

SPREADSHEET IMPLEMENTATION OF IRRIGATION SCHEDULING BY THE CHECKBOOK METHOD FOR NORTH DAKOTA AND MINNESOTA

D. D. Steele, T. F. Scherer, D. G. Hopkins, S. R. Tuscherer, J. Wright

ABSTRACT. A water balance irrigation scheduling algorithm and supporting crop evapotranspiration (ET) tables have been available in a paper format for North Dakota and Minnesota irrigators for over 20 years, yet a need exists for explanation and documentation of the algorithms in a computerized format accessible to students, technical personnel, consultants, farmers, and others who do not possess a computer programming background. The objectives of this article are: 1) to present a useable spreadsheet implementation of a checkbook-type water balance algorithm for irrigation scheduling, and 2) to provide documentation sufficient to use the algorithms as teaching and learning tools. The spreadsheet uses rows for days in the growing season and columns for various date, weather, and water balance components. Use of macros was avoided for simplicity, accessibility, and to preclude user concerns about viruses. Advantages of the spreadsheet include relative ease of understanding the underlying algorithms and their implementation, ability to forecast irrigation schedules and examine other “what-if” scenarios, flexibility for note-taking and simple alterations, speed of calculation, and transferability to other regions if local ET data or algorithms are available. Disadvantages of the spreadsheet include demands on the user to collect input data and manage files. Limitations of the algorithms are discussed for situations involving possible contributions of shallow ground water to ET; slowly-drained soils; variable topography; and salinity and sodicity effects on soils, crop growth, and ET. The spreadsheet has been used in instructional and research settings to teach and manage irrigation scheduling tasks for a variety of situations.

Keywords. Irrigation scheduling, Water balance method, Evapotranspiration, Soil water, Water management, Algorithms, Mathematical models, Computer simulation, Prediction, Spreadsheet.

Irrigation scheduling has been defined as “the process of determining when to irrigate and how much water to apply, based upon measurements or estimates of soil water or water used by the plant” (ASABE Standards, 2007) and has been divided into methods based on either soil

or plant monitoring or soil water balance estimates (Martin et al., 1990). Methods for monitoring or estimating the soil water status or ET include the hand feel and appearance of soil, gravimetric soil water sampling, tensiometers, electrical resistance blocks, water balance approaches, and modified atmometer (Broner, 2005). While detailed reviews of irrigation scheduling methods and algorithms are beyond the scope of this article, water balance irrigation scheduling software may be generally categorized into spreadsheet applications, compiled software, and Internet-based services. Spreadsheets have been developed for users in locations such as California (Snyder et al., 2007), Kansas (Rogers et al., 1997; Clark et al., 1998), and Colorado (Northern Colorado Water Conservancy District, 2006). Bland (no date) developed a water balance spreadsheet relying on externally-supplied evapotranspiration (ET) estimates; Allen et al. (1998) developed a spreadsheet to calculate reference ET, crop ET, and an irrigation schedule; and McCann et al. (2008) modified the latter for use in scheduling deficit irrigations in a Mediterranean climate. Compiled programs have been developed for Kansas (Clark et al., 2002; Rogers et al., 2002a, 2002b; Rogers and Alam, 2007), Arizona (Fox et al., 1993; Martin et al., 2007), Arkansas (Tacker, 2009), and other locations. Web-based services such as the North Dakota Agricultural Weather Network (NDAWN; North Dakota Agricultural Weather Network Center, 2010) and the Washington Agricultural Weather Network (AgWeatherNet; Washington Agricultural Weather Network, 2010) provide weather data for use in irrigation scheduling. The NDAWN system provides an

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application for irrigation scheduling (Scherer and Morlock, 2008) and both NDAWN and AgWeatherNet provide crop disease forecasting models. It should be noted that while applications for irrigation scheduling may provide a scientific method for estimating ET, they may also require the user to determine how the data will be used, whether on a replacement basis, a soil water accounting system, etc. Some applications are state- or region-specific because they retrieve weather data from specific networks. Compiled programs and internet-based services have the advantage of reducing the work required by users in their home location. Their limitations include the following: the data, data interfaces, and code are not generally portable for use in other regions; they may be constrained to a particular computer operating system; and they may have limited or no note-taking capabilities. Similarly, complex spreadsheets may be constrained to a particular version of that spreadsheet.

The objectives of this article are: 1) to present a useable spreadsheet implementation of a checkbook-type water balance algorithm for irrigation scheduling, and 2) to provide documentation sufficient to use the algorithms as teaching and learning tools. The algorithms, data requirements, and layout of a spreadsheet-based implementation of a checkbook algorithm (Lundstrom and Stegman, 1988; Wright, 2002) for water balance irrigation scheduling are presented. The spreadsheet models changes in the root zone depth as the season progresses and reduces ET as the soil-water deficit (SWD) increases (Stegman and Coe, 1984). Although we emphasize the development of methods implemented in North Dakota and Minnesota it should be noted that the water balance approach to irrigation scheduling is universal, the methods presented can be adapted for use in other regions, and variations in the algorithms are illustrated throughout this article. To encourage widespread use and to preclude concerns about viruses, we present only conventional spreadsheet algebra and built-in functions and do not invoke macros or use programming languages. Computer programming experience is not required to run the spreadsheet or to examine “what-if” scenarios. The spreadsheet approach is expected to have educational value for a broad audience including farm managers, technical personnel, crop consultants, teachers, and students.

BACKGROUND

SOIL WATER BALANCE ALGORITHM

The soil water balance is based on the conservation of mass, i.e., Inflow – Outflow = ΔS . See the Nomenclature appendix for definitions of symbols and variables. A one-dimensional form for use in irrigation scheduling is:

$$R_i + I_i - ET_i - WL_i = S_{i+1} - S_i \quad (1)$$

where all measurements are expressed on a depth equivalent (length) basis. Soil-water content can be expressed as a deficit rather than S, i.e.,

$$SWD_i = FC - S_i \quad (2)$$

The soil water concepts (ASABE Standards, 2007) for water balance irrigation scheduling can be expressed on the basis of volume, depth equivalent, or percentage and are

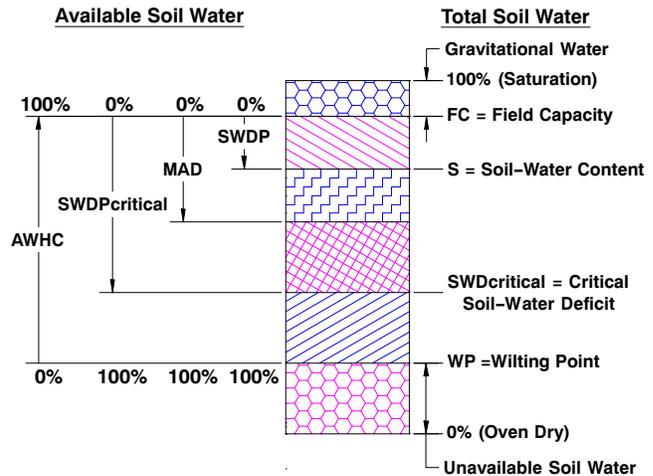


Figure 1. Soil-water terminology related to water balance irrigation scheduling. See the Nomenclature appendix for abbreviations. The MAD and SWD_{critical} values are not necessarily equal. All values are arbitrary and not intended to represent a particular soil.

illustrated in figure 1. Additional details are provided in the following discussion.

For irrigation scheduling purposes, daily time steps are common and users are most often interested in estimating the irrigation amount(s) and date(s) of application needed to maintain the SWD at some future date at or above the MAD, the latter being “the desired soil-water deficit at the time of irrigation” (ASABE Standards, 2007). The SWD value at a future date is obtained by combining equations 1 and 2 to obtain:

$$SWD_{i+1} = SWD_i + ET_i + WL_i - R_i - I_i \quad (3)$$

Evapotranspiration is often estimated as the product of ET_r and K_c curves, where ET_r is estimated from weather parameters using Penman-type equations (Allen et al., 2007) and the K_c curves are crop- and location-specific. The Jensen and Haise (1963) algorithm for ET_r requires fewer weather parameters than Penman-type equations and has long been used in North Dakota to implement K_c curves (Stegman et al., 1977).

