Presentation of James R. Brownell, Ph. D[1].

The Vernalis Agricultural Water Quality Objective is based on the quality of water sufficient to maintain a 100% yield of agriculture crops irrigated with water diverted from the San Joaquin River in the Southern Delta. The major crops, at the time that the objectives were set, were alfalfa, dry beans and corn. The crop tolerance to irrigation water salinity has been published in several sources, Maas and Hoffman (1977), Ayers and Westcot (1985) and most recently by Grattan (2002)

Review of terms:

Salinity refers to the total dissolved ionic solids in water.

Salinity has been reported in a number of units:

Total Dissolved Solids (tds) as either parts per thousand (ppt), parts per million (ppm) or milligrams per kilogram (mg/Kg), ppm and mg/Kg are numerically equal.

Electrical Conductivity (EC). Since salts are charged particles their concentration can be estimated by the electrical conductivity of the solution. Earlier salinity measurements were reported as millemhos per centimeter (mmhos/cm), with the International Standardization of Nomenclature (ISN) the EC values are now reported as deciSiemens per meter (dS/m), units selected to be numerically equal to the earlier mmhos/cm. Total dissolved solids (tds) are estimated from EC in dS/m by; EC_w X 700 = total dissolved solids, in ppm or mg/Kg.

EC values are often subscripted to indicate the source of the water evaluated:

EC_w is the electrical conductivity of a water source; EC_{iw} as an example, for irrigation water.

EC_e is the electrical conductivity of the saturation extract of a soil.

Review of Field Work

San Joaquin River salinity objectives were based on the salinity model and studies presented by Ayers and Westcot, based on earlier work at the USDA Salinity Laboratory in Riverside California, Maas and Hoffman (1977). This work on establishing crop salinity relationships was done in large pots, under controlled conditions and did not take into consideration leaching that occurs with natural rainfall. Early salinity work resulted in a salinity threshold for irrigation water (EC_{iw}) of 1.3 dS/m for alfalfa, 0.7 dS/m for beans and 1.1 dS/m for corn. The threshold is the maximum salinity that will maintain 100% yield potential. Scientifically there is uncertainty in any value resulting from experimentation and it is now known these salinity objectives are too conservative. The 100% yield potential, itself, is suspect, since plant nutritionists have observed that given

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variability of field conditions, due to factors such as weather, seeds, and all the other factors that can affect yield, a 10% yield loss, absent specific plant symptoms, cannot be observed (Uhlrich, 1959 and Epstein, 2004).

A number of field experiments on the impact of irrigation water salinity on corn production in the South Delta, reported by Hoffman, et al (1983), found that an EC_{iw} of 1.3 dS/m was sufficient to maintain maximum yield potential.

Plant – Soil – Water Relationships

The conductivity of irrigation water ($EC_{iw)}$ is an easily measured value and can be used to compare the impact of different irrigation water supplies on crop production. However, the crop actually responds to the average salinity of the soil water, often measured as the salinity of the saturated extract (EC_e) in the crop root zone. The average EC_e can be estimated from the EC_{iw} using the following assumptions:

1. Water is extracted from the root zone in a 40-30-20-10 % pattern from succeeding quarters of the root zone, that is 40 % of the water used by the plant is extracted from the top fourth of its active root zone, 30 % from the second, etc.
2. Soil salinity can be predicted from water salinity (EC_e = 1.5 EC_{iw}), with an EC_{iw} of 0.7 dS/m EC_{iw} than a crop threshold of 1.1 EC_e is predicted.
3. 50 % of the soil water is utilized between irrigations, typical of furrow or sprinkler irrigation scheduling.
4. The irrigation water is the only source of salinity, i.e. no major additions of soil amendments.
5. There is no significant rainfall.

