use?

Once an actual or estimated efficiency is determined, the consumptive portion of the efficiency term can be obtained from Table 1.[12]

- If the estimated or calculated efficiency is *equal* to the average Ea, the consumptive portion and average return flow portion of the Ea can be read directly from the table. For ACQ or consumptive use calculations, the crop ET can be divided by the term CU Eff to obtain the consumptive water duty per acre of land. Multiplying this value by the total acres provides the

[10] See POL 1120 for a more comprehensive discussion of tentative determinations.
[11] Ecology is currently working with USDA on adoption of a standard for the State in the calculation/estimation of ET. This guidance document may be updated in the future when Ecology identifies a preferred methodology.
[12] The permit writer should verify efficiency and consumptive use estimates by comparing the estimates to information obtained from the water right file and from the site investigation. Information on the farmers irrigation scheduling can be used to ground-truth irrigation efficiency and consumptive use estimates (e.g. system capacity and irrigation set times).

DRAFT

total consumptive use under the water right.

  - Example. Power meter data and the WIG are used to calculate an actual efficiency of 75% for handline sprinklers (an average system). Of the Ea term, 10% is consumed and 15% is return flow. For a crop ET of 3 feet, the total water duty (including return flow) is 3 feet / 0.75 or 4 feet. The consumptive water duty is 3 feet / 0.90 or 3.3 feet. 0.7 feet per acre is return flow.

- If the estimated or calculated efficiency is *less* than the average Ea, the consumptive portion of the Ea can be read directly from the table subject to site-specific information collected in the field by the permit writer. The return flow portion of the Ea will be the average return flow portion plus the difference in *project* efficiency and the *average* efficiency.

  - Example. Water meter data and the WIG are used to calculate an actual efficiency of 58% for handline sprinklers. The water right in question did not specify a maximum annual volume. The permit writer considers the factors under RCW 90.03.005 and the Supreme Court Case *Grimes* and concludes that 58% efficiency for handlines is reasonable and non-wasteful in this case. Of the Ea term, 10% is consumed and 32% is return flow. For a crop ET of 3 feet, the total water duty is 3 feet / 0.58 or 5.2 feet. The consumptive water duty is 3 feet / 0.9 or 3.3 feet. 1.9 feet per acre is return flow.

- If the estimated or calculated efficiency is *greater* than the average Ea, the consumptive portion of the Ea and the average return flow must also be consumed. Typically, systems that are more efficient than the average will first reduce return flow and then reduce consumptive use (e.g. deficit irrigation). The permit writer should obtain information on irrigation scheduling for the project to determine the consumptive / non-consumptive balance.

  - Example. Power meter data and the PAWS are used to calculate an actual efficiency of 85% for wheelline sprinklers. The site investigation and interview demonstrates that the farmer scheduled his irrigation in response to crop needs. The farmer routinely visited the AgriMet website and obtained ET rates, dug holes for hand-moisture sensing, and changed the wheelline on 12-hour sets which was sufficient to refill the root zone. Based on this information, the permit concluded that of the Ea term, 10% is consumed and 5% is return flow. For a crop ET of 3 feet, the total water duty is 3 feet / 0.85 or 3.5 feet. The consumptive water duty is 3 feet / 0.9 or 3.3 feet. 0.2 feet per acre is return flow.

How Do I Use Table 1 When Making Permitting Decisions on Applications for a New Water Right?

Applications for a new irrigation right may involve developed or undeveloped land. Where land is currently under irrigation and a new water right is sought (e.g. for additional water to meet a higher crop duty or a new source), Ecology will typically conduct a tentative determination of the extent and validity of the existing water right(s). This can inform the permit writer as to the actual efficiency of the project.

If the project involves undeveloped land or changes to existing land for new infrastructure, the permit writer may select an average efficiency from the table. The permit writer may also consider local custom in selecting an appropriate irrigation efficiency.

DRAFT

The Origin of GUID-1210:
Irrigation Efficiency and Consumptive Use (CU)

Dan Haller, PE, CWRE – Aspect Consulting







SUMMARY

1. Background / Timeline
2. Litigation
3. Time-out for some science fun
4. 2004 Experts Workshop
5. Resolution and adoption of GUID 1210
6. Updates to GUID 1210

In the Beginning . . . The Legislature created the Water Code

- **1917 to 1997 → Acres was a "fixed" water right attribute like quantity and priority date.**

  When a permit or certificate limits irrigation to a specific number of acres within a larger legal description, irrigation of no more than that specific number of acres may occur during any irrigation season. Moving the water over the entire described acreage during any crop year is an unauthorized expansion of the right. Kummer v. Ecology, PCHB No. 85-188 (1987); Benningfield v. Ecology, PCHB No. 87-106 (1987).

- **After 1997 → "Spreading" and "adding new uses" became legal subject to a new statutory "consumptive use" test.**

Where am I in the statute? Why do I care?

- **The Legislature put ACQ in the "no impairment" section of RCW 90.03.380. The test is focused therefore on what will diminish another's right not, for example, other tests like public interest.**

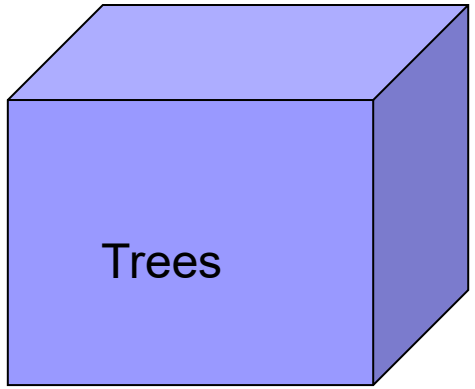
RCW 90.03.380. Right to water attaches to land—Transfer or change in point of diversion

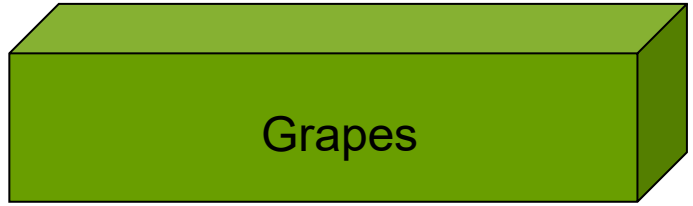
- (1) The right to the use of water which has been applied to a beneficial use in the state shall be and remain appurtenant to the land or place upon which the same is used: PROVIDED, HOWEVER, That the right may be transferred to another or to others and become appurtenant to any other land or place of use without loss of priority of right theretofore established if such change can be made without detriment or injury to existing rights. The point of diversion of water for beneficial use or the purpose of use may be changed, if such change can be made without detriment or injury to existing rights.
  - (a) A change in the place of use, point of diversion, and/or purpose of use of a water right to enable irrigation of additional acreage or the addition of new uses may be permitted if such change results in no increase in the annual consumptive quantity of water used under the water right.
  - (c) For purposes of this section, "annual consumptive quantity" means the estimated or actual annual amount of water diverted pursuant to the water right, reduced by the estimated annual amount of return flows, averaged over the two years of greatest use within the most recent five-year period of continuous beneficial use of the water right.

Background / Timeline (1997 to 2002)



- During this time period, Ecology's processing of ACQ changes were primarily related to crop change. → For example, I want to convert 50 acres of apples trees to 100 acres of grapes.
- 50 acres of trees x 4 feet = 200 ac-ft
- 100 acres of grapes x 2 feet = 200 ac-ft





Then in 2002, the Benton Board approved CG4-23101C

The applicant is making this request based on recent (within past 5-years) water application system efficiencies, where an older generation, center pivot system (high pressure, overhead impact sprinklers, with end gun) was upgraded (low pressure, drop-tubes with efficiency application emitters), resulting in less consumptive water-use per crop acre. The new efficiency measure costs were paid for by the applicant. The applicant proposes to use the "water savings" gained through the efficiency measures for application to a residential home development. As such, the water right would reflect an added purpose of use, place of use, and time of use.

- Before = 140 acres
- After = 140 acres, no crop change, and a subdivision of houses
- How is there no increase in CU?



Savings were based on conservation only

Relying on the pre-and post-change water application efficiency rates (minus return flows) of 75% and 87.5%, the water "savings" gained through efficiency improvements would be about 89 acre-ft. (622 acre-ft. minus 533 acre-ft., at 140 acres).

- Can consumptive use be saved only through sprinkler changes?
- Is the magnitude right?
- Ecology approved the decision, but . . . began studying CU science in earnest because similar changes followed.



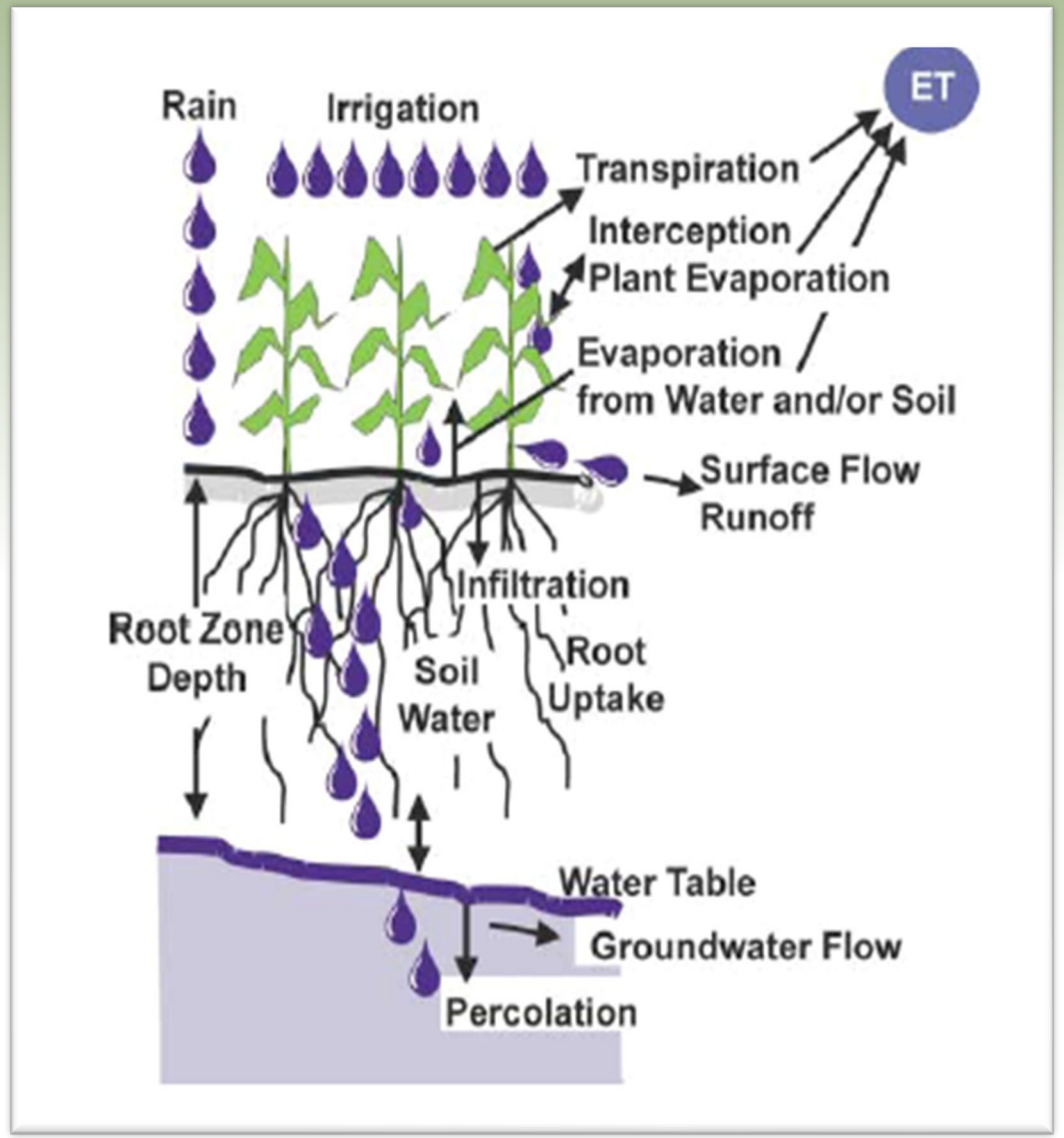
How did we investigate CU?

- **First, we reviewed the literature and contacted the authors of the research referenced in the Board decision.**

Saved Water Discussion. In 2001, Wiser Farms converted the irrigation system for the subject water right to high-efficiency low-pressure center pivot technology. The prior system was an old-generation high-pressure center pivot, with overhead impact sprinklers. The new system reduces the required water application for a given crop, primarily by reducing spray evaporative and water drift losses. Spray evaporative water losses are highest for high-angle, high-pressure, overhead sprinklers, which were used prior to 2001. The literature reports a value of 12% for spray evaporative losses using this old-generation technology, under calm wind conditions (Kincaid et al, 1986). These evaporative losses increase with wind speed, and at an exponential rate when wind speeds exceed 10 miles per hour (Frost and Schwalen, 1955; Inoue, 1963; Yazar, 1984). Under extreme conditions (high radiation, high temperature, low humidity) spray evaporative losses as high as 42% and 45% have been reported (Christiansen, 1942; Frost and Schwalen, 1955). With respect to the newly installed center pivot to be used by Wiser Farms, the literature reports that spray evaporation is reduced with lower nozzle pressure and lower nozzle elevation. Low elevation spray nozzles were shown to have a mean spray evaporation loss of 2% (Kincaid et al, 1986).

Wiser Farms Water Use Report, Reierson, 2002

And now, a time-out for science



Can't calculate CU without knowing how irrigation water budget works

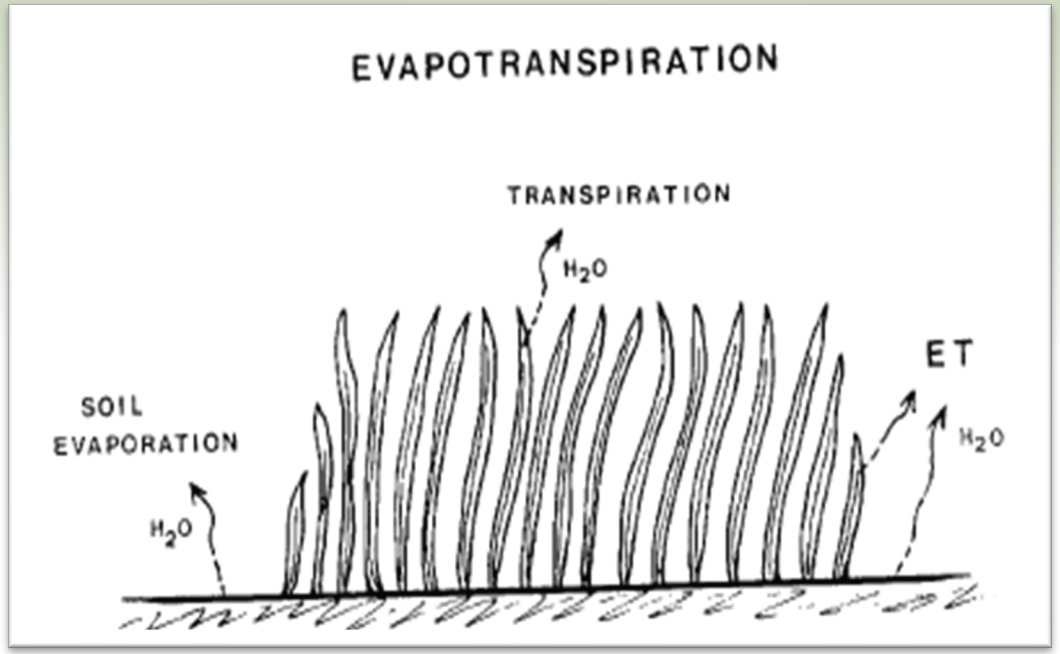
- ET
- Rainfall
- Irrigation
- Soil "Reservoir"
- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application

Evapotranspiration (ET)





- **Evapotranspiration (ET) is the loss of water from a vegetated surface through soil evaporation and plant transpiration.**
- **Sources of ET data**
  - **Washington Irrigation Guide**
    - 60 crops; 1951 – 1980
  - **WSU Irrigation Bulletin**
    - 39 crops; 1948 – 1973
  - **WSU PAWS**
    - 42 crops; 1989 – present
  - **ET Derivation Methods (> 50 methods)**
    - Modified Blanney-Criddle (Temperature-Based, WIG)
    - Penman-Montieth (Energy-Based, ASCE, New Standard Adopted by USDA)
    - FAO Radiation (Radiation)
    - Pan Evaporation



Difference Between Plant Need and Plant Use

WSU Research: Measuring Whole-Canopy Net Transpiration

(Dr. Matthew Whiting, WSU Prosser)










ZIMMATIC





How Consumptive is Application Efficiency?

- Washington Irrigation Guide gave Ea values
- Other similar ranges existed in the literature for new technology
- The debate was about how much of these terms was consumed vs. return flow

Table WA684.20.4 - Expected Irrigation Method Efficiencies in Washington 1/

Method	Efficiency
Level Border	75
Graded Border	70
Flood Irrigation	50
Contour Ditch	50
Level Furrow	65
Graded Straight Furrow	60
Graded Contour Furrow	60
Corrugations	60
Subirrigation-Water Table Control	65
Subirrigation-Trickle	70
Trickle-Point Source Emitter	90
Trickle-Spray Emitter	85
Trickle-Continuous Tape	90
Handline/Wheel line	65
Big Gun (Fixed Place)	60
Traveling Gun	65
Solid Set (Above Canopy)	65
Solid Set (Below Canopy)	70
Center Pivot	70
Linear Move	70

We started reading some *fascinating* papers

- Relative performance of sprinkler and drip irrigation in Southern Idaho (1999)
- Spray losses and uniformity with low pressure center pivots (1986)
- Drop size distributions for irrigation sprinklers (1996)
- Spraydrop kinetic energy from irrigation sprinklers (1996)
- A water droplet evaporation and temperature model (1989)
- Evaporation and drift losses from sprinklers irrigation systems under various operating conditions (1984)
- A sprinkler water droplet evaporation and plant canopy model(1993)
- Yikes.

Spray Evaporative Loss

High and Low Elevation Sprays on a Center-Pivot



Where were we headed between 2002-2004?