NORTH DAKOTA AND MINNESOTA APPLICATIONS

Stegman and Valer (1972) developed K_c curves for sugar beets, corn, potatoes, alfalfa, spring wheat, and flax in east-central North Dakota. Stegman et al. (1977) continued this work by developing K_c curves in southeastern North Dakota for sugar beet, corn, spring wheat, soybean, potato, and alfalfa. In both studies, the K_c curves were based on days past emergence (days past 1 May for alfalfa) and were referenced to ET_r from the Jensen and Haise algorithm, which requires measurement of T_{min} , T_{max} , and R_s .

Lundstrom and Stegman (1977, 1983, 1988) reduced the input data requirements of the Jensen and Haise ET_r method by assuming that long-term mean values for T_{min} and R_s in the state were sufficiently accurate. Their resulting tables of water use were based on WPE and 5.6°C (10°F) intervals of T_{max} . Tables were developed for the crops listed by Stegman et al. (1977) along with pinto bean, sunflower, and barley. For example, ET estimates for alfalfa are shown in table 1. Subtables were added to account for reduced alfalfa water use for three weeks after the first and second cutting (table 2) and

Table 1. Alfalfa ET for the uncut condition.

Daily Maximum Temperature (°C)	Estimated Evapotranspiration ^[a] (mm day ⁻¹)																					
	Week after 1 May																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
10.0	1.0	1.3	1.5	1.8	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.8	1.8	1.5	1.5	1.3	1.3	1.3	
15.6	1.8	2.3	2.8	3.0	3.3	3.3	3.3	3.6	3.6	3.6	3.6	3.6	3.3	3.3	3.0	2.8	2.5	2.5	2.3	2.0	2.0	
21.1	2.3	3.0	3.8	4.3	4.6	4.6	4.8	4.8	4.8	4.8	4.8	4.8	4.6	4.3	4.3	4.1	3.8	3.6	3.3	3.0	2.8	
26.7	3.0	4.1	4.8	5.6	5.8	5.8	6.1	6.1	6.4	6.4	6.4	6.4	6.1	5.8	5.6	5.3	5.1	4.8	4.3	4.1	3.8	3.6
32.2	3.8	4.8	5.8	6.9	7.1	7.4	7.4	7.6	7.6	7.6	7.6	7.6	7.4	7.4	6.9	6.6	6.4	5.8	5.3	5.1	4.6	4.3

^[a] Adapted from table 14 of Lundstrom and Stegman (1988). Note the original was written in U.S. customary units and some rounding errors may be present in this table.

Table 2. Alfalfa ET for the first three weeks after the first and second cuttings.

Daily Maximum Temperature (°C)	Estimated Evapotranspiration ^[a] (mm day ⁻¹)		
	Week after First and Second Cut		
	1	2	3
10.0	1.3	1.5	2.0
15.6	2.0	2.8	3.3
21.1	2.8	3.8	4.6
26.7	3.8	4.8	5.8
32.2	4.6	5.8	7.1

^[a] Adapted from table 14 of Lundstrom and Stegman (1988). Note the original was written in U.S. customary units and some rounding errors may be present in this table.

a similar table (not shown) for the third cutting. The “Checkbook” algorithm was presented in worksheets to be completed by hand. Killen (1984), Wright and Bergsrud (1991), and Wright (2002) adapted the North Dakota application for use in Minnesota. The North Dakota and Minnesota publications have helped farmers schedule irrigations and understand crop water requirements. A disadvantage of a paper-based approach is that the computations become time-consuming for irrigators with several fields to manage and for those who wish to examine “what-if” scenarios such as forecasting future irrigation needs or comparing deficit versus full irrigation.

Stegman and Coe (1984) developed computer code in BASIC to implement a soil water balance algorithm for irrigation scheduling. They used Stegman et al.’s (1977) earlier K_c curves for spring wheat, corn, soybean, and alfalfa; added curves for sunflower, pinto bean, and barley; and omitted the curves for sugar beet and potato. The algorithm was documented by Steele et al. (1997), who implemented it in a spreadsheet format for comparison of Stegman et al.’s (1977) corn K_c curve, K_c curves developed for corn using nonweighing lysimeters (Steele et al., 1996), and the checkbook water use tables of Lundstrom and Stegman (1988) to measurements of S in nonweighing lysimeters at another site.

In 1995, Egeberg and Scherer (1998) integrated crop water use tables and maps into the NDAWN system (NDAWN Center, 2010). The tables and maps provide daily crop ET estimates for ten commonly irrigated crops in North Dakota for each station on the NDAWN network. The Jensen and Haise (1963) equation is used to obtain ET_r and the crop ET values (for the ten crops) are calculated using the K_c curves of Stegman et al. (1977).

Steele et al. (1999) developed a stand-alone computer program based on the checkbook crop water use tables for North Dakota (Lundstrom and Stegman, 1988) and Minnesota (Wright and Bergsrud, 1991). The algorithm was implemented in a Lotus 123 spreadsheet environment and compiled into a stand-alone program (TechTools, 1996) so users were not required to have a particular brand of spreadsheet. An advantage of a spreadsheet environment is that users can easily see the effects of changes in variables. For example, future SWD values can be estimated by changing weather variables according to a local weather forecast and users can play what-if scenarios for different irrigation amounts, timing, etc. Stegman and Valer (1972) discussed the forecasting concept as “days to next irrigation.”

Scherer and Haq (2004) developed an irrigation scheduling program for use on a personal digital assistant (PDA). Estimated daily crop water use values could be obtained the following ways: 1) the user entered T_{max} and the crop ET value was obtained from the Lundstrom and Stegman (1988) tables, or 2) the user entered R_s and average air temperature values and the program calculated ET using the Jensen and Haise (1963) ET_r equation and K_c curves. The algorithm was later updated to accommodate cut dates for alfalfa, but the PDA application was discontinued due to a lack of interest by irrigators. The algorithm for alfalfa cut dates was incorporated into the web-based irrigation scheduling application by Scherer and Morlock (2008).

METHODS

OVERVIEW

Equation 3 was implemented with Microsoft Office Excel 2007 (Microsoft Corp., 2006) and the reader is referred to the software’s documentation for names and descriptions of built-in functions. It is assumed that the reader has basic familiarity with spreadsheets. Refer to figure 2 for the following discussion of the spreadsheet layout and formulas. Worksheets named “Sheet1_ND_SI” and “Sheet1_ND_Inch” are provided for calculations in SI and U.S. customary units, respectively, for North Dakota, and a sheet named “Sheet1_MN_Inch” is provided for Minnesota. In the following discussion, we assume the reader can adjust the worksheet names such as “Sheet1” and “Sheet1!” as needed for SI or U.S. customary units. We also assume that the reader is familiar with copying, renaming, reorganizing, and other worksheet operations; sheet operations become important when managers need records and computations for different crops, water balance locations, fields, years, states, etc.

Formulas in this section of the article are written as they would be entered in the spreadsheet with additional explanations in traditional mathematical format as needed. Spreadsheet formulas are included to help the reader understand how the mathematics of water balance irrigation scheduling are implemented in a spreadsheet and to increase users' abilities to edit the spreadsheet for their particular situation. Names are used extensively in the spreadsheet, e.g., "Alfalfa" refers to the spreadsheet range Sheet1_ND_SI!\$BA\$365:\$BW\$370 and contains a lookup table of ET values for alfalfa from Lundstrom and Stegman (1988) and corresponding to table 1. Names are limited in scope to the current worksheet rather than the entire workbook to provide flexibility for copying and deleting sheets. Comments are used throughout the spreadsheet to provide instructions and explain variables (Buckmaster, 2006). Data validation is used to provide user prompts and minimize errors. Various working sections or blocks of the worksheet are arranged in a top-left to lower-right diagonal fashion to provide flexibility for insertion of new rows and columns for tasks such as use of additional weather data, modification of the ET algorithm, etc. That is, the diagonal layout is intended to minimize or preclude problems such as interruption of lookup tables which may be caused by insertion, deletion, and rearrangement of rows and columns. The main water balance computational area occupies the range A1:T165, crop and soil information occupies AA170:AH224, ET tables occupy BA230:BW372, a chart occupies CA400:CO437, etc. Hyperlinks are provided at the top of the water balance area for navigation within the worksheet. External hyperlinks are also provided for the NDAWN system (NDAWN Center, 2010) and the Web Soil Survey (Soil Survey Staff, 2009) web sites to help users obtain weather and soils data, respectively. For links to locations within the current worksheet, the HYPERLINK function (Softartisans, Inc., 2008; Ozgrid, no date) was used rather than inserting conventional hyperlinks via the cell

