Crop Yield Predictor for Deficit Irrigation Scheduling

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ABSTRACT

Many irrigators face the prospect that they will not be able to fully irrigate their crops. They still need to schedule their water applications to make the best economic use of available water. Major scheduling questions for deficit irrigation include: will pre-season irrigation be beneficial, and when should irrigation be initiated and terminated during the growing season. A computerized decision tool, the Crop Yield Predictor (CYP) has been developed to predict yields from alternative irrigation schedules. The user determines soil water status before or during the cropping season and formulates a potential schedule of irrigation dates and amounts. CYP uses a daily soil water balance coupled with computations of effective evapotranspiration (ETe) to predict crop yields from regional yield-ET relationships. Multiple executions of CYP with alternative irrigation schedules lead to the schedules that project optimum net economic returns from the management scenarios.

INTRODUCTION

Maximum net economic returns for irrigators with adequate water supplies usually have corresponded to irrigation management that is geared to obtain maximum crop yields. Irrigation in excess of crop water needs reduces net economic return, but the marginal increases in crop yields, especially for corn, usually are more than marginal production costs. When water supplies cannot match crop needs and deficit irrigation management is anticipated, optimum net economic return from irrigation is the appropriate measure of best management (English 2002). Crop selection for optimum net return may involve multiple crops in rotation, a single crop with reduced irrigation, or irrigation on a smaller area (Martin et al. 1989). In addition to crop selections, irrigation needs to be allocated among crops, using crop production functions and production costs for optimum economic return (English, 1981, Klocke et al. 2006).

When the water supply for irrigation is less than the water required for non-stressed crops, water deficits can be anticipated. Irrigation schedules for deficit irrigation need to anticipate the potential crop yields and net economic returns prior to and during the growing season. The major irrigation scheduling decisions for deficit irrigation are: (1) whether or not pre-season irrigation is needed (Stone et al., 2008), (2) when should the first irrigation event start, and (3) when should the last irrigation event be applied. Between the start date and stop date, irrigation systems often operate on a fixed frequency depending on the water supplied by surface or ground water.

The objective for this study was (1) to develop an interactive decision tool that would help users predict optimum irrigation schedules for crops that are expected to experience water stress and (2) to illustrate the use of the decision tool to predict irrigation schedules for a range of annual precipitation, application amounts, and preseason irrigation.

Crop Yield Predictor Description and Operation

The CYP was designed as an interactive decision tool to predict crop yields and economic returns for deficit irrigated crops. CYP uses the Kansas Water Budget (KSWB) simulation model to predict crop yields, reference ET (ETr), effective ET (ETe), crop yields, and daily available soil water (ASW) (Stone et al., 1995; Stone and Schlegel, 2006; Khan et al., 1996; Klocke et al., 2009). The KSWB is designed to use average daily values from 30 years of weather data (maximum and minimum air temperature, solar radiation, and precipitation) for each location to calculate ETr, ETc, daily ASW, and crop yields. CYP users can designate potential irrigation schedules to optimize yields and net returns. These schedules can be tested for a range of annual precipitation to find yield and income risks from several input scenarios including wet, average, and dry years; different dates and amounts of irrigation events; inclusion or exclusion of pre-season irrigation (Stone et al., 1987); different soil types; different irrigation system application efficiencies; or different soil water contents before or during the growing season.

User Inputs

The CYP is structured with a series of tabs and sub-tabs that activate screens for input and output information (figure 1). The first level of tabs is for "general input" and "results". The general input tab activates a series of sub-tabs including "location and rainfall", "soil information", "irrigation efficiency", "crop selection and irrigation schedule" and "runoff and soil water" that require the user to enter the information needed to execute the program.

The **"location and rainfall"** tab shows the screen for choosing the nearest location to the user's field and the desired annual rainfall. Annual rainfall can be entered manually or by clicking onto the average value for the location or the amounts based on probability of occurrence. Probabilities indicate the rainfall amounts that occur during 8 out of 10 years (80%), 5 out of ten years (50%), or 2 out of 10 years (20%). Each day's rainfall is adjusted up or down with the ratio of the user's annual precipitation and the average annual precipitation from weather records.