- **Seemed like . . .**
  - New literature suggested spray evaporative losses were small.
  - Big drops have low consumption (e.g. big gun sprinklers, end guns, wheel lines with large spacing).
  - Small drops have high consumption (e.g. microspray, smaller sprinklers with closer spacing)
  - The higher off the ground water was applied, higher consumption.
  - The consumptive portion of Ea in many non-windy settings would be low (a few percent)
- **We started policy work on this issue, but the workflow of change applications kept coming.**
- **As "technical assistance" on the topic was requested and provided, tension ensued until . . .**

Benton and Franklin Boards sued Ecology

- Did Ecology's technical assistance amount to an illegal rule?
- Was Ecology wrong on its consumptive use position?
- Injunction prevented Ecology from issuing ACQ decisions until court ruled.

SUPERIOR COURT OF THE STATE OF WASHINGTON
FOR BENTON COUNTY

BENTON COUNTY WATER CONSERVANCY BOARD and FRANKLIN COUNTY WATER CONSERVANCY BOARD,

Plaintiffs,

vs.

DEPARTMENT OF ECOLOGY, a department of the State of Washington; LINDA HOFFMAN, Director, Department of Ecology; JOSEPH STOHR, Program Manager, Water Resources Program,

Defendants.

No. 24 – 2

COMPLAINT

The case settled fairly quickly under these terms

- Two-day experts' technical workshop convened.
- Experts invited from institutions with expertise on these topics, plus appointed by conservancy boards and one appointed by Ecology.
- Ecology had to timely produce a policy informed by the experts.

Irrigation Experts Workshop

- Tom Spofford, P.E., USDA National Engineer
- Leigh Nelson, P.E., USDA State Engineer (WA)
- Dr. Robert Stevens, WSU Prosser
- Dr. Allan Thompson, University of Missouri
- Dr. Dennis Kincaid, USDA-ARS Idaho
- Mark Nielson, Franklin County Conservation District
- Robert Montgomery, P.E., Montgomery Water Group
- Paul Wattenburger, P.E., IRZ Consulting
- Dan Haller, P.E., Department of Ecology
- Dr. Darryll Olsen, Benton Co. Water Conservancy Board

*Selected slides adapted from presenters listed above and from WSU Prosser.

Conference Agenda and Goals

Tuesday, November 30th, 2004

8:30 – 10:30 a.m.	From current understanding and information, which factors should be considered when determining irrigation efficiency, and how are those factors defined and bounded? (Facilitated Discussion for All) 1. What ET values should be used? 2. What efficiency values should be used? 3. What are the consumptive and nonconsumptive portions of irrigation efficiency for different irrigation systems? 4. What is the accuracy of our estimation methods? 5. How sensitive is the outcome to different assumptions?
10:30 – 10:45 a.m.	Break
10:45 – 12:00 p.m.	Recommendations on a Practical Approach. (Facilitated Discussion for All) For the task of estimating the consumptive use of water in a given irrigation water rights case, how can irrigation efficiency be determined in a practical manner?

Came down to key papers and recommendations tied to height of irrigation application

- **Dr. Blaine Hansen, University of California, Davis, 1995 measured efficiencies of nearly 1000 different irrigation systems (below).**
- **Dr. Terry Howell, USDA-ARS Texas, 2002, collected and summarized existing irrigation efficiency research.**
- **Experts Workshop recommendation was to use this data and include ranges to allow adjustment for site-specific conditions.**
  - If high off the ground, 15% additional water consu
  - If medium height, 10% consumed.
  - If low elevation, 5% consumed

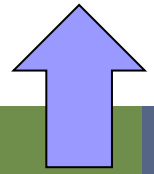
Irrigation Method	Sample Size	Average DU (%)	Standard Deviation (%)
Sprinklers			
Continuous-move	57	75a	10
Portable Solid-set	56	64b	11
Periodic-move	109	61b	17
Under-tree	28	79ade	16
Micro-irrigation			
Microsprinklers	276	71c	14
Drip emitters	163	77ae	14
Surface			
Furrow	157	81d	15
Border	72	84d	14

DU Range	CM	SS	PM	MS	D	F	B
0-10	0	0	1.8	0	0	0	0
11-20	0	0	0.9	0	0	0	0
21-30	0	0	2.8	1.4	1.2	0	0
31-40	1.8	0	7.3	2.5	1.8	2.0	2.9
41-50	1.8	12.5	14.6	4.3	2.4	2.6	1.4
51-60	1.8	21.4	13.8	14.5	6.1	9.2	1.4
61-70	22.8	39.2	29.3	21.3	14.7	5.9	12.9
71-80	38.6	21.4	20.2	27.2	27.0	20.4	10.0
81-90	33.3	5.4	8.2	25	35.0	27.3	35.7
91-100	0	0	0.9	3.6	11.6	32.9	35.7

CM = continuous-move sprinklers, SS = solid-set sprinklers, PM = periodic-move sprinklers, MS = microsprinklers, D = drip emitters, F = furrow, B = border.

GUID 1210 Table for Estimating CU

Method		Application Efficiency, Ea (%)[2]		%Total Evaporated	% Total Use Consumed	Return Flow
		Range	Average, Ea_{avg}	%Evap	%CU, Average[3]	%RF, Average[4]
Surface:	Graded Furrow	50 – 80	65	5	70	30
	w/ tailwater reuse	60 – 90	75	5	80	20
	Level Furrow	65 – 95	80	5	85	15
	Graded Border	50 – 80	65	5	70	30
	Level Basins	80 – 95	85	5	90	10
	Flood	35 – 60	50	5	55	45
Sprinkler:	Periodic Move (Handline)	60 – 85	75	10	85	15
	Side Roll (Wheelline)	60 – 85	75	10	85	15
	Moving Big Gun	55 – 75	65	10	75	25
	Solid-Set—Overtree	55 – 80	70	15	85	15
	Solid Set--Undertree	60 – 85	75	10	85	15
	Pop-Up Impact	60 – 85	75	10	85	15
Center-Pivot	Impact heads w/end gun	75 – 90	80	15	95	5
	Spray heads w/o end gun	75 – 95	90	10	100	0
	LEPA[5] w/o end gun	80 – 98	92	5	97	3
Lateral-Move	Spray heads w/hose feed	75 – 95	90	10	100	0
	Spray heads w/canal feed	70 – 95	85	10	95	5
Microirrigation:	Trickle/Drip	70 – 95	88	5	93	7
	Subsurface Drip	75 – 95	90	0	90	10
	Microspray	70 – 95	85	10	95	5



Under what conditions is CU test applied?

- **From 2004 to 2023, the guidance said:**

2. Ecology must determine the consumptive use of an irrigation right:

   a. When a change in purpose is proposed that could increase the consumptive use of a water right and such increase could result in impairment of existing water rights; and
   b. When a change to enable irrigation of additional acres or an additional purpose of use is proposed, requiring application of the Annual Consumptive Quantity (ACQ) test[1].

[1] See RCW 90.03.380. While an ACQ change requires averaging of the two highest years of consumptive use, consumptive increases that could lead to impairment may be evaluated using the highest year of consumptive use.

Under what new conditions is CU test applied?

- **In 2023, Ecology "reformatted" GUID 1210 and omitted the page with this guidance.**
- **The ACQ language is still in statute, but there is no official guidance on the time period to consider when CU is calculated for impairment review.**

[1] See RCW 90.03.380. While an ACQ change requires averaging of the two highest years of consumptive use, consumptive increases that could lead to impairment may be evaluated using the highest year of consumptive use.

  - The impairment position is grounded in case law (e.g. Big Creek Water Users v. Ecology and Trendwest), literature (R. Beck, Waters and Water Rights, 1991), and Ecology decisions (e.g. Sullivan Lake ROE (S3-30635).
- **When asked about whether the page was omitted in error I was told:**
  - "We looked into this and determined that there is no missing page or information. The current version reflects our current guidance on consumptive use."
- **Since impairment CU reviews are often triggered, the deletion of impairment guidance with no replacement could lead one to many conclusions about its implications.**

Questions?







GUID-1210
Irrigation Efficiency and Consumptive Use

Daniel R. Haller, P.E., February 2007





Summary

1. Background / Timeline
2. 2004 Experts Workshop
3. Irrigation 101
   a) Irrigation Water Budget
   b) Evapotranspiration (ET)
   c) Components of Irrigation Efficiency
4. Irrigation Efficiency – What Number Do We Use?
5. Within the Irrigation Efficiency – What is the Consumptive / Non-Consumptive Balance?
6. Using the Guidance Document
   a) Examples, examples, examples

Background / Timeline



- 1969 → Circular 512 Issued (WSU)
- 1982 → XB0925 Irrigation Bulletin (EB0153)
- 1985, 1990, 1994 → Washington Irrigation Guide
- November 29-30, 2004 → Experts Workshop
- 2005 → Guid-1210 Distributed

Irrigation Experts Workshop

- Tom Spofford, P.E., USDA National Engineer
- Leigh Nelson, P.E., USDA State Engineer (WA)
- Dr. Robert Stevens, WSU Prosser
- Dr. Allan Thompson, University of Missouri
- Dr. Dennis Kincaid, USDA-ARS Idaho
- Mark Nielson, Franklin County Conservation District
- Robert Montgomery, P.E., Montgomery Water Group
- Paul Wattenburger, P.E., IRZ Consulting
- Dan Haller, P.E., Department of Ecology
- Dr. Darryll Olsen, Benton Co. Water Conservancy Board

*Selected slides adapted from presenters listed above and from WSU Prosser.

Why do plants need water?

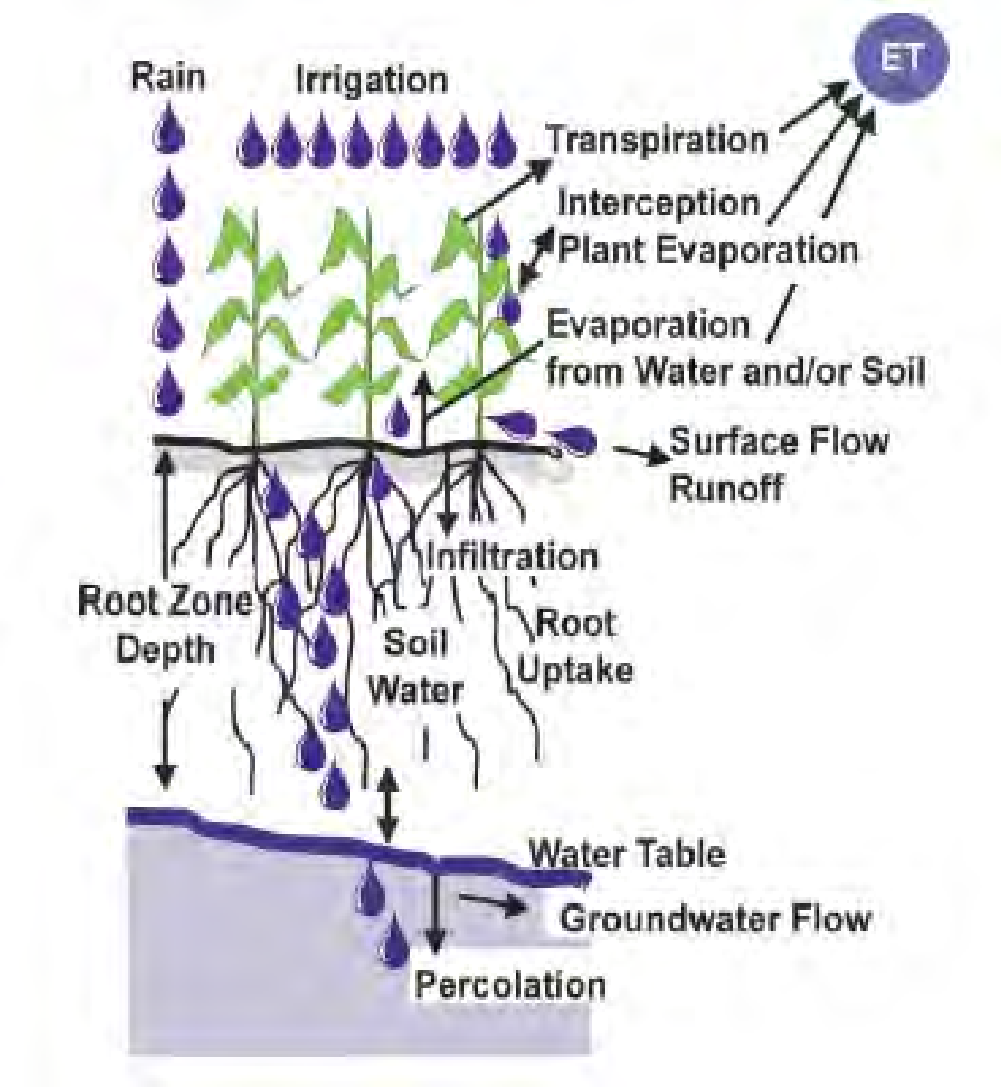


Water is a . . .

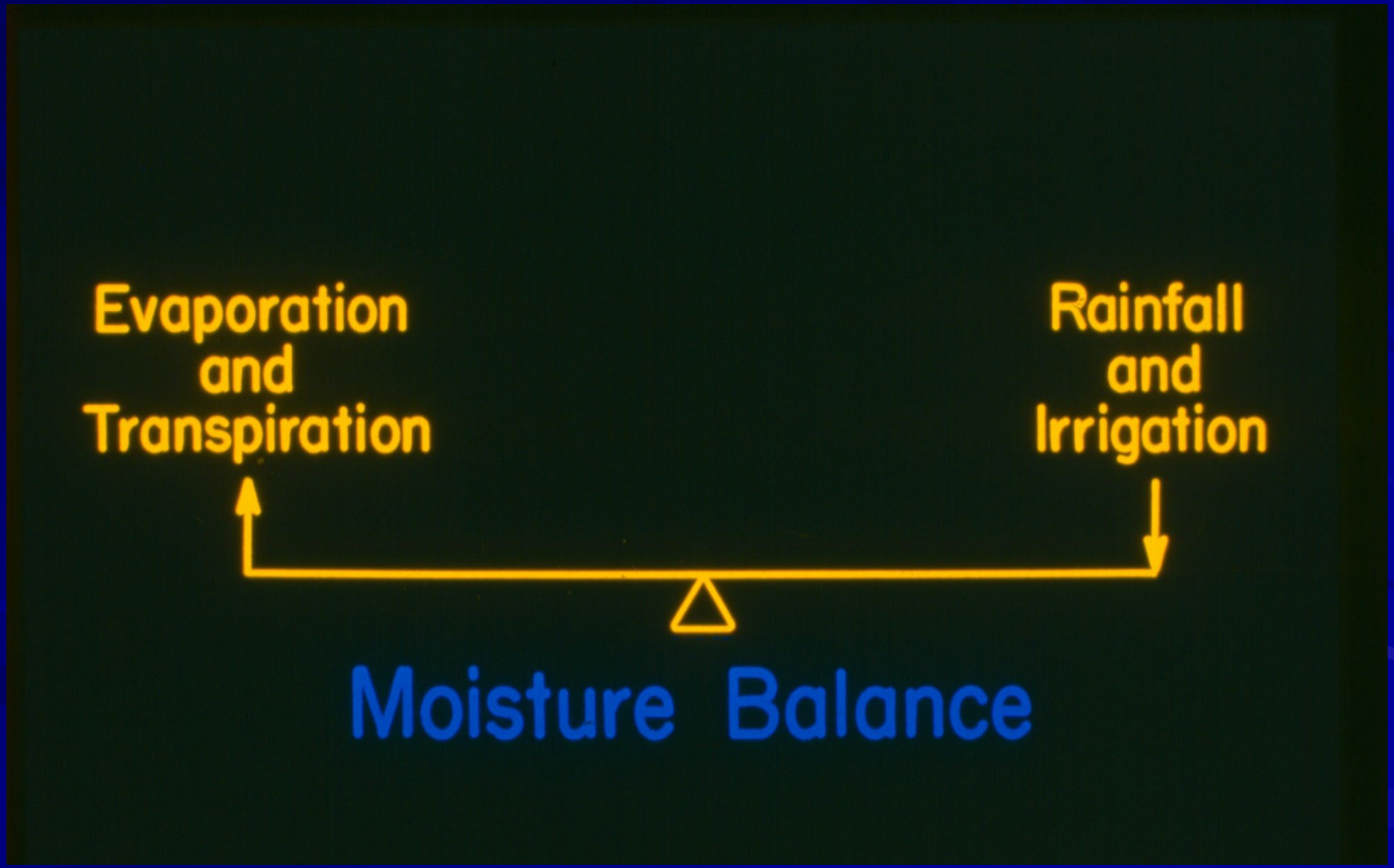
1. Constituent
   - 80-90% fresh weight of fruit, 50% fresh weight of wood
2. Solvent
   - Gases, minerals enter and transported within plant
3. Reactant
   - Key substrate in many processes (e.g. photosynthesis)
4. Maintenance of turgor
   - Essential for cell enlargement, growth, stomatal functions
5. Cool leaves
   - maintain leaf temperature

Irrigation 101
The On-Farm Water Budget

- ET
- Rainfall
- Irrigation
- Soil “Reservoir”
- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application



Irrigation 101
Supply and Demand



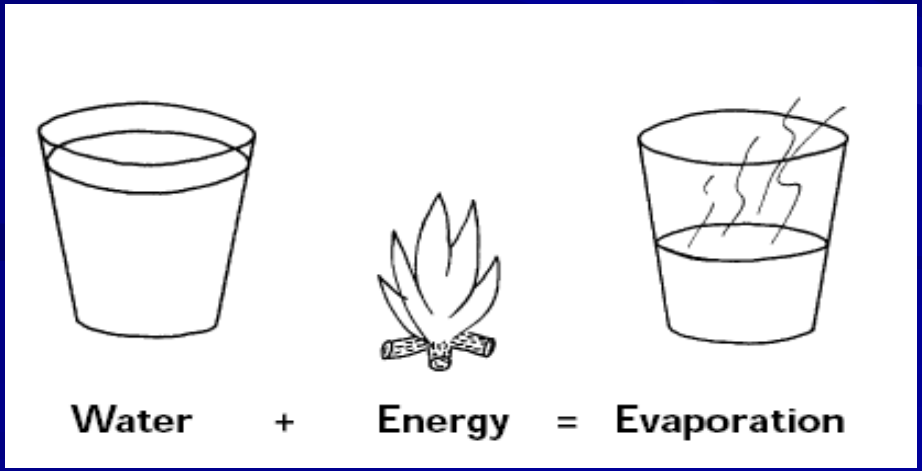


Evaporation



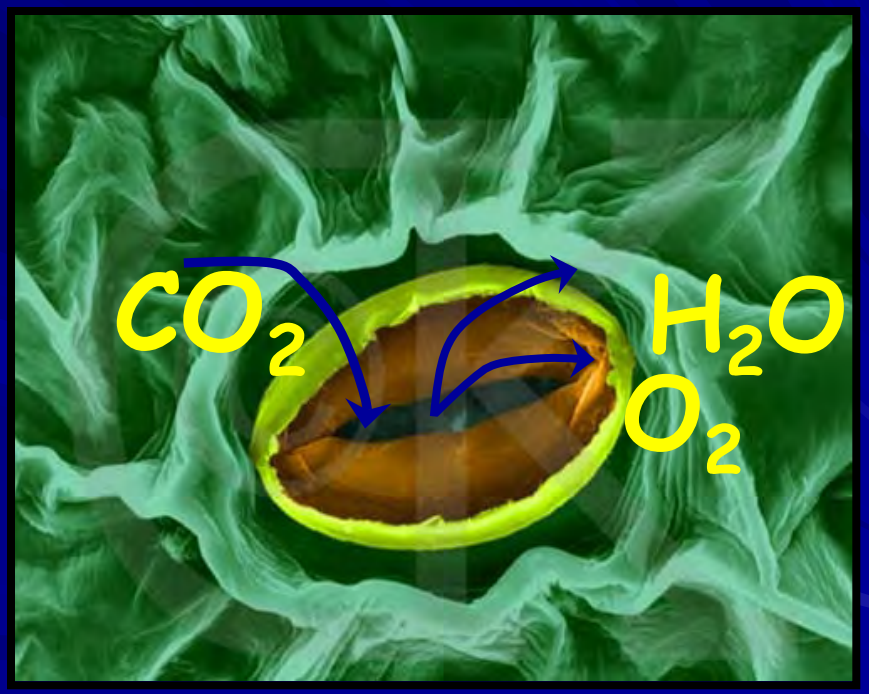
- Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (vapor removal).

