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10/31/11

Dear Fethi and all A1 subcommittee participants,

> **Note:** This paper is a draft for discussion purposes only for the SBX7-7 A1 subcommittee and has not been properly formatted regarding references and figures. Some form of the example at the end will eventually be submitted for peer-reviewed publication.

RE: Using salinity / chloride balance to track field level WUE in the San Joaquin Valley

As we have continued our discussions on providing the state legislature with suitable methodology for measuring AgWUE from the field to basin level I have listened intently to the discussion and points made by various participants. The general consensus appears to emphasize the need for finding the best, most practical methodology for measuring WUE at the district and/or basin level. This makes great sense as the WD's and umbrella agencies are already the main reporting units and in the best position, potentially, to sort out real "recoverable", versus "non-recoverable" (lost) water, and thereby the best estimate of real efficiency for that basin. I agree, completely with this premise.

However, we are also charged with submitting a methodology for determining "field level" WUE, the level at which I have spent most of my career. Most of the discussion at this level (and others) has centered on using crop coefficients and CIMIS, and/or published crop production functions and measured crop yield to determine field ET. If we know the ET and have a true measure of the applied water (with no runoff) then we can calculate the deep percolation and thus:

$$\text{Field WUE} = \text{ETc} / \text{Applied Water}$$

(We'll let the WD worry about whether or not the deep percolation is "recoverable" or not.)

This approach can be initially done without collecting any field data at all. We have "normal year" and real-time ETo estimates using CIMIS and published Kc's for most of the major crops, and the WD's have the water orders for most fields (even metered ac-ft totals for many of these) already collected. Just assume no runoff for sprinkler or micro irrigated fields, true field ET estimates and that water meters and orders are all accurate. Do I hear some laughter by this time? I should!

All these assumptions have big error bars on them and are very expensive to document/monitor over the entire season. I personally have documented ETc's in citrus, alfalfa, grapes and most notably in almonds that exceed published values by 10 to 25% (58 inches in microsprinkler irrigated almonds, most recently. As a county-based extension advisor I have also seen many fields where salinity, pest pressure and/or other agronomic/management factors have reduced the vigor of the crop/orchard and thereby real crop ETc. Roger Reynolds from Summers Engineering pointed these issues out in response to the insistence by some of our group that we include a methodology to measure "economic WUE". There are a host of other factors that impact crop water use and yield that are not a part of the direct irrigation process and really beyond the scope of this committee to enumerate.

SALINITY / CHLORIDE MASS BALANCE:

Some of our group have balked at the idea of including a leaching fraction in our calculations as a beneficial use. Anyone farming in the San Joaquin Valley knows that salt accumulation is a problem and is ignored at ones peril. An ac-ft of CA Aqueduct water by the time it reaches Kern County has 800 to 900 pounds of salt in it, about 70 to 80 pounds of chloride alone! It is relatively simple to get an average salt / chloride content in your irrigation water over the season. The ratio of this concentration divided by the salt concentration of the water percolating below the rootzone is the leaching fraction. This straightforward mass balance serves as the core to several empirical models equating the ratio of the irrigation water salinity to the average rootzone soil saturation extract salinity (measured as electroconductivity (ECe) or chloride):

In its simplest form, the leaching fraction (LF) or water percolating below the rootzone can be reduced to a simple mass balance of salt in, salt out:

$$\frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}}$$

Where:

D_{dw} = depth of drain water below rootzone

D_{iw} = depth of irrigation water

EC_{iw} = electroconductivity (or chloride concentration) of irrigation water

EC_{dw} = electroconductivity (or chloride concentration) of drain water

The use of natural chloride concentrations in irrigation water is the best choice as total crop uptake is minimal as is precipitation or soil adsorption of this highly soluble anion. The trick is in identifying the real bottom of the rootzone and obtaining a truly representative number for the salinity / chloride concentration in the water draining below this depth.