The **"soil information"** tab shows a screen with four soil types, including medium and coarse textured soils that can be highlighted by the user for the predominant soil type in the field. Soil water characteristics, including available soil water (ASW) storage capacity, field capacity, and permanent wilting for each soil are displayed so the user can choose the one that is closest to their field soil type. Soil type influences the default runoff coefficient, which is the percentage of daily precipitation that does not infiltrate into the soil.

The **"irrigation efficiency"** tab displays suggested irrigation application efficiencies by system types. Application efficiency is defined as the percentage of water that infiltrates into the soil (net irrigation) from the water pumped or supplied to the field (gross irrigation). The user needs to enter irrigation efficiency manually from values in the table or enter the desired efficiency.

The **"crop selection and irrigation schedule"** tab activates two sub-tabs, one for selecting a crop and one for building an irrigation schedule for that crop. The crop selection sub-tab allows the user to highlight a crop from a list which includes corn, grain sorghum, wheat, soybean, sunflower and alfalfa. CYP fills a default growth stage table for the chosen crop, but the user can adjust these dates from field observations. The user also fills a “maximum yield” box for the field’s non-stressed yield potential. This yield is based on the field’s history of non-stressed production and a reasonable expectation for yield increases from better cropping practices or technology improvements. CYP simulates a crop yield for a given input scenario and the maximum yield for a non-stressed crop. A ratio of predicted yield, calculated from the inputs, and maximum non-stressed yield produces a relative yield. The relative yield is multiplied by the user’s maximum field yield to produce a field based crop yield.

The **“irrigation schedule”** sub-tab allows the user to select one of two sub-sub tabs. The “gross irrigation entries” tab prompts the user to build a customized irrigation schedule by entering specific dates and gross irrigation amounts applied on that date. The irrigation dates can be entered manually or imported from schedules that are developed in Excel.

An alternative to building a customized schedule is for the user to choose the sub-sub tab for “uniform frequency of irrigation events”. This option determines irrigation schedules based on the same number of days between irrigation events from user entries of (1) starting dates and ending dates for the growing season irrigation, (2) gross irrigation for each irrigation event, where the gross irrigation was the same for all irrigation events, and (4) area irrigated. The user then needs to determine whether the irrigation schedule needs to be based on pumping capacity or the amount of total irrigation for the season. When pumping capacity is the limiting factor, CYP calculates the number of the irrigation events that are possible between the starting date and ending dates for the entire irrigation season and enters those irrigation events into the irrigation schedule. When the total irrigation amount controls the schedule, all of the water is applied with a uniform frequency without regard to the pumping capacity. The uniform frequency schedules can be modified after they are entered into the scheduling table.

The **“runoff and soil water”** tab sets the runoff coefficient, ASW on January 1, and any ASW updates after January 1. The runoff coefficient is the percentage of daily precipitation that does not infiltrate. The user manually enters the runoff percentage or CYP calculates a default runoff factor using crop type, total annual precipitation, and soil type.

CYP calculates available soil water (ASW) on January 1 from annual precipitation and anticipated irrigation, but this value can be modified by clicking onto the ASW input box. The user can modify the ASW on any date during the year except January 1 by checking the “Use ASW and Date values below” box. The value of ASW is entered into the input box and the calendar drop down gives the choice of a date.

CYP Outputs

Results of a simulation are tabulated and presented in graphs of daily available soil water, crop ET, and drainage. Results from additional scenarios can be retained in additional columns on the results table.

Evaporation during the non-growing season is calculated for water loss from bare soil. A daily evaporation coefficient (Doorenbos and Pruitt, 1977) is multiplied by ETr to calculate evaporation.

