IRRIGATION OF GRAPEVINES IN CALIFORNIA

Dr. Larry E. Williams
Department of Viticulture and Enology, UC-Davis
Kearney Agricultural Research and Extension Center
9240 S. Riverbend Ave., Parlier, CA
lewilliams@ucanr.edu

INTRODUCTION

The Coachella Valley has a desert climate characterized by very hot summers (maximum temperatures of 50 °C (120 °F) are not uncommon) and mild winters. Budbreak will occur in mid-January when vines are sprayed with hydrogen cyanamide (used to overcome lack of chilling temperatures or chilling units), and harvest is concluded by late May – early June. Fortunately, extremely high summer temperatures don't occur until July and August. Rainfall is usually less than 50 mm (there are 25.4 mm per inch) per year. The soils are sandy with low water and nutrient holding capacities. Rooting depth in these soils is limited because they are highly stratified. The evaporative demand (reference ET or ET_o) in the Coachella Valley from mid-January to the end of harvest can range from 650 to 800 mm (26 to 31 in). Year-long ET_o can be 2000 mm (79 in). The maximum ET_o value will approach 8.5 mm (0.33 in) per day close to harvest.

The San Joaquin Valley is a semi-arid region with hot summers (maximum temperatures approximately 44 °C (111 °F) and cool winters. Grapevines and deciduous fruit trees will generally accumulate enough chilling units each winter so as not to affect budbreak. Budbreak of grapevines will occur early to mid-March and harvest (depending upon grape type) will occur from the end of July to September. Rainfall is a function of location within the valley, more to the north and less to the south. For example, rainfall in Stockton (at the northern end of the valley) may approach 400 mm (15.5 in) per year. Rainfall in the central San Joaquin Valley (Fresno) averages 250 mm (10 in) per year while that in Bakersfield (southern end of the valley) is approximately 180 mm (7 in). The major portion of the rainfall will occur during the winter months. The majority of grapevines are grown in the eastern portion of the San Joaquin Valley where the soils are mostly sandy loams, although there are small areas that can be very sandy. Soils in the western portion of the San Joaquin Valley are heavier, clay loam type soils. The rooting depth of the eastern San Joaquin Valley can be limited by clay-pans. The soil water and nutrient holding capacities of these soils are moderate to good. There can water infiltration problems on some of the soils. Reference ET from the time of budbreak to the end of October will range from 1000 to 1250 mm (39 to 49 in) in the San Joaquin Valley. Daily maximum ET_o may approach 7 mm (0.28 in).

The coastal, wine grape production areas of California are characterized by warm days and cool nights although high temperatures (40 to 47 °C; 104 to 116 °F) may occur for a few days each growing season depending upon location. Some areas may have fog lasting late into the morning. Rainfall is greater in coastal valleys located further north and diminishes as one travels south. For example, rainfall in the Napa and Sonoma Valleys will range from 500 to 1000 mm (20 to 39 inches) per year while the Salinas Valley averages only 250 mm (10 inches) per year. Reference ET between budbreak and harvest will range from 800 to 1000 mm (31 to 39 inches) in the coastal valleys. Most of the soils in the coastal production areas are clay loam to clay type soils of good water and nutrient holding capacities. Since the majority of rainfall occurs during the dormant portion of the growing season and vineyard water use is probably greater than the soil water reservoir, supplemental irrigation of vineyards in these valleys may be required at some point during the summer months

IRRIGATION TYPES AND SOURCE OF WATER

Due to the high evaporative demand and the amount of rainfall and its timing (during the dormant portion of the growing season) irrigation of vineyards is required at most locations in the State of California. Many raisin grape vineyards are still being flood irrigated but the newer plantings are utilizing drip irrigation. Water used for irrigation is primarily obtained from wells (ground water) but a small fraction of the raisin growers in specified irrigation districts will use water stored in reservoirs with runoff from the Sierra Nevada. Ground water may contain nitrates in sufficient amounts that meet vineyard nitrogen demands. There are also locations where the well water contains excess nitrates that can be detrimental to grapevines.