- The driving force to remove water vapor from the evaporating surface is the difference between the water vapor pressure at the evaporating surface and that of the surrounding atmosphere. Solar radiation, air temperature, air humidity and wind speed are climatological parameters to consider when assessing the evaporation process.



Transpiration

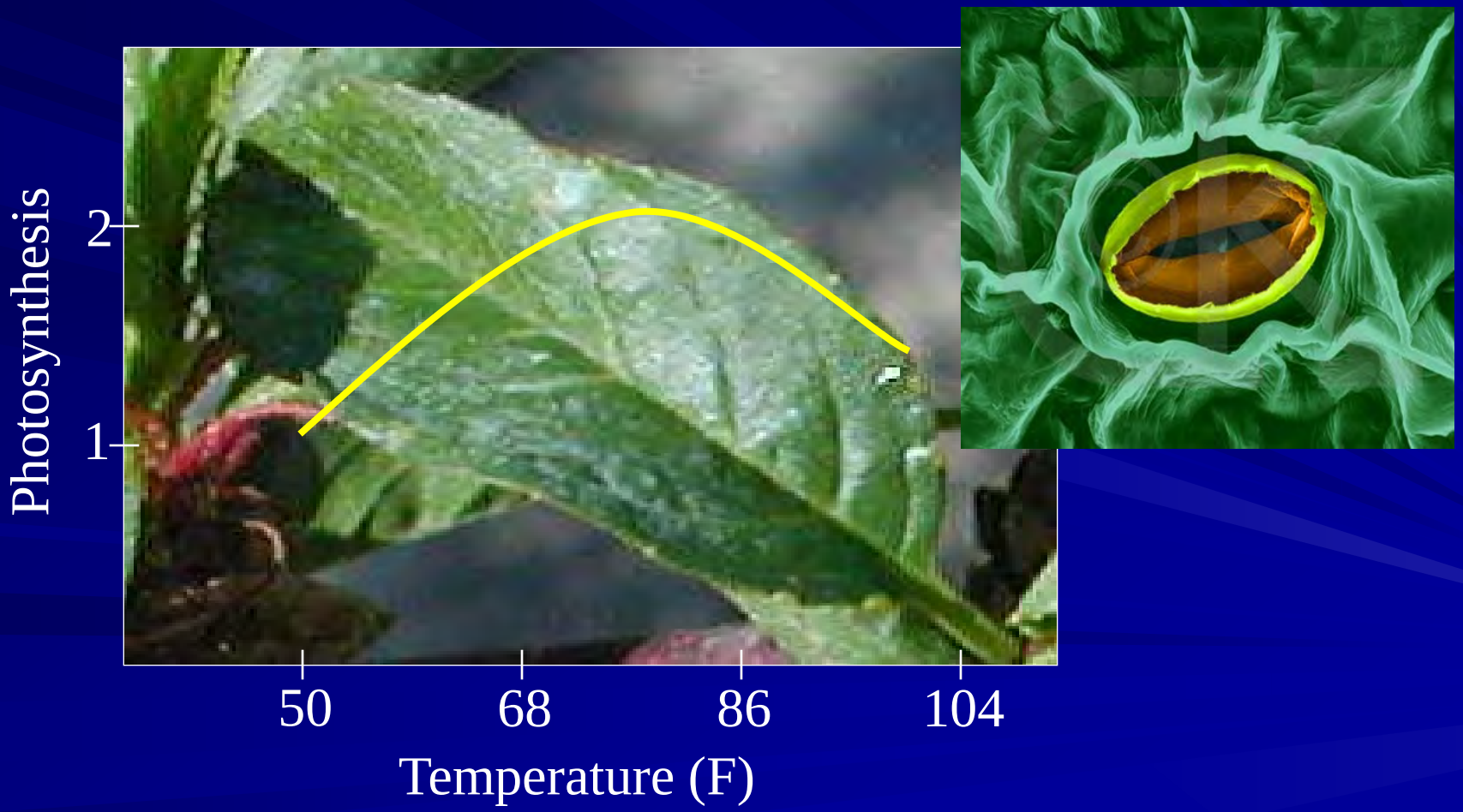
- Transpiration is the evaporation of water from plants. It occurs chiefly at the leaves while their stomata are open for the passage of CO_2 and O_2 during photosynthesis.
- Transpiration is the "engine" that pulls water up from the roots to:
  - supply photosynthesis (1%-2% of the total)
  - bring minerals from the roots for biosynthesis within the leaf
  - cool the leaf
- Photosynthesis is the synthesis of organic molecules (glucose) using the energy of light.



- **6CO2 + 12H2O -> C6H12O6 + 6H2O + 6O2**

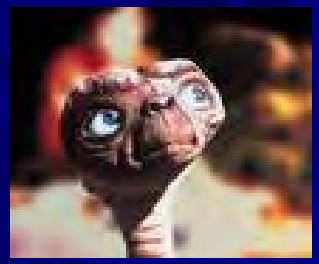
Temperature & Photosynthesis*

*Dana Faubion, WSU Yakima

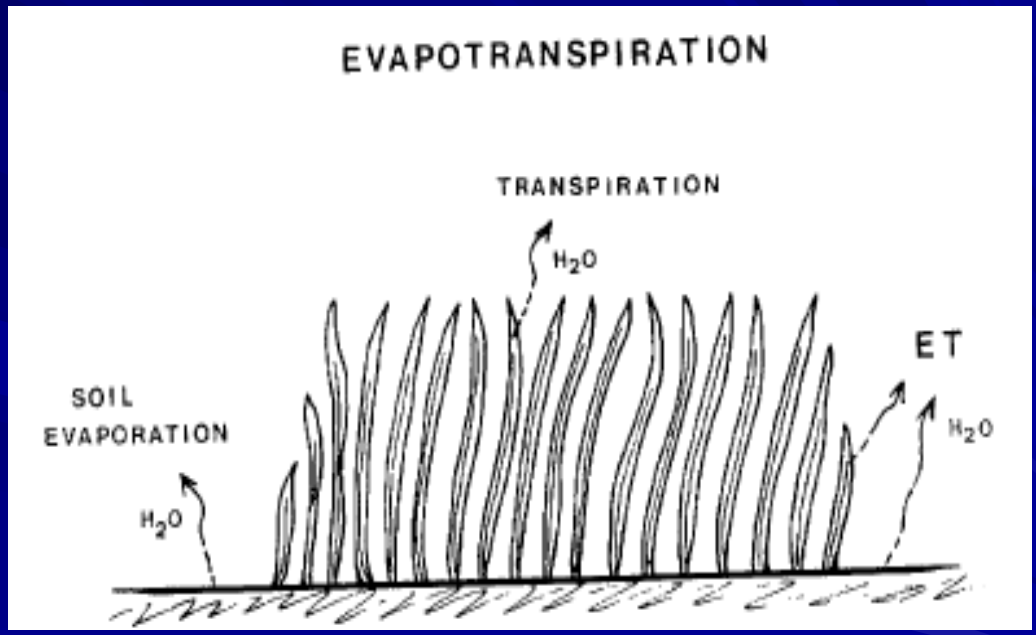




Evapotranspiration (ET)



- Evapotranspiration (ET) is the loss of water from a vegetated surface through soil evaporation and plant transpiration.
- Sources of ET data
  - Washington Irrigation Guide
    - 60 crops; 1951 – 1980
  - WSU Irrigation Bulletin
    - 39 crops; 1948 – 1973
  - WSU PAWS
    - 42 crops; 1989 – present
  - Derivation Methods
    - Modified Blanney-Criddle (Temperature-Based, WIG)
    - Penman-Montieth (Energy-Based, ASCE, New Standard Adopted by USDA)
    - FAO Radiation (Radiation)
    - Pan Evaporation





Limitations of ET



- ET is the theoretical maximum uptake of the plants based on the model assumptions
  - WIG and Bulletin data sets increasingly outdated
  - WIG based on “average” conditions
  - Statewide coverage of monitoring locations incomplete
- ET doesn’t tell you what the farmer actually did
- Plants can use < Max ET with no change in yield

Difference Between Plant Need and Plant Use

WSU Research: Measuring Whole-Canopy Net Transpiration*

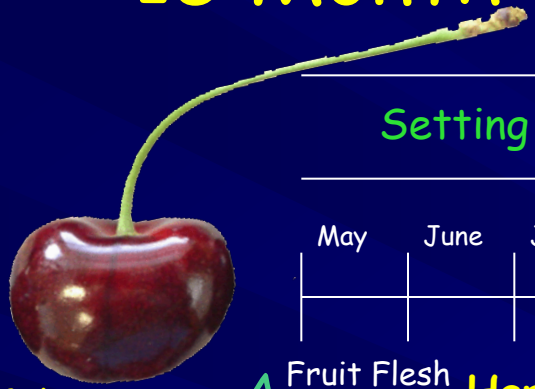
*Dr. Matthew Whiting, WSU Prosser







15 Month Sweet Cherry Fruiting Timeline



Setting Up the Future Crop

Actual Fruit Growth

May | June | July | Aug | Sept | Oct | Nov | Dec/Jan/Feb | Mar | Apr | May | June | July

Crop Development Stage:

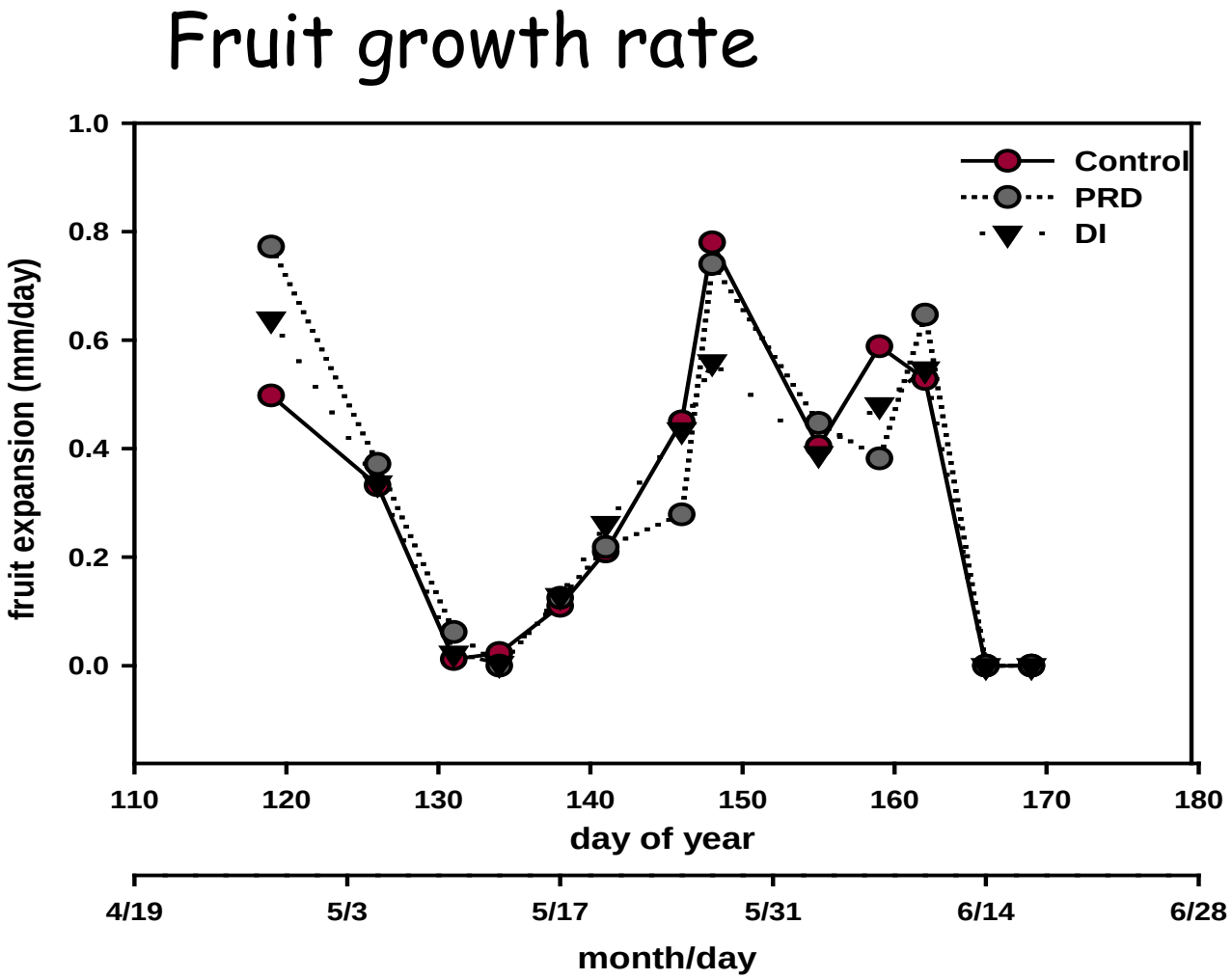
A Fruit Flesh Expansion **Harvest**

B Flower Bud Induction | Flower Organ Differentiation | Bud Growth Stops | Final Flower Development | Bloom | Cell Division | Cell Expansion **Harvest**

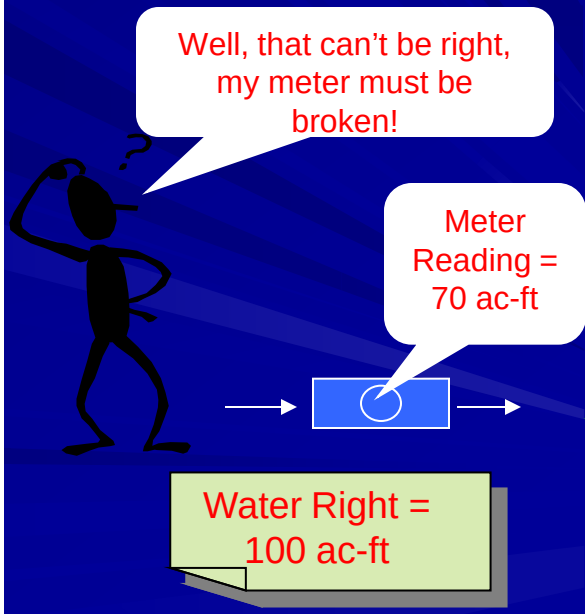




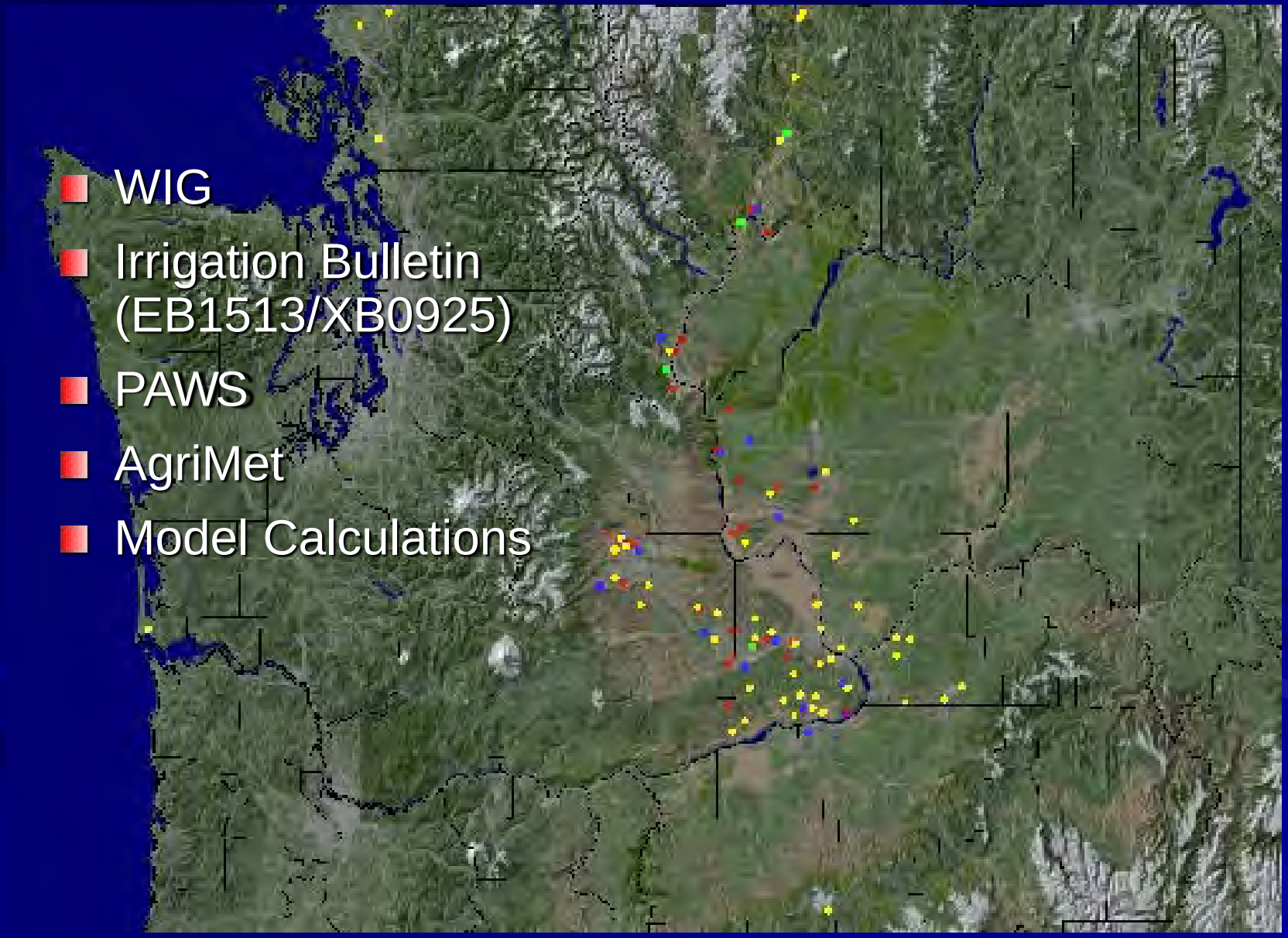
Cherry Tree Study, 2001-2004



- Control based on full ET, irrigation scheduling
- Experiment gave cherry trees 50% less water
- No effect on yield or quality