editing shortcut menu. For example, the formula in cell N2 is:

```
=HYPERLINK("#"&MID(CELL("filename",A1),FIND("[",CELL("filename",A1))+1,256)&"!"&ADDRESS(ROW(Crops_and_Soils),COLUMN(Crops_and_Soils),1,TRUE),"Crops & Soils")
```

where "Crops_and_Soils" is a spreadsheet name at the upper-left corner of a block of cells used for crop information and soil profile information. The dynamic HYPERLINK function keeps a link's destination within the current worksheet regardless of the number of times a worksheet has been copied. By contrast, if Sheet1 is copied to Sheet2 for another field or growing season, conventional or static hyperlinks within Sheet2 bring the user to the desired cell location (row and column) on Sheet1 rather than Sheet2. The HYPERLINK function outlined here also accommodates row and column insertions and deletions, a characteristic which maintains navigability after user modifications (row or column insertions or deletions) for other algorithms or site-specific needs. Dynamic return hyperlinks are provided throughout each worksheet to bring the user back to the upper left corner of the water balance area (cell B8) of that worksheet. Users are encouraged to create dynamic and external hyperlinks for their own navigational needs.

GENERAL WATER BALANCE

Rows 1 through 5 in figure 2 contain a brief instruction set; site information; internal and external links, crop type and emergence date, and cut dates if alfalfa is used. Rows 6 and 7 contain column headers and units, respectively. Rows 8 through 161 contain the water balance components for each day within the typical North Dakota and Minnesota growing season of 1 May through 30 September. The water balance estimates for a given date are assumed to represent daily totals for R, I, ET, and WL, while SWD values represent the soil water status at the end (11:59 P.M.) of each day.

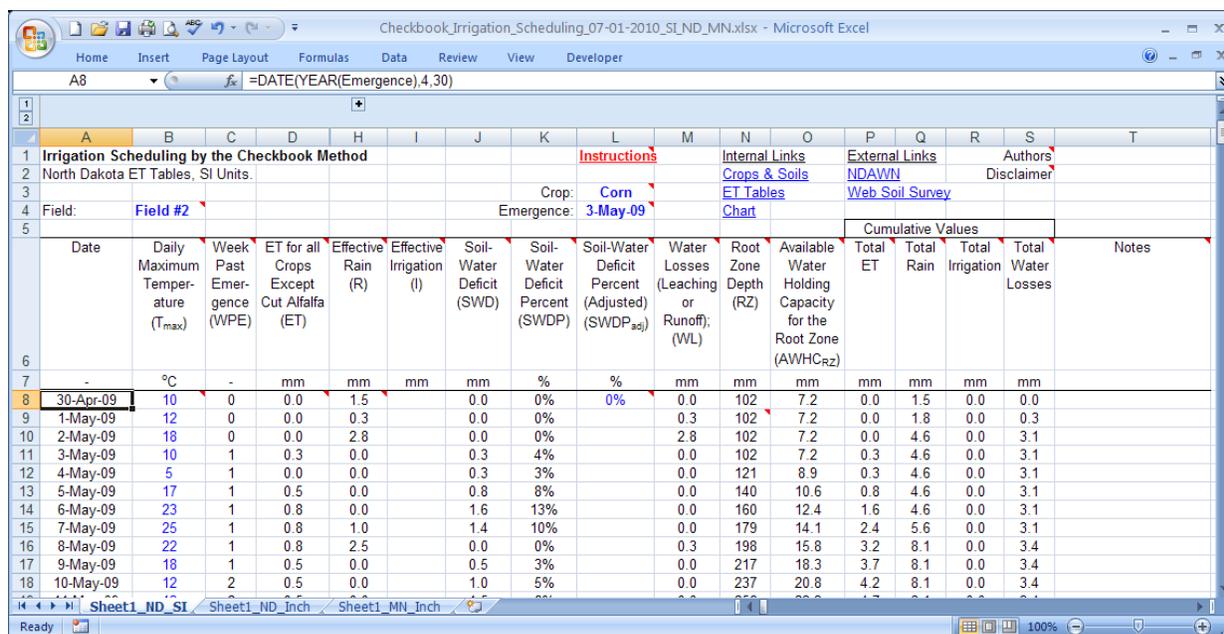


Figure 2. Spreadsheet layout for water balance irrigation scheduling. Columns E, F, and G for ET calculations related to alfalfa cut and regrowth periods are hidden in this view because the crop (cell L3) is not alfalfa.

Initialization of growing conditions at the end of 30 April for each year is included in row 8 and summary statistics for the season are included in rows 163 through 165.

Columns of the spreadsheet are used for date, weather, and water balance components. The columns are described later, with particular emphasis on formulas used for 1 May. Values of R, I, SWD, WL, and AWHC are water depth equivalents unless indicated otherwise.

Column A contains a sequential series of days (dimensionless) from 30 April through 30 September. The 30 April line can be used to initialize the SWD value for the start of the alfalfa season, in which green-up is assumed to be 1 May (Lundstrom and Stegman, 1988). The user enters the date of crop emergence in cell L4 (assigned the name “Emergence”) in (mm/dd/yyyy) format. The formula for 30 April in cell A8 is:

=DATE(YEAR(Emergence),4,30)

which adjusts the sequence of date values in the spreadsheet so they apply for that year and no additional editing of dates is required. The formula is =A8+1 in cell A9, =A9+1 in cell A10, etc. through the end of the season. The length of this section of the spreadsheet can be adjusted for regions with longer or shorter growing seasons by inserting or deleting rows as needed. For winter growing seasons or use in the Southern Hemisphere, the user will need to adjust date-related cells and formulas.

Column B requires the user to enter measured or estimated values of T_{max} for past or future dates. Weather forecasts can be used to predict future SWD values and plan irrigation applications accordingly. We recommend a maximum forecast not exceeding 1 week because of uncertainties in weather predictions. Rogers and Alam (2007) provide forecast capabilities of 5 d. Users should also be aware that spatial variability of AWHC affects irrigation scheduling. In the spreadsheet, users can insert columns as necessary to accommodate additional weather variables for more complex — and perhaps more accurate — ET algorithms such as Penman-type equations (Allen et al., 2007), additional columns for K_c values, etc.

Column C computes the WPE based on the user-supplied emergence date. The formula for 30 April is:

=IF(A8<Emergence,0,INT((A8-Emergence)/7)+1)

The IF function assigns a zero value to WPE if the current date is less than (before) the emergence date. Users can employ K_c algorithms based on days past emergence or growing degree days within this column or by the addition of more columns. Users can also enter ET values from other sources but should be aware that entering new ET data overwrites and disables the spreadsheet lookup formulas used to retrieve ET data from the water use tables. As with temperature data, users can play what-if scenarios by entering estimated ET values to determine effects on irrigation dates and amounts.

Column D computes ET_i for 1 May with the formula:

=IF(C9>0,IF(K8<=SWDcritical,1,((1-K8)/(1-SWDcritical)))*VLOOKUP(B9,INDIRECT(Crop),C9+1),0)

If WPE > 0, the crop has emerged and the formula computes ET_i based on values in a lookup table; otherwise ET_i is zero.