The majority of table grape vineyards will use drip irrigation. This provides access to the grapevines at any time in order to control fungal pathogens and to perform hand labor for canopy and fruit management. In the Coachella Valley water is obtained from the All-American canal supplied with water from the Colorado River. Water quality is generally very good. Table grape vineyards in the San Joaquin Valley are similar to raisin vineyards in that most irrigation water is obtained from wells. Water quality problems are the same as mentioned previously for raisin vineyards.

Wine grape vineyards in the northern, coastal valleys of California are dependent upon both ground water and the collection of winter rainfall in small reservoirs for irrigation purposes. Along the central coast of California irrigation water is obtained from wells. There are a few locations (such as the Paso Robles area) where the water from individual wells is somewhat saline and therefore leaching is required in years where winter rainfall is insufficient.

IRRIGATION MANAGEMENT

When to start irrigating

The decision to initiate irrigations as the season progresses can be determined several ways. Currently remote sensing has gained interest among the agricultural sector and such methods are highly correlated with grapevine water status (Zarco-Tejada et al., 2013). The possibility of measuring actual vineyard ET_c cheaply has been demonstrated and may provide information necessary to assist in vineyard irrigation management (Shapland et al., 20103). However, many growers and crop consultants still use soil and/or plant based methods as an aid in irrigation scheduling. The use of a tensiometer or Watermark resistance sensor (both of which provide a measure of soil matric potential) and neutron probe, capacitance sensors and other techniques that measure the volumetric amount of water in the rooting zone of grapevines are frequently employed. For neutron probes and capacitance sensors a tube is inserted into the ground to a depth of the rooting zone and the sensor is either taken from one site to another or may be left permanently at one spot. Usually a single tube is placed within the vine row so as not to be disturbed by equipment passing between rows. The number of tubes used on a given ranch will be determined by cost and time required to take readings at all sites. Once a pre-determined value (such as soil matric potential, soil volumetric water content or a relative number) has been reached, an irrigation event would take place. The use of soil sensors will provide the individual with the desired results early in the growing season as one can assume the moisture in the soil is fairly uniform. Once irrigations commence, especially with the use of low volume, drip irrigation the placement of the tube within the vine row may not provide a true picture of the water available to the grapevine. This is due to the fact that only a small portion of the total rooting zone of the grapevine is wetted, that directly beneath an emitter. The usefulness of a tensiometer and Watermark sensors are also dependent upon their placement and the range of soil matric potential they can accurately measure. That range is usually from 0 to -0.1 MPa (0 to a minimum of -100 centibars) for tensiometers. The range for Watermark sensors is from 0 to -200 centibars. Soil matric potential may become much more negative than those minimum values when deficit irrigating grapevines.

Some growers and crop consultants are using a pressure chamber to measure leaf water potential as an aid in determining when to start irrigating. Leaf water potential is a measure of vine water status, it will measure the tension of water within the xylem. Research I've conducted has indicated that midday leaf water potential (measured ½ hour on either side of solar noon, 1 p.m. PDT) is generally never more negative than –1.0 MPa (which is -10 bars) if the vines are irrigated at 100% of water use (Williams et al., 2010a; Williams and Trout, 2005). An exception to this would be if the vapor pressure deficit (VPD) is greater than 5 kPa at the time measurements are taken (Williams and Baeza, 2007). I generally do not initiate irrigation in the Spring/Summer until midday leaf water potential reaches –1.0 MPa in my studies. At present many growers and vineyard consultants may not initiate the irrigation of white wine grape cultivars until a midday leaf water potential value of –1.0 MPa has been reached or –1.2 MPa or at more negative values for red wine cultivars. The date during the season these values are obtained is dependent upon VPD (a low relative humidity will result in a high VPD), rooting depth of the vines, soil texture, row spacing and trellis type.

A pressure chamber is used to take leaf water potential measurements. Leaf water potential is measured by selecting a mature leaf exposed to direct solar radiation. The lowest value of leaf water potential is generally measured between 12:30 and 3:00 pm on east/west rows and between 1:30 and 4:00 pm for vines situated on north/south rows. The leaf is enclosed inside a plastic bag (I use plastic sandwich bags) just before the petiole is cut with a sharp razor blade. It is important that the leaf is first placed in the plastic bag since the leaf will continue to transpire (lose water from the leaf blade) if this procedure is not used. Failure to do so will result in erroneous values of leaf water potential (the values will be more negative; appear more stressed than they really are). The leaf is placed inside the chamber and then pressurized with compressed nitrogen. The time from enclosing the leaf inside the plastic bag, cutting the petiole and placing it inside the chamber should be 10 seconds or less. The values one gets using this technique is dependent upon ambient VPD and temperature, light, soil moisture content and time of day the measurement is made. One should limit the time measurements are taken to those suggested above.

