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ET-BASED IRRIGATION SCHEDULING

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The water requirement of a crop must be satisfied to achieve potential yields. The crop water requirement is also called crop evapotranspiration and is usually represented as ET_c. Evapotranspiration is a combination of two processes – evaporation of water from the ground surface or wet surfaces of plants; and transpiration of water through the stomata of leaves. The water requirement can be supplied by stored soil water, precipitation, and irrigation. Irrigation is required when ET_c (crop water demand) exceeds the supply of water from soil water and precipitation. As ET_c varies with plant development stage and weather conditions, both the amount and timing of irrigation are important. Estimates of ET_c can be included in a simple water balance (accounting) method of irrigation scheduling to estimate the required amount and timing of irrigation for crops. This method can be used if initial soil water content in the root zone, ET_c, precipitation, and the available water capacity of the soil are known.

The soil in the root zone has an upper as well as a lower limit of storing water that can be used by crops. The upper limit is called the field capacity (FC), which is the amount of water that can be held by the soil against gravity after being saturated and drained; typically attained after 1 day of rain or irrigation for sandy soils and from 2 to 3 days for heavier-textured soils that contain more silt and clay. The lower limit is called permanent wilting point (PWP), which is the amount of water remaining in the soil when the plant permanently wilts because it can no longer extract water. The available water capacity (AWC), or total available water, of the soil is the amount of water between these two limits (AWC = FC – PWP) and is the maximum amount of soil water that can be used by the plants. The AWC of soil is typically expressed in terms of inches of water per inch of soil depth. Available water capacity values for specific soils can be obtained from county soil surveys or online at http://websoilsurvey.nrcs.usda.gov/app/.

SIMPLE WATER BALANCE FOR IRRIGATION SCHEDULING

As the crop grows and extracts water from the soil to satisfy its ET_c requirement, the stored soil water is gradually depleted. In general, the net irrigation requirement is the amount of water required to refill the root zone soil water content back up to field capacity. This amount, which is the difference between field capacity and current soil water level, corresponds to the soil water deficit (D). The irrigation manager can keep track of D, which gives the net amount of irrigation water to apply. On a daily basis, D can be estimated using the following accounting equation for the soil root zone:

$$D_c = D_p + ET_c - P - Irr - U + SRO + DP \qquad [1]$$

where D_c is the soil water deficit (net irrigation requirement) in the root zone on the current day, D_p is the soil water deficit on the previous day, ET_c is the crop evapotranspiration rate for the current day, P is the gross precipitation for the current day, Irr is the net irrigation amount infiltrated into the soil for the current day, U is upflux of shallow ground water into the root zone, SRO is surface runoff, and DP is deep percolation or drainage.

The last three variables in equation 1 (U, SRO, DP) are difficult to estimate in the field. In many situations, the water table is significantly deeper than the root zone and U is zero. Also, SRO and DP can be accounted for in a simple way by setting D_c to zero whenever water additions (P and Irr) to the root zone are greater than $D_p + ET_c$. Using these assumptions, equation 1 can be simplified to:

$$D_c = D_p + ET_c - P - Irr \qquad \text{(if } D_c \text{ is negative, then set it to 0.0)} \qquad [2]$$

Take note that D_c is set equal to zero if its value becomes negative. This will occur if precipitation and/or irrigation exceed ($D_p + ET_c$) and means that water added to the root zone already exceeds field capacity within the plant root zone. Any excess water in the root zone is assumed to be lost through SRO or DP.

The amounts of water used in the equations are typically expressed in depths of water per unit area (e.g., inches of water per acre). Equation 2 is a simplified version of the soil water balance with several underlying assumptions. First, any water additions (P or Irr) are assumed to readily infiltrate into the soil surface and the rates of P or Irr are assumed to be less than the long term steady state infiltration rate of the soil. Actually, some water is lost to surface runoff if precipitation or irrigation rates exceed the soil infiltration rate. Thus, equation 2 will under-estimate the soil water deficit or the net irrigation requirement if P or Irr rates are higher than the soil infiltration rate. Knowledge of effective precipitation (P – SRO – DP), irrigation, and soil infiltration rates (e.g. inches per hour) are required to obtain more accurate estimates of D_c. Secondly, water added to the root zone from a shallow water table (U) is not considered. Groundwater contributions to soil water in the root zone must be subtracted from the right hand side of the equation in case of a shallow water table. Equation 2 will over-estimate D_c if any actual soil water additions from groundwater are neglected.