The advantage to this method is that the chloride tracer is free! It comes with the water and needs no batteries, meteorological equipment or moving parts. The downside is that representative soil sampling to the bottom of the rootzone is necessary for the most accurate answer. If one wants to simply use one of the empirical coefficients then sampling to a depth of 3 feet might be sufficient for most fields. Four methods are presented. The first three utilize empirical models from real field data equating the leaching fraction with average rootzone salinity. The fourth method simply uses the above mass balance with real data from the end of 2010 from a SJV almond orchard producing over 4,000 lbs/ac of nuts.

SIGNIFICANCE: The balance of chloride is exactly specific to that field and will reach a reasonably steady state over the years. Most of these models show that average rootzone salinity about doubles with a 15% leaching fraction / deep percolation, triples with 10% LF and quadruples with a 5% leaching fraction. This mass balance automatically integrates all the other agronomic and management factors that impact field-level deep percolation.

METHOD 1: Avg Rootzone ECe (Rhodes, 1974 and FAO 29, 1994)

Ayers, R.S., D.W. Westcot. Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29 Rev. 1, Reprinted 1989, 1994 . http://www.fao.org/DOCREP/003/T0234E/T0234E00.htm

Originally in: Rhoades J.D. 1974. "Drainage for salinity control". Drainage for Agriculture. Van Schilfgaarde J. (ed). Amer. Soc. Agron. Monograph No. 17, pp 433–462.

The necessary leaching requirement (LR) can be estimated from Figure 7 for general crop rotations. For more exact estimates for a particular crop, the leaching requirement equation (9) (Rhoades 1974; and Rhoades and Merrill 1976) should be used:

FAO 29

$$LR = \frac{EC_w}{5\ (EC_e) - EC_w} \qquad (9)$$

where:
- LR = the minimum leaching requirement needed to control salts within the tolerance (ECe) of the crop with ordinary surface methods of irrigation
- EC_w = salinity of the applied irrigation water in dS/m
- EC_e = average soil salinity tolerated by the crop as measured on a soil saturation extract. Obtain the ECe value for the given crop and the appropriate acceptable yield from Table 4. It is recommended that the ECe value that can be expected to result in at least a 90 percent or greater yield be used in the calculation. (Figure 7 was developed using ECe values for the 100 percent yield potential.) For water in the moderate to high salinity range (>1.5 dS/m), it might be better to use the ECe value for maximum yield potential (100 percent) since salinity control is critical to obtaining good yields.

The total annual depth of water that needs to be applied to meet both the crop demand and leaching requirement can be estimated from equation (7).

$$AW = \frac{ET}{1 - LR}$$

$$LR = \frac{ECi}{5ECe - ECi}$$

$$FieldWUE = 1 - LR$$

where:
- AW = depth of applied water (mm/year)
- ET = total annual crop water demand (mm/year)
- LR = leaching requirement expressed as a fraction (leaching fraction)

EXAMPLES		**Rhodes 1974**		**Applied**	
Irrig Water	Rootzone	Avg ECe /		**Water**	**Final**
EC (dS/m)	ECe (dS/m)	Irrig EC	LR- Flood	**as %ET**	**WUE**
0.5	1	2.0	0.111	**113%**	**88.9%**
0.5	2	4.0	0.053	**106%**	**94.7%**
0.5	3	6.0	0.034	**104%**	**96.6%**
0.5	4	8.0	0.026	**103%**	**97.4%**
0.5	5	10.0	0.020	**102%**	**98.0%**
0.5	6	12.0	0.017	**102%**	**98.3%**
0.5	7	14.0	0.014	**101%**	**98.6%**
0.5	8	16.0	0.013	**101%**	**98.7%**
1.0	1	1.0	0.250	**133%**	**75.0%**
1.0	2	2.0	0.111	**113%**	**88.9%**
1.0	3	3.0	0.071	**108%**	**92.9%**
1.0	4	4.0	0.053	**106%**	**94.7%**
1.0	5	5.0	0.042	**104%**	**95.8%**
1.0	6	6.0	0.034	**104%**	**96.6%**
1.0	7	7.0	0.029	**103%**	**97.1%**
1.0	8	8.0	0.026	**103%**	**97.4%**

EXAMPLE REQUIREMENTS

DATA: -Average applied water electroconductivity (ECi) or chloride concentration.
-Average soil saturation extract rootzone EC (ECe) or chloride concentration.