The term “SWDcritical” value is supplied by the user. “Crop” is a name for cell L3. Use of the INDIRECT function allows the user to select a crop from a validation list in the Crop cell while directing the VLOOKUP function to the appropriate named table of ET values (Corn, Spring_Wheat, etc.). The ET used in the water balance (eq. 3) is calculated as $ET_i = K_a ET_{tabulated}$. Stegman and Coe’s (1984) algorithm for K_a is as follows: $K_a = 1$ if $AWP \geq 50\%$ and $K_a = AWP / 50\%$ if $AWP < 50\%$. The K_a parameter was described by Allen et al. (1998; K_s in their notation). Note that $SWDP = 1 - AWP$ and the K_a factor can be written as:

$$K_a = 1 \text{ if } SWDP_{i-1} \leq SWDP_{critical} \quad (4)$$

$$K_a = \left[\frac{1 - SWDP_{i-1}}{1 - SWDP_{critical}} \right] \text{ if } SWDP_{i-1} > SWDP_{critical} \quad (5)$$

The $SWDP_{critical}$ value in the spreadsheet is not restricted to the 50% value used by Stegman and Coe (1984); its value can be changed in the crop and soil information area of the spreadsheet, discussed later. The $SWDP_{critical}$ parameter has been described as a depletion fraction or soil water content threshold by Allen et al. (1998), who listed values at which soil water stress begins to reduce ET for a variety of crops. Data validation ensures $0\% \leq SWDP_{critical} \leq 100\%$. Continuing the calculation of ET for 1 May, if the $SWDP$ value (at 11:59 P.M. on the previous day or 12:01 A.M. today; $SWDP_{i-1}$) is less than or equal to $SWDP_{critical}$, then $K_a = 1$ and $ET_i = ET_{tabulated}$. The value of $SWDP_{i-1}$ is found from the previous day, hence the need for the initial value of $SWDP$ for 30 April in cell L8. The VLOOKUP formula proceeds to the appropriate lookup table for ET as a function of T_{max} , the crop type specified by the user, and WPE. If $SWDP > SWDP_{critical}$, then $0 \leq K_a < 1$, i.e., K_a reduces ET in direct proportion to the amount $SWDP$ exceeds $SWDP_{critical}$. From a modeling standpoint, the K_a factor prevents ET from continuing unabated under water-stressed conditions and causing $SWDP$ values to exceed their physical upper limit of 100%. Additional columns can be inserted to accommodate other ET and K_a algorithms.

It should be noted that $SWDP_{critical}$ is not necessarily the same as the MAD value (fig. 1). For example, an agronomist or plant physiologist may indicate that yield-reducing stress is expected at $SWDP_{critical} = 40\%$, but a crop manager may want to have a margin of safety and therefore chooses to irrigate at a target of $MAD = 30\%$. The spreadsheet allows $SWDP_{critical}$ and MAD values to be entered separately in the crop and soil information area of the spreadsheet. Conditional formatting changes the $SWDP$ values in column K to red color if they exceed the MAD value. The MAD value and the associated color coding of $SWDP$ values serve only to remind the user of the targeted $SWDP$ value and do not affect the soil water balance.

The ET table for alfalfa (table 1) spans 22 weeks (154 days), which exceeds the 153 days between 30 April and 30 September included in the scheduling season for North Dakota. The ET tables for crops with growing seasons shorter than 22 weeks are appended with zeros to avoid VLOOKUP errors. Each crop’s ET table also includes a top row of zero (0) values to avoid VLOOKUP errors for days when $T_{max} < 10^\circ\text{C}$ (50°F).

Columns E, F, and G are grouped and are normally hidden (fig. 2). If the crop is alfalfa, the user should select the outline symbol (+) above column H to display the columns for the alfalfa cut dates and ET calculations. These columns are used for calculations related to alfalfa's cut and regrowth periods and are discussed later.

Columns H and I allow the user to enter rain and irrigation amounts, respectively. The entries can be measured values from the past or, in the case of irrigation, scheduled values in the future. The ability to enter future water additions allows the user to play "what-if" scenarios similar to those possible for T_{max} . The rainfall and irrigation amounts entered in the spreadsheet should be effective values, i.e., the net amounts which contribute to ET and/or the soil water balance. Rain and irrigation amounts need not be separated, e.g., the average value of measurements from rain gauges under a center pivot irrigation system can be entered in either column.

Column J implements the water balance (eq. 3) with the formula:

$$=IF(L9<>"",L9*O9,J8+IF(Crop="Alfalfa",G9,D9)+M9-H9-I9)$$

in which the nested IF function [IF(Crop="Alfalfa",G9,D9)] determines whether to read ET from column G for alfalfa or column D for other crops. If the user enters an estimated SWDP value for the current day (column L), the formula overrides equation 3 with the product of SWDP and the AWHC of the soil (column O). The logical test in the first argument of the IF function [L9<>""] is intended for compatibility with Microsoft Office Excel 2003 and can be replaced by ISNUMBER(L9) in Excel 2007. The formula =L8*O8 is required in cell J8 for the initial value of SWDP on 30 April.

Column K expresses $SWDP_i$ with the formula =J9/O9, which is equivalent to:

$$SWDP_i = \frac{SWD_i}{AWHC_{RZ_i}} \quad (6)$$

Column L provides capability for the user to adjust or override the SWDP values in column K with estimated or measured values ($SWDP_{adj}$). An initial estimate of SWD is required for 30 April; values at later dates can be entered if available. Data validation restricts entries to $0\% \leq SWDP_{adj} \leq 100\%$. If column L is left blank, no in-season corrections in SWDP values are made. Steele et al. (1997) recommended at least monthly corrections to SWD or SWDP estimates for the water balance irrigation scheduling methods they studied; semi-monthly corrections generally improved the accuracy of the algorithms. The adjustment column can be modified for other measures of soil water status, such as SWD on a depth equivalent basis or through the use of conversion tables between soil-water tension and SWD (Wright and Bergsrud, 1991).

Column M assesses whether the SWD value at the end of the day will be negative, in which case the excess water is assumed lost to deep percolation or surface runoff during the same day and is not available for ET. The spreadsheet formula is:

$$=IF((J8+IF(Crop="Alfalfa",G9,D9)-H9-I9)<0,-J8-IF(Crop="Alfalfa",G9,D9)+H9+I9,0)$$

If $SWD \geq 0$ at the end of the day, $WL = 0$. Wright and Bergsrud (1991) noted that in many soils, some of the water in excess of FC ("gravitational water" as defined by *ASABE Standards*, 2007; see fig. 1) may not drain within one day, thus making additional water available for ET. They recommended holding the soil water content at FC for an extra day or two in slowly-drained soils. This can be accomplished in the spreadsheet with no additional programming by entering zero (0) in column L for as many days as the soil is considered at FC. Alternatively, the user can modify the algorithm to more accurately model slowly drained soils.

Column N calculates a linearly-expanding root zone management depth (RZ) with the formula:

$$=IF(VLOOKUP(Crop,CropInfo,4)=1,VLOOKUP(Crop,CropInfo,3),IF(A9<=Emergence,RZinitial,IF(AND(A9>Emergence,C9<VLOOKUP(Crop,CropInfo,4)),N8+(VLOOKUP(Crop,CropInfo,3)-RZinitial)/((VLOOKUP(Crop,CropInfo,4)-1)*7),VLOOKUP(Crop,CropInfo,3))))$$

This is equivalent to:

$$RZ_i = RZ_{max} \text{ if } WRZ_{max} = 1 \quad (7)$$

$$RZ_i = RZ_{initial} \text{ if } WRZ_{max} \neq 1 \text{ and } Date_i \leq Emergence \quad (8)$$

$$RZ_i = RZ_{i-1} + 7 \left[\frac{RZ_{max} - RZ_{initial}}{WRZ_{max} - 1} \right] \quad (9)$$

$$\text{if } WRZ_{max} \neq 1, Date_i > Emergence,$$

$$\text{and } WPE < WRZ_{max}$$

$$RZ_i = RZ_{max} \text{ if } WRZ_{max} \neq 1 \text{ and } WPE \geq WRZ_{max} \quad (10)$$

The name "CropInfo" refers to the contents of table 3, excluding the header. Values for RZ_{max} [VLOOKUP(Crop,CropInfo,3) in the formula] and WRZ_{max} [VLOOKUP(Crop,CropInfo,4)] can be changed by the user. For example, Stegman et al. (1977) presented data on root zone development versus days past emergence for sugar beets, corn, potatoes, spring wheat, and soybeans. The value of WRZ_{max} was set to 7 weeks to approximate the time from emergence to maximum ET as specified by the ET tables in Lundstrom and Stegman (1988). If WRZ_{max} is set to 1 (eq. 7), the root zone is assigned its maximum value RZ_{max} immediately (week 1) and remains constant throughout the season; this feature is intended for use with established alfalfa but may be used with any crop. In earlier versions of the spreadsheet, if the crop was alfalfa, the root zone was assumed constant at 1220-mm (48-in.) depth throughout the season. However, this approach provided no flexibility to accommodate a gradually-increasing root zone during the year of alfalfa establishment, so the present algorithm treats alfalfa like other crops — the root zone increases in depth over a specified time interval. The formula next compares the current date with the crop emergence date and if the crop has not emerged, RZ is set to $RZ_{initial}$ specified in a cell named "RZinitial" (eq. 8), which is the same for all crops. If the crop

Table 3. Example of crop information for North Dakota.

