KEY IRRIGATION MANAGEMENT PRACTICES FOR ALFALFA

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ABSTRACT

Alfalfa production is basically a linear function of plant transpiration and stomatal conductance that drives carbon dioxide uptake to build plant carbohydrates and biomass. Cutting schedules, irrigation non-uniformity and poor scheduling can result in plant stress which decreases transpiration, CO2 assimilation, yield and water use efficiency. Assuming fertility is not limiting and the stand is not in decline, the difference between an 8 and 12 ton/ac crop in the San Joaquin Valley boils down to water management: simply the right amount at the right time. This paper discusses alfalfa water use (evapotranspiration, ET), soil water holding capacity, irrigation uniformity and scheduling.

Key Words: alfalfa, irrigation, CIMIS, distribution uniformity, soil moisture

INTRODUCTION

Declining water supply: The average allocation of surface water to most San Joaquin Valley growers has been reduced by 30 to 65% over the last ten years, depending on the watershed and irrigation district. But for most Westside growers a 100% allocation means only 2.5 feet of "normally priced" district water. If you're growing alfalfa or almonds and need 4 to 4.5 feet to meet crop demand you have to pump or buy "surplus" or "emergency pool" water to make up the difference. In some cases this has cost as much as $700/ac-ft. In addition to the unpredictability over natural drought cycling are the continued legal issues surrounding the pumping of fresh water from the Sacramento/San Joaquin River Delta. These issues have a huge impact on both the quantity and quality of water exported for irrigation and municipal needs south of the Delta.

The drive for conservation and increased efficiency: Of course you can't grow hay with water costs of $700/ac-ft, but the squeeze is on across the southwestern states as water costs everywhere are increasing and growers are asking how to make the most *profitable* amount of crop/drop. This equation is simple – as costs go up, you either 1) go broke, 2) become more efficient and produce the same tonnage for less cost, 3) get more price for your crop, or 4) you produce more tonnage for only a slight increase in production costs. Most of the time it's a combination of (3) and (4) with new technology (chemical and/or mechanical) and varieties that drive the productivity increases. This paper will review alfalfa water requirements, the impact of irrigation uniformity on yield and then explore the potential for improving alfalfa water use efficiency and tonnage with improved irrigation scheduling and alternative irrigation systems.

PRACTICE 1 - Know the expected crop water use: ***Evapotranspiration (ET,) "potential" ETo, Crop coefficients (Kc) and average ET***

Assuming your field fertility and pest pressure is not a problem, understanding these two concepts is the key to top alfalfa yields. The fuel of forage production is carbon dioxide (CO_2) assimilation through the stomata on the alfalfa leaves. This provides the carbon base for carbohydrate production powered by pho-

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tosynthesis and root nutrient uptake. The more open the stomata, the greater the CO_2 uptake, the greater your hay tonnage and the greater your crop water use.

Climate determines your "potential or reference crop" ETo – essentially maximum water use by unstressed pasture for your region. Since most forage crops are planted dense and cover the ground like a pasture then it's natural to assume that their ET would be the same as ETo, and as a first guess this isn't too bad. But there are developmental differences due to initial seedling growth, physiology of the particular forage compared to pasture and cutting schedules. Basically, the crop coefficient, Kc, is the ratio of actual crop water use for a particular stage of growth compared to ETo. We have typical Kc values for the developmental stages of most crops. Crop ET is then calculated as follows:

$$\textbf{ETcrop} = \textbf{ETo} * \textbf{Kc} * \textbf{E}_\textbf{f}$$

ETo = **reference crop** (tall grass) ET

Kc = **crop coefficient** for a given stage of growth as a ratio of grass water use. May be 0 to 1.3, standard values are good starting point.

E_f = an "**environmental factor**" to account for immature permanent crops, salinity, low fertility, poor stand, etc. May be 0.1 to 1.1 depending on field. Usually 1 for good ground and water.

Figure 1 illustrates the changes in alfalfa ET in the southern San Joaquin Valley over the year due to serial cutting. The real picture of actual ET, even when averaged on a weekly basis, can be much more variable and can actually have some Kc values in excess of 1.5, more than 150%

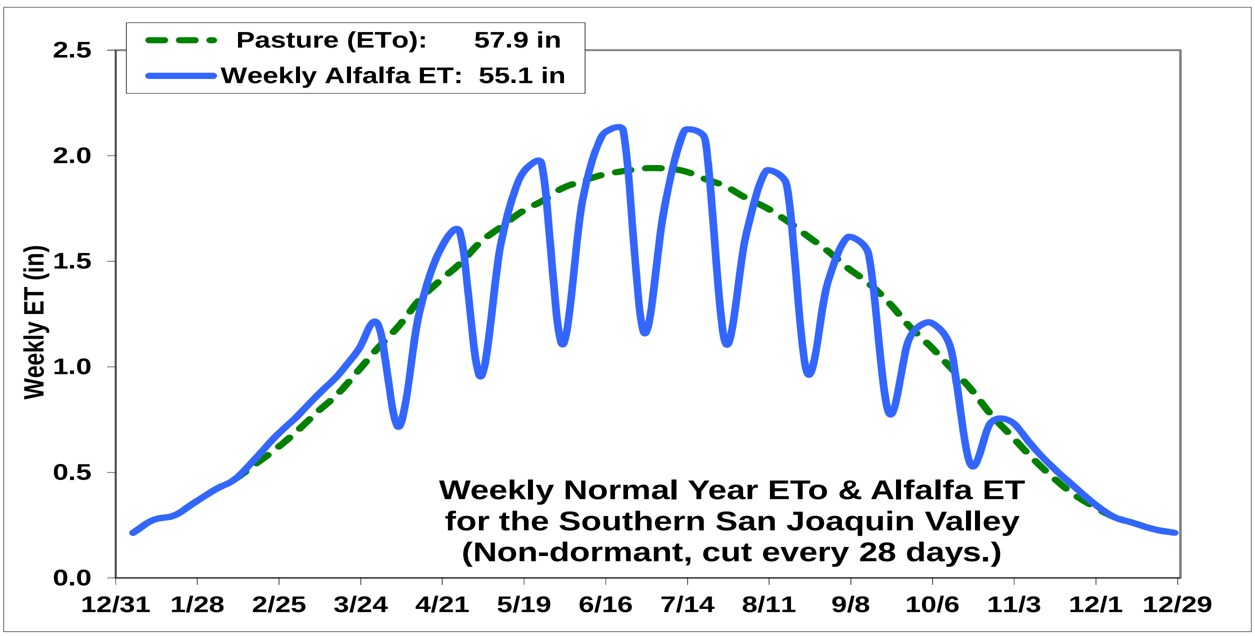


Fig. 1. Weekly ET for an established stand of non-dormant alfalfa in the SJV with 8 cuttings. Crop ET is calculated using peak crop coefficient (Kc) values of 1.1 immediately upon irrigating after bale pickup and a low of 0.6 for one week immediately after cutting as the hay cures prior to baling.

of ETo. Since most alfalfa is flood irrigated 1 to 3 times per cutting we usually ignore this variation and assume an average Kc of 0.95 during the growing season – with the drier soil storing the extra water for the irrigation following pickup of bales when the Kc is low (<0.8) and providing the extra water needed for the Kc that can be > 1.1 when the hay is more than 6 inches tall. Table 1 gives biweekly Kc values and "normal year" estimated ET based on the "normal year" ETo of 57.9 inches calculated by the California Irrigation Management Information System (CIMIS, http://wwwcimis.water.ca.gov/cimis) for the southern San Joaquin Valley. This is a state-wide weather station network that provides both “normal year” and real-time ETo free of charge.