This example assumes no specific rootzone depth; only that an average end of season rootzone soil saturation extract ECe has been obtained for the entire crop rootzone. The calculated Leaching Requirement (LR) then represents the actual leaching fraction, allowing for a calculation of the field level Water Use Efficiency.

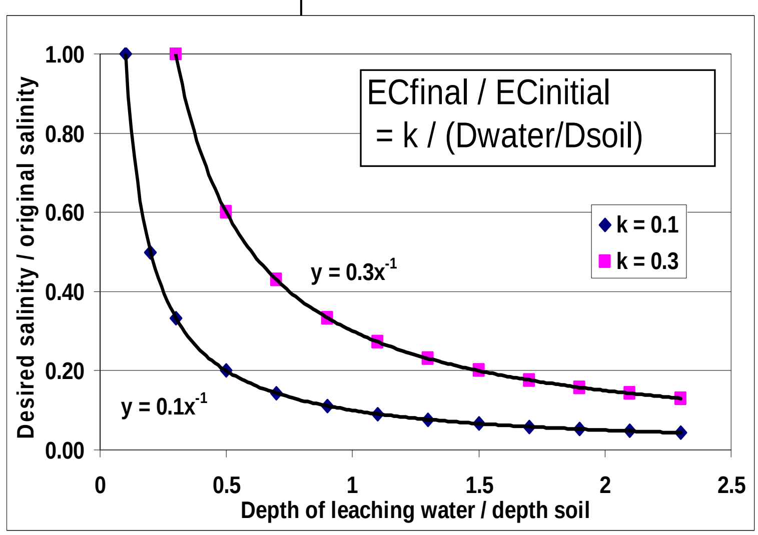
Conditions: No significant precipitation of dissolved salts carried in with irrigation water nor dissolution of native salts within the soil profile has occurred. Calculating this mass balance using chloride concentrations is prone to less error than using ECe.

CAUTION: A single heavy irrigation event at the end of the season when there is reduced crop ET can result in considerable leaching and displacement of salts in the top 3 to 4 feet of soil. This final salinity or chloride mass balance will more reflect that final application efficiency then the true average for the whole season -- giving an erroneously low seasonal WUE. Conversely, a "light" irrigation or rain event at the end of the season with close to 100% WUE will not artificially increase the seasonal WUE as the salts are retained within the rootzone and will just be added in with the total seasonal mass balance.

METHOD 2: Avg Rootzone ECe and Reclamation (Hoffman, 1980)

BASIC RECLAMATION
Required Leaching (ft water/ft depth soil) = K / (Desired EC/Original EC)
(K factor of 0.3 for continuous ponding.)
(K can be as small as 0.1)
(K factor of 0.15 for sprinkling or drip.)

$$RqdLeaching\left(\frac{Dwater}{Dsoil}\right) = \frac{k}{\frac{ECdesired}{ECoriginal}}$$



$$FieldWUE = 1 - RqdLeaching$$

Karen, R. 1996. "Reclamation of saline, sodic, and boron-affected soils." Agricultural Salinity Assessment and Management. ASCE. New York, N.Y. Manual No. 71:410-415

Original Ref:
Hoffman G.J. 1980 Guidelines for reclamation of salt-affected soils. Proc. Inter-American Salinity and Water Management Technology Conference. Juarez, Mexico. 11–12 December1980. pp. 49–64.