Crop Type	Crop No.	Root Zone Maximum Depth (mm)	Week of Root Zone Maximum
Alfalfa	1	1220 ^[a]	1 ^[b]
Barley	2	910	7
Corn	3	910	7
Pinto_Bean ^[c]	4	610	7
Potato	5	610	7
Soybean	6	610	7
Sugarbeet	7	910	7
Sunflower	8	910	7
Spring_Wheat	9	910	7

- ^[a] The name “CropInfo” is assigned in the spreadsheet for rows “Alfalfa” through “Spring_Wheat” and all columns of this table. To avoid confusion, dual units are not reported in this table because the VLOOKUP(Crop,CropInfo,4) formula refers to the fourth column in this table. In the spreadsheet, separate worksheets and tables are provided for SI and U.S. customary units.
- ^[b] Or established alfalfa, a value of 1 assigns a root zone depth equal to its maximum for 30 April through 30 September; other values between 2 and 7 provide a linear root zone increase as for other crops.
- ^[c] The underscore character (_) is used because a space is invalid in Excel names.

has emerged and $WPE < WRZ_{max}$, a linear root zone depth increase is calculated for each day (eq. 9). The root zone reaches RZ_{max} by the start of the week specified for root zone development, e.g., if $WRZ_{max} = 7$, the linear increase in root zone depth occurs during weeks 1 through 6. If the crop has emerged and $WPE > WRZ_{max}$, the root zone depth is set to RZ_{max} (eq. 10). Data validation ensures $RZ_{initial} \leq RZ_{max} \leq 1220$ mm (48 in.); the lower limit ensures internal consistency and values greater than 1220 mm (48 in.) are expected to be uncommon. Values for WRZ_{max} are constrained to lie between 1 and 22, the latter being the season length from 1 May through 30 September. Alternative algorithms for root zone development, including initial and maximum depths, can be supplied by the user.

Column O calculates $AWHC_{RZ}$ values based on the depth of the current root zone (column N) with the formula:

$$=IF(N8=MAX(Zbj),VLOOKUP(N8,AWHCsite,6),((N8-VLOOKUP((MATCH(N8,Zbj,1)-1),SoilProp,3)))/(VLOOKUP(MATCH(N8,Zbj,1),SoilProp,3)-VLOOKUP((MATCH(N8,Zbj,1)-1),SoilProp,3)))*(VLOOKUP(MATCH(N8,Zbj,1),SoilProp,8)-VLOOKUP((MATCH(N8,Zbj,1)-1),SoilProp,8))+VLOOKUP((MATCH(N8,Zbj,1)-1),SoilProp,8))$$

in which Zbj is an array containing the bottom depths (mm) of each layer in the soil profile and the remaining variables are explained below. The preceding formula is equivalent to linear interpolation of TAWHC values, i.e.,

$$AWHC_{RZ_i} = TAWHC_{profile} \text{ if } RZ_i = z_{max} \quad (11)$$

$$AWHC_{RZ_i} = \left(\frac{RZ_i - z_j}{z_{j+1} - z_j} \right) [TAWHC_{j+1} - TAWHC_j] + TAWHC_j \text{ if } RZ_i < z_{max} \quad (12)$$

The total AWHC for k soil layers ($TAWHC_k$) is the sum of the products of the layer thicknesses and corresponding AWHC values for each layer, i.e.,

$$TAWHC_k = \sum_{j=1}^k [\Delta Z_j \times AWHC_j] \quad (13)$$

If the entire profile is considered, then $k = n$ and $TAWHC_k = TAWHC_{profile}$. Values of ΔZ_j , $AWHC_j$, and $TAWHC_k$ are retrieved from columns (e), (g), and (h), respectively, in table 4. In the spreadsheet formula, MATCH functions are used to identify table rows corresponding to the depths z_j and z_{j+1} and the TAWHC values in equation 12. For example, if $RZ = 140$ mm (5.52 in.) for 5 May 2009 (fig. 2, cell N13), (MATCH(N13,Zbj,1)-1) returns a value of 1 corresponding to the soil horizon number of the largest value [(100 mm (4 in.))] in the Zbj column (a named array) “less than or equal to” (Microsoft Corporation, 2006) the lookup value of 140 mm (5.52 in.). The expression VLOOKUP((MATCH(N8,Zbj,1)-1),SoilProp,3) returns the value of 100 mm (4 in.) for z_j . Continuing through equation 12 and using the values in table 4, the value of $TAWHC_i$ for $i = 5$ May 2009 is $((140 - 100)/(200 - 100))(16 - 7) + 7 = 10.6$ mm [or in U.S. customary units, $((5.52 - 4)/(8 - 4))(0.64 - 0.28) + 0.28 = 0.42$ in.] as shown in cell O13 of figure 2. In table 4, the user can change soil horizon boundaries in column (c) and select soil types in column (d) to match field conditions at the location of interest. Data validation ensures horizon depths increase continuously, restricts soil choices to a list of predefined types, constrains the maximum root zone depth to 1220 mm (48 in.), and constrains the RZ_{max} to equal 1220 mm (48 in.) exactly. Careful editing of the data validation entries will enable alternate scenarios to be modeled, e.g., more or fewer soil horizons, a deeper profile, etc. Values of AWHC for various soil textures in column (f) were taken from Lundstrom and Stegman (1988). A line for “Rocks” with $AWHC = 0$ was added to the spreadsheet (not shown in table 4) to represent horizons with $AWHC \approx 0$ or which are impenetrable to roots. Users are cautioned that if the Rocks layer is used to represent an impenetrable layer, all deeper soil layers should be set to the “Rocks” soil type because S values in equation 1 and SWD values in equation 3 assume all layers with water storage capacity are active in the water balance. That is, if a “Rocks” soil layer is specified for an intermediate soil horizon, the algorithm assumes roots can extract water from deeper horizons when in reality the roots may not extend to horizons deeper than the rocky layer.

Columns P, Q, R, and S calculate cumulative values of ET, R, I, and WL, respectively, throughout the season. Column T provides space for user annotations such as crop development information, field scouting notes, chemical application records, etc.

ALFALFA EVAPOTRANSPIRATION

Estimation of ET values during alfalfa cut and regrowth periods using table 1 and 2 involves diverting from the former to the latter for three weeks following a cutting. One way to implement this in a spreadsheet is to insert table 2 into the appropriate weeks (columns) of table 1. If this approach is used, the subtables for cut and regrowth periods (table 2 and its corollary for the third cutting) must be able to shift left or right depending on the week in which they are inserted into the main table (table 1). Although this can be done in a spreadsheet, it presents the following limitations. First, the resulting spreadsheet formula is complicated, requiring, for example, nesting of multiple levels of IF, AND, and OR functions within a VLOOKUP function (not shown). Second,

Table 4. Soil layering, textures, and available water holding capacities (AWHC) by layer for a hypothetical soil.