Effective crop evapotranspiration (ETe) is the water that contributes to crop yield. ETe is calculated in four steps. First, long-term average daily weather data, including maximum temperature, minimum temperature, and solar radiation, were derived from at least thirty years of records at each geographic location. Theses average daily weather data combine for a calculation of reference ET (ETr) with the method described by Jensen and Haise (1963) for a well-watered crop with full canopy cover in semi-arid regions. When the maximum air temperature is more than 33°C, ETr is adjusted to account for additional advective energy. Second, daily ETr is multiplied by a crop coefficient (Kc) to produce a value for maximum ET (ETm) that accounts for increasing ETm during vegetative growth, nearly constant ETm during reproduction and early grain fill, and declining ETm as the crop matures. Adjusting growth stage dates allows CYP to recalculate daily crop coefficients (Kc) for the duration of the growing season (figure 2). Calculation of ETm assumes that the crop is not experiencing water stress and there are no "spikes" in soil water evaporation immediately after surface wetting because the Kc values were developed to account for surface evaporation. Third, ETm is multiplied by a soil water stress coefficient (Ks) (Jensen et al., 1971) producing an actual crop ET (ETa), which is the water extracted from the soil and accounts for the effect of soil water depletion on the ETm (figure 3). Finally, ETa is reduced to account for the crop's susceptibility to water stress to stress during four growth periods (vegetative, flowering, seed formation, and ripening) to produce ETe. The ratio of ETa to ETm and water stress factors by crop and growth periods convert ETa to ETe. These four steps combine the effects of weather parameters, crop development during the growing season, the amount of water stress from soil water availability, and the crop's susceptibility to stress during four growth periods. Klocke et al. (2009) described the derivation of ETr, ETm, ETa, and ETe in more detail.

Maximum crop yield (Ym) is calculated from linear relationships of crop yield and maximum ET (ETm) where the crop is not experiencing stress due to soil water or the crop's susceptibility of the crop to stress during different growth stages.

Estimated crop yields (Ye) are calculated by from linear relationships of yield as a function of effective ET (ETe), developed from long-term field studies in west-central Kansas:

Yield [Mg ha^{-1}] = 0.042 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 12.33 [Mg ha^{-1}] for corn,
Yield [Mg ha^{-1}] = 0.030 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 5.67 [Mg ha^{-1}] for sorghum,
Yield [Mg ha^{-1}] = 0.015 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 4.04 [Mg ha^{-1}] for wheat,
Yield [Mg ha^{-1}] = 0.10 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 1.3 [Mg ha^{-1}] for sunflower,
Yield [Mg ha^{-1}] = 0.011 [Mg ha^{-1} mm^{-1}] *ETe [mm] – 2.39 [Mg ha^{-1}]] for soybean,

where ETe is the water that actually contributes to crop yield.

Relative crop yield is the ratio of the crop yield (Ye), calculated by CYP, and the non-stressed yield (Ym). Relative yield is what was actually produced as a percentage of the yield that would have been produced with no water stress.

Adjusted crop yield is the relative yield multiplied by the program user's maximum field yield provided by the user. The CYP calculates relative yield, but the adjusted crop yield is a better indicator of the expected field yields from the simulated scenario.

Net return is the gross income minus operational and irrigation costs. Net return is income before fixed costs are considered. For deficit irrigation, net return is a better indicator of the optimum irrigation scheduling scenario than considering only crop yield results

Drainage during the growing and non-growing seasons is calculated using a Wilcox-type drainage equation (Miller and Aarstad, 1972) that was field calibrated for each soil type. Drainage depends on the relationship of total soil water described by an exponential function relating drainage to total soil water.

The **"graph"** tab accesses three graphs for the current simulation including (1) daily ASW throughout the year, (2) ETr, ETm, and ETa (figure 3) , and (3) drainage, each on a daily basis throughout the year. The ASW on December 31 can be entered manually for next year's simulation if the user wants to add the same crop or other crops in subsequent years.

Daily available soil water (ASW) is graphed by CYP from a soil water balance of:

$$ASW_t = ASW_y + P_y + I_y - D_y - ETa_y$$

where ASW_t is the available soil water at the beginning of today; ASW_y is the available soil water at the beginning of yesterday; P_y is the precipitation that infiltrated into the soil yesterday, I_y is the irrigation that infiltrated into the soil yesterday; D_y is the water that drained from the six foot depth in the soil yesterday; and ETa_y is the water that the crop consumed yesterday (figure 3).

EXAMPLES OF CYP SIMULATIONS

CYP was executed with the input values in table 1. The simulations were designed to show the effects of annual precipitation probabilities, growing season irrigation amounts, and pre-season irrigation on ETe, crop yield, income, and net return.

Annual precipitation probabilities (20 to 80%) were chosen to represent the range of precipitation to evaluate the resulting range of ETe and yields. ETe from the 20% and 80% precipitation was ± 5% of the ETe from the 50% precipitation probability, while yield expectations were ± 9% of the 50% precipitation probability (table 2). Operational and pumping costs were calculated for the 50% rainfall probability and applied to all precipitation probabilities because input costs would be spent in without knowledge of future precipitation. Net return for the 80% and 20% precipitation probabilities were from -60% to + 25% of the net return for the 50% precipitation probability. Annual precipitation had a strong influence on net return.