Hoffman 1980 EXAMPLES Irrig Water EC (dS/m)	Rootzone ECe (dS/m)	Avg ECe / Irrig EC	Required Leaching (ft irr/ft soil) ($k_{0.1}$)	**$k_{0.1}$ Applied Water as %ET**	**Final WUE**	Required Leaching (ft irr/ft soil) ($k_{0.15}$)	**$k_{0.15}$ Applied Water as %ET**	**Final WUE**
0.5	1	2.0	0.050	**143%**	**70.0%**	0.075	**182%**	**55.0%**
0.5	2	4.0	0.025	**118%**	**85.0%**	0.038	**129%**	**77.5%**
0.5	3	6.0	0.017	**111%**	**90.0%**	0.025	**118%**	**85.0%**
0.5	4	8.0	0.013	**108%**	**92.5%**	0.019	**113%**	**88.8%**
0.5	5	10.0	0.010	**106%**	**94.0%**	0.015	**110%**	**91.0%**
0.5	6	12.0	0.008	**105%**	**95.0%**	0.013	**108%**	**92.5%**
0.5	7	14.0	0.007	**104%**	**95.7%**	0.011	**107%**	**93.6%**
0.5	8	16.0	0.006	**104%**	**96.3%**	0.009	**106%**	**94.4%**
1.0	1	1.0	0.100	**250%**	**40.0%**	0.150	**1000%**	**10.0%**
1.0	2	2.0	0.050	**143%**	**70.0%**	0.075	**182%**	**55.0%**
1.0	3	3.0	0.033	**125%**	**80.0%**	0.050	**143%**	**70.0%**
1.0	4	4.0	0.025	**118%**	**85.0%**	0.038	**129%**	**77.5%**
1.0	5	5.0	0.020	**114%**	**88.0%**	0.030	**122%**	**82.0%**
1.0	6	6.0	0.017	**111%**	**90.0%**	0.025	**118%**	**85.0%**
1.0	7	7.0	0.014	**109%**	**91.4%**	0.021	**115%**	**87.1%**
1.0	8	8.0	0.013	**108%**	**92.5%**	0.019	**113%**	**88.8%**

EXAMPLE REQUIREMENTS

DATA: -Average applied water electroconductivity (ECi) or chloride concentration.
-Average soil saturation extract rootzone EC (ECe) or soil chloride concentration.
-Rootzone depth: assumed 6 foot for this example.

This example assumes that a roughly steady-state ratio of the average rootzone EC (or Cl) / average applied water EC (or Cl) concentration will result from a given amount of leaching -- basically the same mass balance principle as the above example. The difference here is that Hoffman developed the empirical constant "k" (see chart) from hundreds of before and after soil analyses given a certain depth of leaching (either continuous, flood, or serial applications by sprinkler, but essentially as one leaching event over a short period of time) where the final required leaching is given in terms of depth of water / depth of soil.

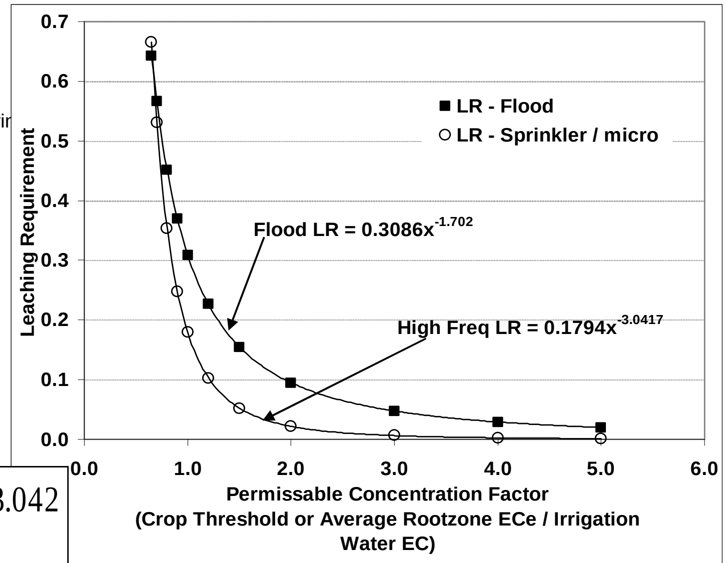
This example simply takes this calculated leaching requirement and multiplies it by a 6 foot rootzone to estimate a total leaching depth necessary to maintain the desired rootzone soil ECe / ECirrig ratio, and final WUE.

The same conditions and caution apply as for Method 1.