It is a good practice to occasionally check (e.g., once a week) if D_c from equation 2 is the same as the actual deficit in the field (soil water content readings using soil moisture sensors). Remember that D_c is the difference between field capacity and current soil water content. Therefore, the actual deficit in the field can be determined by subtracting the current soil water content from the field capacity of the root zone. If D_c from equation 2 is very different from the observed deficit, then use the observed deficit as the D_c value for the next day. These corrections are necessary to compensate for uncertainties in the water balance variables. Field measurements of current soil water content can be performed using the gravimetric method (weighing of soil samples before and after drying) or using soil water sensors like gypsum blocks (resistance method).

In irrigation practice, only a percentage of AWC is allowed to be depleted because plants start to experience water stress even before soil water is depleted down to PWP. Therefore, a management allowed depletion (MAD, decimal fraction) of the AWC must be specified. Values of MAD can range from 0.20 for crops highly sensitive to water stress to 0.65 for crops with high tolerance to water stress. Also, MAD is lower for more sensitive growth phases of the crop (e.g., reproductive phase). The rooting depth and MAD for a crop will change with developmental stage. The MAD can be expressed in terms of depth of water (d_{MAD}; inches of water) using the following equation.

$$d_{MAD} = (MAD) * AWC * D_{rz} \qquad [3]$$

where MAD is management allowed depletion (decimal fraction), AWC is available water capacity of the root zone (inch of water per inch of soil), and D_{rz} is depth of root zone (inches).

The value of d_{MAD} can be used as a guide for deciding when to irrigate. Typically, irrigation water should be applied when the soil water deficit (D_c) approaches d_{MAD}, or when $D_c \geq d_{MAD}$. To minimize water stress on the crop, D_c should be kept less than d_{MAD}. If the irrigation system has enough capacity, then the irrigator can wait until D_c approaches d_{MAD} before starting to irrigate. The net irrigation amount equal to D_c can be applied to bring the soil water deficit to zero. Otherwise, if the irrigation system has limited capacity (maximum possible irrigation amount is less than d_{MAD}), then the irrigator should not wait for D_c to approach d_{MAD}, but should irrigate more frequently to ensure that D_c does not exceed d_{MAD}. However, keep in mind that more frequent irrigations increase evaporation of water from the soil surface, which is considered a loss. In addition, when rainfall is in the forecast, the irrigator might want to leave the root zone below field capacity to allow for storage of forecasted precipitation.

ESTIMATING CROP ET

Crop evapotranspiration (ET_c), in inches per day, is estimated as:

$$ET_c = ET_r * K_c * K_s \quad [4]$$

where ET_r is the evapotranspiration rate (inches/day) from a reference crop (e.g., alfalfa), K_c is a crop coefficient that varies by crop development stage (ranges from 0 to 1), and K_s is a water stress coefficient (ranges from 0 to 1). A K_s of 1 means that the crop is not experiencing water stress, so a value of 1 can be assumed for fully irrigated conditions. At any given point in the growing season, the K_c for a crop is simply the ratio of its ET over the reference crop ET. The K_c can be thought of as the fraction of the reference crop ET that is used by the actual crop. Values of K_c typically range from 0.2 for young seedlings to 1.0 for crops at peak vegetative stage with canopies fully covering the ground. In some instances, peak K_c might reach 1.05-1.10, for crops showing similar biomass characteristics as alfalfa, when the soil and canopies are wet (after irrigation/rain). An example crop coefficient curve (K_c values that change with crop development) is shown in Figure 1. Crop coefficient values for commonly grown crops are provided by Allen et al. (1998; 2007).

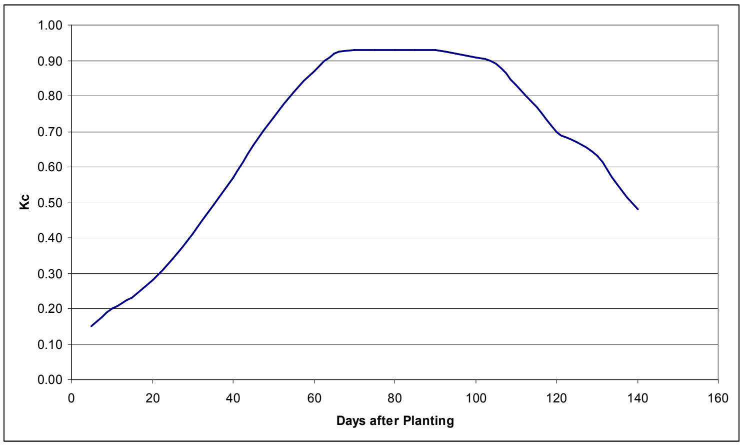

Figure 1. Example crop coefficient curve that shows *K_c* values that change with crop development.