One can also assess vine water status by taking water potential readings prior to sunrise (pre-dawn leaf water potential) or by measuring stem water potential at midday. It is thought by some researchers that pre-dawn leaf water potential provides a measure of soil matric potential. However, under drip irrigation grapevine pre-dawn leaf water potential may come into equilibrium with the wettest part of the soil profile or the driest (Williams and Trout, 2005). Therefore, it may not represent the mean value of soil matric potential the vine is exposed to. Stem water potential is determined by enclosing a leaf 30 to 90 minutes prior to the time readings are to be made, in a plastic bag surrounded by aluminum foil. This procedure eliminates transpiration (the aluminum foil is used to minimize heating of the leaf) and the leaf will come into equilibrium with the water potential of the stem (i.e. stem water potential). Some in the research community feel that stem water potential is better than leaf water potential as it eliminates the effects of the environment on the leaf as outlined above. However, I have demonstrated that pre-dawn leaf, midday leaf and midday stem water potential of *Vitis vinifera* cultivars are all linearly correlated with one another (Williams 2012a; Williams and Araujo, 2002; Williams and Trout, 2005). I also have found that stem water potential is affected by ambient weather conditions, just like leaf water potential and it will vary due to the placement of the shoot (whether the shoot is mostly in the sun or shade) from which the leaf is selected (Williams 2012a; Williams and Baeza, 2007). Therefore, the most convenient means of measuring vine water status is taking midday leaf water potential measurements if one follows precisely, the techniques I outlined in the previous paragraph.

How much water to apply

I have spent numerous years determining irrigation requirements for raisin, table grape and wine grape vineyards in all major grape-growing regions of California. Regardless of grape type, irrigation requirements are dependent upon evaporative demand (ET_o) at the location of the vineyard, stage of vine development, percent ground cover and the amount of water in the soil profile. Evaporative demand or ET_o will vary seasonally, low at the beginning of the season and highest mid-summer. The greatest demand by the vine will be at full canopy, again occurring mid to late summer. Most of the above listed generalizations have been validated by the author with the use of a weighing lysimeter (a sensitive piece of equipment able to measure water use of mature vines) at the Kearney Agricultural Research and Extension Center (Williams and Ayars, 2005a; 2005b; Williams et al., 2003; 2011). It was determined that vine water use (ET_c) of Thompson Seedless grapevines growing in the lysimeter was a linear function of the shaded area measured beneath the vine at solar noon (Williams and Ayars, 2005b). There are several reasons why such a relationship would exist: 1.) The driving force of ET, net radiation, is greatest between 11 a.m. and 2 p.m., 2.) Approximately, 75% of the water used by vines growing in the lysimeter on a daily basis is between 10 a.m. and 2 p.m., 3.) The shade beneath a vine is an indirect measure of how much solar radiation the vine is intercepting, 4.) The shade beneath the vines varies only slightly between 9 a.m. and 3 p.m. for east/west rows (row direction in the lysimeter vineyard), and 5.) As the season progresses, the vine's canopy gets larger resulting in more light being intercepted (more shaded area on the ground) and greater water use.

There are numerous trellis systems used for wine grape production in California today. There are systems in which little management is used (sprawl systems) and those, which are highly manipulated. The latter systems include the VSP (vertical shoot positioned trellis) and vertically divided canopies such as the Scott Henry or Smart/Dyson trellises. Horizontally divided canopy trellis systems include the lyre or U trellises and the GDC (Geneva Double Curtain). Any of the above wine grape trellis systems that increase the percent (or fraction of) ground cover will also increase vineyard irrigation requirements based upon the results of Williams and Ayars (2005b). In addition, as the row spacing decreases, the percent ground cover will increase. For example, a VSP trellised vineyard with a row spacing of 6 ft. will use more water per unit land area than one with a row spacing of 9 ft. (Table 2) or 10 ft. (Williams 2010).