CYP users can compare anticipated irrigation amounts to find the potential range in crop yields and net returns (table 3). Growing season irrigation amounts were ± 20% of 254 mm. Irrigation events commenced earlier and ceased later with the additional irrigation events because the capacity for delivering water to the field limited the irrigation frequency. Over the range or irrigation, ETe was ± 2% and yield was ± 8% of the 254 mm growing season irrigation. Growing season irrigation of 203 mm had a net return that was 14% more than the 254 mm irrigation and 5% less net return for the 305 mm irrigation. Operational costs, including fertilizer, seed, and harvesting, were scaled with the yield expectations for the amount of irrigation. Even though more net return resulted from the least irrigation, income variability would increase from year to year with less irrigation (Klocke et al., 2009b). The CYP considered average results over years rather than possible results for individual years.

The value of pre-season irrigation is an issue when non-growing season precipitation is less than average and irrigators perceive that they will not be able to keep up with ET requirements later in the growing season (Stone et all, 2008). Often precipitation during April, May, and early June occurs in the Great Plains region that is not anticipated during March when irrigators usually make pre-season irrigation decisions. The CYP can be used to forecast the advantage of pre-season irrigation to impact potential crop yields and net returns (table 4). In this example, either 53 or 102 mm of pre-season irrigation was applied in late March and early April on corn in 2 or 4 irrigation events. ETe was 3% and 5% more for 53 and 102 mm pre-season irrigation compared with no pre-season irrigation. Likewise, yields 10% and 20% more for 53 and 102 mm of pre-season irrigation compared with no pre-season irrigation. However, net returns were 17% and 28% less for 53 and 102 mm of pre-season irrigation compared with no pre-season irrigation. Projected operational costs and pumping costs did not compensate for the added crop yield for pre-season irrigation.

SUMMARY

The Crop Yield Predictor (CYP) has been adapted from the Kansas Water Budget (KSWB) to become an interactive model where the user can enter a western Kansas location. Annual precipitation, soil type, crop type, a potential irrigation schedule, runoff, initial soil water (SW) content, crop production costs, and commodity prices are inputs to the CYP. These inputs combine to predict effective ET, grain yield, relative grain yield, daily SW content, daily drainage, daily crop ET, and net economic returns. Alternative irrigation schedules and annual precipitation can be entered into CYP to predict changes in results. The alternative schedules can guide CYP users in choosing irrigation starting dates ending dates and irrigation frequencies.

Multiple executions of the CYP illustrated that: (1) increases in annual precipitation, from 380 to 584 mm, had a positive impacts on crop yields and positive impacts on net economic returns; (2) increases in growing season irrigation, from 203 to 305 mm, had positive impacts on crop yields but a negative impacts on net returns; (3) pre-season irrigation, from 0 to 103 mm, had positive impacts on crop yields but negative impacts on net returns.

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Table 1. Input values for scenarios in tables 3, 4, and 5.

Location	Garden City
Crop	Corn
Soil Type	Ulysses Silt Loam
Runoff	5%
Application Efficiency	90%
Gross Irrigation	25 mm per event
Crop Price	\$165 Mg^{-1}
Irrigation Costs	\$0.14 ha^{-1} mm^{-1}

Table 2. Effects of the amount of annual precipitation with Probabilities of 80, 50, and 20% with growing season irrigation equal to 254 mm and 45% ASW at the beginning of the year.

	Annual Precipitation (mm)		
	380	483	584
Effective ET (mm)	533	559	584
Yield (Mg ha^{-1})	10.0	11.5	12.5
Gross Income (\$ ha^{-1})	1647	1901	2056
Operational Costs (\$ ha^{-1})	1040	1040	1040
Pumping Cost (\$ ha^{-1})	233	233	233
Net Return (\$ ha^{-1})	374	628	783

Table 3. Effects of growing season irrigation with annual precipitation equal to 483 mm and 45% ASW at the beginning of the year.