Horizon No. ^[a]	Horizon Boundaries		Soil Texture ^[b]	Horizon Thickness (mm)	Texture AWHC ^[c] (mm mm ⁻¹)	Horizon AWHC (mm)	Total AWHC (mm)
	From (mm)	To (mm)					
(a)	(b)	(c)	(d)	(e)	(f)	(g) = (e) × (f)	(h)
0	0	0	(Blank)	0	0.00	0.0	0.0
1	0	100	Sand	100	0.07	7.0	7.0
2	100	200	Loamy sand	100	0.09	9.0	16.0
3	200	300	Sandy loam	100	0.13	13.0	29.0
4	300	510	Fine sandy loam	210	0.16	33.6	62.6
5	510	710	Loam & silt loam	200	0.20	40.0	102.6
6	710	910	Clay loam & silty clay loam	200	0.18	36.0	138.6
7	910	1020	Silty clay & clay	110	0.16	17.6	156.2
8	1020	1220	Coarse sand & gravel	200	0.04	8.0	164.2
9	1220	1220	(Blank)	0	0.00	0.0	164.2

[a] Spreadsheet names have been assigned as follows in this table: “SoilProp” contains the entire table [rows 0 through 9 and columns (a) through (h)], “Zbj” contains rows 0 through 8 of column (c), “AWHCsSite” contains rows 0 through 8 and columns (c) through (h), “dZj” contains rows 0 through 9 of column (e), and “AWHCj” contains rows 0 through 9 of column (g). To avoid confusion, dual units are not reported in this table because lookup formulas in the article refer to specific columns and column offsets in this table. In the spreadsheet, separate worksheets and tables are provided for SI and U.S. customary units.

[b] Soil textures in column (d) and available water holding capacity values in column (f) were taken from table 1 of Lundstrom and Stegman (1988). The layering sequence shown here is unlikely to represent a soil profile in a field situation. Textures were selected to illustrate available choices (“Rocks” with AWHC = 0 mm mm⁻¹ (0 in. in.⁻¹) (not shown) and depths were chosen to illustrate the computations.

[c] AWHC -- available water holding capacity.

the resulting composite table incorrectly estimates ET if a cut date falls in the middle of a week past emergence, i.e., an ET value may be retrieved from a subtable such as table 2 prior to the actual cut date rather than from the main alfalfa ET table.

To simplify the calculation of ET during alfalfa cut and regrowth periods, we assume ET for alfalfa can be represented by:

$$ET_{\text{alfalfa}} = K_{\text{acr}} ET_{\text{uncut alfalfa}} \quad (14)$$

where $ET_{\text{uncut alfalfa}}$ is given by table 1 and adjusted for dry soil conditions by equations 4 and 5. The K_{acr} factor is based on the assumption that alfalfa ET is reduced to a fraction of its normal value on the day it is cut and that ET increases linearly to its normal value during the regrowth period. The K_{acr} factor is given by the equations:

$$K_{\text{acr}} = 1 \text{ if } i < \text{Alfalfa_Cut_1 or } DAC \geq t_{\text{acr}} \quad (15)$$

$$K_{\text{acr}} = (1 - K_{\text{acr0}}) \left[\frac{DAC}{t_{\text{acr}}} \right] + K_{\text{acr0}} \text{ if } 0 \leq DAC \leq t_{\text{acr}} \quad (16)$$

where Alfalfa_Cut_1 is a name for the first cut date (discussed later). Equation 15 represents the uncut condition and equation 16 represents the cut condition.

Based on the work of Lundstrom and Stegman (1988), values of $K_{\text{acr0}} = 0.6$ and $t_{\text{acr}} = 21$ d were assigned in the spreadsheet. The K_{acr0} estimate was based on comparisons of the average value of the ratios of ET for each temperature range for the first week after cutting (table 2) to corresponding values for uncut alfalfa (table 1). For example, ET values in the first data column of table 2 are 1.3, 2.0, 2.8, 3.8, and 4.6 mm day⁻¹ (0.05, 0.08, 0.11, 0.15, and 0.18 in. day⁻¹, respectively); ET values for the ninth week after emergence in table 1 are 2.0, 3.6, 4.8, 6.4, and 7.6 mm day⁻¹ (0.08, 0.14, 0.19, 0.25, and 0.30 in. day⁻¹, respectively); and the corresponding ratios are 1.3/2.0, 2.0/3.6, ..., and 4.6/7.6

(0.05/0.08, 0.08/0.14, ..., and 0.18/0.30 for U.S. customary units), which produce an average of 0.60. Similar analyses were performed for other WPE pairs to confirm 0.6 as an approximate value for K_{acr0} . The assignment of $t_{\text{acr}} = 21$ d was based on the 3-week duration of the ET subtable (table 2). The linear form of the ET regrowth function was verified by linear regression of ET ratios vs. WPE. Continuing the analysis, the average of the ET ratios for the first week after cutting (WPE = 9 for this example) was 0.60. The corresponding averages for the second and third weeks after cutting are 0.77 and 0.95, respectively, and continuing to the fourth week after cutting, in which use of the table for uncut alfalfa is resumed, the average of the ET ratios is 1.0. Linear regression of the (WPE, ET ratio) data pairs (9, 0.60), (10, 0.77), (11, 0.95), and (12, 1) gives $r^2 = 0.95$. For the first and second cutting and $3 \leq \text{WPE} \leq 13$, all similarly-derived r^2 values exceed 0.85, while for the third cutting and $13 \leq \text{WPE} \leq 16$, all r^2 values exceeded 0.80. This analysis indicates that a linear form of Equation (16) is reasonable for the expected grower practice of not cutting alfalfa very early or very late in the growing season. To put the values for K_{acr0} and t_{acr} in perspective, Stegman et al. (1977) reported that the basal crop coefficient value for alfalfa fell to approximately 0.6 after cutting and took 15 to 20 days to recover to full values. Users can enter their own values for K_{acr0} and t_{acr} in the present spreadsheet and a small amount of programming would enable the use of nonlinear ET regrowth functions. Adjustments may be desired, for example, to accommodate drying, baling, transport, and associated haying operations where wheel traffic may delay regrowth.

Columns E, F, and G in the spreadsheet implement equations 15 and 16 as shown in figure 3. When alfalfa is selected as the crop, IF functions in cells H3 and H4 display a reminder to show (unhide) the columns using the spreadsheet’s group and outline feature (the “+” or “-” sign above column H). The user can enter cut dates in cells E4, F4, and G4, which are named Alfalfa_Cut_1 , Alfalfa_Cut_2 , and