Reference crop evapotranspiration (ET_r) can be calculated from daily weather data. One equation that is being widely adopted for estimating ET_r is the ASCE standardized reference ET equation (Allen et al., 2005). The Colorado Agricultural Meteorological Network (www.CoAgMet.com) is one example of an online source of daily ET_r values for various locations. Similar sources of ET_r can also be found in other states.

In cases when water availability is limited (e.g., lack of precipitation or irrigation), then K_s will be less than 1, and crop ET_c will not occur at the potential (nonwater-limited) rate. The water stress coefficient can be estimated by (Allen et al., 1998):

$$K_s = [TAW - D] / [(1 - MAD) * TAW] \qquad (K_s = 1 \text{ if } D < d_{MAD}) \qquad [5]$$

where TAW is total available water in the soil root zone (inches), D is the soil water deficit (inches), and MAD is management allowed depletion (decimal fraction). The value of TAW can be calculated from:

$$TAW = AWC * D_{rz} \qquad [6]$$

where AWC is available water capacity of the root zone (inch of water ⁄ inch of soil) and D_{rz} is the total depth of the root zone (inches). In equation 5, MAD is specifically defined as the fraction of AWC that a crop can extract from the root zone without suffering water stress. Note that K_s should be set equal to one when D is less than d_{MAD}.

Crop Coefficients from a Weighing Lysimeter

An accurate way to measure ET rates of crops is to use a precision weighing lysimeter that directly measures ET based on changes in weight of an intact block of soil (monolith) containing an actively growing crop. A diagram of a precision weighing lysimeter is shown in Figure 2 and detailed descriptions have been given by Marek et al. (1988). As the crop actively growing in the monolith consumes water via ET, a sensitive weighing scale detects the drop in weight that can easily be converted to equivalent ET. The scale can also detect water inputs (precipitation, irrigation) and drainage. The lysimeter and surrounding field are managed similarly so that crop ET values from the lysimeter are representative of the entire field.

In the lower Arkansas River Basin of Colorado, two weighing lysimeters were installed to directly measure the ET of locally-grown crops and develop crop coefficients that are representative of local growing conditions. The lysimeters are located at the Colorado State University (CSU) – Arkansas Valley Research Center (AVRC) at Rocky Ford, Colorado. The monolith tank dimensions of the large lysimeter are 10 feet wide by 10 feet long by 8 feet deep (3 m x 3 m x 2.4 m). A smaller lysimeter, which is meant to grow an alfalfa reference crop, has monolith tank dimensions of 5 feet wide x 5 feet long x 8 feet deep (1.5 m x 1.5 m x 2.4 m). More details about the lysimeters at Rocky Ford, Colorado are given by Andales et al. (2010).

Daily crop coefficients are calculated by taking the ratio of crop ET from the lysimeter and alfalfa reference ET calculated from the ASCE standardized reference ET equation (Allen et al., 2005). So far, preliminary crop coefficient curves for 4 cutting cycles of alfalfa hay have been developed (2008-2010 data).

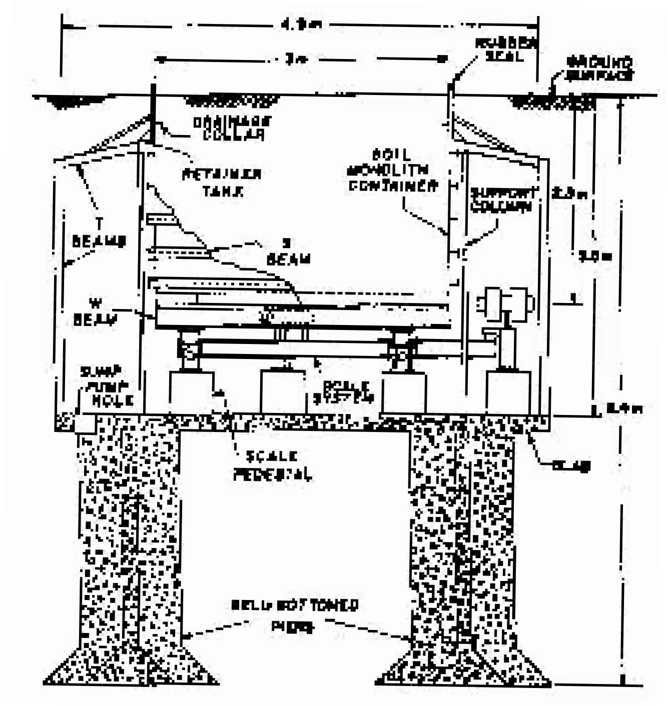

Figure 2. Diagram of a precision weighing lysimeter (Marek et al., 1988), similar to one installed at Rocky Ford in the lower Arkansas River Basin of southeast Colorado.