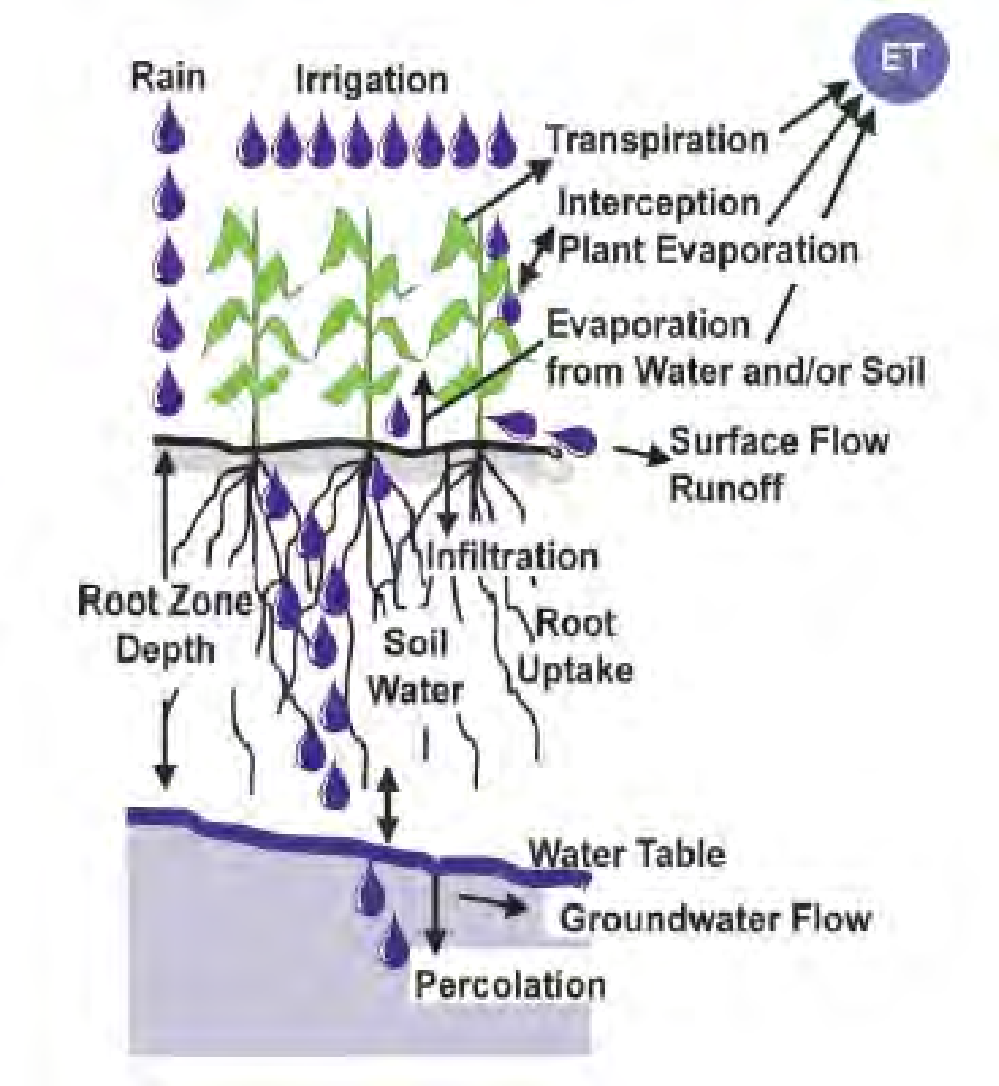
Sources of ET Data



- WIG
- Irrigation Bulletin (EB1513/XB0925)
- PAWS
- AgriMet
- Model Calculations

Irrigation 101
The On-Farm Water Budget

- ET
- Rainfall
- Irrigation
- Soil “Reservoir”
- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application



Crop Irrigation Requirement (CIR) vs. Rainfall



- Living in a desert means rain can't supply all the water to the crop . . .
- CU in the WIG is consumptive use, or ET.
- CIR = ET – Effective Rainfall
- Other demands must also be met:
  - Conveyance loss to the farm
  - Frost Protection
  - Cooling
  - Germination
  - Leaching

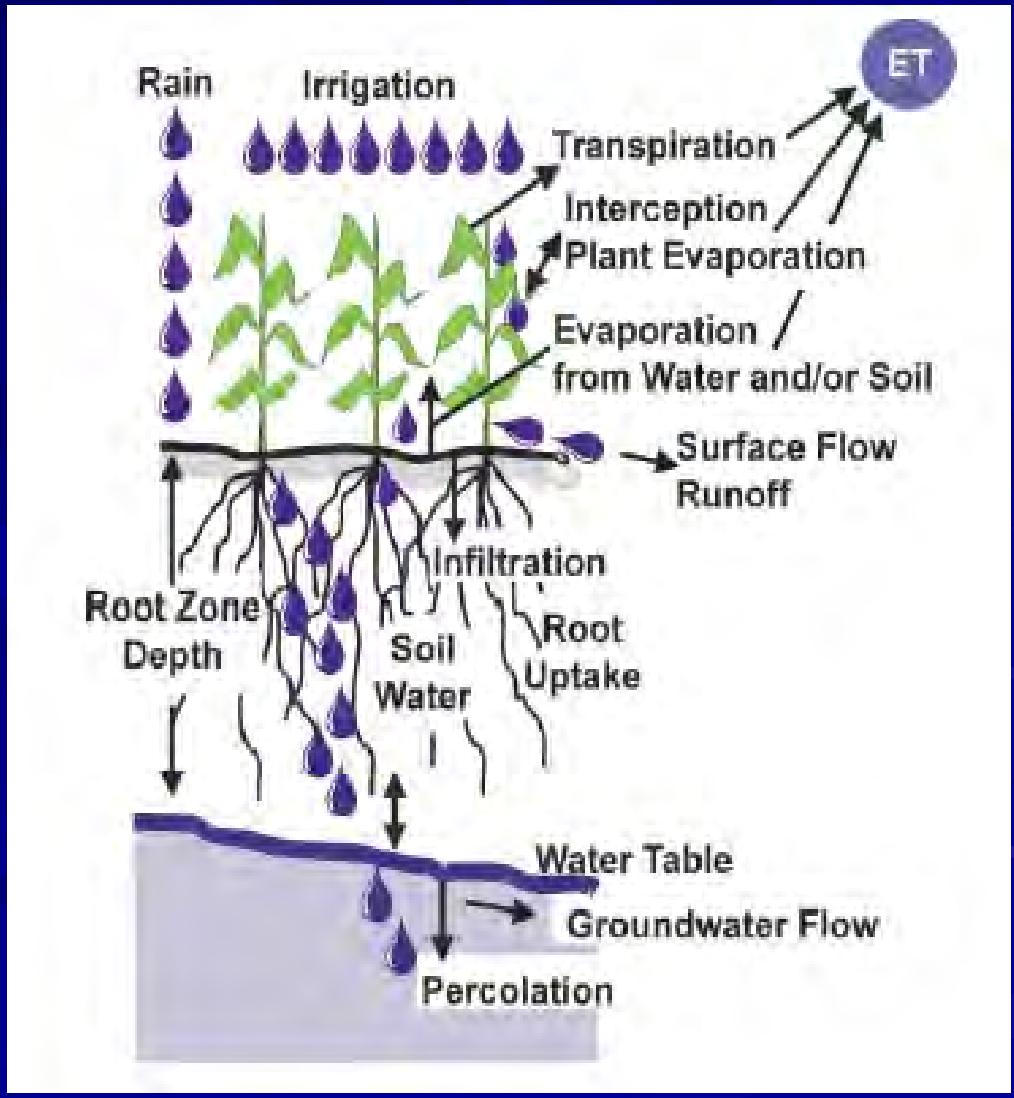
What's so tough about irrigation?

- How much water do I need?
- How often do I water?
- How long should I water?
- What type of soils do I have?
- Is my water applied uniformly?



Irrigation 101
The On-Farm Water Budget

- ET
- Rainfall
- Irrigation
- Soil “Reservoir”
- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application

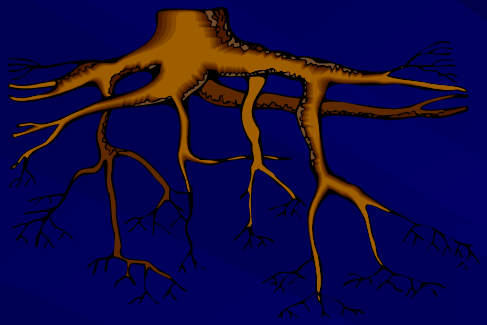


Irrigation Scheduling Starts With The Soil Reservoir.

How Big is our Bucket?!



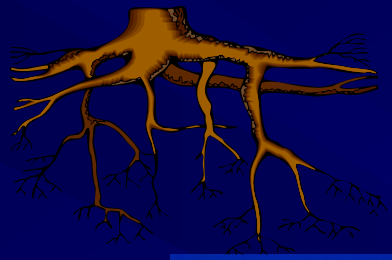
= ?



How Big is Your Bucket?
or
Why Does Soil Type Matter?

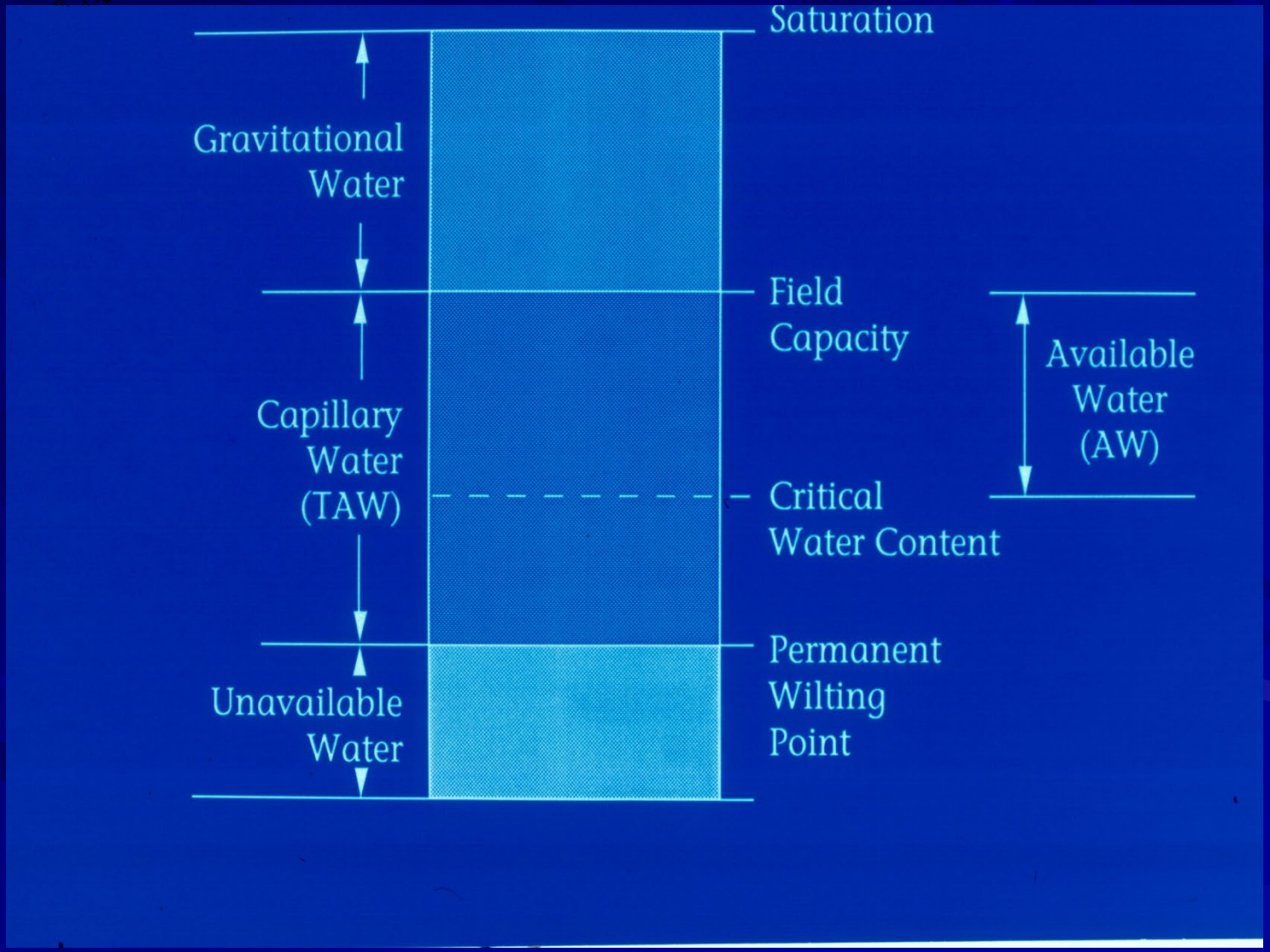


- Plants obtain the water they need from their roots.
- Knowing the Root Zone Depth for your crops determines how much soil storage is available during irrigation. 80 to 90 percent of a plant feeder roots contained in the upper 60-75 percent of the root zone.
- The Root Zone Depth and the Type of Soil determine the Available Water Capacity (AWC). AWC = the amount of water available to the plant typically expressed in inches/foot or inches/inch.
- Don’t let your bucket go completely dry before refilling it! Management Allowed Deficiency, expressed in percent, is the portion of water in the root zone that plants can utilize before experiencing stress. Plants under stress will shift from growth to reproduction cycles. Yield declines.



The Soil Reservoir

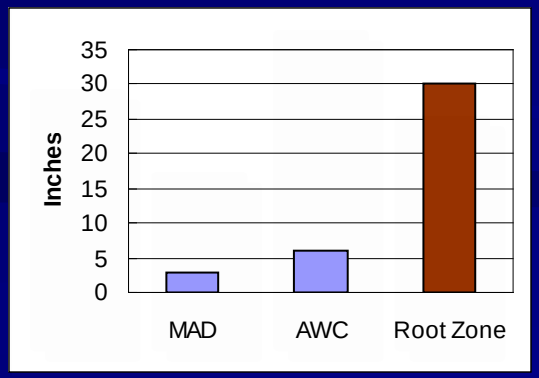




The “How Big is My Bucket” Example 1

Wenas Silt with High AWC

- Crop = Pasture/Turf
- Root Zone = 2.5 feet = 30 inches
- Soil Type = Wenas Silt
- AWC = 0.20 in/in x 30 in = 6 inches
- MAD = 50% = 3 inches

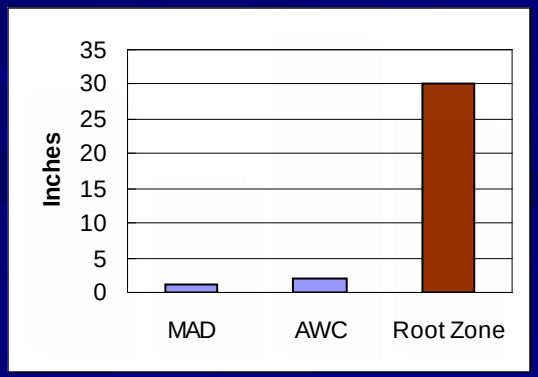




The “How Big is My Bucket” Example 2

Quincy Fine Sand with Low AWC

- Crop = Pasture/Turf
- Root Zone = 2.5 feet = 30 inches
- Soil Type = Quincy Fine Sand
- AWC = 0.07 in/in x 30 in = 2.1 inches
- MAD = 50% = 1.05 inches





Why Does Irrigation Scheduling Matter?

Irrigation Scheduling Dictates Return Flows

- Irrigation Scheduling for Pasture
  - 7 acres
  - Handline sprinklers
  - 24 hour sets, 7 day rotation
  - 1 acre / set
  - 45 gpm (0.1 cfs/ac)
  - 45 gpm is 0.2 ac-ft / day
- Snapshot of Applied Water (Soil Issues – 1 Day)
  - 0.2 ac-ft = 2.4 inches applied
  - Wenas, assume bucket @ MAD = 3 inches
    - Return Flow = 0
  - Quincy MAD? = 1.05 inches
    - Return Flow = 1.35 inches
  - What if Empty Bucket?
- How Fast Does the Bucket Empty?
  - WIG, Yakima Station
  - May = 0.19 in/day = 1.4 in/week
  - June = 0.24 in/day = 1.7 in/week
  - July = 0.30 in/day = 2.2 in/week
- Let's Go Deeper in the Bucket!



Let's Go Deeper in the Bucket!