	-Gross Irrigation (mm)-----		
	203	254	305
Effective ET (mm)	533	546	559
Yield (Mg ha^{-1})	10.9	11.9	12.9
Gross Income ($ ha^{-1})	1791	1957	2123
Operational Costs ($ ha^{-1})	859	1074	1233
Pumping Cost ($ ha^{-1})	188	233	275
Net Return ($ ha^{-1})	744	650	615

Table 4. Effects of pre-season irrigation for growing season irrigation equal to 203, annual precipitation equal to 483 mm, and 25% ASW at the beginning of the year.

	Pre-season Irrigation (mm)		
	0	53	102
Effective ET (mm)	508	521	533
Yield (Mg ha^{-1})	9.8	10.9	11.7
Gross Income ($ ha^{-1})	1625	1791	1924
Operational Costs ($ ha^{-1})	859	1074	1233
Pumping Cost ($ ha^{-1})	188	233	275
Net Return ($ ha^{-1})	578	484	416

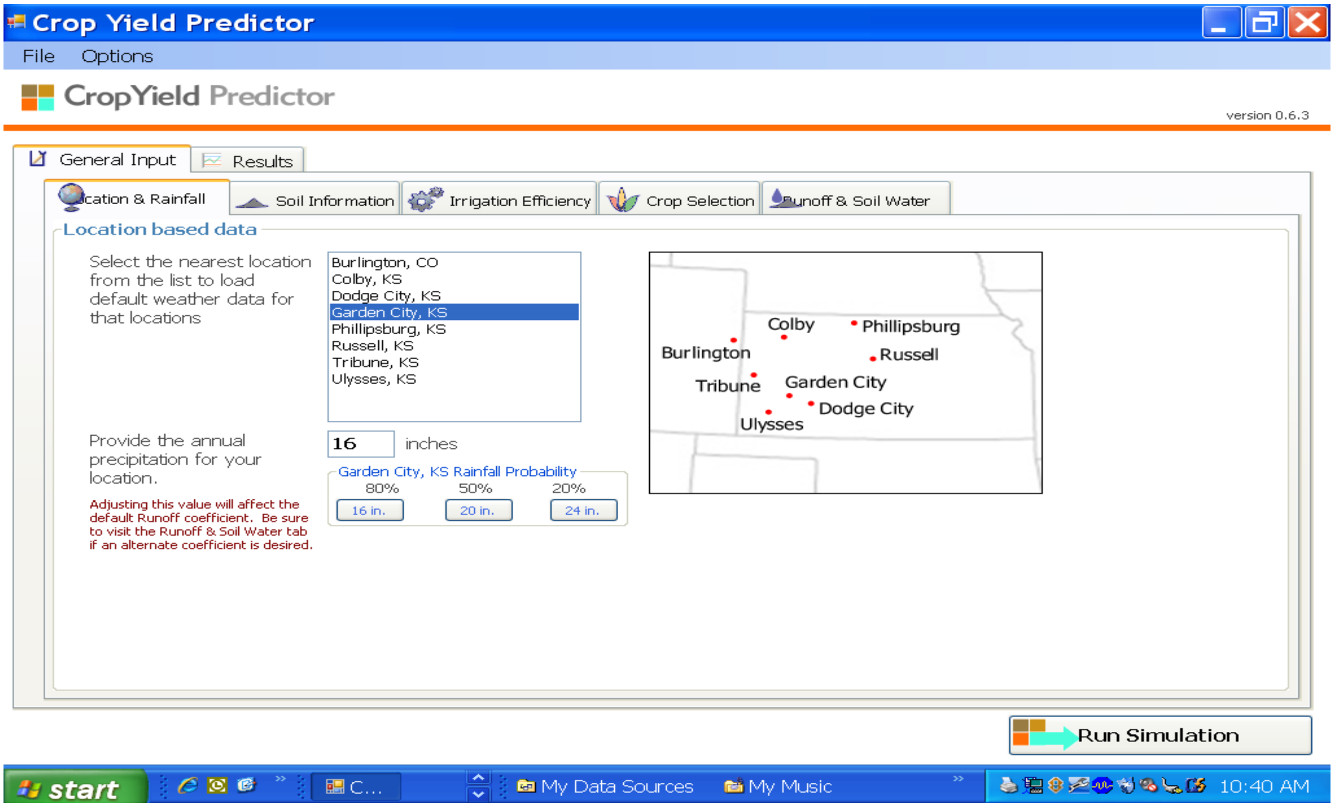
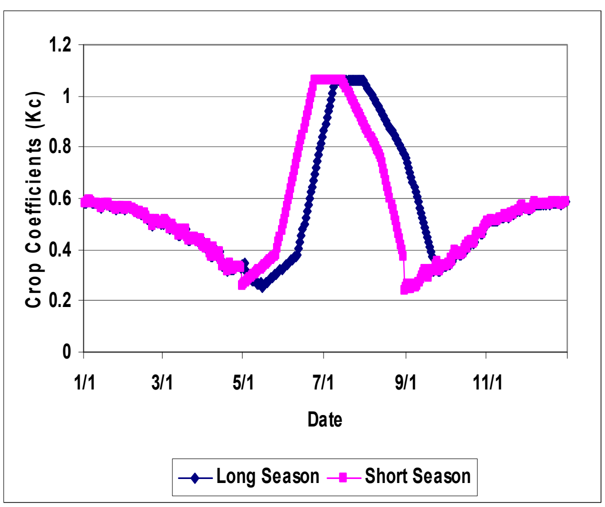