The information needed to schedule irrigations throughout the current growing season is daily ET_o and reliable seasonal crop coefficients (K_c). Reference ET is the water used per unit time by a short green crop completely shading the ground and ideally is of uniform height and never short of water. Reference ET is expressed in mm or inches. As pointed out above, reference ET is a measure of the evaporative demand of a particular region throughout the year. Current (or real-time) ET_o data are available from the California Irrigation Management Information System (CIMIS) operated by the California Department of Water Resources. There are greater than 150 weather stations located around the state where environmental data are collected to calculate ET_o. Reference ET may also be obtained from weather stations operated by other entities (such as those stations operated by the Paso Robles Vintners and Growers Association in the Paso Robles region). For comparison purposes, ET_o is approximately 80 to 85% of Class A pan evaporation.

The crop coefficient (K_c) is the fraction of water a non-water stressed crop uses in relation to that of ET_o such that the $K_c = ET_c \div ET_o$ (where ET_c is crop ET). The K_c is dependent upon the stage of vine growth, degree of cover, height and canopy resistance (stomatal regulation by the vine or crop). The K_c will vary throughout the growing season; it is not a constant fraction of ET_o. It is low early on and then as the canopy develops, it will increase. The seasonal crop coefficients of Thompson Seedless grapevines grown at the University of California Kearney Agricultural Research and Extension Center have been determined with the use of a weighing lysimeter (Williams and Ayars 2005a, 2005b; Williams et al., 2003). The trellis system used for the vines was a 0.6-m (2-ft.) crossarm approximately 1.55 m (5 ft.) above the soil surface. The vines within the lysimeter were automatically irrigated whenever they used 2 mm of water (8 liters or approximately 2 gallons) and were therefore assumed not to be under water stress.

Daily water use of vines growing within the lysimeter averaged 40 to 45 liters (10 to 12 gallons) at maximum canopy. The percent ground cover (shaded area) at that time was approximately 50% (area per vine is 7.59 m^2 or approximately 84 ft^2). During the 1999-growing season an overhead trellis system was simulated using the vines within the lysimeter. Shoots of the two vines growing within the lysimeter were allowed to grow across the row. The ground cover at that time was about 60%. A support system was constructed that allowed us to raise the shoots (simulating an overhead trellis system) and the percent ground cover increased to approximately 75%. Actual water use prior to raising the canopy was 48 liters (12.7 gallons) per day while after raising the canopy it increased to 63 liters (16.7 gallons) per day. The crop coefficient prior to raising the canopy was 0.95 and after raising the canopy was 1.25. Results from this study indicated that it is the orientation of the vine's canopy (determined by the trellis system) and not the total leaf area that dictates how much water a vine will use or the crop coefficient, if it is not water-stressed (Williams and Ayars, 2005b). The results also demonstrated that the crop coefficient was a linear function of percent shaded area beneath the vine at solar noon. The relationship between the crop coefficient and the percent shaded area (a whole number) was: $K_c = 0.008 + 0.17x$, where x is the percent shaded area per vine. I've also developed the relationship between the seasonal crop coefficient and the accumulation of degree days after the approximate date of budbreak or March 15th in the San Joaquin and April 1st in the coastal valleys. The use of growing degree-days should improve the precision of the estimate by removing year to year variation in crop development at a single location and normalize differences in the time of budbreak among locations (i.e. Coachella Valley vs. San Joaquin Valley).

I've used this relationship to develop seasonal crop coefficients for different trellis systems and row spacings (Williams 2010; 2012b). I have also developed crop coefficients for wine grapes using a VSP trellis and quadrilateral cordon trained vines using a 4 ft. crossarm (a modified GDC trellis). These crop coefficients were developed using the water balance technique in commercial vineyards. The maximum K_c for a VSP trellis system in a vineyard with a row spacing of 2.13 m (7 ft.) was 0.7 (Williams 2014a) while the maximum K_c for the modified GDC trellis (row spacing of 3.66 m or 12 ft.) was 0.75. The VSP trellis crop coefficients developed for the 2.13 m row spacing (Williams 2014a) have been validated in vineyards with row spacings of 1.83 (6 ft.) (unpublished data from Napa Valley), 2.44 (8 ft.) and 3.05 m (10 ft.) (Williams, 2010), using different cultivars and rootstocks and at different locations. I have found that the maximum K_c for VSP vineyards with row spacings of 1.83 (6 ft.), 2.44 (8 ft.) and 3.05 m (10 ft.), are 0.85, 0.64 and 0.51, respectively (Table 1). The basic premise of the crop coefficients I've developed is that water use per unit row length is the same, even though row spacings differ, as long as the trellis system is similar and no mutual shading occurs between rows. This is why water use on a per vine basis is the same for a VSP trellis planted on 6 and 9 ft. row spacings but water use per unit land area differs between the two (Table 2).