Irrigation Scheduling Over Several Months (Wenas Soil in May)

Assume Uniform Application for Now

Day	Starting Bucket Level	Applied Water (+)	Demand (-)	Ending Bucket Level	Return Flow
5/1	3 in	2.4 in	0.19 in	5.21 in	0
5/6	5.21 in	0	1.14 in	4.07 in	0
5/7	4.07 in	2.4 in	0.19 in	6.00 in	0.28 in
5/13	6.00 in	0	1.14 in	4.86 in	0
5/14	4.86 in	2.4 in	0.19 in	6 in	1.07 in
5/20	6.00 in	0	1.14 in	4.86 in	0
5/21	4.86 in	2.4 in	0.19 in	6 in	1.07 in
5/27	6.00 in	0	1.14 in	4.86 in	0
5/28	4.86 in	2.4 in	0.19 in	6 in	1.07 in

- Total Return Flows in May = 3.49 inches over 7 acres, or 2 ac-ft
- May Efficiency = 1 – (Return Flows / Applied Water) = 3.5 / 12 = 71%
- What would this look like for other months?
  - Crop demand increases in June and July, which would reduce return flows and increase efficiency

How Could Efficiency Be Improved & Return Flows Be Reduced?

- Do a better job of matching applied water to crop demand
  - Reduce set times (can be tough given labor constraints)
  - Reduce sprinkler discharge (still need to accommodate max demand)
  - Reduce rotation (go 12 days in May, 10 days in June, 7 days in July)





Irrigation 101
The On-Farm Water Budget

- ET
- Rainfall
- Irrigation
- Soil “Reservoir”
- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application

“Application Efficiency (Ea)”. The ratio of the average depth of water infiltrated and stored in the root zone to the average depth of water applied, expressed as a percentage.

“The values presented here have been discounted for evaporation, wind drift, deep percolation, runoff and component uniformity”. WIG, WA 684.20.4.

Canopy Loss

- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application



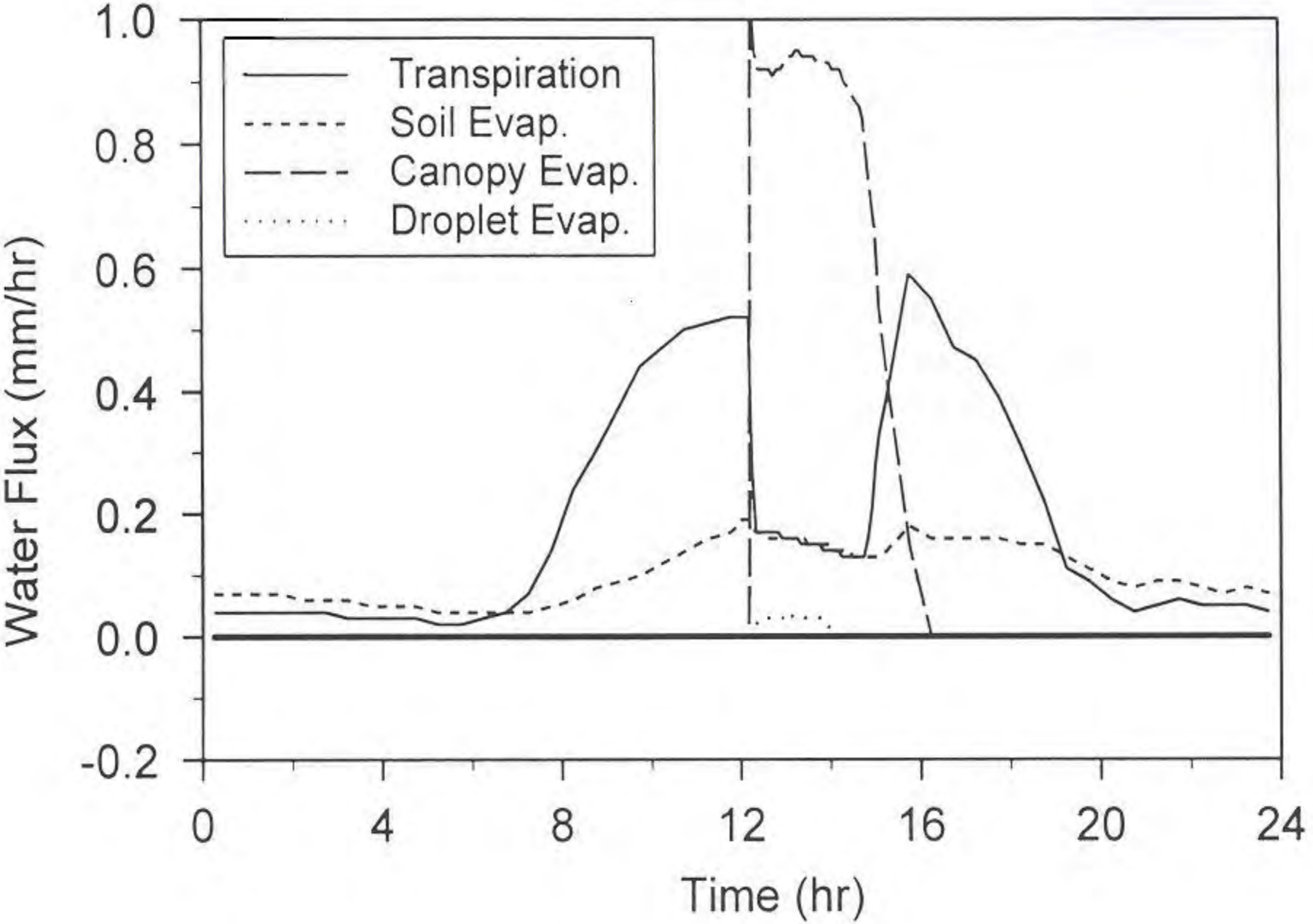
- During irrigation, some water lands on the plant canopy and is retained there, rather than falling to the soil below.
- While this water is not available for uptake by the plant, evaporation of this water cools the plant, which reduces plant uptake from the roots.
- During actual sprinkler irrigation, canopy evaporation typically > pre-irrigation transpiration loss, because there is less resistance to direct evaporation than through stomata.




ZIMMATIC






Transpiration
Soil Evap.
Canopy Evap.
Droplet Evap.
Water Flux (mm/hr)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
4
8
12
16
20
24
Time (hr)

Spray Evaporative Loss

- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application



- During irrigation, some water evaporates as it travels through the air.
- While this water is not available for uptake by the plant, evaporation of this water cools the plant, which reduces plant uptake from the roots.
- For moderate wind conditions (e.g. 5 mph or less), spray losses averaged 0.5% to 1% per foot of elevation.

Spray Evaporative Loss

High and Low Elevation Sprays on a Center-Pivot



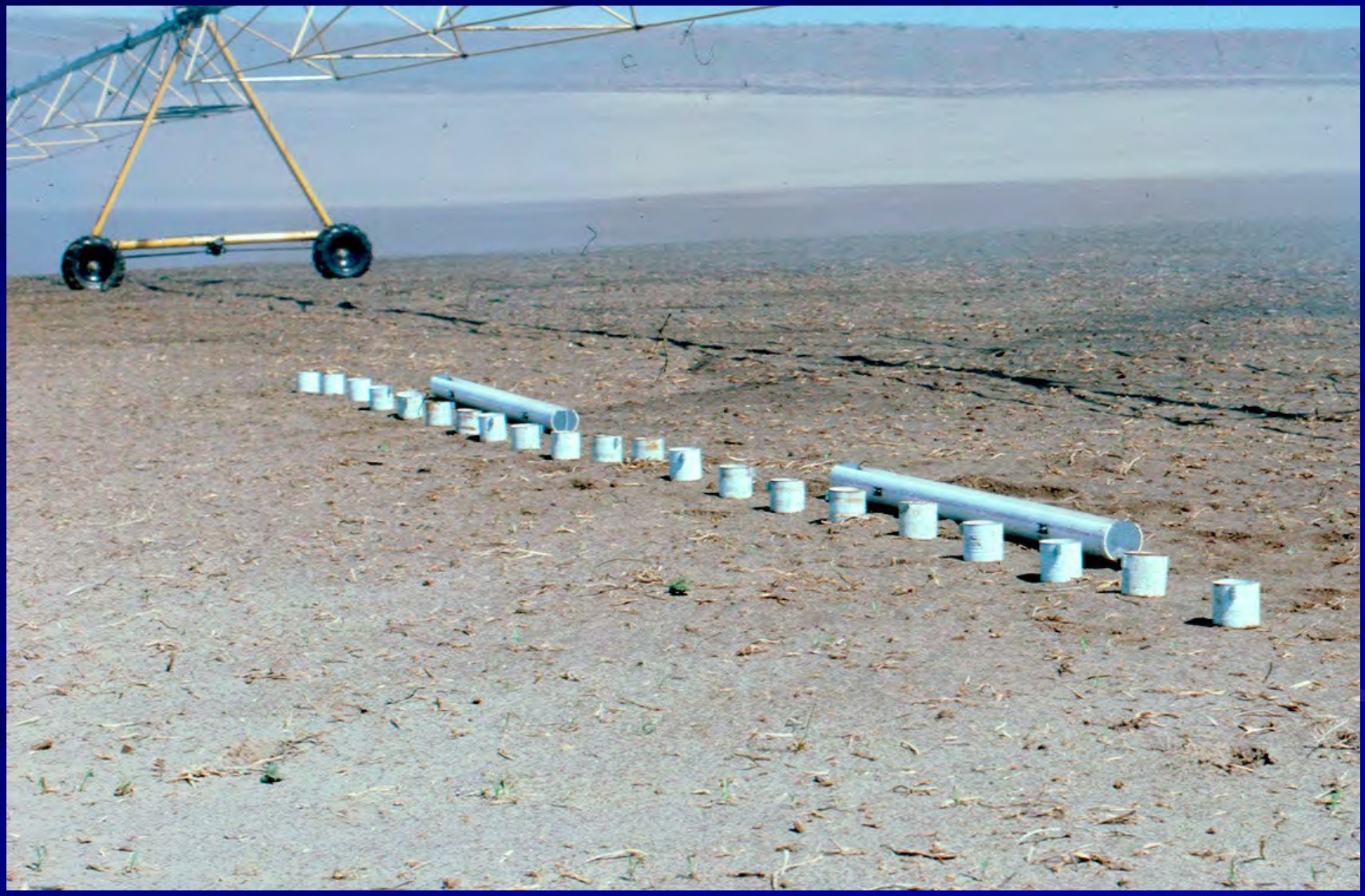
Wind Drift

- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application

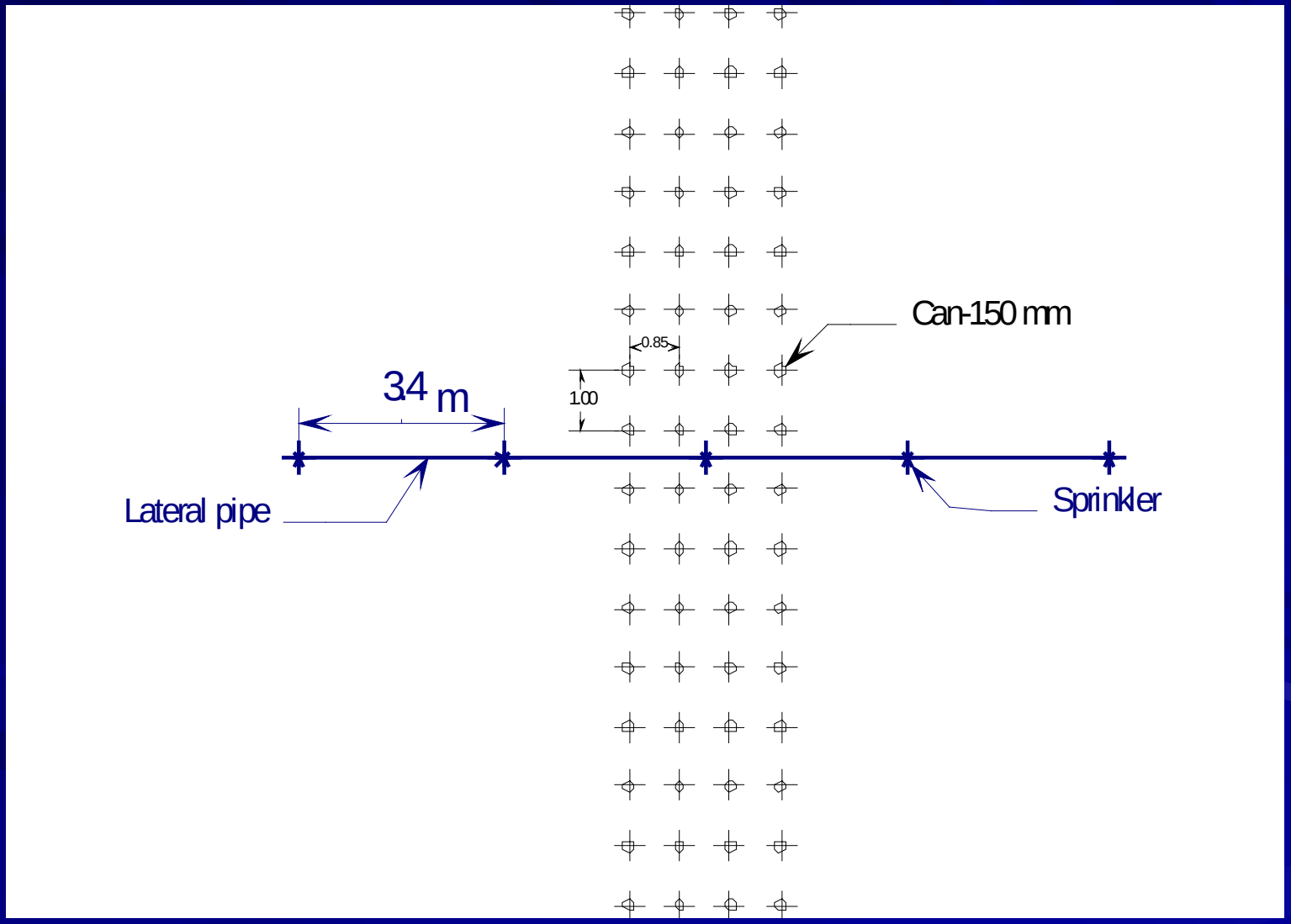


- Wind can cause sprinkled water to drift out of the application area.
- Smaller droplets (<1 mm in size) are most susceptible to wind drift.
- Wind decreases sprinkler uniformity.
- Water that drifts off the field is generally considered consumed, while water that drifts within the field helps to cool the crop, reducing uptake from roots.
- For wind conditions >10 mph, spray losses can increase dramatically.

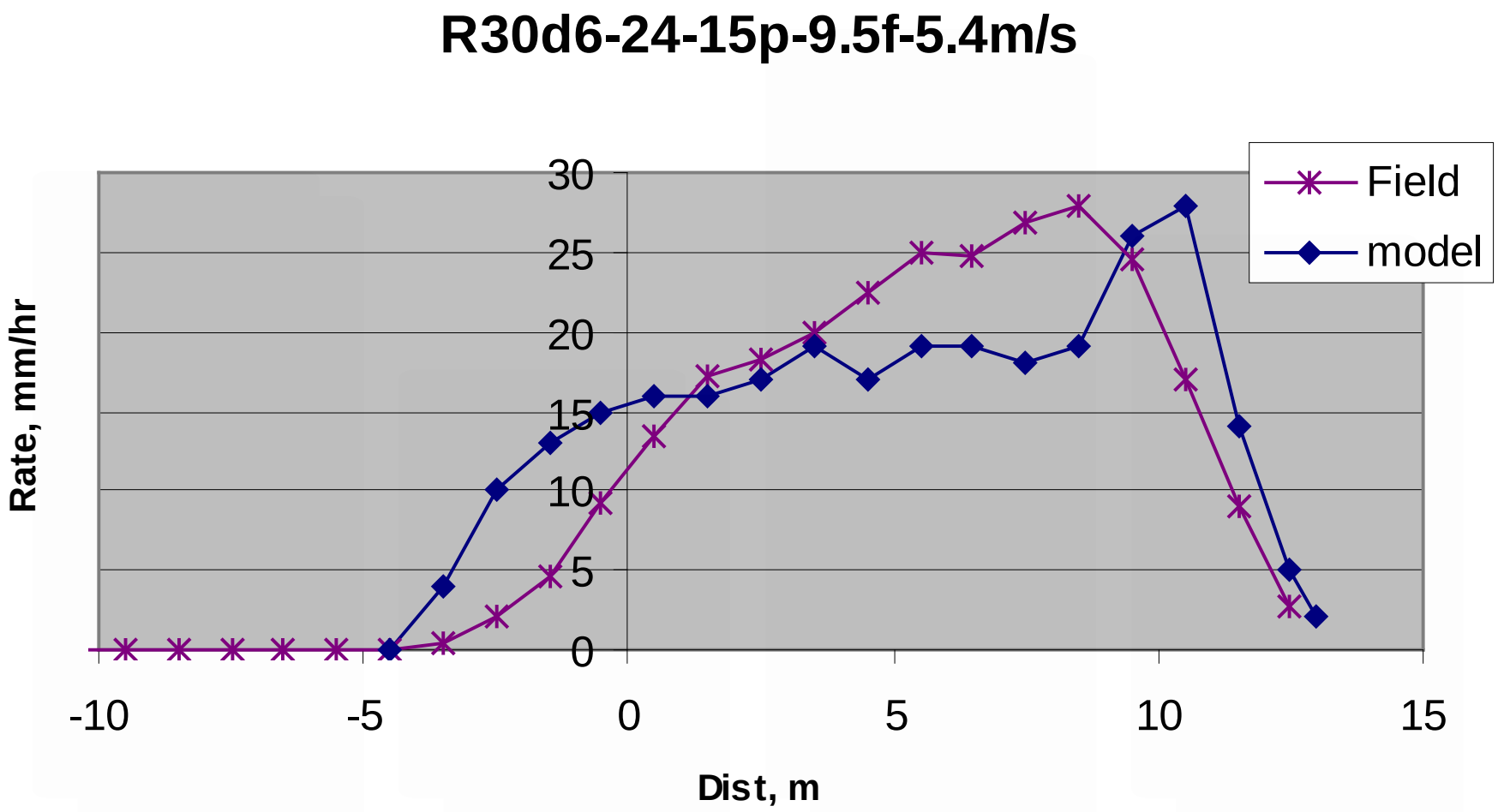
Measuring Wind Drift



Field test layout for drift measurement



Wind drift test #7232 (Kincaid)
AV=6.1 m, Max=74 m Ev=1.9% Drift=4.0%



Deep Percolation, Runoff & Leaks

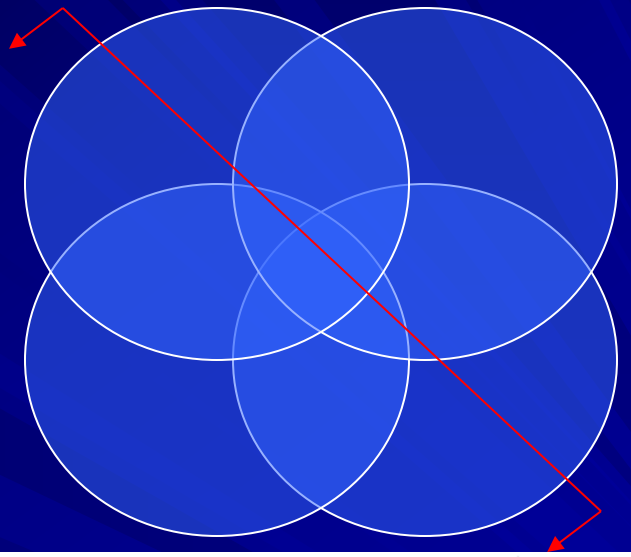
- Irrigation Efficiency
  - Canopy Loss
  - Spray Evaporative Loss
  - Wind Drift
  - Deep Percolation
  - Runoff
  - Leaks
  - Non-Uniform Application



- Leaks, over-application and non-uniform application can all lead to Deep Percolation. Leaks are influenced by system installation and O&M.
- When water is applied at a rate greater than the soil can infiltrate, it can lead to Runoff.
- Deep Percolation and Runoff are heavily influenced by irrigation scheduling and soil type. Deep percolation occurs when water passes below the root zone.
- If Deep Percolation or Runoff returns to waters of the State, or is intercepted but would otherwise return to waters of the State, it is considered return flow.