Tables 1 through 5 contain examples showing the predicted EC_e resulting from different irrigation scenarios, assigned by quarters of the active root zone. These tables show the predicted salinity of the soil water (EC_e in dS/m) available to the crop roots just prior to the next crop irrigation. In Tables 1-5, the column labeled “Event” shows the irrigation event, the column labeled “Effective rooting depth” shows the effective crop rooting depth in inches at the time of the irrigation event, the column labeled ”Depth” shows the depth of applied water in inches, the column labeled “Total water” shows the accumulated water applied in inches, the column labeled “EC_w weighted ave.” shows the weighted average irrigation water salinity, based on the plant absorbing 40% of its water from the top quarter of the root zone, 30% from the second quarter of the root zone, 20% from the third quarter of the root zone, and 10% from the bottom quarter of the root zone, the column labeled “Leaching” shows the leaching percentage that is assumed to take place during that water application, the column labeled “Total irrigation water” shows the accumulated irrigation water application in inches, and the column labeled “Cumulative leaching” shows the cumulative leaching percentage for the applied water and crop water use. Finally, the columns labeled “1^{st}”, “2^{nd}”, “3^{rd}”, “4^{th}” and “Average”, represent the quarter segments of the active crop root zone at the end of that irrigation application and the predicted soil salinity (EC_e) in dS/m that the crop roots experience just prior to the next irrigation. Each quarter, or thickness, of the active root zone, at the time of the first crop irrigation, is one fourth of twelve inches or three inches. During the winter ”Rain” and ”Pre-irrigation” events, the plant has yet to grow roots and there is no active root zone. As the crop matures the root zone expands to 36 inches and each quarter of the active crop root zone is then nine inches.

The leaching percentages change over time (see columns labeled “Leaching”). A normal winter rain fills the soil profile to the three foot depth with about twice as much rain occurring than is needed to rewet the soil profile based on an average annual rainfall of 12 inches. The pre-irrigation is assumed to refill the soil profile to the extent the soil has dried from evaporation or from the use of soil water by non-crop plants. Irrigation efficiencies improve over the irrigation season as the crop uses more of the soil water between irrigations. Assumed water applications are conservative for a well designed and operated furrow irrigation system. The cumulative leaching percentage (see columns labeled “Cumulative leaching”) is a simple average of all leaching that has occurred to date.

Table 1 shows the soil salinity levels for a three foot root zone using irrigation water with an EC_w of 0.7 dS/m and no rainfall. The predicted soil salinity (EC_e) indicates the condition produced by this widely accepted model for estimating 100 % yield potential. This provides a baseline for comparison of irrigation water quality and quantity. In this estimation, irrigation water application was at the 22-inch annual bean water requirement with a 15% leaching factor and irrigation water salinity of 0.7 dS/m. of irrigated crops. The Ayers & Westcot model results in an average EC_e of 2.6 dS/m in the root zone at harvest. The average EC_e 2.6 dS/m is that estimated for 100% yield of beans by Ayers and Westcot with a 15 % leaching factor and no rainfall.

Table 1. Ayers & Westcot model without rainfall and irrigation water salinity (EC_w) of 0.7 dS/m

								EC_e predicted (dS/m) by quarters of the root				
Event	Effective rooting depth (in.)	Depth (in)	Total water (in.)	**EC_w weighted ave. (dS/m)**	Leaching (%)	Total irrigation water (in.)	Cumulative leaching (%)	1st	2nd	3rd	4th	**Ave.**
Irrigation water only		NA	22	**0.7**	15	22	15	1.1	1.7	3.0	4.7	**2.6**

Table 2 adds 12 inches of rainfall with the 0.7 dS/m irrigation water. The predicted soil salinity (EC_e) indicates the results likely to be produced with normal field conditions and reasonable irrigation practices. With no crop roots, water is lost only by evaporation until the first crop irrigation. Therefore soil salinities are uniform through out the soil profile. Considering an annual rainfall of 12 inches and the interaction of rain and irrigation water in the soil profile, crop-rooting depth, crop water use and leaching fractions shown in Table 2, the average salinity is much lower than the Ayers and Westcot model without rainfall (see Table 1).