I also developed crop coefficients for vineyards using a lyre trellis and a high-density vineyard (planted 1 m x 1 m; 4049 vines per acre) using a smaller version of the VSP trellis. The K_c at maximum canopy development (i.e. late in the summer) was 0.83 for the lyre (planted to a 9 ft. row spacing) and 0.91 for the 1 x 1 m planting (Table 2). The results indicate that trellises, which spread the canopy, will have a higher per vine water requirement but may not necessarily increase water use per unit land area when compared to a smaller canopied trellis with narrow rows.

To schedule the current season's daily irrigation requirements the following equation can be used: $ET_c = K_c \times ET_o$. Reference ET can be obtained from CIMIS while the crop coefficient is calculated at a function of degree-days after a starting point. One must remember that this equation is for water application amounts that replace the amounts of water the vineyard uses daily or at other intervals at 100% of full ET_c. The above equation will give crop water use in mm or inches. To determine water application amounts per vine or to calculate pump run times, one must convert mm or inches into liters or gallons. The metric conversion is one mm covering one hectare equals 10,000 liters. The English conversion is one inch covering one acre equals approximately 27,500 gallons. Once the amounts have been determined, one will divide the liters or gallons required per unit land area by the number of vines per hectare or acre (Tables 2 and 3). The pump run time also is dependent upon the number and sizes of emitters per vine. The seasonal progression of vine water use for a VSP trellis, planted on 10 ft. row spacings is shown in Table 3. The data illustrate how vine water use is lower early in the season due to a smaller canopy. Once the canopy is established and fills the trellis (beginning the middle of July), differences in ET_o from week to week, will result in differences in vine water requirements when this technique to irrigate vines is used. Weather (evaporative demand and temperature) is the variable exerting the most influence on irrigation requirements during the growing season. Thus, the benefits of calculating vine water use with the above method is that both evaporative demand (ET_o) and the seasonal progression of a canopy's development (based upon temperature or degree days after budbreak) are taken into account as is trellis type and row spacing in determining how much water to apply.

Effect of water amounts on growth and yield

The equation in the above paragraph will provide an estimate of how much water a non-stressed vine will use. However, research conducted in my laboratory and elsewhere, indicates that one can deficit irrigate (apply less than full ET_c) with minimal effects on berry growth or yield and possible advancement in date of harvest and increase in fruit quality. In each one of my irrigation trials I include irrigation amounts that are fractions of estimated full ET. This allows me to determine the effects of both under- and over-irrigation on vine growth, berry characteristics and yield of raisin and table grapes and wine quality of wine grape cultivars. I have found that irrigation amounts, at approximately 80% of full ET, maximized berry size for raisin and table grapes (Williams et al., 2010b). Yield of Thompson Seedless vines grown at the Kearney Ag Center, is maximized at applied water amounts that are 80% of lysimeter water use whether used for raisin (Williams et al., 2010b) or table grape production (unpublished data). It has been found that yield of Thompson Seedless grapevines used for raisin production actually decreases when applied water amounts are greater than 100% of measured ET. This is due to reduced bud fruitfulness and less cluster numbers per vine. Vegetative growth of Thompson Seedless generally increases as applied water amounts increase from no irrigation to 120% of ET (Williams et al., 2010a). Similar results have been found on Merlot grapevines grown in the San Joaquin Valley (Williams, 2012 a). Studies I've conducted in various table grape vineyards in both the Coachella and San Joaquin Valleys have demonstrated that packable yields were only slightly reduced at applied water amounts at 50% of full ET when imposed subsequent to berry set (or after the vines had been girdled). It should be pointed out that the above results were obtained in vineyards that were irrigated daily. Therefore, the irrigation frequency used in those studies may have mitigated possible negative effects of deficit irrigation.