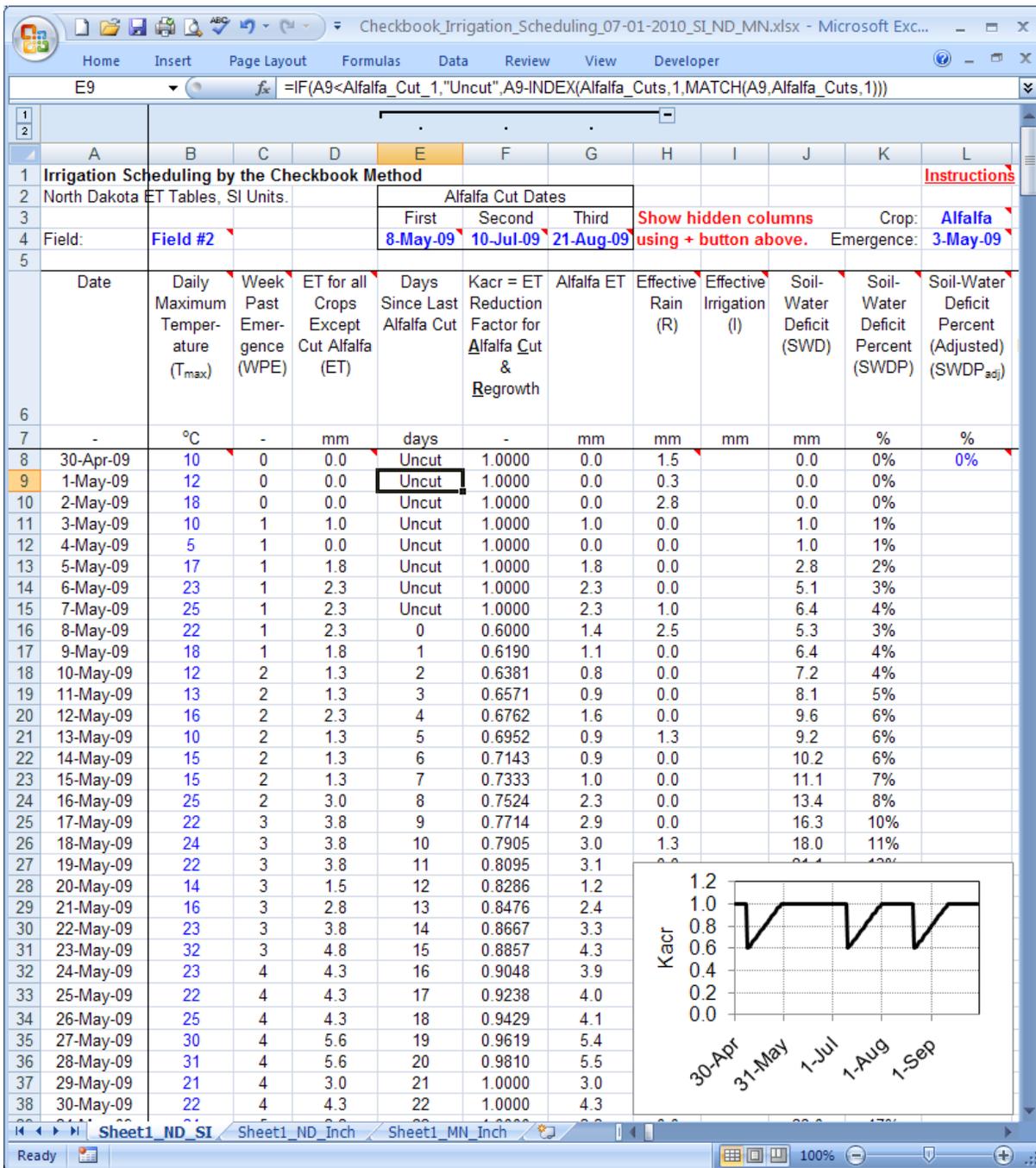


Figure 3. Spreadsheet calculation of alfalfa ET during the first cut and regrowth period. The first alfalfa cut date is set unusually early in the season only to illustrate results for columns E, F, and G. The inset shows K_{acr} vs. time for the cut dates shown in cells E4:G4 and with a 40% reduction in ET on the day of the cut ($K_{acr} = 0.6$) and a 21-d regrowth period ($t_{acr} = 21$).

Alfalfa_Cut_3, respectively. Additional programming would be required to add more cut dates for users in warmer climates or for situations in which agronomic practices require four or more cuttings. Conditional formatting changes the text in columns E through G to a gray color when a crop other than alfalfa has been selected.

Column E calculates DAC using the formula:

$$=IF(A9<Alfalfa_Cut_1, "Uncut", A9-INDEX(Alfalfa_Cuts, 1, MATCH(A9, Alfalfa_Cuts, 1)))$$

in which the IF function reports an uncut condition if the current date is earlier than the first cut date and calculates

DAC otherwise. Note the progression of "Uncut," 0, 1, 2, ..., 20, 21, and 22 in column E of figure 3.

Column F implements equations 15 and 16 using the formula:

$$=IF(AND(Crop="Alfalfa", AND(E9>=0, E9<=tacr)), ((1-Kacr0)*(E9/tacr)+Kacr0), 1)$$

where cell E9 is the DAC value for the current date and the other variables were defined earlier. Note the progression of values from $K_{acr} = 1$ on the day before the cut (7 May), $K_{acr} = 0.6$ on the day of the cut (DAC = 0 on 8 May), linearly-increasing values of K_{acr} for $0 \leq DAC \leq 21$, and K_{acr}

= 1 again at $t_{acr} = 21$ days (29 May). Over the course of a season with multiple cut dates, K_{acr} vs. time takes on a saw-toothed shape as shown in the inset in figure 3.

Column G implements equation 14 with the formula =D9*F9.

GENERAL PARAMETERS

A section for entry and adjustment of general parameters is contained in the crops and soils area of the spreadsheet. The parameter input section (fig. 4) follows the five-column spreadsheet problem solving format described by Buckmaster (2006). Additional rows and columns can be inserted as needed. Data validation is used to restrict user inputs, minimize errors, and provide suggestions to the user.

DISCUSSION

The spreadsheet can be used by farmers to schedule deficit or full irrigations, keep water management records, and focus on decision making rather than the computations which would be required in paper-based implementations of a checkbook approach. The spreadsheet environment provides access to the algorithms for those requiring further understanding of the processes or adapting the algorithms to different regions, crops, ET algorithms, season lengths, etc.

Data requirements include historical or forecasted maximum daily temperatures, AWHC values, crop type and emergence date, rainfall and irrigation data, and periodic field visits to monitor crop development and SWC status. The ET tables (Lundstrom and Stegman, 1988; Wright, 2002) provide approximate dates (WPE) of phenological stages of the crop. If a particular growing season produces accelerated or delayed crop development, even after accounting for temperatures, the user may be able to adjust or shift the ET tables in time by entering a fictitious emergence date slightly different from the actual emergence date.

A farmer managing multiple fields in close proximity can copy worksheets as needed for each field. Similarly, two or more crops served by one irrigation system can be scheduled independently by creating separate sheets for each crop. Temperature data for each worksheet can be copied from the original worksheet or the user can enter formulas in the temperature column to retrieve temperature data from another worksheet. For example, suppose Sheet1 is used for corn at one location and Sheet2 is used for soybeans at a

nearby location. Temperature data are entered as usual in column B of Sheet1 (fig. 2) and the formula =Sheet1!B9 can be used in cell B9 of Sheet2 to retrieve the temperature data for 9 May from Sheet1.

Instruction in irrigation scheduling concepts and applications can be achieved by using this article as a user's guide for the spreadsheet. Instructors can provide weather data and hypothetical or actual scheduling data for workshops or classes in a computer cluster setting. One approach is to provide increments of weather data and have students make irrigation scheduling decisions and entries, repeating the process as additional data are provided. Another approach is to provide weather data up to a specified date and let students explore variations in weather data, irrigation dates, and irrigation amounts to examine "what-if" scenarios.

Rows can be inserted in the spreadsheet to accommodate additional crops or locations. For example, water use tables for South Dakota (Werner, 1993) could be added to the list of available crops or in another worksheet. The ET tables for each crop may be edited as needed, including adjustments for more or fewer rows in the tables. Relatively simple changes in the spreadsheet would include selection of appropriate names for each additional crop, editing of data in the CropInfo spreadsheet table (table 3), and modification of data validation procedures for the Crop name and the CropInfo table.

Users can define their own charts as needed. A chart for soil-water deficit, rainfall, and irrigation vs. time (fig. 5) is provided in the "Chart" area of the spreadsheet as a starting point for users.

LIMITATIONS

In some cases, specific soil and landscape properties can strongly influence applicability of the one-dimensional water balance algorithm modeled by this spreadsheet and users are advised to exercise caution under these circumstances. One limitation of the spreadsheet is that it does not model upward fluxes of water from shallow ground water. The likelihood of a ground water source can be determined by evaluating soil colors in the subsoil. If subsoils are relatively uniform in color and somewhat brownish in nature, oxidizing conditions exist and drainage is generally considered adequate for irrigation. If variegated patterns dominate subsoils above

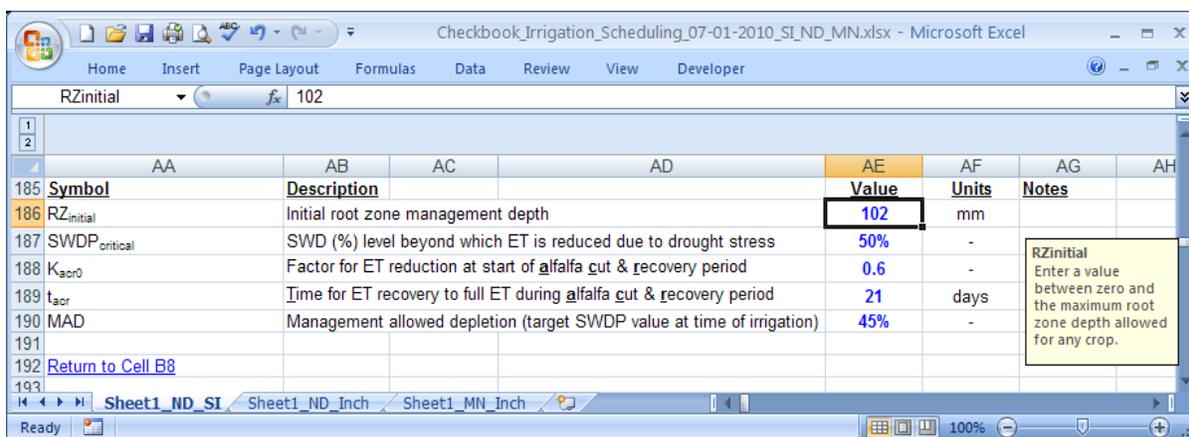


Figure 4. Spreadsheet section for general parameters.