Actual alfalfa ET measured in a Buttonwillow field on heavy, cracking black clay irrigated once per cutting showed that mid-season Kc’s occasionally ran 115 to 150% (0.33 to 0.45 inches/day) in July and August. The net result was that the average May-October Kc for this field was 1.10 instead of the 0.95 normally used. __Bottom line:__ **Normal year ET tables are a good guideline for planning irrigations, BUT actual crop ET can be +/-15%. Therefore, you must check soil moisture and irrigation uniformity over the season to maximize yield and efficiency.**

Table 1. Biweekly crop coefficients and estimated water use for various forage crops in the SJV

DATE	Pasture *ETo (inch)	[1]Crop Coefficient Values (Kc)						[4]Normal Year Crop ET (inches)					
		[2]Alfalfa	Silage 4/1-8/25	Silage 6/1-10/15	[3]Sudan	Winter Forage	Triple Crop	[2]Alfalfa	Silage 4/1-8/25	Silage 6/1-10/15	[3]Sudan	Winter Forage	Triple Crop
1/15	0.54	0.95				0.62	0.62	0.51				0.33	0.33
2/1	0.70	0.95				0.80	0.80	0.67				0.56	0.56
2/15	0.98	0.95				0.95	0.95	0.93				0.93	0.93
3/1	1.26	0.95				1.15	1.15	1.20				1.45	1.45
3/15	1.64	0.95				1.15	1.15	1.56				1.89	1.89
4/1	2.08	0.95	Plant			1.20	1.20	1.98	*1.04*			2.50	2.50
4/15	2.55	0.95	0.14			1.20	Silage90	2.42	0.35			3.06	*1.28*
5/1	3.15	0.95	0.18		Plant	1.15	0.14	2.99	0.55		*1.58*	3.62	0.44
5/15	3.50	0.95	0.31		0.58		0.22	3.33	1.09		2.03		0.77
6/1	3.79	0.95	0.94	Plant	0.80		0.45	3.60	3.55	*1.90*	3.03		1.71
6/15	4.00	0.95	1.14	0.14	0.95		1.00	3.80	4.55	0.55	3.80		4.00
7/1	4.25	0.95	1.18	0.25	1.05		1.10	4.04	5.02	1.06	4.46		4.68
7/15	4.35	0.95	1.18	0.56	1.10		1.20	4.13	5.13	2.45	4.79		5.22
8/1	4.33	0.95	1.15	1.00	1.10		Sudan	4.11	4.98	4.33	4.76		*2.17*
8/15	4.11	0.95	1.06	1.15	0.60		0.60	3.90	4.36	4.72	2.46		2.46
9/1	3.64	0.95	0.98	1.20	1.10		0.90	3.46	3.55	4.37	4.01		3.28
9/15	3.10	0.95		1.20	1.10		1.05	2.95		3.72	3.41		3.26
10/1	2.70	0.95		1.06	0.60		1.10	2.57		2.87	1.62		2.97
10/15	2.20	0.95		0.98	1.10		0.60	2.09		2.16	2.42		1.32
11/1	1.73	0.95			1.10		1.10	1.65			1.91		1.91
11/15	1.20	0.95			1.00	Plant	TriGrain	1.14			1.20	*0.60*	*0.60*
12/1	0.88	0.95				0.25	0.25	0.84				0.22	0.22
12/15	0.70	0.95				0.36	0.36	0.67				0.25	0.25
12/31	0.52	0.95				0.52	0.52	0.49				0.27	0.27
TOTALS	57.90							55.01	34.18	28.12	41.47	15.68	44.45

*Jones, D.W., R.L. Snyder, S. Eching and H. Gomez-McPherson. 1999. California Irrigation Management Information System (CIMIS) Reference Evapotranspiration. Climate zone map, Dept. of Water Resources, Sacramento, CA.

[1]Adapted from Pruitt, W.O., E. Fereres, K. Kaita, and R.L. Snyder. 1987. "Reference Evapotranspiration (ETo) for California." UC Bull. 1922. Pp. 12-13.

[2]Kc of 0.95 takes into account reduced ET during cuttings over season.

[3]Total of 3 cuttings. ET reduced for 1 to 2 weeks after cutting 7/15 and 9/1.

[4]ET numbers in italics are evaporation losses from water at planting.

Yield/ET production functions and water use efficiency (WUE): Much research over the last 30 years has examined the WUE, **crop per drop** so to speak, of most field crops. The production function for a given crop predicts the yield as a function of crop ET. The final WUE is a ratio of final yield over total applied water. Figure 2.a. shows the variety of alfalfa production functions that have been developed from many different locations and research trials throughout the West (Hanson et al., 2007). A few growers

I've known over the years have obtained 12 t/ac under flood and yields of 14 to 24 t/ac have been reported for subsurface drip irrigation and pivots with intensive fertigation (Ludwick, 2000.) Figure 2.b. is a more realistic picture from my

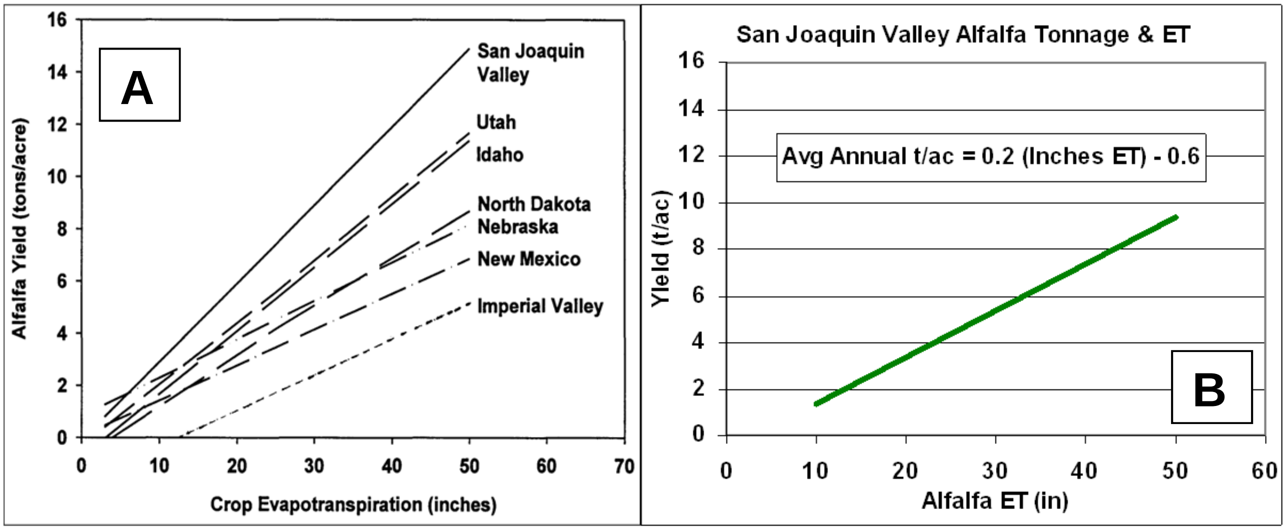


Fig. 2. Optimal alfalfa production functions for various locations in the West (left, Hanson et al., 2007). More realistic field production function for well-managed established alfalfa in the SJV (right, Sanden, personal observation, 3 year trial in Buttonwillow).

observation of production conditions (and a 3 year trial measuring ET/yield of alfalfa in Buttonwillow) where leaf loss in the field is unavoidable and top hay yields are around 10 t/ac. What this function says is that it takes about 5 inches of ET to make one ton of alfalfa hay. You'll notice that the lowest production line in Fig. 2a. is for the Imperial Valley. Excessive heat during the day and night result in high "respiration losses" in alfalfa, where the plant actually burns up some stored carbohydrates as it transpires large amounts of water to maintain cooling. CO_2 assimilation is high, but so are metabolic losses. Alfalfa is a C3 plant that prefers cooler temperatures (50-80^{o}F) for the most efficient photosynthesis. But these findings were based mostly on flood irrigation with significant periods of stress and water logging/scald problems. One grower using state of the art subsurface drip irrigation (SDI) in the Coachella Valley is reportedly making 14 to 16 ton/ac with daily irrigation to avoid stress and water logging using about 6 feet of applied water, which is about right for 5 inches of ET/ton of alfalfa.

PRACTICE 2 – Know your soil moisture storage and irrigate to avoid stress/water logging: ***Soil texture, water holding capacity, infiltration***

Soil texture will determine how much water you can store in the rootzone and, in conjunction with the chemistry of the irrigation water and soil salinity, affect how fast water infiltrates when it moves over the field. This "infiltration function" should be considered when you decide what "fall"/slope you want to level the field to, how fast and how often you want to run the water to achieve good uniformity of irrigation/recharge across the field.