Studies I've conducted in Chardonnay (Williams, 2014b) and Cabernet Sauvignon vineyards in Napa Valley and along the central coast of California (Williams, 2010) have somewhat mimicked the results found with Thompson Seedless. In these studies irrigation frequency is only once to twice per week. Berry size is usually maximized at applied water amounts at 75% of estimated full ET (Table 4). Yields are slightly diminished at applied water amounts at 75% of full ET (Table 5). In some instances, yields have been maximized at applied water amounts equal to 50% of full ET, but this is dependent upon year (years in which rainfall may have occurred late into the spring) (see Williams 2014a; 2014b), location, soil type and rooting depth. Pruning weights, a measure of vegetative growth, generally increased as applied water amounts increased (Table 6).

The wine grape studies I have conducted also included at least three different rootstocks at each location (five in Paso Robles - Williams 2010). I have found no differences in vine water use or vine water relations among individual rootstocks at a specific location. This is probably due to the fact that all vineyards utilized the VSP trellis system. Shoot hedging and positioning, as performed for the VSP trellis, does not allow possible differences in vine vigor among the rootstocks to be expressed. In addition, I rarely have found significant interactions between rootstocks and irrigation amounts among the different parameters measured at each site. Lastly, small wine lots have been made of Cabernet Sauvignon grown at Oakville and Paso Robles and Chardonnay from Carneros and sensory analysis performed. There has been no consensus as to preferences among the irrigation treatments. One possible reason for this is that the irrigation amounts that I calculate as full ET_c for the VSP trellis is much less than previously thought. For example, calculated ET_c for the Paso Robles Cabernet Sauvignon vineyard (with 10 ft. row spacing) from budbreak to the end of September has only been between 250 and 300 mm (12 to 17 inches) per growing season (Williams 2010). This is much less water than many growers presently apply.

REFERENCES

Shapland, T.M., Synder, R.L., Smart, D.R. and Williams, L.E. 2013. Estimation of actual evapotranspiration in winegrape vineyards located on hillside terrain using surface renewal analysis. Irrig. Sci. 30:471-484.

Zarco-Tejada, P.J., González-Dugo, V., Williams, L.E., Suárez, L., Berni, J.A.J., Goldhamer D. and Fereres, E. 2013. A PRI-based water stress index combining structural and chlorophyll effects: Assessment using diurnal narrow-band airborne imagery and the CWSI thermal index. Remote Sensing Envir. 138:38-50

Williams, L. E. 2010. Interaction of rootstock and applied water amounts at various fractions of estimated evapotranspiration (ET_c) on productivity of Cabernet Sauvignon. Austral. J. Grape Wine Res. 16:434-444.

Williams, L.E. 2012a. Interaction of applied water amounts and leaf removal in the fruiting zone on grapevine water relations and productivity of Merlot. Irrig. Sci. 30:363-375.

Williams, L.E. 2012b. Leaf water potentials of sunlit and/or shaded grapevine leaves are sensitive alternatives to stem water potential. J. Inter. Sci. Vigne Vin. 46:207-219.

Williams, L.E. 2014a. Determination of evapotranspiration and crop coefficients for a Chardonnay vineyard located in a cool climate. Amer. J. Enol. Vitic. 65:159 – 169.

Williams, L.E. 2014b. Effect of applied water amounts at various fractions of evapotranspiration on productivity and water footprint of Chardonnay grapevines. Amer. J. Enol. Vitic. 65:215 – 221.

Williams, L. E. and F. J. Araujo. 2002. Correlations among predawn leaf, midday leaf and midday stem water potential and their correlations with other measures of plant water status in *Vitis Vinifera* L. Journal of the American Society of Horticultural Science 127:448-454.

Williams, L.E. and Ayars, J.E. 2005a. Water use of Thompson Seedless grapevines as affected by the application of gibberellic acid (GA_3) and trunk girdling – practices to increase berry size. Agric. For. Meteor. 129: 85-94.

Williams, L.E. and Ayars J.E.2005b. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. Agric. For. Meteor. 132:201-211.