Figure 1. Example of input screen for the Crop Yield Predictor.



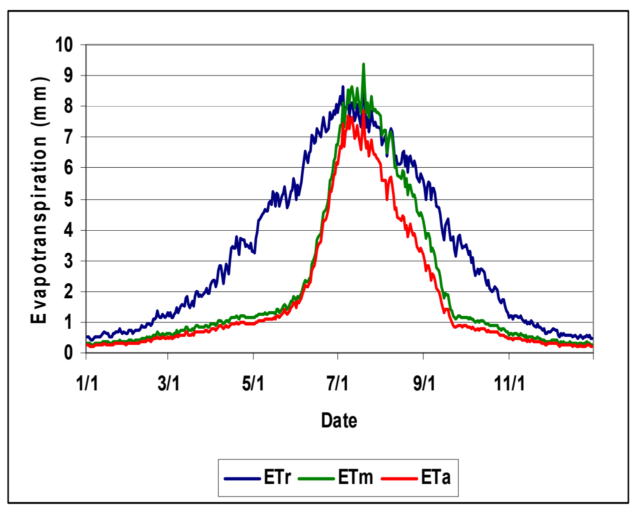


Figure 2. Example of Kc for short season corn planted early and long season corn planted later.

Figure 3. Example of ETr, ETm, and ETa

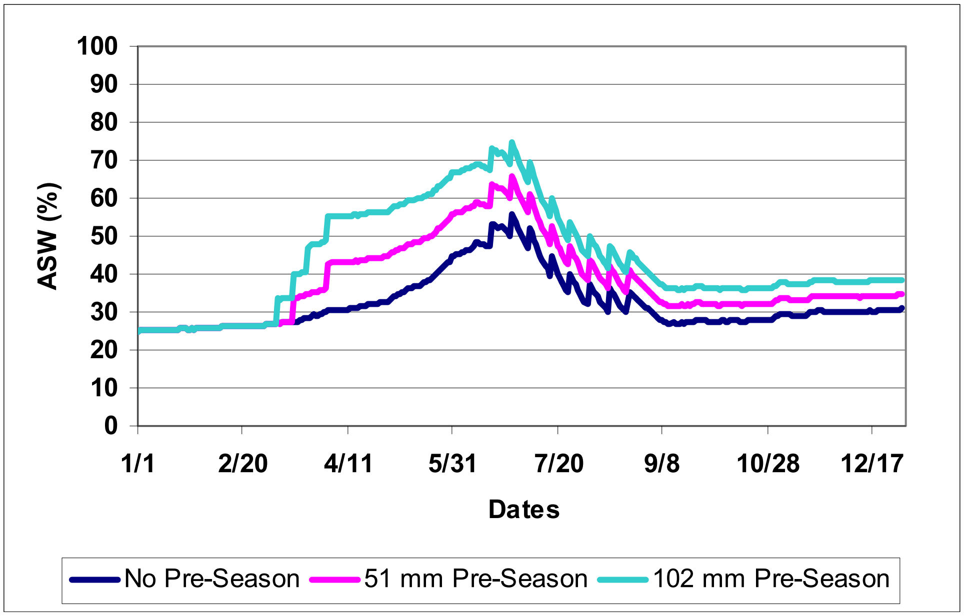


Figure 3. An example of available soil water (ASW) graph for the year with and without pre-growing season irrigation.