SIMPLIFIED SOIL TEXTURE CATEGORIES: For normal field irrigation scheduling it is usually sufficient for the production farmer to identify his soil by 4 basic types: Coarse, Sandy, Medium and Fine. Table 2 lists the characteristics associated with these types and the amount of "available water" at field capacity. But the basic way to estimate AWHC (using the length of the soil ribbon you make with your thumb and forefinger) is: if the wet soil at least makes a ball, but no ribbon your total AWHC is about 0.4 to 1 inch/foot depth of soil. Then for all soils that make a ribbon:

AWHC(in/ft soil) ~ length of ribbon

Table 2. Simplified soil texture categories, associated USDA soil textures, approximate available water holding capacity (AWHC) and length of soil “ribbon”.

Category	Textures	AWHC (in/12 inch soil)	“Ribbon” Length (inches)
Coarse	S / LS	0.6 – 1.2	None. Ball only.
Sandy	LS / SL / L	1.2 – 1.8	0.4 - 1
Medium	L / SCL	1.4 – 2.2	1 - 2
Fine	SiL / SiCL / CL / SiC	1.7 – 2.4	> 2

So how does this play out for scheduling irrigation in the field and figuring out how many days I have between irrigations? Table 3 sums up the estimated available water to a 5 foot depth at field capacity, assumes that 50% is available with little or no stress and divides that moisture storage by the average daily alfalfa ET for a given month to estimate the optimal irrigation interval.

Table 3. Alfalfa flood irrigation interval (days of non-stressed moisture reserve) by month and soil texture.

Established Alfalfa			Apr	May	Jun	Jul	Aug
Soil Texture		Daily	0.18	0.23	0.26	0.27	0.25
Available Soil Moisture to 5 feet @ 50% depletion		(in)	Days of Moisture Reserve for Average Daily ET by Month and Root Delopment				
Sand	Coarse	1.8	10	8	7	6	7
Loamy Sand	Coarse	2.8	15	12	11	10	11
Sandy Loam	Sandy	3.5	19	15	13	13	14
Loam	Sandy	4.5	25	19	17	16	18
Silt Loam	Medium	4.5	25	19	17	16	18
Sandy Clay Loan	Medium	3.3	18	14	12	12	13
Sandy Clay	Medium	4.0	22	17	15	15	16
Clay Loam	Fine	4.3	24	18	16	15	17
Silty Clay Loam	Fine	4.8	26	21	18	17	19
Silty Clay	Fine	6.0	33	26	23	22	24
Clay	Fine	5.5	30	24	21	20	22

After Ratliff LF, Ritchie JT, Cassel DK. 1983. Field-measured limits of soil water availability as related to laboratory-measured properties. Soil Sci Soc Am. 47:770-5

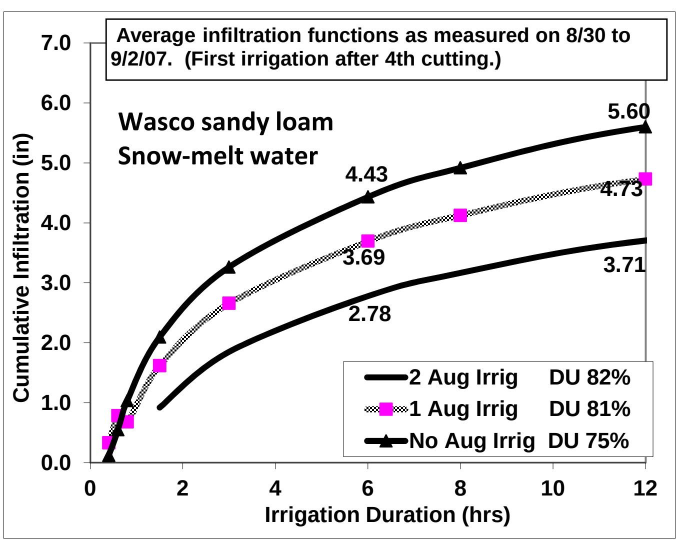


Fig. 3. Infiltration curves for different checks in the same field under deficit or no deficit irrigation.

The first thing you’ll notice is that the interval for 8 out of the 11 soil textures for June and July runs from 10 to 18 days, with most of them in the 13 to 17 day range, which is close to the 12 to 14 day interval a lot of growers run between the first and second irrigation after cutting. That’s great if you know your next irrigation is going to exactly replace that 4 to 4.5 inches the plants sucked out during the previous 2 weeks. In reality, almost no grower knows what his exact infiltration function is, and even if you had it tested at one time the degree to which you let the field dry down just before an irrigation has a huge impact on the real-time infiltration of the next irrigation. Figure 3 is an excellent example of this where the infiltration for the first irrigation in September varies from 3.7 to 5.6 inches depending on whether there were two or no irrigations for the August cutting. Otherwise, 12 hours of "on-time" results in about 3.7 inches of infiltration on this Wasco sandy loam, which is just right for a 13 day irrigation interval in June and July.

Okay, that makes sense – a sandy soil that dries out more infiltrates more water. But what about a clay soil, water percolates more slowly in the finer texture, right? So if I don't want to stress the hay and still stick with 12 hour sets then I need to irrigate more often? In some very sodic silty soils that seal over this might apply, but Figure 4 shows that a heavy almost pure black cracking clay alfalfa field in Buttonwillow infiltrates almost twice the depth of water as the Wasco sandy loam. Why? Large cracks in the Buttonwillow clay open up almost down to 4 feet between irrigations. Most of these fields are irrigated only once between cuttings for two reasons: 1) the infiltration, subsurface moisture storage and availability to the hay is about sufficient for well-established alfalfa with roots down to 6 feet and 2) trying to apply a second irrigation 10 to 14 days before cutting often leaves wet areas in the field, which not only cause equipment problems but lead to scald and phytophthora. Having some kind of flowmeter for the field in combination with hand probing or checking with soil moisture sensors is essential to know if you are under or over irrigating and to know if you are irrigating at a high degree of uniformity.

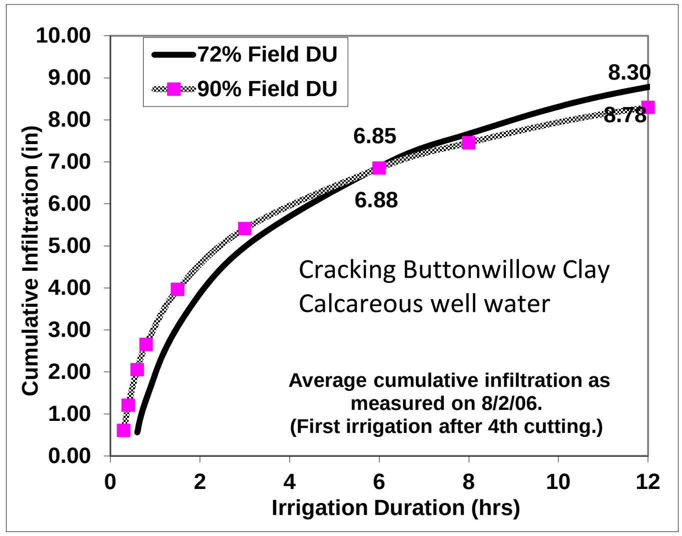


Fig. 4. Infiltration for different checks in the same field after harvest, 28 days after the preceding irrigation.

PRACTICE 3 – Make your irrigation as uniform as possible: ***Land leveling, "distribution uniformity" (DU) and the impact on yield, timing border irrigation cutoff***

Stress from dry soil, disease and salinity can all add up to decrease the stomatal conductance and uptake of CO_2. So it follows that you want to irrigate the field as uniformly as possible to avoid having some parts too dry while avoiding saturating other areas that leads to disease. That way every part of the field can produce hay at the optimum rate. The usual measure of field uniformity is the "distribution uniformity":

DU (%) = 100 * "low quarter infiltration" / average whole field infiltration

Figure 5 illustrates how this plays out in your crop rootzone for a field DU of about 80% with some deficit irrigation on the end. To insure that no more than about 12% of the field gets less than full ET, you divide the expected ET of the crop by the field application DU. So if the alfalfa has a 50 inch requirement for ET and the field has an **80% DU** then the **applied water required = 50/0.8 = 62.5 inches.** That's an extra foot of water! If the **DU is 90%** (which is achievable with quarter mile runs, the right on-flow rate, a tail water return system and proper scheduling) then **applied water = 50/0.9 = 55.5 inches.** So you can save 7 inches of water by improving the uniformity and still adequately water the field.