Williams, L.E. and Baeza, P. (2007) Relationships among ambient temperature and vapor pressure deficit and leaf and stem water potentials of fully irrigated, field-grown grapevines. American Journal of Enology Viticulture **58**, 173–181.

Williams, L. E., Baeza, P. and Vaughn, P. 2011. Midday measurements of leaf water potential and stomatal conductance are highly correlated with daily water use of Thompson Seedless grapevines. Irrigation Science. 30:201-212

Williams, L.E., Grimes, D.W. and Phene, C.J. 2010a. The effects of applied water at various fractions of measured evapotranspiration on water relations and vegetative growth of Thompson Seedless. Irrig. Sci. 28: 221-232.

Williams, L.E., Grimes, D.W. and Phene, C.J. 2010b. The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless. Irrig. Sci. 28: 233-243.

Williams, L.E., Phene, C.J., Grimes, D.W. and Trout, T.J. 2003 Water use of mature Thompson Seedless grapevines in California. Irrig. Sci. 22: 11-18.

Williams, L.E. and Trout, T.J. 2005. Water relations of field-grown *Vitis vinifera* L. in response to high frequency drip irrigation. Amer. J. Enol. Vitic. 56:357-366.

Table 1. Crop coefficients for a VSP trellis as a function of degree-days (DDs) from budbreak and row spacing. Degree-days (DDs) are expressed in Centigrade (C) and Fahrenheit (F). Base temperatures used in calculating DDs are 10^{o}C and 50^{o}F.

DDs (C)	DDs (F)	K_c 6 ft*	K_c 7 ft	K_c 8 ft	K_c 9 ft	K_c 10 ft
100	180	0.17	0.15	0.13	0.12	0.10
200	360	0.22	0.19	0.17	0.15	0.13
300	540	0.28	0.24	0.21	0.19	0.17
400	720	0.35	0.30	0.26	0.23	0.21
500	900	0.42	0.36	0.31	0.28	0.25
600	1080	0.49	0.42	0.37	0.33	0.29
700	1260	0.56	0.48	0.42	0.37	0.33
800	1440	0.62	0.53	0.46	0.41	0.37
900	1620	0.67	0.58	0.51	0.45	0.40
1000	1800	0.72	0.62	0.54	0.48	0.43
1100	1980	0.76	0.65	0.57	0.50	0.45
1200	2160	0.79	0.67	0.59	0.52	0.47
1300	2340	0.81	0.69	0.61	0.54	0.48
1400	2520	0.82	0.71	0.62	0.55	0.49
1500	2700	0.82	0.71	0.62	0.55	0.49

*The equation used to calculate K_cs for the 6-foot row was: $K_c = 0.87/(1 + e^{(-(x - 525)/301)})$ where x is degree-days in centigrade from a starting point (1 April) and e equals 2.71828.

Table 2. The effect of trellis type and row spacing on estimated vine water use of grapevines assuming an ET_o of 1.5 inches for the time frame used (say a week). HD stands for a high density planting, 1 m x 1 m, using a smaller version of a VSP trellis.

Trellis Type	Row Spacing	ET_o (in.)	K_c	ET_c (inches)	ET_c (gal/acre)	ET_c (gal/vine)
VSP	6 ft.	1.5	0.81	1.22	33,550	27.8
VSP	9 ft.	1.5	0.54	0.81	22,275	27.6
Lyre	9 ft.	1.5	0.83	1.25	34,375	42.5
HD	1 m	1.5	0.91	1.37	37,675	9.3
GDC	12 ft.	1.5	0.75	1.13	31,075	51.4

Assumptions: Vine spacing for all trellises is 6 ft., except in the HD vineyard. Therefore vines densities are 1208, 808, 808, 604 and 4049 vines per acre for the VSP 6 ft row, VSP 9 ft. row, Lyre, and GDC trellises and HD planting, respectively. The K_cs used for the VSP 6 and 9 ft. rows is from DDs (C) 1300 row in Table 1. Other K_cs used are from L.E. Williams, unpublished data. ET_c in inches was obtained by multiplying ET_o by the K_c. It was assumed that there is 27,500 gallons per acre-inch of water.