METHOD 3: Permissible Concentration Factor (Rhodes, 1982)

Avg ECe Rootzone/ECe Irrig Water

Concentration Factor X	(Rhodes 1982) LR - Flood	LR - Sprinkler / micro	Applied Water Needed as %ET LR- Flood	LR- High Freq (sprir
5.00	0.02	0.001	**102%**	**100%**
4.00	0.03	0.003	**103%**	**100%**
3.00	0.05	0.006	**105%**	**101%**
2.00	0.09	0.022	**110%**	**102%**
1.50	0.15	0.052	**118%**	**106%**
1.20	0.23	0.103	**129%**	**111%**
1.00	0.31	0.179	**145%**	**122%**
0.90	0.37	0.247	**159%**	**133%**
0.80	0.45	0.354	**182%**	**155%**
0.70	0.57	0.531	**231%**	**213%**
0.65	0.64	0.665	**280%**	**299%**



$$LR_{sprinkler/micro} = 0.179\left(\frac{ECe}{ECi}\right)^{-3.042}$$

$$FieldWUE = 1 - LR$$

Rhodes, J.D. and J. Loveday. 1990 "Salinity related processes operating in irrigated soil-plant-water systems". Irrigation of Agricultural Crops. Eds B.A. Stewart and D.R. Nielsen. Amer. Soc. Agron., Madison, WI. Monograph No.30:1107-1114

Also in: Ayers, R.S., D.W. Westcot. Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29 Rev. 1, Reprinted 1989, 1994 . http://www.fao.org/DOCREP/003/T0234E/T0234E00.htm

Original Ref:

Rhoads, J.D. 1982. Reclamation and management of salt-affected soils after drainage. p.123-197. In Proc. 1st Annual Western Provincial Conference Rationalization Water Soil Resources Manage. Lethbridge, Alberta, Canada, November.

EXAMPLES **(Rhodes 1990)**

Irrig Water EC (dS/m)	Rootzone ECe (dS/m)	Conc. Factor Avg ECe / Irrig EC	LR - Flood	Applied Water as %ET	Final WUE	LR-Micro / Sprinkler	Applied Water as %ET	Final WUE
0.5	1	2.0	0.095	**110%**	**90.5%**	0.022	**102%**	**97.8%**
0.5	2	4.0	0.029	**103%**	**97.1%**	0.003	**100%**	**99.7%**
0.5	3	6.0	0.015	**101%**	**98.5%**	0.001	**100%**	**99.9%**
0.5	4	8.0	0.009	**101%**	**99.1%**	0.000	**100%**	**100.0%**
0.5	5	10.0	0.006	**101%**	**99.4%**	0.000	**100%**	**100.0%**
0.5	6	12.0	0.004	**100%**	**99.6%**	0.000	**100%**	**100.0%**
0.5	7	14.0	0.003	**100%**	**99.7%**	0.000	**100%**	**100.0%**
0.5	8	16.0	0.003	**100%**	**99.7%**	0.000	**100%**	**100.0%**
1.0	1	1.0	0.309	**145%**	**69.1%**	0.179	**122%**	**82.1%**
1.0	2	2.0	0.095	**110%**	**90.5%**	0.022	**102%**	**97.8%**
1.0	3	3.0	0.048	**105%**	**95.2%**	0.006	**101%**	**99.4%**
1.0	4	4.0	0.029	**103%**	**97.1%**	0.003	**100%**	**99.7%**
1.0	5	5.0	0.020	**102%**	**98.0%**	0.001	**100%**	**99.9%**
1.0	6	6.0	0.015	**101%**	**98.5%**	0.001	**100%**	**99.9%**
1.0	7	7.0	0.011	**101%**	**98.9%**	0.000	**100%**	**100.0%**
1.0	8	8.0	0.009	**101%**	**99.1%**	0.000	**100%**	**100.0%**

EXAMPLE REQUIREMENTS: same as Method 1

METHOD 4: Mass Balance only, Kern County Almond Example (Sanden, 2011)