We know irrigation uniformity is important to optimize water use efficiency and yield. So all I need to do is convert my field to pivot or drip to be more uniform, right? Sorry, but the data show that converting to pressure or micro is no guarantee of operational uniformity. Figure 6 shows the average and +/- one standard deviation distribution uniformity for a variety of flood, sprinkler and micro systems measured in Kern County from 1988-2005. The furrow, linear, solid set and hand-move sprinkler evaluations are mostly from field and vegetable crops. Most of the border, drip and micro-sprinkler evaluations were done in orchards, but many alfalfa fields were included in the border numbers.

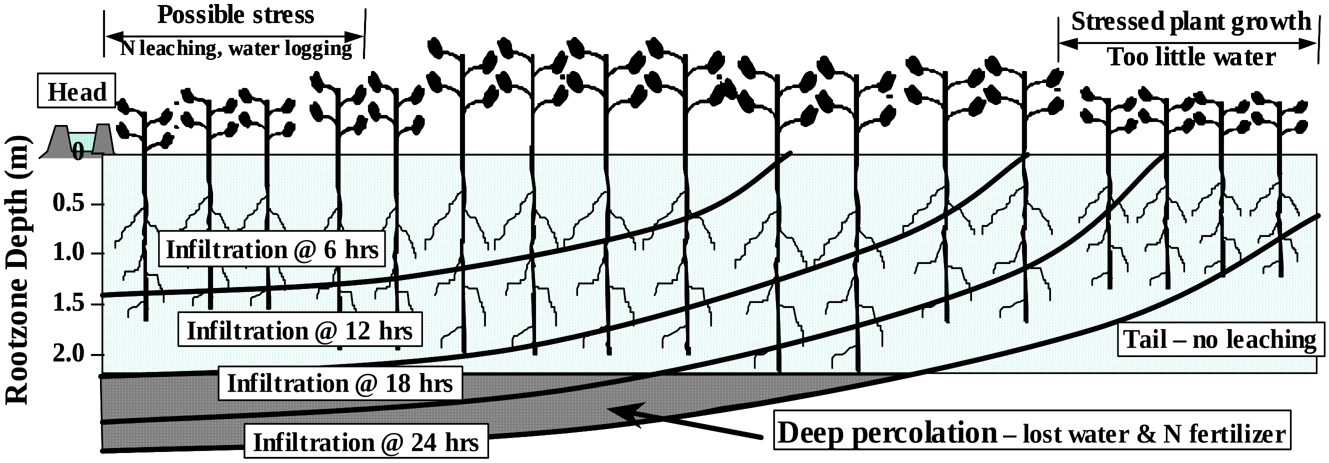
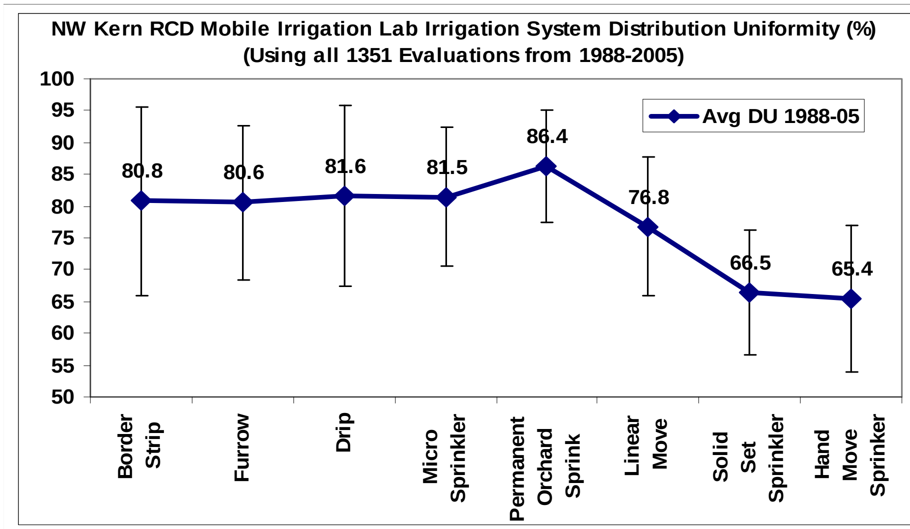


Fig. 5. Cross-section of crop rootzone during a 24 hour flood irrigation.

The range of DU's listed to the right brackets about 70% of the fields tested. Wait a minute – from flood to micro systems the average DU is almost the same – about 80%, and sprinklers are even worse! Why? These are real fields managed by real people that have a wide range of ability in fine-tuning their operation. Yes, micro irrigation and pivot systems have the best engineering potential for maximum uniformity and efficiency, but to attain these levels requires a lot more maintenance than flood.



SYSTEM	Avg DU -1 S.D.	Avg DU +1 S.D.
Border Strip	66	96
Furrow	68	93
Drip	67	96
Micro Sprinkler	71	92
Orchard Sprinkler	78	95
Solid-set Sprinkler	57	76
Hand-move Sprinker	54	77
Linear Move	66	88
**Side Roll*	*60*	*85*
**Center Pivot*	*75*	*95*
**Sub-surface Drip*	*75*	*95*

Fig. 6. Average and +/- 1 standard deviation field distribution uniformity for 1351 various irrigation systems in Kern County from 1988-2005. (*These systems not evaluated. Low/High effiiciency numbers from Howell, 2003)

So how does this play out in a production field? Figure 7 is a hypothetical alfalfa field that can yield 12 ton for the areas in the field where the irrigation schedule is just right. But this field does not drain well and where there is too much water you lose stand and yield to scald and phytophthora (the blocked end of the border and some of the head end in this case). Obviously, where the infiltration is too little (about 900 to 1150 feet from the head) the tonnage also decreases. Table 4 gives three yield scenarios using a theoretical production function (Fig. 7) for a potentially high producing field in Kern County for a 70, 80 or 90% DU and the field average applied water for the season is 42, 48, 54 or 60 inches. Remember that a 55 inch water application is about right for a 50 inch ET requirement and a field with 90% DU.

		Average Field Irrig (in)				Qtr Yield by Avg Depth (t/ac)			
	Field Qtr	**42**	**48**	**54**	**60**	**42**	**48**	**54**	**60**
70% DU	Wettest	55	62	70	78	11.2	10.0	6.8	1.5
	Wet	46	53	59	66	10.1	11.1	10.7	8.8
	Drier	38	43	49	54	6.6	9.1	10.6	11.2
	Dry	29	34	38	42	0.7	3.9	6.6	8.6
	Field Average Yield (t/ac):					**7.1**	**8.5**	**8.7**	**7.5**
		Average Field Irrig (in)							
		42	**48**	**54**	**60**	**42**	**48**	**54**	**60**
80% DU	Wettest	50	58	65	72	10.9	11.0	9.2	5.7
	Wet	45	51	58	64	9.7	11.0	11.0	9.5
	Drier	39	45	50	56	7.3	9.7	10.9	11.1
	Dry	34	38	43	48	3.9	6.9	9.1	10.5
	Field Average Yield (t/ac):					**7.9**	**9.6**	**10.0**	**9.2**
		Average Field Irrig (in)							
		42	**48**	**54**	**60**	**42**	**48**	**54**	**60**
90% DU	Wettest	46	53	59	66	10.1	11.1	10.7	8.8
	Wet	43	50	56	62	9.2	10.8	11.1	10.1
	Drier	41	46	52	58	8.0	10.1	11.1	10.9
	Dry	38	43	49	54	6.6	9.1	10.6	11.2
	Field Average Yield (t/ac):					**8.5**	**10.3**	**10.9**	**10.2**

Table 4. Average seasonal applied water on the wettest to driest areas of an alfalfa field and the resulting yield for those areas for for various irrigation amounts and DU.