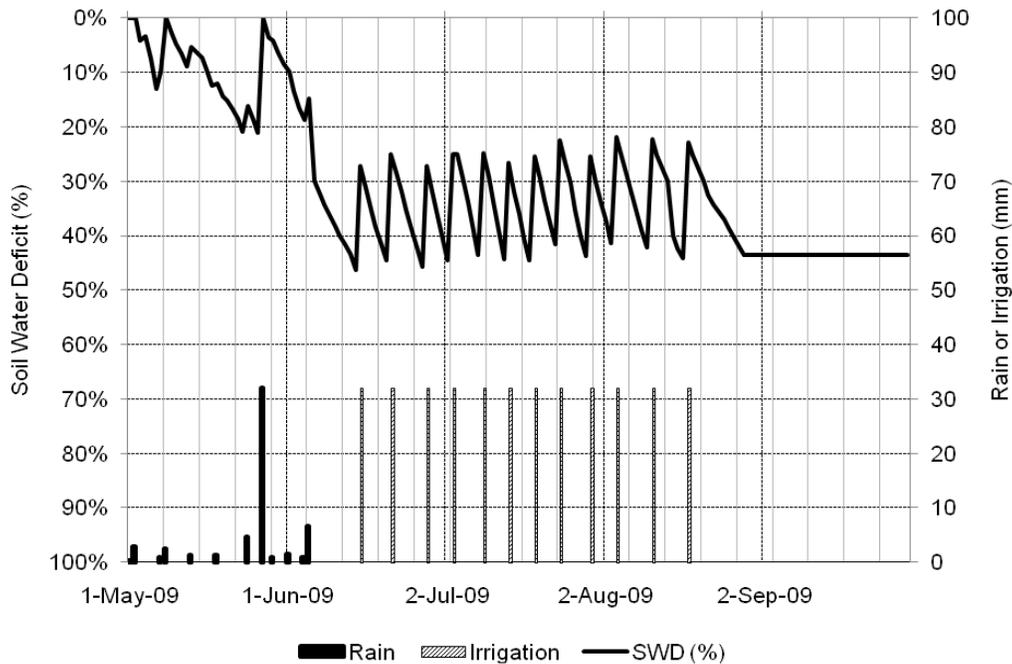


Figure 5. Example of the soil-water deficit and water inputs vs. time for a hypothetical irrigation scheduling scenario.

about 0.76 m (30 in.) and are characterized by bright irregular zones interspersed with grayer, bland colors, the influence of a fluctuating water table is likely. Dull olive or grey colors are often associated with poorly drained soils, so such soils would not be amenable to irrigation. It is also important to investigate internal soil drainage conditions because these can influence applicability of the water balance model described in this article. If the soil is slowly drained due to low hydraulic conductivity of the parent material or impeding soil layers, the model's removal of excess water (WL in column M, fig. 2) may not occur within the one-day time period assumed by the model. We indicated earlier in this article that slow drainage situations such as this could be modeled by setting $SWDP_{adj} = 0\%$ for days on which gravitational drainage is still occurring. This approach requires careful monitoring of field conditions and the user is advised that other models of soil water movement (Šimůnek et al., 2008) may be more appropriate. Topography effects are not modeled by the spreadsheet, so the soil water balance at field locations where depression-focused recharge or hillslope runoff are significant would not be accurately represented. The algorithms presented herein do not address salinity or sodicity effects on soils, crop growth, or ET, so caution is advised for situations where elevated salinity or sodicity levels may be present in the soil or in the irrigation water source. Application of mineralized ground water as a source for irrigation can induce changes in the proportion of cations adsorbed by the soil's cation exchange sites and can degrade a soil's water transmitting properties as well as cause surface crusting. Users are advised to refer to county soil surveys and soil and water compatibility literature such as Franzen et al. (1996) or the USDA-NRCS (2005) and to obtain assistance from a soil science professional before implementing and during the management of any irrigation system.

SUMMARY

The spreadsheet provides a basic tool for irrigation scheduling by farmers, managers, students, and researchers. It also provides a platform for instruction in irrigation scheduling concepts and spreadsheet programming for a variety of users. We have used the spreadsheet algorithms in instructional and research settings to teach and manage irrigation scheduling tasks for a variety of situations. Improvements in the spreadsheet can be made in many areas, including adaptation for other regions, crops, season lengths, and soil properties; changes in the algorithms for ET, root growth, and alfalfa cutting and regrowth; and retrieval of weather and soils data. Contact the corresponding author for an electronic copy of the spreadsheet.

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NOMENCLATURE

This section contains abbreviations used in the mathematical equations. A comment or description of each name (text label defining a specified range in the spreadsheet) can be accessed through the Name Manager in the spreadsheet file. Built-in spreadsheet functions are described in the software's help menu.

AWHC = available water holding capacity or plant available water [mm (in.)]
 AWHC_j = available water holding capacity for the soil in layer j [mm (in.)]
 AWHC_{RZ} = available water holding capacity of the soil profile to the depth of the root zone [mm (in.)]
 AWP = available soil water on a percent basis
 DAC = days after cutting, i.e., number of days after the most recent alfalfa cut date (d)
 ET = evapotranspiration [mm (in.)]
 ET_{alfalfa} = ET for alfalfa for either the cut or uncut condition [mm d⁻¹ (in. d⁻¹)]
 ET_r = reference ET [mm d⁻¹ (in. d⁻¹)]
 ET_{tabulated} = expected crop water use with nonlimiting soil water as listed in the crop water use table [mm (in.)]
 ET_{uncut alfalfa} = ET for alfalfa for the uncut condition [mm d⁻¹ (in. d⁻¹)]
 FC = field capacity [mm (in.)]
 i = (subscript) beginning of time period of interest or current day
 I = effective irrigation [mm (in.)]
 i+1 = (subscript) end of time period of interest or next day
 i-1 = (subscript) previous day
 j = (subscript) soil horizon number

k = (subscript) index for summation, e.g., soil horizon number
 K_a = water (drought) stress coefficient
 K_{acr} = alfalfa cut and regrowth factor
 K_{acr0} = ET fraction on day 0 of the alfalfa cut and regrowth period
 K_c = crop coefficient value or crop coefficient curve
 MAD = management allowed depletion [mm (in.)]
 n = number of soil horizons or layers
 R = effective rainfall [mm (in.)]
 R_s = daily solar radiation [W m⁻² (Ly)].
 RZ_{initial} = initial value of root zone management depth [mm (in.)]
 RZ_{max} = maximum root zone management depth [mm (in.)]
 S = profile total of soil-water content for a specific time period [mm (in.)]
 SWD = soil water deficit [mm (in.)]
 SWDP = soil water deficit on a percent basis
 SWDP_{adj} = user-adjusted or measured value of soil water deficit on a percent basis
 SWDP_{critical} = critical value of SWDP above which ET is limited, percent basis
 t_{acr} = time (duration, d) of the alfalfa cut and regrowth period, i.e., the time required for alfalfa ET to recover to its full value
 TAWHC = cumulative or total available water holding capacity of the soil profile [mm (in.)]
 T_{max} = daily maximum temperature [°C (°F)]
 T_{min} = daily minimum temperature [°C (°F)]
 WL = water losses from deep percolation or runoff [mm (in.)]
 WPE = weeks past emergence (weeks)
 WRZ_{max} = number of weeks after emergence at which the maximum root zone depth is reached (weeks)
 Z_j = depth of the bottom of soil horizon j, the deepest horizon fully penetrated by the roots on day (i) [mm (in.)]
 Z_{j+1} = depth of the bottom of soil horizon j+1, the horizon partially penetrated by the roots on day (i) [mm (in.)]
 Z_{max} = depth of the bottom of the deepest soil horizon [mm (in.)]
 Δ = change or increment, e.g., ΔS or ΔZ
 ΔZ_j = thickness of soil layer j [mm (in.)]