In its simplest form, the leaching fraction (LF) or water percolating below the rootzone can be reduced to a simple mass balance of salt in, salt out:

$$\frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}}$$

Where:

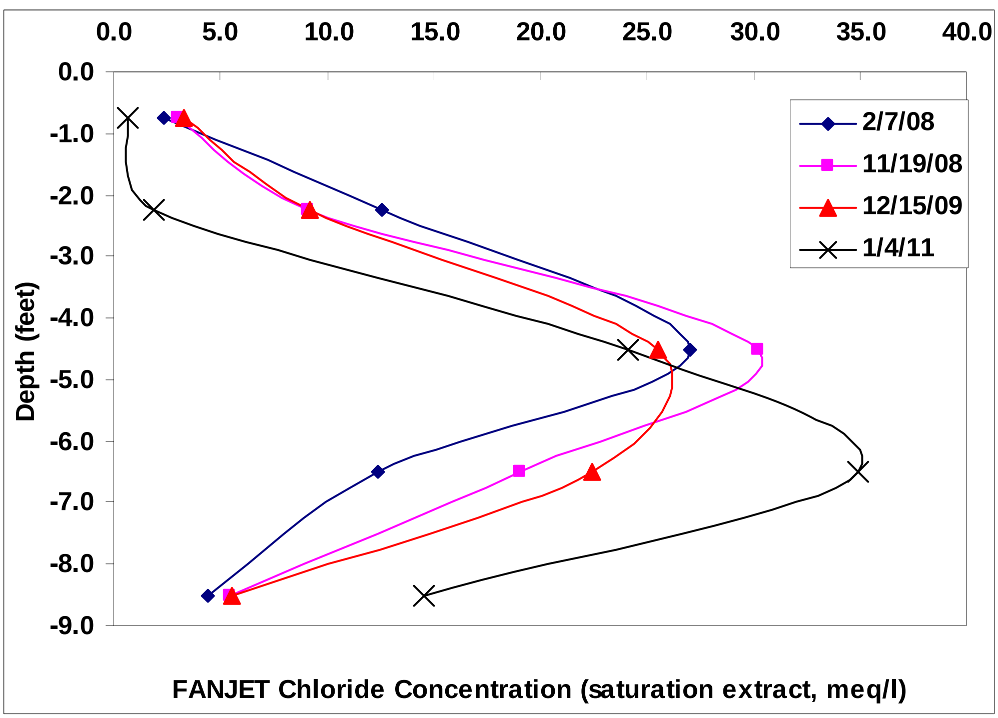
D$_{dw}$ = depth of drain water below rootzone