Table 2. Ayers & Westcot model with a 22-inch water application, 12 inches of rainfall, and irrigation water salinity (EC_w) of 0.7 dS/m

								EC_e predicted (dS/m) by quarters of the root				
Event	Effective rooting depth (in.)	Depth (in.)	Total water (in.)	**EC_w weighted ave. (dS/m)**	Leaching (%)	Total irrigation water (in.)	Cumulative leaching (%)	1st	2nd	3rd	4th	**Ave.**
Rain	0	12	12	**0.09**	50	0	NA	0.1	0.1	0.1	0.1	**0.1**
Pre-irrigation	0	6	18	**0.29**	40	6	45	0.4	0.5	0.5	0.5	**0.5**
Crop irrigation 1	12	4	22	**0.37**	40	10	43	0.5	0.6	0.8	0.9	**0.7**
Crop irrigation 2	24	4	26	**0.42**	20	14	33	0.6	0.8	1.1	1.3	**0.9**
Crop irrigation 3	36	4	30	**0.46**	10	18	28	0.6	0.9	1.3	1.6	**1.1**
Crop irrigation 4	36	4	34	**0.48**	10	22	24	0.7	1.0	1.5	2.0	**1.3**

Table 3 presents the prediction of the Ayers and Westcot model, with a 22 inch water application, 12 inches of rainfall, and irrigation water of salinity 1.1 dS/m. The predicted soil salinity (EC_e) indicates the results likely to be produced with normal field conditions and reasonable irrigation practices with water of a higher EC than the current objective. At the end of the growing season the average EC_e is less than that predicted by the Ayers and Westcot model that does not include rainfall (see Table 1), and well within the salinity tolerance of beans for 100% crop yield.

Table 3. Ayers & Westcot model with a 22-inch water application, 12 inches of rainfall, and irrigation water salinity (EC_w) of 1.1 dS/m

								EC_e predicted (dS/m) by quarters of the root				
Event	Effective rooting depth (in.)	Depth (in.)	Total water (in.)	**EC_w weighted ave. (dS/m)**	Leaching (%)	Total irrigation water (in.)	Cumulative leaching (%)	1st	2nd	3rd	4th	**Ave.**
Rain	0	12	12	**0.09**	50	0	NA	0.1	0.1	0.1	0.1	**0.1**
Pre-irrigation	0	6	18	**0.43**	40	6	45	0.6	0.6	0.6	0.6	**0.6**
Crop irrigation 1	12	4	22	**0.55**	40	10	43	0.7	0.9	1.1	1.3	**1.0**
Crop irrigation 2	24	4	26	**0.63**	20	14	33	0.9	1.2	1.6	1.9	**1.4**
Crop irrigation 3	36	4	30	**0.70**	10	18	28	1.0	1.4	2.0	2.5	**1.7**
Crop irrigation 4	36	4	34	**0.74**	10	22	26	1.1	1.6	2.3	3.1	**2.0**

Table 4 presents the prediction of the Ayers and Westcot model, with a 22 inch water application, 12 inches of rainfall, and irrigation water salinity of 1.5 dS/m. The predicted soil salinity (EC_e) indicates the condition likely to be produced in this area with real field conditions, and careful irrigation with more saline water than the current objective. At the end of the growing season the average ECe is about the same as that predicted by the original model that does not include rainfall.

Table 4. Ayers & Westcot model with a 22-inch water application, 12 inches of rainfall, and irrigation water salinity (EC_w) of 1.5 dS/m

								EC_e predicted (dS/m) by quarters of the root				
Event	Effective rooting depth (in.)	Depth (in.)	Total water (in.)	**EC_w weighted ave. (dS/m)**	Leaching (%)	Total irrigation water (in.)	Cumulative leaching (%)	1st	2nd	3rd	4th	**Ave.**
Rain	0	12	12	**0.09**	50	0	NA	0.1	0.1	0.1	0.1	**0.1**
Pre-irrigation	0	6	18	**0.56**	40	6	45	0.7	0.7	0.7	0.7	**0.7**
Crop irrigation 1	12	4	22	**0.73**	40	10	43	0.9	1.2	1.5	1.7	**1.3**
Crop irrigation 2	24	4	26	**0.85**	20	14	33	1.2	1.6	2.1	2.6	**1.9**
Crop irrigation 3	36	4	30	**0.94**	10	18	28	1.3	1.9	2.7	3.4	**2.3**
Crop irrigation 4	36	4	34	**1.00**	10	22	27	1.4	2.0	2.9	3.7	**2.5**