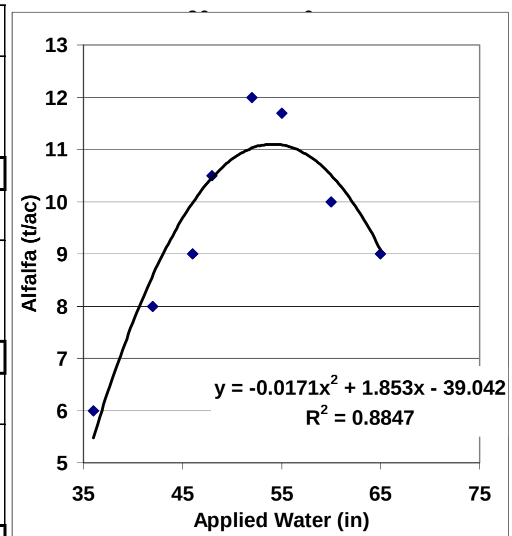


Fig. 7. Alfalfa production function for field sensitive to waterlogging.

Timing border irrigation cutoff: Figures 3 and 4 above do show one generally true fact for most surface irrigation – it's usually easier to get better DU on a finer textured soil than a sandy soil. But as shown in Figure 4 even checks in the same field with almost the same infiltration curves can drop from a 90% DU to a 72% DU if the volume of on-flow and cutoff timing is not adjusted right. As a general rule of thumb, you need to have the "on-time" at the tail quarter end of the field be 2/3 to ¾ as long as the "on-time" at the head quarter to get close to a 90% DU. For example: you have a 1200 foot long check, you run 12 hours of water into the check then cut it off when the water reaches about 900 feet. You want to have just the right field slope and volume of water stored in the border so there is enough water to reach the end of the check and continue to slowly flow to the end and infiltrate for at least another 8 to 10 hours.

Of course this is almost impossible to do without drowning out or drying out the end of the field. Running some extra water to insure sufficient tail end "on-time" and using a tail-water return system to capture this water to recycle it to the field always produces the highest uniformity and total water use efficiency for flood irrigation. Improving the DU to 90% with tail water return and higher on-flows to reduce infiltration and water-logging at the head and tail you bump our example whole field yield up to 10.9 t/ac with 54 inches of water! This gets you more yield than just adding 6 inches and staying at 70 or 75% uniformity. **Bottom line: improving irrigation DU pays.**

<u>PRACTICE 4 – Check your soil moisture on a real-time basis:</u> *Uncertainty, consultants, technology*

Does it "pay" to check the water status of your crop and soil? Hopefully, the above discussion has convinced you that there is no single perfect irrigation schedule for any given flood alfalfa field. Optimal irrigation and yield require checking infiltration after an irrigation and how quickly the crop extracts the moisture. But unlike insect and disease problems, a little too much water or even deficit irrigation almost never causes a crop failure in alfalfa. Growers know good irrigation scheduling helps, but it's usually not a "make or break" decision and the hay keeps growing. By the end of the season, however, it is usually the difference between having made 10 t/ac or just 8 t/ac.

So you decide, "I want to monitor but where should I check in the field? The infiltration is bad on this side. What about the head versus the tail end? What about weather changes and salinity? What should I check it with? How often do I need to check? Should I be checking both the plant and the soil?"

At the bottom line, the question is a business and logistics decision: "Look, a consultant and/or some equipment to do all this is going to cost me $10 to $25/acre and a bunch of hours over the season to review all the numbers. Besides, I've only got two wells, two irrigators and 10 fields to get across. I have to give the water district my order a week in advance and take the water for 24 hours. We have to crank up a set schedule and keep it going or we won't get across the ranch in time. So can technology really make it practical and economical for me to monitor soil and/or plant water status?"

Soil moisture sensing technology: For more than a half century, a great deal of work has gone into the development of soil moisture monitoring technologies. Much of this work has been done through bench top testing and field calibration in small plots and lysimeters. These are important activities for developing new technology (and generating scientific papers), but the application and reliability of these technologies is often proven out over decades in the field. Comparisons of heat dissipation blocks, gypsum blocks and tensiometers go back more than 70 years (Cummins and Chandler, 1940). Evaluation of the neutron probe was the hot topic of the 1960's (Van Bavel et al., 1961). Some of the common generalities used for this old standard (i.e. probable error ~ 0.1 inch per reading over a 6 inch depth of soil (Stone, 1960)) still stand today.

With the advent of the silicon revolution and desktop computers, microchips have created an exponential increase in the number of devices for monitoring and recording soil moisture changes. This now makes the sophisticated signal tracking needed for TDR and FDR (Time and Frequency Domain Reflectometry) processing possible in small package equipment. Capacitance changes of soil media due to changing water content have been long documented, but only in the last twenty years have the size and expense of these types of sensors become feasible, not cheap – *feasible,* for field use. Papers on the calibration and comparison of these devices were common in the late 1990's (Paltineanu and Starr, 1997).

Growers have been inundated with the presence and promise of high tech offerings for the ag industry; from commodity trading on the internet to GPS driven tractor guidance systems and soil sampling. Whether you want real-time cotton prices, satellite imagery of your operation or web-based access of cell phone up linked weather and/or soil moisture data from automated sensors installed in your field there are lots of vendors to sell you product. An internet search of "soil moisture sensor" returned more than 50,000 references in 2003. At the end of 2012 you now find 423,000 hits. Table 5 describes the different types of equipment out there for checking soil moisture and gives an approximate cost range.

Table 5. Comparison of different soil moisture measurement technologies.

DEVICE	MODE OF OPERATION	ADVANTAGES	COST
Steel rod depth probe	3/8" x 4 to 5 ' rod with handle and "acorn shape" tip is pushed into soil following irrigation to determine depth of wetting.	CHEAP!! Most rapid probe technique to find depth of penetration to 4'.	$2-4 (you make)
Open faced push probe	3' commercial probe with ~ 7/8" bit and 12" open half pipe for retrieving soil sample as deep as 3'. Models available for hand push, foot-jack assist or slide hammer. "Hand-feel" moisture.	Quickest method for retrieving a soil sample to a 3' depth. See profile, hand feel moisture estimate or oven dry sample.	$150-400
Auger	Bucket shape with opposing teeth, screws onto extensions for desired depth. Auger is twisted into soil, cuts about a 2 to 3" depth at a time which must then be extracted and knocked out of the bit to continue cutting. "Hand-feel".	Holes from 2 to 4" in diameter can be cut to secure larger sample than above. Can probe to about 8' in 20 minutes. Easier on the back than push probe.	$100 – 250
Tensi-ometer	Water filled tube with a porous ceramic tip attached to a vacuum gauge. Tip contacts surrounding soil; measures soil moisture 'tension' (matric potential). Monitors one site all season.	Easy install up to a 4' depth, no holes to dig the rest of season. Good for veg crops and most trees and vines. Stress thresholds known.	$60
Re-sistance Block	Often called a gypsum block or Watermark®. Uses changes in electrical resistance to estimate changes in soil moisture. Requires special meter to read. Intimate contact with soil essential. Readings often related to soil moisture tension. Can be a problem on course or cracking soils.	No maintenance required after install. Produces electrical signal so can be hooked up to a data logger for frequent monitoring. Data loggers run from $250 to 1,000. Hand held meter for spot reading $100 – 200.	$12 –49 Sensor $1400 system
Neu-tron Probe	2 to 2.5" hole is augured into monitoring site. PVC or aluminum pipe is installed. Radioactive source lowered into access tube, scatters neutrons into soil profile. 'Slowed' neutrons are counted by a detector and are directly proportional to soil water content. (Radiation License required.)	Largest sampling volume of all probes (basketball size). Usually most accurate, yielding quantitative water content when calibrated to site. Probe to any depth. Can do hundreds of sites with one probe. Cost of PVC tube very small to measure multiple depths/site.	$2 PVC tube. $6,000 probe
Capaci-tance Probes	The "dielectric constant" of soil changes mostly in response to changing water content. These probes, from a buried sensor or strip to probes inserted in access tubes, measure the frequency change of a radio signal and use this to estimate actual water content or a relative 0 to 100 reading. Very small sampling volume.	Most can be installed once and then checked over the season without additional digging. Some can be sensitive to very small changes in water content. Requires hand-held meter or, most often, a data logger to read.	$60 (single sensor) to $13,000 system
Time Domain Reflec-tometry	TDR uses the time delay of a reflected voltage pulse between two electrodes to measure the "dielectric constant" of the soil. Uses either buried sensors or access tubes.	Bigger sample volume than capacitance but electronics and power requirements more. Requires hand-held meter or, most often, a data logger to read.	$150 (sensor) to $15,000 system

Many orchard, vineyard and vegetable growers have tried using tensiometers. The appeal is that the device is simple to install/maintain and the principal of operation easy to understand. For about $150 you can install two of them at one location to give you an estimate of soil moisture "tension" at the 18 and 36 inch depths. Those who are convinced that this effort increased their profits usually continue using the device, but even many of them get busy in the middle of the season and do not maintain a sufficient internal water level and/or lose track of the record of readings. A small minority of growers (mostly wine grape growers and some orchards) know that they don't have the inclination or expertise to mess with monitoring and they will hire an irrigation consulting service for $15 to $25/acre (San Joaquin Valley). A neutron probe monitoring service is about $800/site. Some devices, like liquid filled tensiometers, pose a problem for monitoring in alfalfa because the top of the instrument must stick out of the soil and will be damaged when cutting.