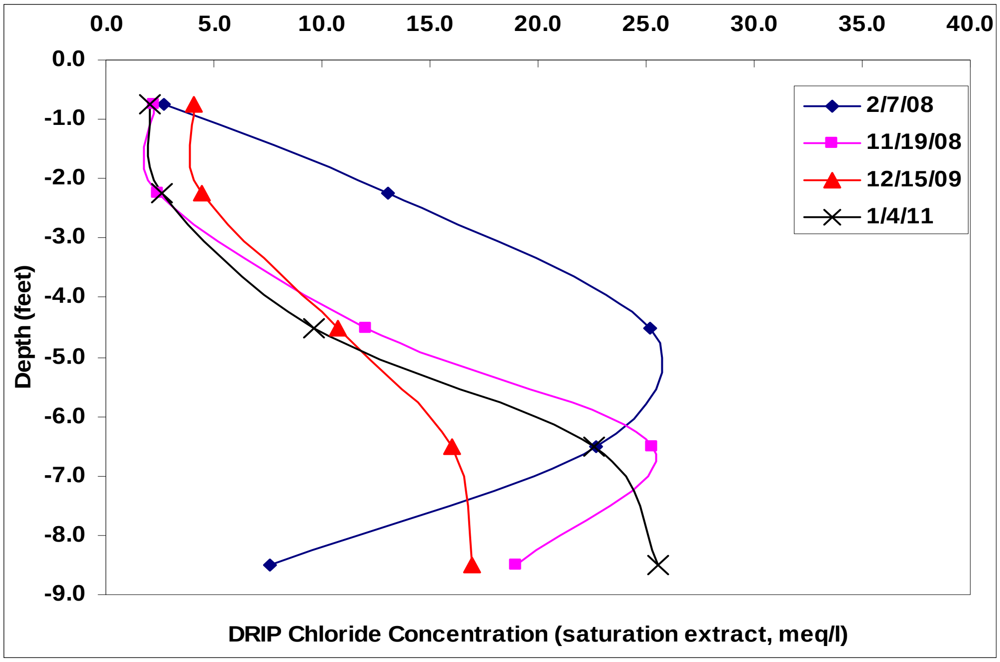
D$_{iw}$ = depth of irrigation water

EC$_{iw}$ = electroconductivity (or chloride concentration) of irrigation water

EC$_{dw}$ = electroconductivity (or chloride concentration) of drain water

In this case we take we take the sampling depth having the highest chloride concentration as the limit of the rootzone and use the calculated LF at that depth to estimate field WUE. The below charts reveal changes in soil Cl concentration over 3 years in a 153 acre almond orchard in NW Kern County where we are doing fertility trials and intense monitoring of individual tree water status, soil moisture depletion using the neutron probe and localized field ETc as measured by eddy covariance and surface renewal systems. Cl concentrations are the average of 20 sites, sampled using a single auger hole about 1 foot distant from PVC neutron probe access tubes to a depth of 9 feet over the 51 acre irrigation set for that system (FANJET or microsprinkler, and DOUBLE-LINE DRIP). The Cl concentration in the CA Aqueduct water used for irrigation over the same period averaged 2.2 meq/l.





Note how the zone of peak has moved only slightly under FANJET irrigation compared to the DRIP. Sampling in the DRIP has been done within a 1 to 2 foot distance of the DRIP emitters – meaning that this is the zone of maximum leaching. Thus, estimates of deep percolation made solely on a leaching fraction in this zone will over estimate the true depth of leaching for the whole DRIP set. This is partially true for the FANJET also, as it only wets about 50% of the orchard floor and, therefore, has some water that subs laterally, but sampling in the middle of the wetted area (which is our practice) will provide a much higher percentage of water moving straight down as one-dimensional flow then in the DRIP system. This should give a final WUE estimate with less possibility of underestimation.

MICROSPRINKLER -- Cl (soil saturation extract, meq/l)					LEACHING FRACTION ESTIMATE				WATER USE EFFICIENCY			
Sample Depth (ft)	2/7/08	11/19/08	12/15/09	1/4/11	2/7/08	11/19/08	12/15/09	1/4/11	2/7/08	11/19/08	12/15/09	1/4/11
-0.75	2.3	3.0	3.33	0.7	0.48	0.42	0.40	0.77	0.67	0.70	0.72	0.57
-2.25	12.6	9.1	9.17	1.9	0.15	0.19	0.19	0.54	0.87	0.84	0.84	0.65
-4.50	27.0	30.2	25.50	24.1	0.08	0.07	0.08	0.08	0.93	0.94	0.93	0.92
-6.50	12.4	19.1	22.44	34.9	0.15	0.10	0.09	0.06	0.87	0.91	0.92	0.94
-8.50	4.4	5.5	5.56	14.6	0.33	0.29	0.28	0.13	0.75	0.78	0.78	0.88
Avg 0-6.5 feet	13.6	15.4	15.1	15.4	(Average Cl_{irrig} concentration = 2.2 meq/l)				$FieldWUE = 1 - LR$			