Table 5 presents the prediction of the Ayers and Westcot model, with a 40-inch water application, no rainfall, and an irrigation water salinity of 1.1 dS/m. The predicted soil salinity (EC_e) indicates the condition likely to be produced in this area with the irrigation practice reported by Banta Carbona Irrigation District, with irrigation water that has the higher salinity objective recommended in this presentation. With the addition of rainfall the actual soil salinities would be expected to be less than 1.0 trough-out the profile.

Table 5. Ayers & Westcot model a 40-inch water application, no rainfall, and an irrigation water salinity (EC_w) of 1.1 dS/m.

								EC_e predicted (dS/m) by quarters of the root				
Event	Effective rooting depth (in.)	Depth (in.)	Total water (in.)	**EC_w weighted ave. (dS/m)**	Leaching (%)	Total irrigation water (in.)	Cumulative leaching (%)	1st	2nd	3rd	4th	**Ave.**
Irrigation water only		NA	40	**1.1**	74	22	15	1.2	1.3	1.4	1.5	**1.4**

In Tables 1 through 5, the lowest soil salinity occurs at the time of crop establishment, when the crop is most sensitive to salinity.

The 22-inch irrigation requirement was the amount estimated by the UC Extension (1999) for dry bean production. A calculated evapotranspiration requirement from CIMIS data for Tracy, 23 inches for dry bean production, generally agrees with this UC estimate. The water application reported by Banta Carbona Irrigation District of about 40 inches in 2004 would produce leaching percentages of nearly 75% and salinity throughout the profile of less than 1.0 dS/m without accounting for rainfall. Using this model with the assumptions listed, EC_{iw} for rain water at 0.09 dS/m, estimated leaching percentages, and allowing for the impact of rainwater, I have estimated that the use of irrigation water with an EC_{iw} of 1.5 dS/m would produce the same results in the soil profile at harvest as the Ayers and Westcot model predicts with no allowance for rainfall.