The most common sensor now used in alfalfa is a “granular matrix” modified electrical resistance block made by Irrometer called the Watermark®. It is a relatively inexpensive and “maintenance free” alternative to the tensiometer. At about $30 each, these sensors are currently the least expensive on the market. Recognizing the potential acceptance and value of these simpler devices some university ag extensionists have continued to examine the accuracy of the tensiometer and Watermark® blocks and compare them to some of the high tech sensors in publications more accessible to growers (Hanson, et al., 2000). These devices can be buried in the field and you can run a connecting wire out of the field to a logger fixed to a standpipe or other protective structure.

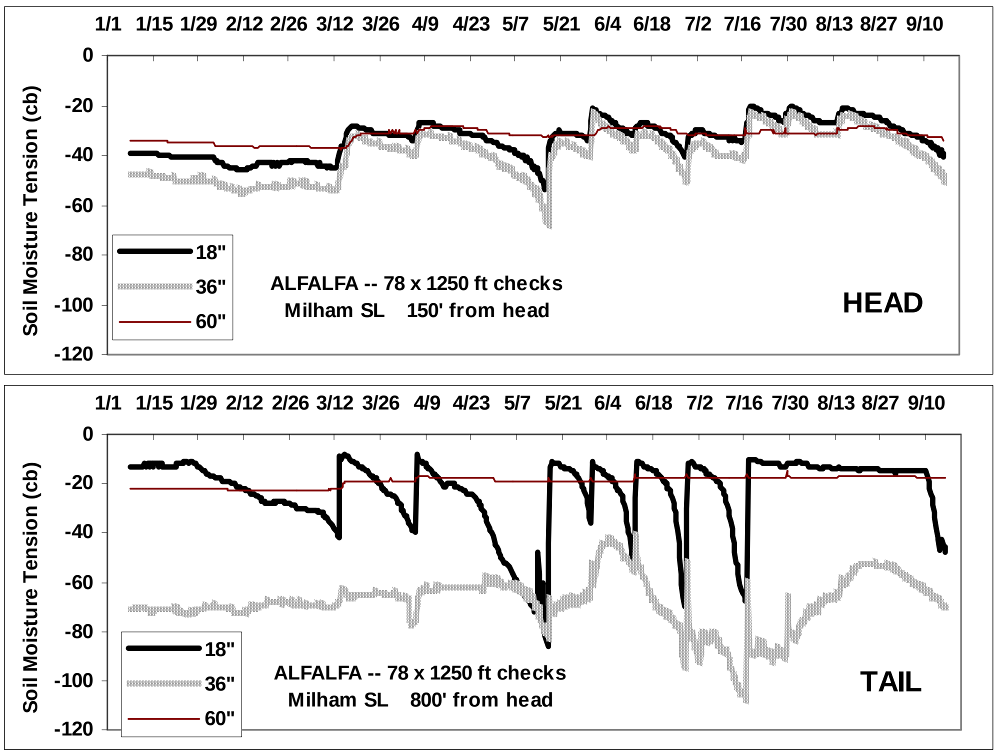


Fig. 8. Soil moisture tension changes for 2003 in a border strip irrigated alfalfa field in Kern County. Irrigated twice per cutting starting in May.

The advantage of a device that connects to a logger to supply continuously recorded readings is that you can actually see if you are over irrigating and pushing water out of the bottom of the rootzone or under irrigating with insufficient recharge. Figure 8 shows very little change in soil moisture tension at the head end of this alfalfa field in Kern County and insufficient recharge to 36 inches for the tail 1/3 of the field. The plants appear to not extract any moisture from the 5 foot depth where the soil moisture tension is only -20 cb. The grower did not use these readings to schedule irrigation as he had a set rotation to manage all his fields. This field yielded 7.5 ton in 6 cuttings and was terminated early in preparation for planting almonds.

Figure 9 illustrates soil moisture changes for a 155 acre alfalfa field on slightly rolling ground in western Kern County in the Belridge Water Storage District and some of the problems that can occur when using this technology. This field is irrigated once per cutting with big gun sprinklers moved down laterals spaced at 135 by 150 feet, applying 7.4 inches of water per 24 hour irrigation. The first thing the reader will notice is the big gap in July and August when the logger was knocked down and the wires cut by the harvester. In the lower chart are lots of horizontal lines that show intermittent bad connections between the sensor and the logger. This problem happened about 15% of the time in other fields until we started soldering connections between cables and sensors in the field.

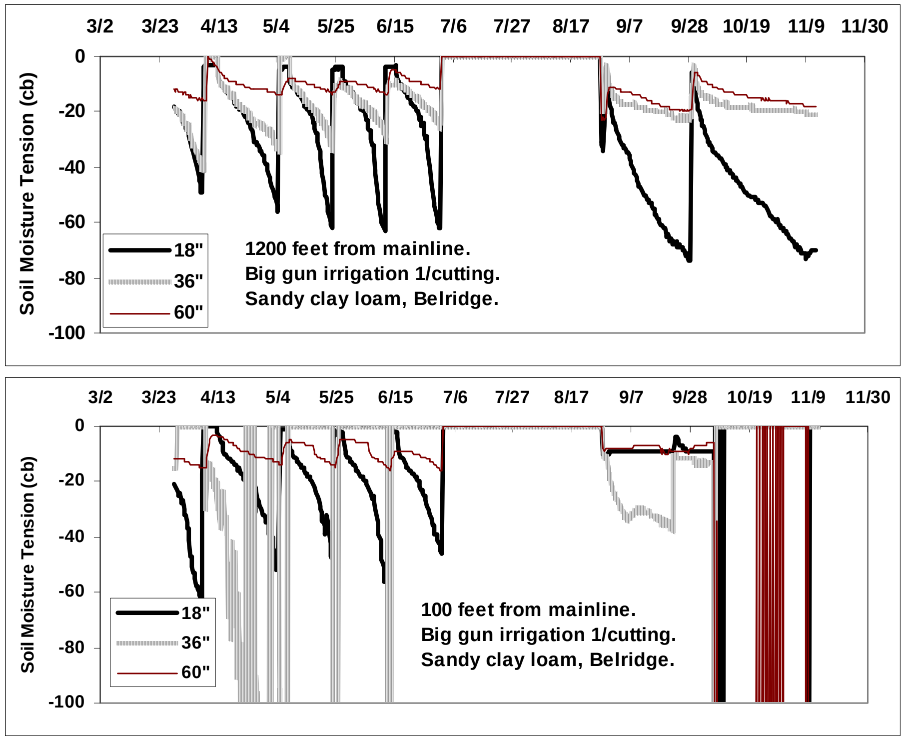


Fig. 9. Soil moisture tension changes for 2002 in an alfalfa field in western Kern County irrigated one time per cutting (7.3 inches over 24 hours) with big gun sprinklers

For both the end of the lateral (top chart) and near the mainline (bottom chart) the sensors show recharge down to 60 inches for every irrigation, with tensions usually going between 0 to -10 cb. This definitely resulted in some deep percolation for the spring irrigation period, but is about the perfect application rate for the summer. The grower applied 55 inches for the season and harvested 9 tons/acre of horse hay. Can he change his irrigation schedule given cutting requirements? No! Is he losing yield by getting too dry between irrigations? No, -60 to -70 cb at the 18" depth with ample moisture storage below will not reduce ET. Can he reduce some of the hours run time in the spring – maybe. Would it pay him to save 4 inches? Water in Belridge is $90 to $300/ac-ft depending on the year's allocation. You do the math.