AN EXAMPLE FROM NORTHEAST COLORADO

Equations 2 through 6 can easily be entered as formulas into a spreadsheet, with columns for daily values of P, Irr, D_{rz}, TAW, ET_r, K_c, K_s, ET_c, and D_c. Values of P, Irr, D_{rz}, and ET_r can be input in the spreadsheet on a daily basis, and D_c calculated automatically. This was done for a center pivot-irrigated corn field near Greeley, Colorado for the 2010 growing season (Figure 3). The daily soil water deficit was calculated using equation 2. At the start of the season, the root zone was approximately at field capacity and the initial deficit (D_p) was assumed to be zero. For simplicity, the K_s value was assumed equal to 1 (no water stress) throughout the season because the field was being fully irrigated. The deficit values in Figure 3 are represented as negative values to intuitively represent reductions in soil water content.

Stored soil moisture and precipitation during the seedling and early vegetative phases of the corn crop were generally adequate, except for a short period from late May to early June when the deficit exceeded the d_{MAD}. However, significant rains from June 10 to 14 brought the deficit to zero and allowed for a further delay in running the center pivot. The center pivot system was turned on June

27, when the soil water deficit began approaching d_{MAD} and rain was not in the forecast. For most of the vegetative and reproductive corn phases, the deficit did not exceed d_{MAD}. Irrigations were reduced after the reproductive phase and eventually stopped as the corn grains matured. This example shows that estimated crop ET used in a simple water balance approach can help track soil water deficits for determining irrigation amount and timing.

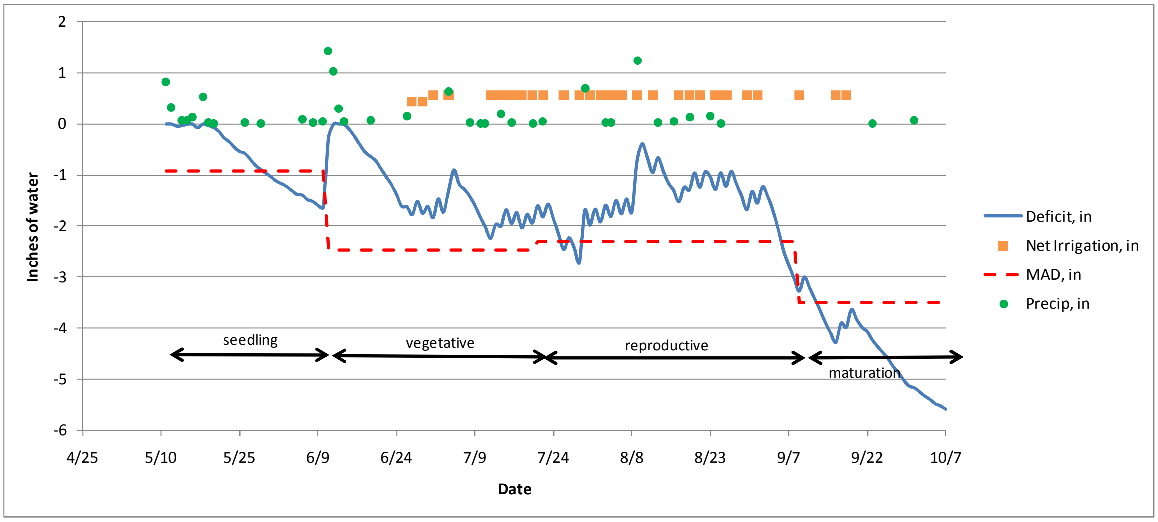

Figure 3. Soil water deficit, net irrigation, and precipitation in a center pivot-irrigated corn field near Greeley, CO during the 2010 growing season. Daily values of corn ET_c estimated from equation 4 were used to estimate daily soil water deficit (equation 2).

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