Non-Uniform Application

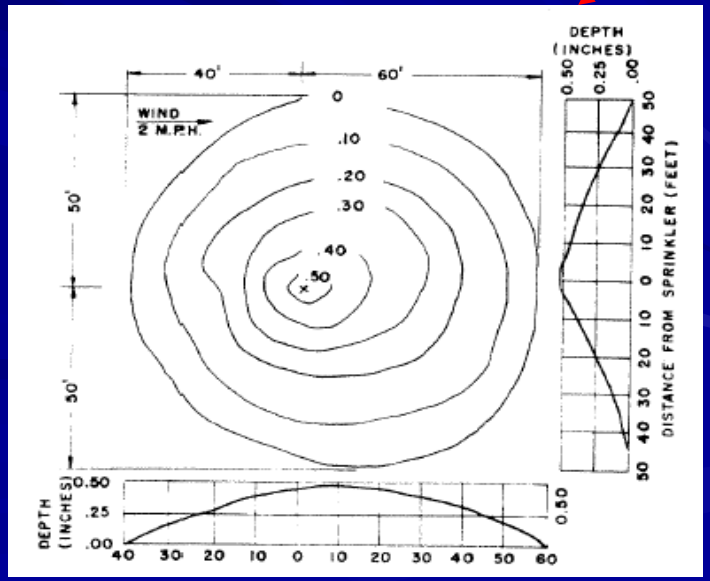
How Does Application Uniformity Affect Irrigation Efficiency?



- Perfect Uniformity = Rain



- Sprinklers are designed to maximize yield
- Some overlap is necessary to ensure the entire field receives enough water
- Design degree of overlap depends on crop type, chemical addition
- Distribution Uniformity (DU) is a percent value indicating degree of overlap
- DU is the ratio of the average low-quarter depth to the average depth of water applied
- DU values in the range 65% - 85% common

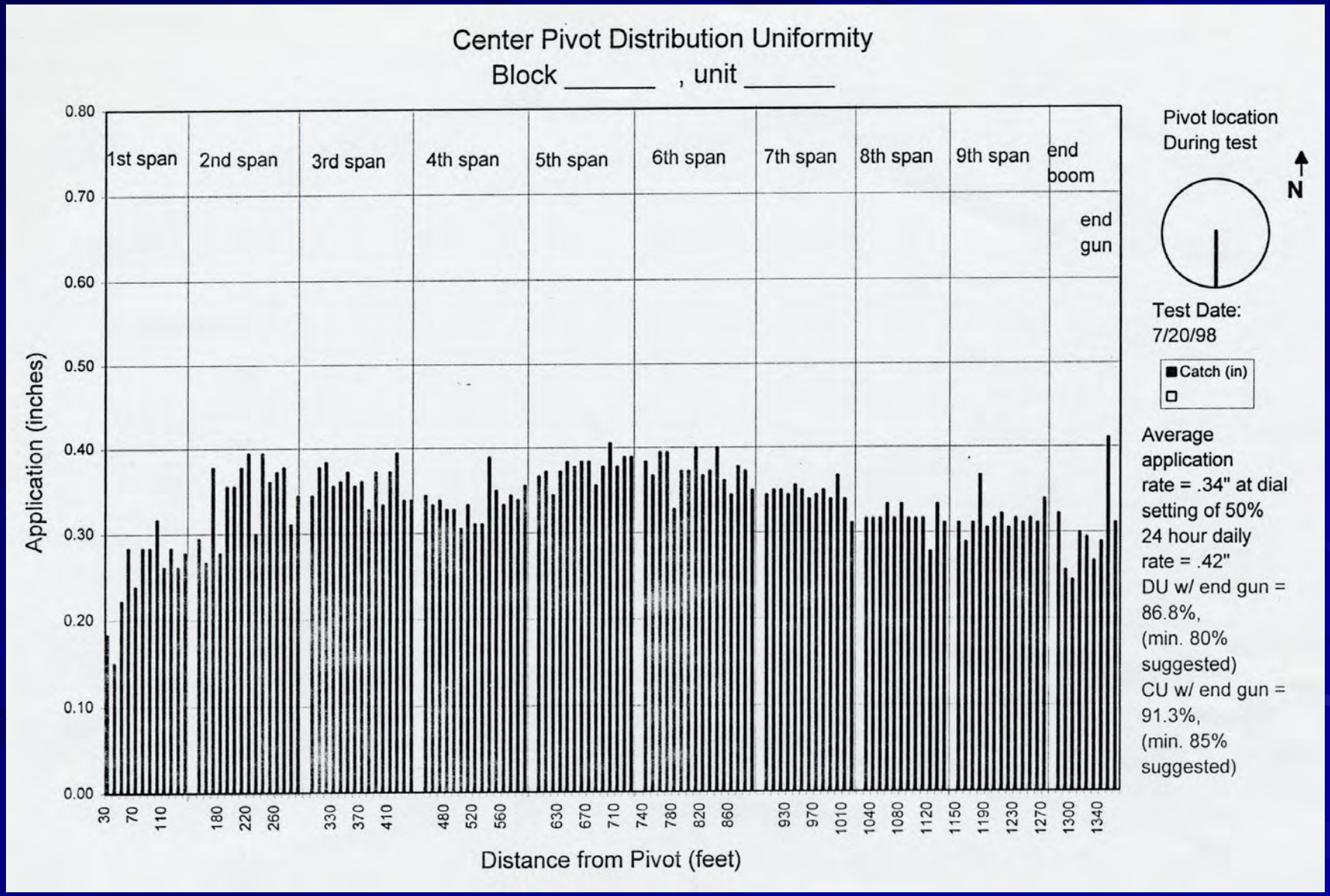


Non-Uniform Application

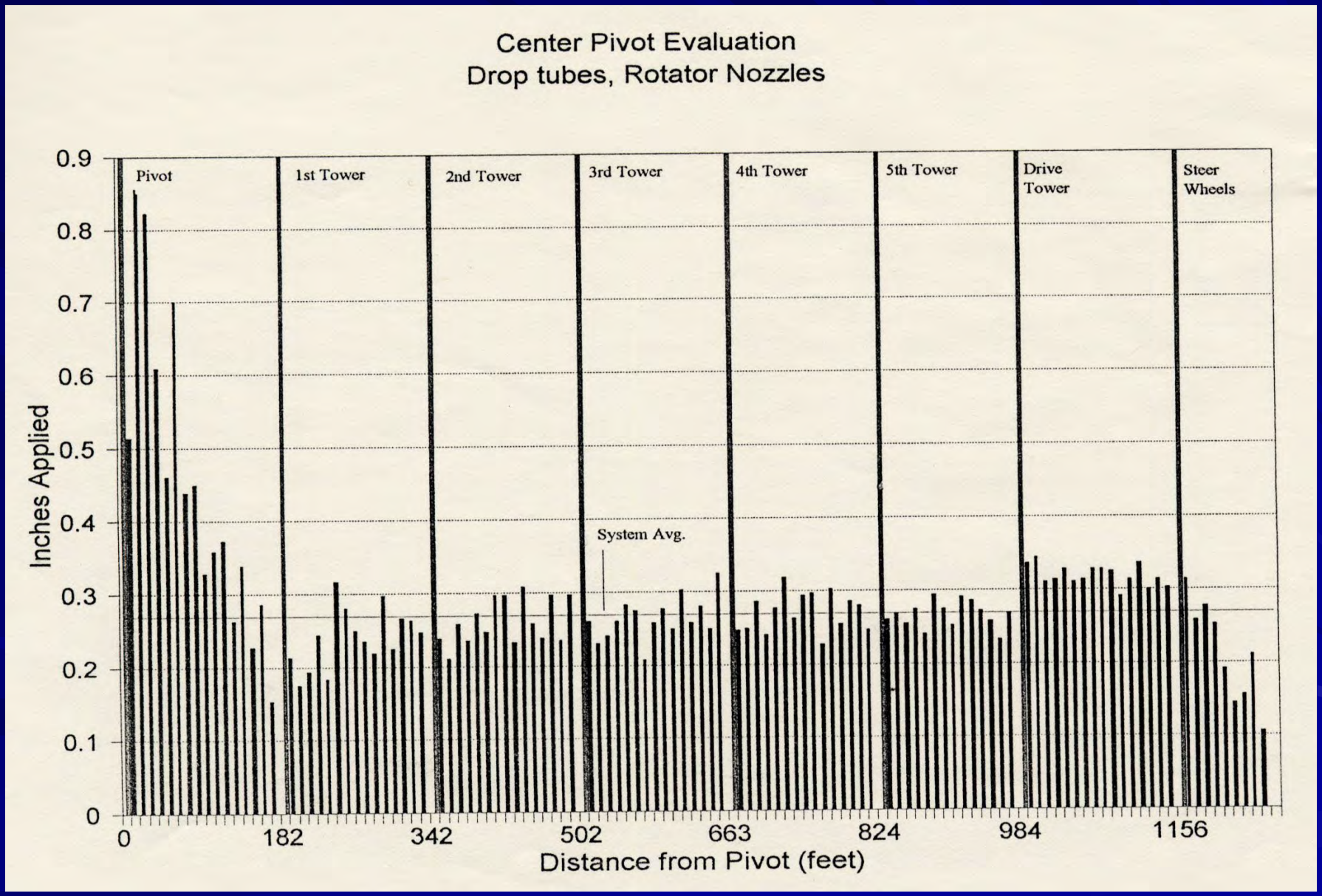
Catch Can Testing, Mark Nielson, Franklin County Conservation District



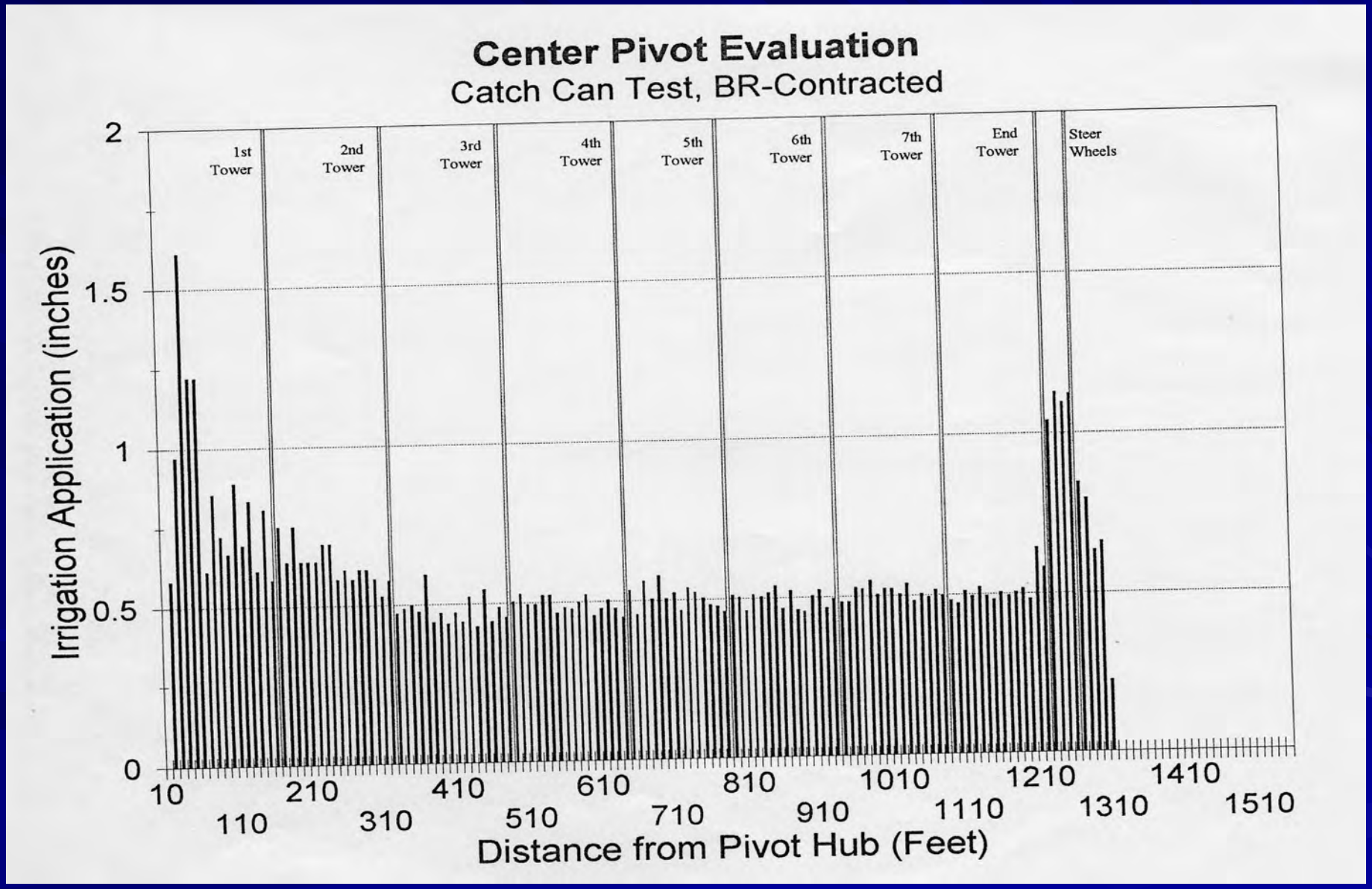
Catch Can Test Results



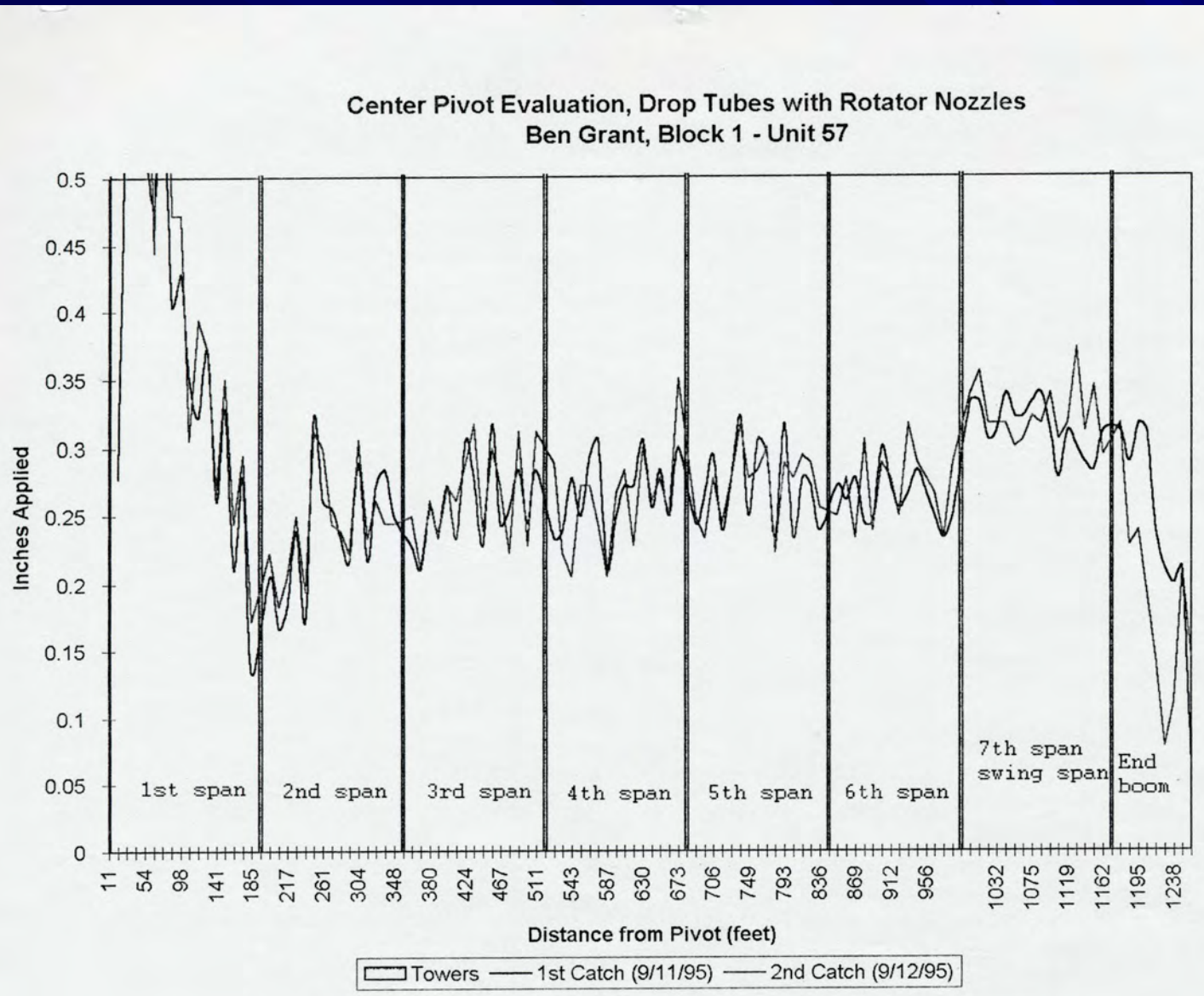
Catch Can Test Results



Catch Can Test Results



Catch Can Test Results



1st Catch
DU = 81.2%
CU = 88.1%
WINDS 10 mph with gusts > 15 mph

2nd Catch
DU = 72.5%
CU = 84.0%
WINDS calm ≤ 5 mph

BETTER uniformity with windy conditions.