Finally, Figure 10 shows a hayfield that is deficit irrigated from mid-August to the end of the year – receiving only one irrigation in September. Soil moisture tension in this chart is pictured as a positive number and with values exceeding 80 cb tension it is likely that alfalfa ET was reduced in September. This was actually a planned strategy to get the hay harvested before the on-set of fall frosts and rain.

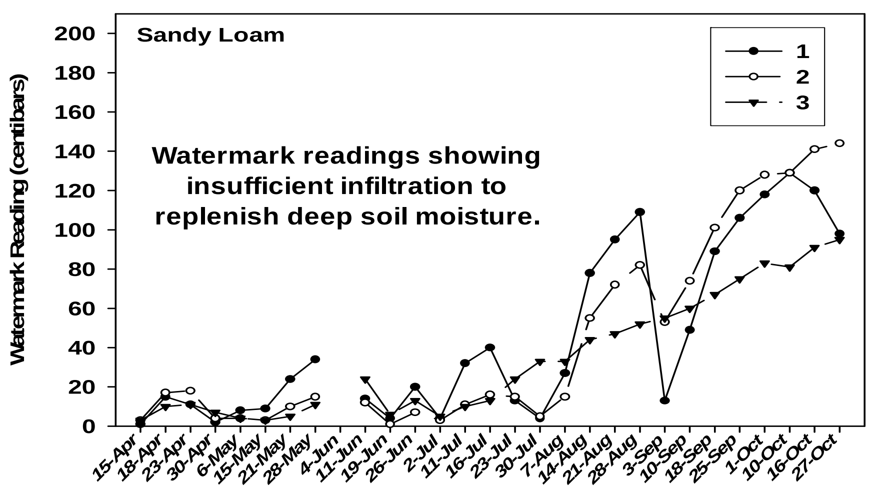


Fig. 10. Soil moisture tension changes for alfalfa irrigated by side-roll sprinklers in the intermountain area.

Table 6. Recommended soil moisture tension levels as a trigger for irrigation of alfalfa.

Applied Irrigation Depth: 0.75 to 1.5"

Soil Type	**Moisture Reading (cb) 12"**	**24"**	**48"**
Sand/loamy sand	70	40	20
Sandy loam	50	30	20
Loam	45	25	20
Clay/Silt Loam	40	25	20

Applied Irrigation Depth: 2 to 4"

Soil Type	**Moisture Reading (cb) 12"**	**24"**	**48"**
Sand/loamy sand	80	50	30
Sandy loam	70	40	25
Loam	65	40	20
Clay/Silt Loam	65	30	20

Applied Irrigation Depth: 4 to 6"

Soil Type	**Moisture Reading (cb) 12"**	**24"**	**48"**
Sand/loamy sand	90	70	60
Sandy loam	90	60	40
Loam	80	50	30
Clay/Silt Loam	70	45	25

Note: Moisture readings in these tables are only a guide. Actual readings for irrigation scheduling will vary for each field. Adjust by watching the 48" depth reading. Too little irrigation will cause this reading to keep increasing over the season. Too much irrigation will push this reading down to 0 to 15 centibars.

Checking soil moisture for scheduling irrigations: This can be very useful in the spring and late summer when you may only need one irrigation between cuttings instead of two. In cooler Intermountain areas and for growers with severe water cutbacks, having some kind of soil moisture sensor can give you the confidence to cut back to one irrigation per cutting all season and still have sufficient moisture for decent tonnage. Table 6 provides approximate soil moisture tension guidelines for scheduling irrigations for coarse to fine soils for various depths of infiltrated water (pivots to flood). The numbers in this table are for an optimum irrigation program and maximum alfalfa ET. If you are irrigating on a deficit program you will want to go with higher numbers. Watching the 48 inch sensor is the key. If it stays wet all the time (<20) you may be irrigating excessively. Alternatively, if it slowly increases and never drops back down to 20 after an irrigation then you are drying out below.

PRACTICE 5 – Changing irrigation systems to improve efficiency and yield: ***System types, capital costs, yield***

The example in Table 4 shows that by just increasing DU/water use efficiency from 70 to 90% you can increase yield by about 2 ton/ac even before the potential advantages for fertigation and pest control offered by SDI and center pivots that you don't have with flood. Of course this tonnage benefit from increased uniformity will change from one field to the next. The advantages and disadvantages of various systems are listed below. We will not include these factors in the following analysis as they tend to be area/field specific and we have no real data on cost differences. Costs have been calculated based on a 160 acre field. The total annual costs include the annualized costs of the capital investment in the system (excluding wells and pumps) plus the annual operating costs that include the water, energy cost for distributing the water, irrigator labor, and maintenance. In the case of flood irrigation, the annual operating costs also include pulling and pushing ditches.

The goal here is to get as much water going directly to crop transpiration as possible. So anything we can do to minimize evaporation, deep percolation/water-logging, runoff and drought stress potentially channels that water to the crop and boosts production efficiency and tonnage. In principal, SDI is the system that should best optimize all these factors. It is also the system which requires the most attention to maintenance and scheduling. Specific advantages and disadvantages of the various system categories are:

Flood: Advantages – gopher control is least problematic, low to no energy cost, no filtration necessary, total infiltrated water depth varies over season, tailwater return systems improve uniformity and provide better stand quality by draining check ends. Disadvantages – land must be leveled, pushing in head ditches, water-logging ends, stress between irrigations and cuttings.

Sprinkler: Advantages – better water application control for stand germination, depth of water controlled by run time, no land leveling, no borders needed, fertigation possible. Disadvantages – more gophers, significant capital cost – highest for solid-set, high energy and labor costs.

Pivot: Advantages – rapid field coverage, usually more uniform than hand-move and side-roll which makes pesticide applications as well as fertigation possible, reasonable capital cost, lower energy cost than other sprinklers, least labor cost. Disadvantages – gophers, high instantaneous application rates, potentially higher evaporation losses, lose field corners, needs filtration.

SDI: Advantages – high frequency daily irrigation possible even when cutting, maximum crop transpiration possible, potentially superior application of P and K fertilizers, uniformity unaffected by wind. Disadvantages – sprinklers needed for establishment, salinity may be a problem, GOPHERS!! Extensive damage to system possible if not controlled, root intrusion/emitter clogging, cannot "see" water – pressure and soil moisture monitoring essential for good yields, quality filtration essential.

The detailed budget sheet on the following page presents the investment costs, amortized investment cost and annual operating costs for 8 different alfalfa irrigation systems on a per acre basis. Presented here are the high end estimates of current system costs we obtained as of Fall 2011. (Irrigation system costs courtesy of Valley Irrigation, Sacramento Valley and US Irrigation, Kern County.) Water cost is fixed at $50/ac-ft, energy costs at $15 to $60/ac-ft depending on low or high pressure and irrigation labor at $11/hr. The DU for a given system has been set at a "good" (siphon/border) to "very good" (pivot, SDI) level consistent with a grower who has decided to invest in irrigation improvements. ET is assumed to be 52 inches.

SUMMARY

PRACTICE 1 - Know the expected crop water use: ***Evapotranspiration (ET,) "potential" ETo, Crop coefficients (Kc) and average ET***

PRACTICE 2 – Know your soil moisture storage and irrigate to avoid stress/water logging: ***Soil texture, water holding capacity, infiltration***

PRACTICE 3 – Make your irrigation as uniform as possible: ***Land leveling, "distribution uniformity" (DU) and the impact on yield, timing border irrigation cutoff***

PRACTICE 4 – Check your soil moisture on a real-time basis: ***Uncertainty, consultants, technology***

PRACTICE 5 – Changing irrigation systems to improve efficiency and yield: ***System types, capital costs, yield***

Bottom line: A 2 ton/ac increase in alfalfa production is definitely possible with optimal irrigation scheduling and will pay for the increased capital cost of an SDI system, but insuring additional yield and profits beyond this level requires much greater management input then simple border flood irrigation.