Table 3. Calculated water use of Cabernet Sauvignon grapevines in Paso Robles during the 2000-growing season. Reference ET (ET_o) was obtained from the Paso Robles Vintners and Growers Association's PR1 weather station. Row spacing was 10 ft. and vine spacing was 6 ft. (726 vines per acre). It was assumed that there were 27,500 gallons per acre-inch.

Month	Week	ET_o (in.)	K_c	ET_c (in.)	ET_c (gal./acre)	ET_c (gal./vine)	Rain (in.)
May	1	1.38	0.14	0.19	5,225	7.2	0
*	8	1.38	0.17	0.23	6,325	8.7	0
	15	1.50	0.18	0.27	7,425	10.2	0
**	22	1.69	0.22	0.37	10,175	14.0	0
	29	1.89	0.25	0.47	12,925	17.8	0
June	5	1.61	0.28	0.45	12,375	17.0	0.2
	12	1.73	0.32	0.55	15,125	20.8	0
	19	1.69	0.36	0.61	16,775	23.1	0
	26	1.97	0.39	0.77	21,175	29.0	0
July	3	1.57	0.41	0.64	17,600	24.2	0
	10	1.61	0.43	0.69	18,975	26.1	0
	17	1.97	0.44	0.87	21,450	29.5	0
***	24	2.05	0.44	0.90	24,750	34.1	0
	31	2.05	0.45	0.92	25,300	34.8	0
August	7	1.89	0.46	0.87	23,925	33.0	0
	14	2.05	0.47	0.97	26,675	36.7	0
	21	1.73	0.48	0.83	22,825	31.4	0
	28	1.26	0.49	0.62	17,050	23.5	0

*, **, and *** denote dates of the initiation of irrigation, approximate date of bloom and approximate date of veraison, respectively. Vines were harvested September 27, 2000.

Table 4. Relative berry weight as a function of applied irrigation amounts (fraction of estimated full ET) at four locations and two cultivars, Cabernet Sauvignon and Chardonnay. All vineyards used a VSP trellis. Values at each location are the mean of three different rootstocks except at Paso Robles, which had five rootstocks, with data collected for a minimum of three growing seasons.

		Irrigation Treatment (fraction of estimated ET_c)				
Location	Cultivar	0.25	0.5	0.75	1.0	1.25
		------------- (percent maximum weight)* -------------				
Oakville	Cabernet	83	93	98	100	98
Paso Robles	Cabernet	78	88	95	98	100
Gonzales	Chardonnay	77	89	96	98	100
Edna Valley	Chardonnay	82	89	97	99	100

* The weights of each treatment were divided by the treatment with the greatest weight. The treatment with the greatest weight was set to 100%.

Table 5. Relative yield as a function of applied irrigation amounts (fraction of estimated full ET) at four locations and two cultivars, Cabernet Sauvignon and Chardonnay. All vineyards used a VSP trellis. Values at each location are the mean of three different rootstocks except at Paso Robles, which had five rootstocks, with data collected for a minimum of three growing seasons.

		Irrigation Treatment (fraction of estimated ET_c)				
Location	Cultivar	0.25	0.5	0.75	1.0	1.25
		------------- (percent maximum weight)* -------------				
Oakville	Cabernet	77	96	100	99	99
Paso Robles	Cabernet	61	70	81	91	100
Gonzales	Chardonnay	65	81	87	89	100
Edna Valley	Chardonnay	92	90	92	98	100

* The weights of each treatment were divided by the treatment with the greatest weight. The treatment with the greatest weight was set to 100%.

Table 6. Relative pruning weight as a function of applied irrigation amounts (fraction of estimated full ET) at four locations and two cultivars, Cabernet Sauvignon and Chardonnay. All vineyards used a VSP trellis. Values at each location are the mean of three different rootstocks except at Paso Robles, which had five rootstocks, with data collected for a minimum of three growing seasons.

		Irrigation Treatment (fraction of estimated ET_c)				
Location	Cultivar	0.25	0.5	0.75	1.0	1.25
		------------- (percent maximum weight)* -------------				
Oakville	Cabernet	85	89	100	96	99
Paso Robles	Cabernet	61	67	79	88	100
Gonzales	Chardonnay	75	83	87	96	100
Edna Valley	Chardonnay	87	87	92	98	100

* The weights of each treatment were divided by the treatment with the greatest weight. The treatment with the greatest weight was set to 100%