Summary

1. Background / Timeline
2. 2004 Experts Workshop
3. Irrigation 101
   a) Irrigation Water Budget
   b) Evapotranspiration (ET)
   c) Components of Irrigation Efficiency
4. Irrigation Efficiency – What Number Do We Use?
5. Within the Irrigation Efficiency – What is the Consumptive / Non-Consumptive Balance?
6. Using the Guidance Document
   a) Examples, examples, examples

Irrigation Efficiency – What Number Do We Use?

- The literature (e.g. WIG) provides average efficiency values.
- Actual efficiencies vary significantly according to local conditions and management (e.g. irrigation scheduling) by the farmer.
- Dr. Blaine Hansen, University of California, Davis, 1995 measured efficiencies of nearly 1000 different irrigation systems (below).
- Dr. Terry Howell, USDA-ARS Texas, 2002, collected and summarized existing irrigation efficiency research.
- Experts Workshop recommendation was to use this data and include ranges to allow adjustment for site-specific conditions.

Irrigation Method	Sample Size	Average DU (%)	Standard Deviation (%)
Sprinklers			
Continuous-move	57	75a	10
Portable Solid-set	56	64b	11
Periodic-move	109	61b	17
Under-tree	28	79ade	16
Micro-irrigation			
Microsprinklers	276	71c	14
Drip emitters	163	77ae	14
Surface			
Furrow	157	81d	15
Border	72	84d	14

DU Range	CM	SS	PM	MS	D	F	B
0-10	0	0	1.8	0	0	0	0
11-20	0	0	0.9	0	0	0	0
21-30	0	0	2.8	1.4	1.2	0	0
31-40	1.8	0	7.3	2.5	1.8	2.0	2.9
41-50	1.8	12.5	14.6	4.3	2.4	2.6	1.4
51-60	1.8	21.4	13.8	14.5	6.1	9.2	1.4
61-70	22.8	39.2	29.3	21.3	14.7	5.9	12.9
71-80	38.6	21.4	20.2	27.2	27.0	20.4	10.0
81-90	33.3	5.4	8.2	25	35.0	27.3	35.7
91-100	0	0	0.9	3.6	11.6	32.9	35.7

CM = continuous-move sprinklers, SS = solid-set sprinklers, PM = periodic-move sprinklers, MS = microsprinklers, D = drip emitters, F = furrow, B = border.

Irrigation Efficiency: What Numbers Do We Use?

Method		Application Efficiency, Ea (%)		%Total Evaporated	% Total Use Consumed	Return Flow
		Range	Average, Ea_{avg}	%Evap	%CU, Average	%RF, Average
Surface:	Graded Furrow	50 – 80	65	5	70	30
	Flood	35 – 60	50	5	55	45
Sprinkler:	Periodic Move (Handline)	60 – 85	75	10	85	15
	Moving Big Gun	55 – 75	65	10	75	25
	Solid-Set—Overtree	55 – 80	70	15	85	15
Center-Pivot	Spray heads w/o end gun	75 – 95	90	10	100	0
Microirrigation:	Trickle/Drip	70 – 95	88	5	93	7
	Microspray	70 – 95	85	10	95	5

Waste? ⟷ Deficit Irrigation?

Using the Guidance Document to Determine Efficiency



- Determine Actual Use, then Calculate Efficiency
  - Metering Data
  - Power Data
  - Flow x Time

➢Ea = CIR / Total Water Use

CIR from WIG
Total Water Use from Actual Data

- Assume Efficiency, then Estimate Use
  - WIG / Eff
  - Status Quo for Permit Writers

Summary

1. Background / Timeline
2. 2004 Experts Workshop
3. Irrigation 101
   a) Irrigation Water Budget
   b) Evapotranspiration (ET)
   c) Components of Irrigation Efficiency
4. Irrigation Efficiency – What Number Do We Use?
5. Within the Irrigation Efficiency – What is the Consumptive / Non-Consumptive Balance?
6. Using the Guidance Document
   a) Examples, examples, examples

Within Irrigation Efficiency—

What is the Consumptive / Non-Consumptive Balance?

- Experts recommendations:
  - System complexity does not reward quantification of individual components of Ea
  - Some non-target evaporation occurs in every above-ground irrigation system (5% is reasonable)
  - As elevation increases, opportunities for evaporation increases (e.g. canopy, spray and wind losses)
  - Allow for site-specific conditions, inform yourself about irrigation scheduling

Irrigation Efficiency: What Numbers Do We Use?

Method		Application Efficiency, Ea (%)		%Total Evaporated	% Total Use Consumed	Return Flow
		Range	Average, Ea_{avg}	%Evap	%CU, Average	%RF, Average
Surface:	Graded Furrow	50 – 80	65	5	70	30
	Flood	35 – 60	50	5	55	45
Sprinkler:	Periodic Move (Handline)	60 – 85	75	10	85	15
	Moving Big Gun	55 – 75	65	10	75	25
	Solid-Set—Overtree	55 – 80	70	15	85	15
Center-Pivot	Spray heads w/o end gun	75 – 95	90	10	100	0
Microirrigation:	Trickle/Drip	70 – 95	88	5	93	7
	Microspray	70 – 95	85	10	95	5

What is the Con / Non-Con Balance?

- Step 0: Calculate (or estimate) Total Use
- Step 1: Calculate (or assume) reasonable Ea
- Step 2: %CU = Ea + %Evap
- Step 3: %RF = 100 - %CU
- Step 4: CU = %CU x Total Use
- Step 5: RF = %RF x Total Use

Example 1: Typical Farmer With No Data

- Background: 10 acres of pasture, handline irrigation, CIR from WIG = 3 ac-ft/ac, water right Qa = 40 ac-ft based on 75% Ea, no power or meter data available.

- Step 0: Calculate (or estimate) Total Use, Total Use = 3 / 0.75 = 4 ac-ft / ac. 4 ac-ft / ac x 10 acres = 40 ac-ft.

- Step 1: Calculate (or assume) Ea, Ea = 75%.

- Step 2: %CU = 75 + 10, %CU = 85%.

- Step 3: %RF = 100 - 85, %RF = 15%.

- Step 4: CU = 85% x 40 ac-ft, CU = 34 ac-ft.

- Step 5: RF = 15% x 40 ac-ft, RF = 6 ac-ft.

Example 2: Atypical Farmer With Metering Data

- Background: 10 acres of pasture, handline irrigation, CIR from WIG = 3 ac-ft/ac, no water right Qa specified, meter data available (51.7 ac-ft).

- Step 0: Calculate Total Use, Total Use = 51.7 ac-ft.
- Step 1: Calculate Ea, Ea = (3 ac-ft/ac) x (10 ac) / 51.7 ac-ft = 58%.
  Reasonable? (waste, local custom, labor constraints, type of system)
- Step 2: %CU = 58 + 10, %CU = 68%.
- Step 3: %RF = 100 - 68, %RF = 32%.
- Step 4: CU = 68% x 51.7 ac-ft, CU = 35.16 ac-ft.
- Step 5: RF = 32% x 51.7 ac-ft, RF = 16.54 ac-ft.

Example 3: Farmer With Power Data & PAWS

- Background: 10 acres of pasture, wheelline irrigation, ET from PAWS = 3.4 ac-ft/ac, irrigation scheduling, water right Qa = 52 ac-ft based on 65% Ea, power data available (13,000 kW-hr), site visit yielded TDH (200 feet), Peff (70%), and Meff (90%).

- Step 0: Calculate Total Use, WAC 173-173-160, Metering Rule, V = 318,600 x kW-hr x Peff x Meff / TDH = 13 MG = 40 ac-ft. Assuming no sufficient causes, 12 ac-ft relinquished.

- Step 1: Calculate Ea, Ea = (3.4 ac-ft/ac) x (10 ac) / 40 ac-ft = 85%. Reasonable? (irrigation scheduling, AgriMet, set-times, soils, site-inspection)

- Step 2: %CU = 85 + 10, %CU = 95%.

- Step 3: %RF = 100 - 95, %RF = 5%.

- Step 4: CU = 95% x 40 ac-ft, CU = 38 ac-ft.

- Step 5: RF = 5% x 40 ac-ft, RF = 2 ac-ft.

Example 4: Farmer With Pump Run-Times

- Background: 10 acres of pasture, solid-set irrigation, CIR from WIG = 3 ac-ft/ac, water right Qa = 46 ac-ft based on 65% Ea, pump capacity 100 gpm, 184 day season (4/1 to 10/1), 14 day harvest—no water, otherwise runs continuously.

- Step 0: Calculate Total Use, 100 gpm x 1440 x (184 – 14 days) / 325851 = 75 ac-ft, which exceeds authorized Qa. Perform calculations based on authorized use of 46 ac-ft.

- Step 1: Assume Ea, Ea = 65%.

- Step 2: %CU = 65 + 10, %CU = 75%.

- Step 3: %RF = 100 - 75, %RF = 25%.

- Step 4: CU = 75% x 46 ac-ft, CU = 34.5 ac-ft.

- Step 5: RF = 25% x 46 ac-ft, RF = 11.5 ac-ft.

Example 5: 2005 Conservancy Board Decision

- Background: In 2004 Ecology completed a proof exam and issued a certificate to a farmer for 80 ac-ft for irrigation of 20 acres. The farmer then filed a change to spread this quantity to additional acres. Ecology AFFIRMED the Board's decision with clarification.

- Ecology evaluated the Board's ACQ analysis consistent with its consumptive use policy, procedure and guidance document (POL-1210, PRO-1210, and GUID-1210 (draft)) and concluded that the ACQ was 74 ac-ft, which is within 1% of the Board's calculation. Ecology AFFIRMS the Board's determination that the ACQ is 73.2 ac-ft.

- Given the Board's calculations, 6.8 ac-ft of the applicant's valid water right is return flow (e.g. 80 – 73.2 ac-ft). Although this still represents a portion of the applicant's valid water right, Ecology AFFIRMS the Board's determination that only the ACQ of 73.2 ac-ft may be transferred in this instance, because the proposed uses (e.g. deficit irrigation of grapes with drip irrigation) are expected to be entirely consumptive.

Example 6: What About Deficit Irrigation?

- Background: Irrigation present in site inspection and in aerial photos, but not a lush crop. Dry spots evident and interview suggests full irrigation duty not applied. What do you do?

- WIG CU is based on “use of an extensive surface of 3 in. to 6 in. tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water”.
- WIG estimates generally reflect intensive farming practices where the goal is to maximize crop yield.
- What constraints exists that prevent the use of a full WIG CIR?
  - Labor Constraints
  - Site Constraints
  - Infrastructure Constraints
  - Operational Constraints
- Reductions in the CIR are a matter of best professional judgment.

Conclusions



- How big is your bucket?



- WIG is still the champ,
  but getting soft in the belly.



- Empower yourself to use your best professional judgment.
- Return flows are no longer the “Where’s Waldo” of the water rights world.





Questions?

Other Examples?





In. 2002 Proc. of the Central Plains Irrigation Short Course & Exposition, Colorado State University, Kansas State University, University of Nebraska, and Central Plains Irrigation Assn., Lamar, CO. pp. 80-92.

IRRIGATION SYSTEM EFFICIENCIES[1]

Terry A. Howell, Ph.D., P.E.
Research Leader (Supervisory Agricultural Engineer)
USDA-Agricultural Research Service
P.O. Drawer 10
2300 Experiment Station Rd. (shipping)
Bushland, TX 79012-0010
Voice: 806-356-5746 Fax: 806-356-5750
Email: tahowell@cprl.ars.usda.gov

INTRODUCTION

"Irrigation efficiency" is a basic engineering term used in irrigation science to characterize irrigation performance, evaluate irrigation water use, and to promote better or improved use of water resources, particularly those used in agriculture (Israelsen and Hansen, 1962; ASCE, 1978; Bos, 1979; and Heermann et al., 1990). Irrigation efficiency is a critical measure of irrigation performance in terms of the water needed to irrigate a field, farm, basin, irrigation district, or an entire watershed. Irrigation efficiency is defined in terms of

- irrigation system performance
- uniformity of the water application
- response of the crop to irrigation

Each of these irrigation efficiency measures is interrelated and will vary with scale and time. Figure 1 illustrates several of the water transport components involved in defining various irrigation performance measures. The spatial scale can vary from a single irrigation application device (a siphon tube, a gated pipe gate, a sprinkler, a microirrigation emitter) to an irrigation set (a basin plot or set, a furrow set, a single sprinkler lateral, a microirrigation lateral) to broader land scales (field, farm, an irrigation canal lateral, a whole irrigation district, a basin or watershed, or a river system, or an aquifer). The time scale can vary from a

---

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S.D.A. or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable. This work was done by a U.S. Government employee and cannot be copyrighted. It may be reproduced for any noncommercial use freely. Adopted, in part, from an article prepared on *Irrigation Efficiency* for the Marcel Dekker, Inc. (New York, NY) *Encyclopedia of Water Science* to be published in 2002.

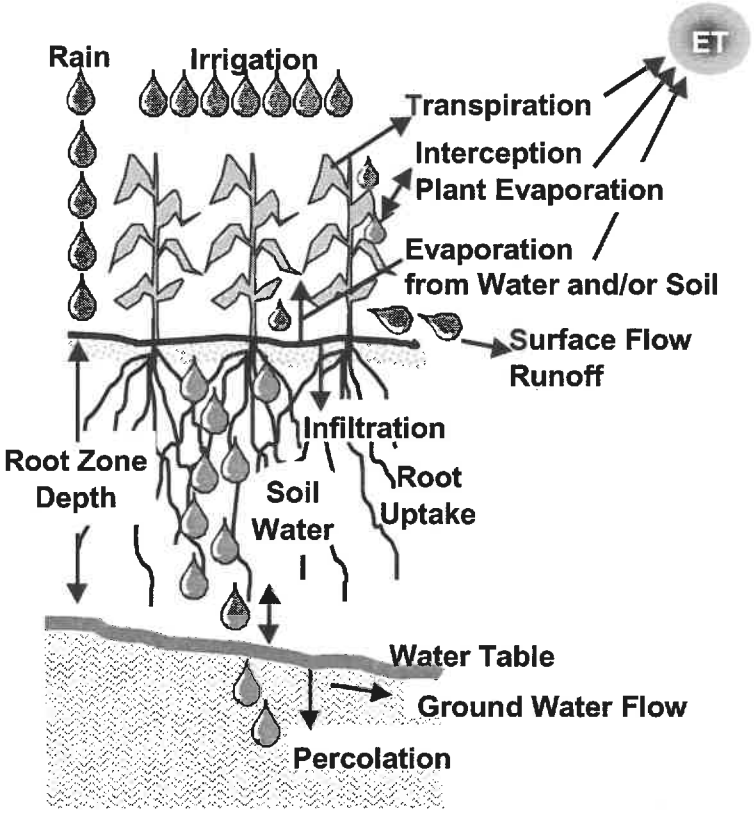


Figure 1. Illustration of various water transport components needed to characterize irrigation efficiency.

single application (or irrigation set), a part of the crop season (preplanting, emergence to bloom or pollination, reproduction to maturity), the irrigation season, to a crop season, or a year, partial year (pre-monsoon season, summer, etc.), or a water year (typically from the beginning of spring snow melt through the end of irrigation diversion, or a rainy or monsoon season), or a period of years (a drought or a "wet" cycle). Irrigation efficiency affects the economics of irrigation, the amount of water needed to irrigate a specific land area, the spatial uniformity of the crop and its yield, and the amount of water that might percolate beneath the crop root zone. It can also affect the amount of water that can return to surface sources for downstream uses or to ground water aquifers that might supply other water uses, and the amount of water lost to unrecoverable sources (salt sinks, saline aquifer, or an unsaturated vadose zone).

The volumes of the water for the various irrigation components are typically expressed in units of depth (volume per unit area) or simply the volume for the area being evaluated. Irrigation water application volume is difficult to measure; so, it is usually computed as the product of water flow rate and time. This places emphasis on accurately measuring the flow rate. The accurate measurement of water percolation volumes, ground water flow volumes, and water uptake from shallow ground water remain difficult under most circumstances.

IRRIGATION SYSTEM PERFORMANCE EFFICIENCY

Irrigation water can be diverted from a storage reservoir and transported to the field or farm through a system of canals or pipelines; it can be pumped from a reservoir on the farm and transported through a system of farm canals or

pipelines; or it might be pumped from a single well or a series off wells through farm canals or pipelines. Irrigation districts often include small to moderate size reservoirs to regulate flow and to provide short-term storage to manage the diverted water with the on-farm demand. Some on-farm systems include reservoirs for storage or regulation of flows from multiple wells. This latter case is often used with longer center pivots (half-mile ones) with a centrifugal pump to boost the water to the desired elevation or pressure for the pivot.

Water Conveyance Efficiency

The conveyance efficiency is typically defined as the ratio between the water that reaches a farm or field to that diverted from the irrigation water source (Israelsen and Hansen, 1962; Bos, 1979; and Heermann et al., 1990). It is defined as

$$E_c = 100\frac{V_f}{V_t} \qquad \ldots[1]$$

where E_c is the conveyance efficiency in percent, V_f is the volume of water that reaches the farm or field (m^3 or gallons[1]), and V_t is the volume of water diverted (m^3) from the source. E_c also applies to segments of canals or pipelines, where the water losses include canal seepage or leaks in pipelines. The global E_c can be computed as the product of the individual component efficiencies, E_{ci}, where i represents the segment number. Conveyance losses include any canal spills (operational or accidental) and reservoir seepage and evaporation that might result from management as well as losses resulting from the physical configuration or condition of the irrigation system. Typically, conveyance losses are much lower for closed conduits or pipelines (Heermann et al., 1990) compared with unlined or lined canals. Even the conveyance efficiency of lined canals may decline over time due to material deterioration or poor maintenance. Limited data exists to document pipeline seepage from older under ground concrete pipelines contrasted with newer PVC pipelines in the Great Plains.