COMPARISON OF IRRIGATION SYSTEM COSTS FOR ALFALFA IN THE SOUTHERN SAN JOAQUIN VALLEY

Higher System Cost

QUARTER SECTION FIELD (160 gross ac), SEASON ET @ 52 INCHES

Head ditch with siphons, 1/4 mile run, no tailwater return. District water, no energy charge.
For border, 1 alfalfa valve every 50 feet, 1/4 mile runs, 2 tail pits, 18" mainline.
Hand-move sprinkler with 45' moves, 30' pipes, 30" risers and 1/8" nozzles.
Drip with 10 mil, 0.900 tape, 1/4 mile runs, shanked in 9 to 12" below grade, 60" centers.
($/ac, Calculations appear in *italics*)

CAPITAL COSTS	Deprec (Yrs)	Head Ditch Siphon	Border (no tail return)	Border (tail return)	Hand Move Sprinkler	Solid Set Sprinkler	Side Roll Sprinkler	Center Pivot	SDI - Tape (60" beds)
	Net acres:	155	155	154	155	155	155	122	155
Land leveling & borders:	4	300	300	300	10	10	10	10	30
Reservoir / tailpit(s):	20			180					
Above ground equip:	20	250	350	585	850	2750	835	900	850
Below ground:	20		480	480			12	150	125
*Sprinkler rent 1st year:	4								230
Drip tape + R&R:	6								733
TOTAL CAPITAL COST		**$550**	**$1,130**	**$1,545**	**$860**	**$2,760**	**$857**	**$1,060**	**$1,968**
Annualized Capital Cost (+ 4.75% int):		***103.75***	***149.31***	***181.91***	***69.57***	***218.82***	***69.34***	***85.28***	***292.75***

RESOURCE COSTS					
ET:	52	inches			
Water Cost:	**50**	**$/ac-ft**			
Irrigation Labor:	11	$/hr	Pivot (40 psi):	40	$/ac-ft
Equipment Operator:	13	$/hr	Drip Energy Cost (20 psi):	25	$/ac-ft
Sprinkler Energy Cost (70 psi):	60	$/ac-ft	Tailpit Energy Cost (15 psi):	15	$/ac-ft

SYSTEM ASSUMPTIONS	Head Ditch Siphon	Border (no tail return)	Border (tail return)	Hand Move Sprinkler	Solid Set Sprinkler	Side Roll Sprinkler	Center Pivot	SDI - Tape (60" beds)
Distribution Uniformity	**78%**	**80%**	**85%**	**75%**	**82%**	**80%**	**90%**	**92%**
Extra Evaporation (inches)	**0.0**	**0.0**	**0.0**	**3.0**	**3.0**	**3.0**	**4.0**	**0.0**
Applied Water (inches)	**67**	**65**	**61**	**72**	**66**	**68**	**62**	**57**
Calculated Number of Irrigations	13	13	12	12	11	17	51	57
Days (sets)/irrigation cycle	10	10	10	12	12	10	1	2
Irrigation Labor Hrs/Irrig-Day	10	10	9	12	8	3	7	10
Layout/Remove Sprinklers				80	180			
Total Season Hours	*1333*	*1300*	*1101*	*1816*	*1243*	*510*	*360*	*1130*
Irrig Labor Hrs/acre	***8.60***	***8.39***	***7.15***	***11.72***	***8.02***	***3.29***	***2.95***	***7.29***
Inches/day (or pass)	*5.0*	*5.0*	*5.0*	*6.0*	*6.0*	*4.0*	*1.2*	*1.0*
Required Flowrate (gpm)	*2320*	*1450*	*1441*	*1450*	*1450*	*1160*	*2739*	*1450*

ANNUAL COSTS	Head Ditch Siphon	Border (no tail return)	Border (tail return)	Hand Move Sprinkler	Solid Set Sprinkler	Side Roll Sprinkler	Center Pivot	SDI - Tape (60" beds)
Water	*277.78*	*270.83*	*254.90*	*301.39*	*276.73*	*283.33*	*257.41*	*235.51*
Energy Cost			*7.65*	*361.67*	*361.67*	*332.07*	*205.93*	*128.70*
Irrigator	*94.62*	*92.26*	*78.66*	*128.88*	*88.19*	*36.19*	*32.49*	*80.22*
Equipment Operator	*9.75*							
Ditch Pulling/Pushing, Equip	12							
Maintenance	19	20	21	19	25	12	12	75
Annualized Capital Cost	*103.75*	*149.31*	*181.91*	*69.57*	*218.82*	*69.34*	*85.28*	*292.75*
TOTAL Annual Irrigation Cost	***$517***	***$532***	***$544***	***$881***	***$970***	***$733***	***$593***	***$812***
Additional tons/ac required @ $160/ton to achieve equal cost with Ditch/Siphon	***0***	***0.1***	***0.2***	***2.3***	***2.8***	***1.4***	***0.5***	***1.8***

WEB RESOURCES

Jones, D.W., R.L. Snyder, S. Eching and H. Gomez-McPherson. 1999. California Irrigation Management Information System (CIMIS) Reference Evapotranspiration. Climate zone map, Dept. of Water Resources, Sacramento, CA. http://wwwcimis.water.ca.gov/cimis/images/etomap.jpg

Excel Comparison and calculator spreadsheet for alfalfa irrigation system costs in this paper: http://cekern.ucdavis.edu/Irrigation_Management, click COMPARISON OF ALFALFA IRRIGATION

Excel spreadsheet for comparing center pivot and SDI economics and is available for free downloading at: http://www.oznet.ksu.edu/sdi/Software/SDISoftware.htm

Excellent website explaining soil moisture sensors: http://www.sowacs.com/sensors/index.html

UC cost of production budgets for alfalfa and other major CA crops: http://coststudies.ucdavis.edu/current.php

2011 field crop cost studies for Imperial Valley: http://ceimperial.ucdavis.edu

REFERENCES

Ayars, J. E., C. J. Phene, R. B. Hutmacher, K. R. Davis, R. A. Schoneman, S. S. Vail, and R. M. Mead. 1999. Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. Agric. Water Manage. 42:1-27.

Cummings, R.W., and R.F. Chandler. 1940. A field comparison of the electrothermal and gypsum block electrical resistance methods with the tensiometer method for estimating soil moisture in situ. Soil Sci. Soc. Proc. 1940:80-85.

DWR. 1993. *Crop Water Use – A Guide for Scheduling Irrigations in the Southern San Joaquin Valley. 1977-1991*. California Dept of Water Resources.

Hanson, B.R., D.Peters, and S.Orloff. 2000. Effectiveness of tensiometers and electrical resistance sensors varies with soil conditions. Calif. Ag. 54:3:47-50.

Hanson, B.R., K.M. Bali, B.L. Sanden. 2007. *Irrigated Alfalfa Production in Mediterranean and Desert Climates.* Technical manual companion to *Arid Land Alfalfa Manual.* Univ. California, Davis, Dept. Land, Air and Water Resources, UC ANR Publication to be announced. 36 pp.

Hutmacher, R.B., C.J. Phene, R.M. Mead, D. Clark, S.S. Vail, C.A. Hawk, M.S. Peters, R. Swain, T. Donovan, J. Jobes And J. Fargerlund. 2001. Subsurface Drip And Furrow Irrigation Comparison With Alfalfa In The Imperial Valley. Proceedings 31st California Alfalfa & Forage Symposium, 12-13 December, 2001, Modsto, CA. Dept. Agron & Range Sci., Univ of California, Davis 85616. http://alfalfa.ucdavis.edu

Lamm, F. R., D. H. Rogers, M. Alam, D. M. O'Brien, and T. P. Trooien. 2009. Twenty years of progress with SDI in Kansas. ASABE paper no. 095923. Available from ASABE, St. Joseph, MI. 23 pp.

Ludwick, A.E. 2000. High Yield Alfalfa 24 tons Irrigated...12 tons Non-Irrigated. Better Crops Vol. 84 No. 1. pp.18-19

Paltineanu, I.C., and J.L.Starr. 1997. Real-time soil water dynamics using multisensor capacitance probes: laboratory calibration. Soil Sci. Soc. of Am. J. 61:1576-1585.

Sammis T. 1981. Yield of alfalfa and cotton as influenced by irrigation. Agronomy Journal, Vol.73:323-329.

Van Bavel, G.H.M, D.R. Neilsen and J.M. Richards. 1961. Calibration and characteristics of two neutron moisture probes. Soil Sci. Soc. of Am. Proc. 25:5:329-334.