MICROSPRINKLER -- *Cl mass (lb/ac-ft soil @ 29.1 SP)					LF as Cl MASS ESTIMATE				WUE - Cl mass estimate			
Sample Depth (ft)	2/7/08	11/19/08	12/15/09	1/4/11	2/7/08	11/19/08	12/15/09	1/4/11	2/7/08	11/19/08	12/15/09	1/4/11
-0.75	97	126	137	28	0.73	0.56	0.52	2.57	0.58	0.64	0.66	0.28
-2.25	519	375	378	78	0.14	0.19	0.19	0.91	0.88	0.84	0.84	0.52
-4.50	1114	1244	1051	994	0.06	0.06	0.07	0.07	0.94	0.95	0.94	0.93
-6.50	509	786	925	1440	0.14	0.09	0.08	0.05	0.88	0.92	0.93	0.95
-8.50	181	225	229	601	0.39	0.32	0.31	0.12	0.72	0.76	0.76	0.89

(*Cl irrig mass = 70.8 lb/ million lbs water. Applied irrig = 54" = 12.20 million lbs. Total applied Cl = 950 lbs/year.)

DOUBLE-LINE DRIP -- Cl (soil saturation extract, meq/l)					LEACHING FRACTION ESTIMATE				WATER USE EFFICIENCY			
Sample Depth (ft)	2/7/08	11/19/08	12/15/09	1/4/11	2/7/08	11/19/08	12/15/09	1/4/11	2/7/08	11/19/08	12/15/09	1/4/11
-0.75	2.7	2.2	4.12	2.0	0.45	0.50	0.35	0.52	0.69	0.67	0.74	0.66
-2.25	13.1	2.4	4.44	2.6	0.14	0.48	0.33	0.46	0.87	0.68	0.75	0.69
-4.50	25.2	12.1	10.73	9.6	0.08	0.15	0.17	0.19	0.93	0.87	0.85	0.84
-6.50	22.7	25.3	15.99	22.6	0.09	0.08	0.121	0.09	0.92	0.93	0.892	0.92
-8.50	7.6	19.0	16.91	25.5	0.22	0.10	0.115	0.08	0.82	0.91	0.897	0.93
Avg 0-6.5 feet	15.9	10.5	8.8	9.2								

The above table illustrates this concept in that MICROSPRINLER WUE is estimated at 94 to 95% over the 3 years, while the DRIP WUE is estimated at 90 to 93%. Using EC mass balance, with its subsequent complications of precipitation and dissolution in this marginally alkaline soil indicated an even higher LF – lowering estimates of MICROSPRINKLER WUE down to 89 to 92% and DRIP WUE from 88 to 90%.

Detailed measurements of heat flux and subsequent estimation of site specific full year ETc by eddy covariance put the yearly 2009-10 average ET for this block (system installed March 2008 so full season not available that year) at 58.2 inches – almost exactly equal to applied irrigation and rainfall. This would yield a 100% field WUE! Average ETc estimated from site specific measured applied water and neutron probe depletion averaged 57.6 and 56.1 inches for the DRIP and MICROSPRINKLER, respectively. Using currently published Kc's for micro irrigated almonds and an ET of 45 inches would have yielded a field WUE of only 77%.

The earlier discussed empirical models, using an average MICROSPRINKLER rootzone Cl concentration of 15 meq/l and irrigation Cl of 2.2 meq/l would have yielded field WUE estimates of 97, 91.2 and 99.7% for Methods 1, 2 and 3, respectively. Inclusion of Cl actually taken up by the crop and exported off the field will further improve the accuracy and magnitude of field WUE. This was the approach taken by Samani, et. al. (2005) in developing field level WUE estimates for several major crops for the Elephant Butte Irrigation District in southern New Mexico.

(Samani, Z., T. Sammis, R. Skaggs, N. Alkhatiri, and J. Deras. 2005. Measuring on-farm irrigation efficiency with chloride tracing under deficit irrigation. J. Irrig. & Drain. Eng., Vol. 131:6:555-559.)

CONCLUSION

A chloride mass balance approach provides a mechanism for calculating specific field level deep percolation (and subsequent WUE if runoff and other losses are negligible) with greater certainty than using estimates of crop ETc. That said, on a district wide basis this method requires extensive work to obtain samples for all fields and, therefore, is most likely more suited to be used as an "indicator" methodology to verify the accuracy of larger scale estimates of ETc made using CIMS, SEBAL, MODIS or other regional predictors for representative fields within a district or basin.
Sincerely,

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