Application Efficiency

Application efficiency relates to the actual storage of water in the root zone to meet the crop water needs in relation to the water applied to the field. It might be

---

[1] The volumetric units used are less important (metric or English), but they need to be consistently applied. Water volume could be in ac-ft or ac-in. or gallons or ft^3.

defined for individual irrigations or parts of irrigations (irrigation sets). Application efficiency includes any application losses to evaporation or seepage from surface water channels or furrows, any leaks from sprinkler or drip pipelines, percolation beneath the root zone, drift from sprinklers, evaporation of droplets in the air, or runoff from the field. Application efficiency is defined as

$$E_a = 100\frac{V_s}{V_f} \qquad \ldots[2]$$

where E_a is the application efficiency in percent, V_s is the irrigation needed by the crop (m^3), and V_f is the water delivered to the field or farm (m^3). The root zone may not need to be fully refilled with each irrigation, particularly if some root zone water holding capacity is needed to store possible or likely rainfall. Often, V_s is characterized as the volume of water stored in the root zone from the irrigation application. Some irrigations may be applied for reasons other than meeting the crop water requirement (germination, frost control, crop cooling, chemigation, fertigation, weed germination). The crop need is often based on the "beneficial water needs" (Burt et al. 1997). In some surface irrigation systems, the runoff water that is necessary to achieve good uniformity across the field can be recovered in a "tailwater pit" and recirculated with the current irrigation or used for later irrigations, and V_f should be adjusted to account for the "net" recovered tailwater. Efficiency values are typically site specific. Table 1 provides a range of typical farm and field irrigation application efficiencies (Howell, 1988; Merriam and Keller, 1978; Keller and Bliesner, 2000) and potential or attainable efficiencies for different irrigation methods that assumes irrigations are applied to meet the crop need. E_a is not to be regarded as a "constant", because many factors can cause it to vary temporally, spatially, and even for differing irrigation methods. Too often E_a is taken as a "constant" for a particular irrigation method in comparison with another irrigation method to estimate potential water savings or irrigation costs when it is intended to be used to characterize system performance and adjust system design or management parameters to achieve improved water use.

Storage Efficiency

Since the crop root zone may not need to be refilled with each irrigation (in this case, E_a can be nearly 100% if no percolation or runoff occurs), the storage efficiency has been defined (Heermann et al., 1990) to account for the root zone storage capacity and the crop water need. The storage efficiency is given as

Table 1. Example farm and field irrigation application efficiencies and attainable efficiencies (Howell, 1988; Merriam and Keller, 1978; and Keller and Bliesner, 2000).

Irrigation Method	Field Efficiency, %			Farm Efficiency, %		
	Attainable	Range	Avg.	Attainable	Range	Avg.
Surface						
Graded Furrow	75	50-80	65	70	40-70	65
w/tailwater reuse	85	60-90	75	85	--	--
Level Furrow	85	65-95	80	85	--	--
Graded Border	80	50-80	65	75	--	--
Level Basins	90	80-95	85	80	--	--
Sprinkler						
Periodic Move	80	60-85	75	80	60-90	80
Side Roll	80	60-85	75	80	60-85	80
Moving Big Gun	75	55-75	65	80	60-80	70
Center Pivot						
Impact heads w/end gun	85	75-90	80	85	75-90	80
Spray heads wo/end gun	95	75-95	90	85	75-95	90
LEPA* wo/end gun	96	80-98	92	95	80-98	90
Lateral Move						
Spray heads w/hose feed	95	75-95	90	85	80-98	90
Spray heads w/canal feed	90	70-95	85	90	75-95	85
Microirrigation						
Trickle	96	70-95	88	95	75-95	88
Subsurface Drip	96	75-95	90	95	75-95	90
Microspray	92	70-95	85	95	70-95	85
Water Table Control						
Surface Ditch	80	50-80	65	80	50-80	60
Subsurface Drain Lines	85	60-80	75	85	65-85	70

*LEPA is low energy precision application.

$$E_s = 100 \frac{V_s}{V_{rz}} \quad \ldots[3]$$

where E_s is the storage efficiency in percent and V_{rz} is the root zone storage capacity (m^3). The root zone depth and the water holding capacity of the root zone determine V_{rz}. The storage efficiency has little utility for sprinkler or microirrigation, because these irrigation methods seldom refill the root zone completely, while it is more often applied to surface irrigation methods (Heermann et al., 1990) in which often the root zone soil water deficit is fully replenished. The storage efficiency and be applied to an individual irrigation event or to various parts of the irrigation season or year.

Seasonal Irrigation Efficiency

The seasonal irrigation efficiency is defined as

$$E_i = 100 \frac{V_b}{V_f} \quad \ldots[4]$$

where E_i is the seasonal irrigation efficiency in percent and V_b is the water volume beneficially used by the crop (m^3). V_b is somewhat subjective (Heermann et al., 1990; and Burt et al., 1997), but it basically includes the required crop evapotranspiration (ET_c) plus any required leaching water (V_l) for salinity management of the crop root zone.

Leaching Requirement (or the leaching fraction)

The leaching requirement (U.S. Salinity Laboratory Staff, 1954), also called the leaching fraction, is defined as

$$L_r = \frac{V_d}{V_f} = \frac{EC_i}{EC_d} \quad \ldots[5]$$

where L_r is the leaching requirement, V_d is the volume of drainage water (m^3), V_f is the volume of irrigation (m^3) applied to the farm or field, EC_i is the electrical conductivity of the irrigation water (dS m^{-1}), and EC_d is the electrical conductivity of the drainage water (dS m^{-1}). The L_r is related to the irrigation application efficiency, particularly when drainage is the primary irrigation loss component.

The L_r would be required "beneficial" irrigation use ($V_l \equiv L_r V_i$) where V_i is beneficial irrigation (m^3), so only V_d greater than the minimum required leaching should reduce irrigation efficiency. Then, the irrigation efficiency can be determined by combining equations [4] and [5]

$$E_i = 100\left(\frac{V_b}{V_f} + L_r\right) \qquad \ldots[6]$$

Burt et al. (1997) defined "beneficial" water use to include possible off-site needs to benefit society (riparian needs or wildlife or fishery needs). They also indicated that V_f should not include the change in the field or farm storage of water but it could include field (tailwater pits) or farm water storage (a reservoir) that wasn't used within the time frame that was used to define E_i.

IRRIGATION UNIFORMITY

The fraction of water used efficiently and beneficially is important to improved irrigation practice. The uniformity of the applied water significantly affects irrigation efficiency. This uniformity is a statistical property of the applied water's distribution. This distribution depends on many factors that are related to the method of irrigation, soil topography, soil hydraulic or infiltration characteristics, and hydraulic characteristics (pressure, flow rate) of the irrigation system. Irrigation application distributions are usually based on depths of water (volume per unit area); however, for microirrigation systems they are usually based on emitter flow volumes because the entire land area is not typically wetted.

Christiansen's Uniformity Coefficient

Christiansen (1942) proposed a coefficient intended mainly for sprinkler systems based on the catch volumes given as

$$C_U = 100\left[1 - \frac{\left(\sum |X - \bar{x}|\right)}{\sum X}\right] \qquad \ldots[7]$$

where C_U is the Christiansen's uniformity coefficient in percent, X is the depth (or volume) of water in each of the equally spaced catch containers in mm or ml, and

$\bar{x}$ is the mean depth (volume) of the catch (mm or ml). For C_U values > 70%, Hart (1961) and Keller and Bliesner (2000) presented

$$C_U = 100\left[1-\left(\frac{\sigma}{\bar{x}}\right)\left(\frac{2}{\pi}\right)^{0.5}\right] \qquad \ldots[8]$$

where σ is the standard deviation of the catch depth (mm) or volume (ml). Equation [8] approximates the normal distribution for the catch amounts.

The C_U should be weighted by the area represented by the container (Heermann and Hein, 1968) when the sprinkler catch containers intentionally represent unequal land areas, as is the case for catch containers beneath a center pivot. Heermann and Hein (1968) revised the C_U formula (equation [8]) to reflect the weighted area, particularly intended for a center pivot sprinkler, as follows:

$$C_{U(H\&H)} = 100\left\{1-\left[\frac{\left(\sum S_i \left| V_i - \left(\frac{\sum V_i S_i}{\sum S_i}\right)\right|\right)}{\sum (V_i S_i)}\right]\right\} \qquad \ldots[9]$$

where S_i is the distance (m) from the pivot to the i^{th} equally spaced catch container and V_i is the volume of the catch in the i^{th} container (mm or ml).

Low-Quarter Distribution Uniformity

The distribution uniformity represents the spatial evenness of the applied water across a field or a farm, as well as within a field or farm. The general form of the distribution uniformity can be given as

$$D_{Up} = 100\left(\frac{\overline{V_p}}{\overline{V_f}}\right) \qquad \ldots[10]$$

where D_{Up} is the distribution uniformity in percent for the lowest "p" fraction of the field or farm (lowest one-half p = ½, lowest one-quarter p = ¼), $\overline{V_p}$ is the mean

application volume (m^3), and $\overline{V_f}$ is the mean application volume (m^3) for the whole field or farm. When p = ½ and C_U > 70%, then the D_U and C_U are essentially equal (Warrick, 1983). The USDA-NRCS (formerly, the Soil Conservation Service) has widely used D_{Ulq} (p = ¼) for surface irrigation to assess the uniformity applied to a field, i.e., by the irrigation volume (amount) received by the lowest one-quarter of the field from applications for the whole field. Typically, D_{Up} is based on the post-irrigation measurement (Burt et al., 1997) of water volume that infiltrates the soil because it can more easily be measured and better represents the water available to the crop. However, the post-irrigation infiltrated water ignores any water intercepted by the crop and evaporated and any soil water evaporation that occurs before the measurement. Any water that percolates beneath the root zone or the sampling depth will also be ignored.

The D_U and C_U coefficients are mathematically interrelated through the statistical variation (coefficient of variation, $\sigma/\bar{x}$, C_v) and the type of distribution. Warrick (1983) presented relationships between D_U and C_U for normal, log normal, uniform, specialized power, beta, and gamma distributions of applied irrigations.

Emission Uniformity

For microirrigation systems, both the C_U and D_U concepts are impractical because the entire soil surface is not wetted. Keller and Karmeli (1975) developed an equation for microirrigation design as follows:

$$E_U = 100\left[1 - 1.27\left(C_{vm}\right) n^{-1/2}\right]\left(\frac{q_m}{\bar{q}}\right) \qquad \ldots[11]$$

where E_U is the design emission uniformity in percent, C_{vm} is the manufacturer's coefficient of variability in emission device flow rate (l/h), n is the number of emitters per plant, q_m is the minimum emission device flow rate (l/h) at the minimum system pressure, and $\bar{q}$ is the mean emission device flow rate (l/h). This equation is based on the D_{Ulq} concept (Heermann et al., 1990), and includes the influence of multiple emitters per plant that each may have a flow rate from a population of random flow rates based on the emission device manufacturing variation. Nakayama et al. (1979) developed a design coefficient based more closely to the C_U concept for emission device flow rates from a normal distribution given as

$$C_{Ud} = 100\left(1 - 0.798\left(C_{vm}\right) n^{-1/2}\right) \qquad \ldots[12]$$

where C_{Ud} is the coefficient of design uniformity in percent and the numerical value, 0.798, is $(2/\pi)^{0.5}$ from equation [8].

Many additional factors affect microirrigation uniformity including hydraulic factors, topographic factors, and emitter plugging or clogging.

WATER USE EFFICIENCY

The previous sections discussed the engineering aspects of irrigation efficiency. Irrigation efficiency clearly is influenced by the amount of water used in relation to the irrigation water applied to the crop and the uniformity of the applied water. These efficiency factors impact irrigation costs, irrigation design, and more importantly, in some cases, the crop productivity. The water use efficiency has been the most widely used parameter to describe irrigation effectiveness in terms of crop yield. Viets (1962) defined water use efficiency as

$$WUE = \frac{Y_g}{ET} \qquad \text{...[13]}$$

where WUE is water use efficiency (kg m^{-3}), Y_g is the economic yield (g m^{-2}), and ET is the crop water use (mm). WUE is usually expressed by the economic yield, but it has been historically expressed as well in terms of the crop dry matter yield (either total biomass or above-ground dry matter). These two WUE bases (economic yield or dry matter yield) have led to some inconsistencies in the use of the WUE concept. The transpiration ratio (transpiration per unit dry matter) is a more consistent value that depends primarily on crop species and the environmental evaporative demand (Tanner and Sinclair, 1983), and it is simply the inverse of WUE expressed on a dry matter basis. Howell (2001) discussed means to enhance WUE in irrigated agriculture including

- agronomic
- engineering
- management
- institutional

aspects that need to be considered. In the future, WUE will become as important as irrigation efficiency as the need for greater productivity from our natural resources develops with our increasing population and urbanization.

Irrigation Water Use Efficiency

The previous discussion of WUE doesn't explicitly explain the crop yield response to just irrigation. WUE is influenced by the crop water use (ET), but ET

often includes a n important component from stored soil water and rainfall. Bos (1979) defined a term for water use efficiency to characterize the influence of irrigation on WUE as

$$WUE = \frac{(Y_{gi} - Y_{gd})}{(ET_i - ET_d)} \quad \ldots[14]$$

where WUE is irrigation water use efficiency (kg m^{-3}), Y_{gi} is the economic yield (g m^{-2}) for irrigation level i, Y_{gd} is the dryland yield (g m^{-2}) (actually, the crop yield without irrigation), ET_i is the evapotranspiration (mm) for irrigation level i, and ET_d is the evapotranspiration of the dryland crops (or of the ET without irrigation). Although equation [14] seems easy to use, both Y_{gd} and ET_d are difficult to evaluate. If the purpose is to compare irrigation and dryland production systems, then dryland rather than non-irrigated conditions should be used. If the purpose is to compare irrigated regimes with an unirrigated regime, then appropriate values for Y_{gd} and ET_d should be used. Often, in most semi-arid to arid locations, Y_{gd} may be zero. Eq. [14] differs principally from Eq. [13] by the yield from rainfed or dryland crop and the influence of rain and stored soil water in these systems that affect ET_d.

Bos (1979) defined irrigation water use efficiency as

$$IWUE = \frac{(Y_{gi} - Y_{gd})}{IRR_i} \quad \ldots[15]$$

where IWUE is the irrigation efficiency (kg m^{-3}) and IRR_i is the irrigation water applied (mm) for irrigation level i. In Eq. [15], Y_{gd} may be often be zero in many arid situations.

For well-managed systems, typically WUE will be maximized near full ET while IWUE will be maximized at an irrigation level below full ET (Howell, 2001). Few examples have been documented over larger spatial scales, but it is apparent that WUE and IWUE can be improved further. In addition, WUE under good irrigation management with efficient irrigation systems almost always is better than WUE from rainfed or dryland systems due to the water offset required to produce enough biomass to create an economic yield.

SUMMARY

Irrigation efficiency is an important engineering term that involves understanding soil and agronomic sciences to achieve the greatest benefit from irrigation. The enhanced understanding of irrigation efficiency can improve the beneficial use of limited and declining water resources needed to enhance crop and food production from irrigated lands. Irrigation efficiency and irrigation uniformity

measures should be used to assess field or design performance (Merriam and Keller, 1978; Pitts et al., 1996) to improve irrigation systems. Pitts et al. (1996) documented in California for 385 systems that were evaluated, improvements were recommended in 80% of the systems. In the systems that adopted recommended improvements, the DU_{lq} was improved by 18% in DU_{lq}.

REFERENCES

ASCE. 1978. Describing irrigation efficiency and uniformity. J. Irrig. Drain. Div., ASCE 104(IR1):35-41.

Bos, M.G. 1979. Standards for irrigation efficiencies of ICID. J. Irrig. Drain. Div., ASCE 105(IR1):37-43.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., and Eisenhauer, D.E. 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Engr. 123(3):423-442.

Christiansen, J.E. 1942. *Irrigation by Sprinkling.* California Agric. Exp. Bull. No. 570, Univ. of Calif.: Berkeley. 94 p.

Hart, W.E. 1961. Overhead irrigation by sprinkling. Agric. Engr. 42(7):354-355.

Heermann, D.F., and Hein, P.R. 1968. Performance characteristics of self-propelled center-pivot sprinkler machines. Trans. ASAE 11(1):11-15.

Heermann, D.F., Wallender, W.W., and Bos, M.G. 1990. Irrigation efficiency and uniformity. pp. 125-149. In G.J. Hoffman, T.A. Howell, and K.H. Solomon, eds., *Management of Farm Irrigation Systems,* Am. Soc. Agric. Engr.: St. Joseph, MI.

Howell, T.A. 2001. Enhancing water use efficiency in irrigated agriculture. Agron. J. 93(2):291-289.

Howell, T.A. 1988. Irrigation efficiencies. pp. 173-184. In R.H. Brown, ed., *Handbook of Engineering in Agriculture, Volume I.*, CRC Press, Inc., Boca Raton, FL.

Israelsen, O.R., and Hansen, V.E. 1962. *Irrigation Principles and Practices*, Third Edition. John Wiley and Sons, Inc.: New York, NY. 447 p.

Keller, J., and Bliesner, R.D. 2000. *Sprinkle and Trickle Irrigation.* The Blackburn Press, Inc.: Caldwell, NJ. 652 p.

Keller, J., and Karmeli, D. 1975. *Trickle irrigation design.* Rainbird Sprinkler Manufacturing Corporation: Glendora, CA. 133 p.

Merriam, J.L., and Keller, J. 1978. *Farm Irrigation System Evaluation: A Guide for Management.* Utah State Univ.: Logan, UT. 271 p.

Nakayama, F.S., Bucks, D.A., and Clemmens, A.J. 1979. Assessing trickle emitter application uniformity. Trans. ASAE 22(4):816-821.

Pitts, D., Peterson, K., Gilbert, G., and Fastenau. 1996. Field assessment of irrigation system performance. Appl. Engr. in Agric. 12(3):307-313.

Tanner, C.B., and Sinclair, T.R. 1983. Efficient use of water in crop production: Research or re-search? pp. 1-27. In H.M. Taylor, W.R. Jordan, and T.R. Sinclair, eds., *Limitations to Efficient Water Use in Crop Production*;. Am. Soc. Agron., Crop Sci. Soc. Am., Soil Sci. Soc. Am.: Madison, WI.

U.S. Salinity Laboratory Staff. 1954. *Diagnosis and Improvement of Saline and Alkali Soils*. Handbook 60, U.S. Govt. Printing Office: Washington, D.C. 160 p.

Viets, F.G. 1962. Fertilizers and the efficient use of water. Adv. Agron. 14:223-264.

Warrick, A.W. 1983. Interrelationships of irrigation uniformity terms. J. Irrig. Drain. Engr., ASCE 109(3):317-332.