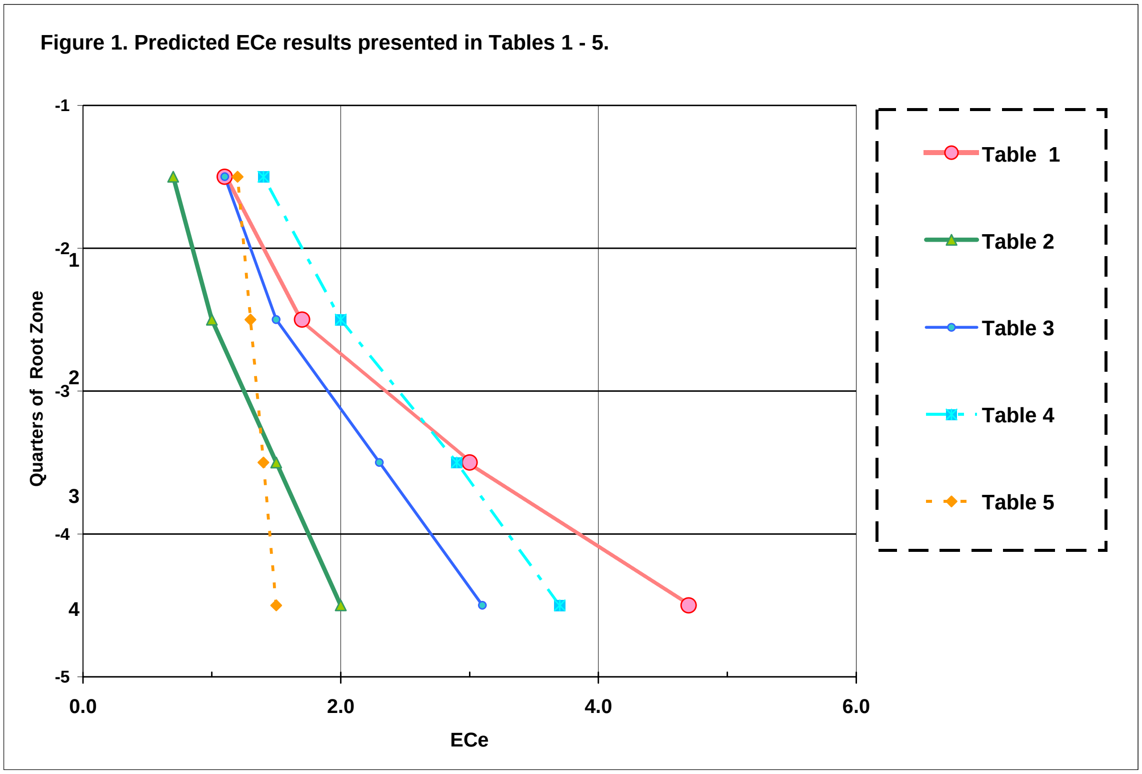


Figure 1 compares the predicted EC_e for the results presented in Tables 1 through 5 after the final crop irrigation. The differences in predicted salinity levels represented by the different lines on Figure 1 represent different soil salinity levels resulting from the application of different amounts and qualities of irrigation water, with and without rainfall. In Table 1, which depicts the conditions Ayers and Westcot demonstrated are sufficient for a 100% yield of beans, the bottom half of the root zone exceeds 2.6 dS/m, and even get as high as 4.7 in the bottom quarter of the root zone. In Table 2, the EC_e reaches 2.0 dS/m in the bottom quarter of the root zone. In Table 3, EC_e reaches 3.1 dS/m in the bottom quarter of the root zone. It should be noted that, in all cases the exceedance of 2.6 dS/m occurs after either the third or forth irrigation, which should have no impact on crop yield. In both Tables 2 and 3, the salinity level throughout the root zone is lower than that in Table 1. Therefore, the scenarios in Tables 2 and 3 would have little or no impact on crop yield. In Table 4, the bottom half of the root zone exceeds 2.6 dS/m, but since the overall average salinity is still lower than that depicted in Table 1, there would still probably be little or no impact on crop yield.

Rainfall in San Joaquin County normally occurs in the winter months of December through February and annually averages 10 to 17 inches (10 inches at Tracy Carbona and 12 inches at the Tracy Pumping Plant weather stations) (Western Regional Weather Center). Table 2 shows that, considering a 12-inch rainfall with the 22-inch irrigation application the average EC_e would be expected to be only 1.3 dS/m with an overall leaching percentage of 24%.

The 6-inch pre-irrigation is based on water being applied to recently prepared land. The relatively high leaching percentage of the pre-irrigation results from the limited soil drying after the rainy season, and since no crop roots were present, only evaporative loss occurred. The 6-inch water application would then result in half of the applied water leaching through the soil profile. Pre-irrigation is required since beans have not been normally established with rain wetted fields in San Joaquin County. This is possibly due to low soil temperatures in May or early June, and by that time the soil has warmed sufficiently, it has dried enough to require pre-irrigation (Silveira, 2005). The high leaching factor for the first crop irrigation results from the shallow rooting depth and limited water extraction, to that date, and the fixed amount of water applied by irrigation is a function of the assumed application method. The effective rooting depth increases to a 36 inch maximum with time and with crop growth, as estimated from Knott's Handbook (Lorenz, and Maynard, 1980) for beans on soils of this area.

This simple addition of rainfall to the Ayers & Westcot model indicates that the 0.7 dS/m is over protective to achieve 100% yields for crops irrigated with San Joaquin River water.

Recent work

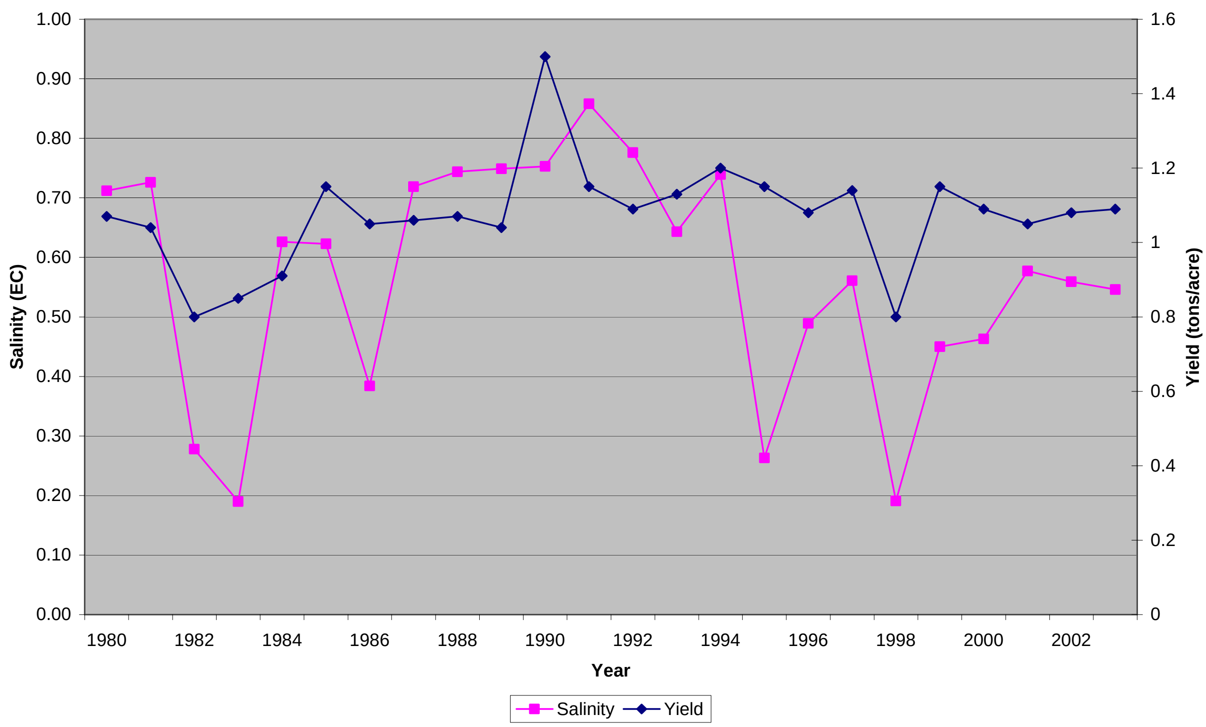
Isidoro-Ramirez, Berenguer-Merelo, and Grattan (2004) recently developed a much more sophisticated and improved model to develop a site-specific criteria for electrical conductivity of irrigation water to protect the agricultural beneficial uses for the Davis, California area. This model was developed specifically for dry bean production sustainability, since beans are the most salt sensitive crop grown in the area. The model was "developed to determine how the electrical conductivity of a given irrigation water supply affects crop production while taking annual rainfall into account." The model was based on Ayers and Westcot, with the root zone divided into four layers.

Water use by the crop to satisfy evapotranspiration demand was partitioned in the classic 40%-30%-20%-10% extraction pattern. Mass transfer of water and salt between soil layers and all water input, both rain and irrigation, was into the top layer. Movement between layers was calculated from known hydraulic conductivity properties of the soil. These values were all calculated daily. The average soil salinity (EC_e) was compared to the crop threshold value from Ayers and Westcot for 100% yield potential. They concluded that when "taking all other factors that potentially impact crop yield (e. g. climate, water stress and biotic stresses) and the conservative nature of all inputs into the model, the use of 1.1 dS/m as the threshold EC value for irrigation water is considered protective for beans, and thus for all other agricultural uses…"

San Joaquin County Dry Bean Culture

Little, if any, relationship between salinity of the San Joaquin River water, measured at Vernalis and San Joaquin County average dry bean yields is evident. Figure 2 shows San Joaquin County average dry bean yields and average crop season salinity of the San

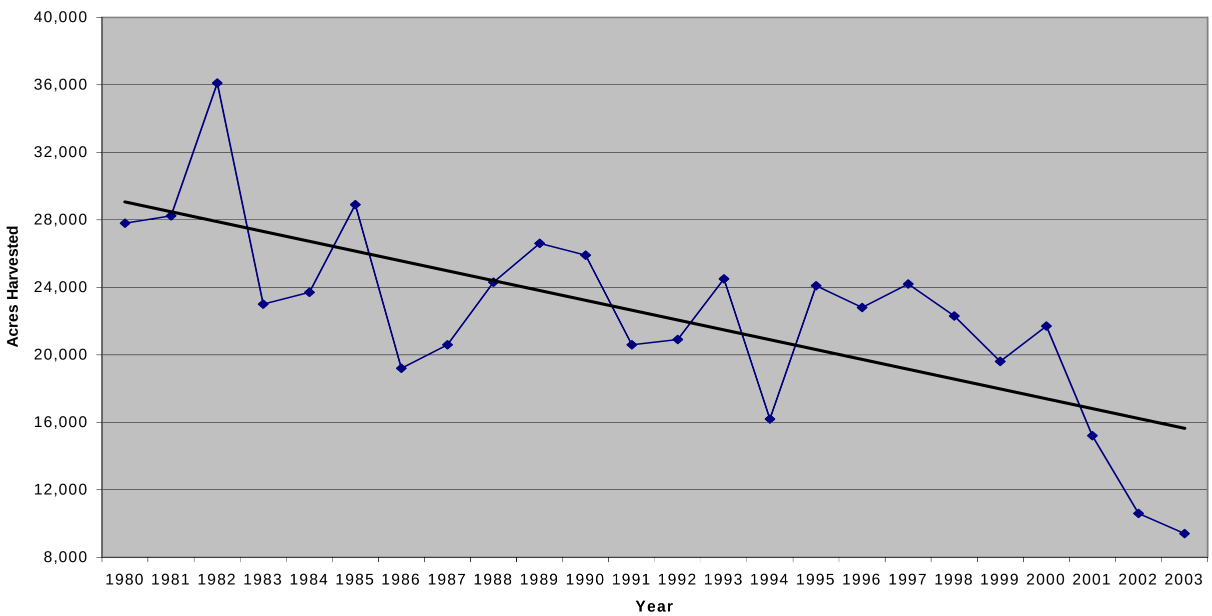
Figure 2. San Joaquin County annual average dry bean yield vs.. Crop Season Average Salinity (dS/m) at Vernalis.



Joaquin River at Vernalis. These data indicate that some other factor – the timing of rains, cold temperature at critical times, other farm management decisions such as pest control or fertilization had a greater influence of bean yields than salinity of the River annual salinity of the San Joaquin River at Vernalis. Department of Water Resources crop reports show that all beans grown in San Joaquin County are grown on mineral soil. They are not grown on the organic soils with sub-irrigation.

Figure 3 shows that, on the average, dry bean acreages have been decreasing since 1982 in San Joaquin County.

Figure 3. Acres of Beans Harvested, San Joaquin County, (1980-2003)



This decrease appears to be a result of factors other than any environmental condition, i.e. salinity or water quality.

Conclusion

The Vernalis Water Quality Objective was based on the model and studies presented by Ayers and Westcot, based on the earlier work at the USDA Salinity Laboratory in Riverside California. That work establishing crop yield - salinity relationships was done in large pots with controlled conditions and did not take into consideration leaching by natural rainfall. The climatic conditions in San Joaquin County indicate that rainfall is significant in regard to salinity management in the production of agricultural crops.

There is no agricultural reason that supports the 0.7 dS/m objective for the Vernalis Agricultural Water Quality Objective. I recommend a new standard of 1.1 dS/m based on the more recent work of Hoffman, Grattan and his co-workers, and my self.

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