PLANNING FOR DEFICIT IRRIGATION

N. L. Klocke, R. S. Currie, L. R. Stone, D. A. Bolton

ABSTRACT. *Irrigators with limited water supplies that lead to deficit irrigation management need to make decisions about crop selection, water allocations to each crop, and irrigation schedules. Many of these decisions need to occur before the crop is planted and depend on yield-evapotranspiration (ET) and yield-irrigation relationships. The Kansas Water Budget (KSWB) predicts crop yields from inputs of daily weather parameters to calculate reference ET (ETr) and irrigation and precipitation events to calculate a soil water balance. Results from the KSWB were compared with data from a 4-year field study conducted in southwest Kansas. The field study had one irrigation treatment to meet full irrigation requirements and five deficit irrigation treatments. Average soil water contents from field data on discrete days during the growing season compared well with KSWB results, but field soil water contents varied among each irrigation treatment replication. Relative crop yields and crop ET (ETc) compared well with KSWB results for the fully irrigated treatment, but the KSWB results tended to underestimate field results as irrigation declined. These differences may be attributed to calibrations of the KSWB with historical data from conventional (tilled) management in contrast to the field study which was managed with no-till techniques. Field and KSWB yield-ET relationship results were almost identical. The KSWB can be a tool for deficit irrigation management decisions that need predictions of crop yields for planning crop rotations, allocations of irrigation to selected crops, and screening of anticipated irrigation schedules.*

Keywords. *Limited irrigation, Deficit irrigation, Irrigation management, Decision tools, Crop models.*

The number of regions worldwide with declining water supplies for irrigation is increasing. With expanding world population, strategies to produce crops with less than full irrigation are needed. Crop simulation models can be the foundation for decision tools that guide irrigators in making management decisions. Boote et al. (1996) pointed out that crop models can integrate the facets of crop physiological processes that may come from studies across scientific disciplines. Models can also answer crop management and public policy decisions that affect individual producers and agricultural communities. However, they also asserted that the complexity of the crop model needs to be appropriate for the questions of concern by the user.

An example of a complex crop model is the Root Zone Water Quality Model (RZWQM) (Ahuja et al., 2001). The model has a comprehensive theoretical base that requires extensive input parameters of physiological, biological, and chemical processes. Many of these parameters, which are theoretical in nature, cannot be measured. The user is left to calibrate these parameters for each application and define which parameters to adjust. Hanson (1999) and Alves and Cameia (2002) suggested that evapotranspiration estimates in RZWQM might be improved by introducing stomatal resistance response to environmental conditions, but the authors concluded that their recommended method would add to the complexity of the model.

Scientists at the Grassland, Soil, and Water Laboratory of the U.S. Department of Agriculture-Agricultural Research Service in Temple, Texas collaborated to build the Crop-Environment Resource Synthesis (CERES)-Maize simulation model (Jones and Kiniry, 1986). This model includes: plant phenological development; leaf, stem, and root biomass accumulation; a soil water balance; and soil nitrogen transformations. Inputs into CERES-Maize include: weather factors, soil albedo, soil evaporation coefficient, drainage coefficient, runoff curve number, soil layer thickness, soil water characteristics, root distribution weighting factor, and crop growth and genetic factors (Ritchie et al., 1986). Important outputs of CERES-Maize include: phenological predictions, leaf area index, biomass, and grain yield. The developers of CERES-Maize found that common input errors that lead to poor performance of the model are the initial soil water content, the lower limit of plant extractable water, the drained upper limit, and rooting depth due to root restricting layers.

Another model related to CERES-Maize is the Erosion-Productivity Impact Calculator (EPIC) that was also developed at Temple, Texas (Williams et al., 1984; Williams et al., 1989; Jones et al., 1991). Soil productivity is derived from estimation of crop yield using processes including: leaf interception of solar radiation; conversion to biomass; division of biomass into roots and above ground biomass; root growth; water use; and nutrient uptake. Determining parameters for these processes is sensitive to local applications of the model and the user cannot always rely on default settings. Cabelguenne et al. (1997) added a

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component to the EPIC model to find the effects of water stress at different phases of crop growth on harvest index. They used five-day weather forecasts as inputs to the EPIC-PHASE model to conduct real time irrigation scheduling. Their results from EPIC-PHASE with observed data showed that the model had its best application for irrigation scheduling for a non-limited water supply.

Irrigators, who know that they do not have adequate water to supply full crop water requirements, need to make long-term, multi-year decisions about potential crop rotations. These decisions need to be based on the best economic return from the available water. They also need to predict the best allocation of water to each crop in a potential cropping rotation. After irrigators choose crop rotations, they need to predict the best irrigation schedules prior to or during the current growing season. Proposed water policies that may reduce water supplies need to be evaluated for economic impacts of these policies on individual irrigators and regional economies. All of these management decisions and economic impacts are based upon predictions of the relationships between crop yields and evapotranspiration and between crop yields and irrigation.

The Kansas Water Budget (KSWB) is one tool that has been developed to predict grain yields from rainfed, deficit irrigated, and fully irrigated crops in western Kansas (Stone et al., 1995; Khan et al., 1996; Stone et al., 2006). In contrast to the RZWQM, CERES-Maize, and EPIC models, the KSWB relies on inputs of daily maximum and minimum air temperature to calculate reference ET (ETr); crop coefficients to calculate non-stressed crop ET; soil water stress coefficients; and plant water stress coefficients to calculate effective ET (ETe) which is related to yield by a regionally calibrated yield-ETe relationship.

A field study conducted in the region offered the opportunity to compare KSWB results with field results. The purpose of this study was to: (1) describe the background theory, structure, and operation of the KSWB and (2) compare KSWB results with four years of field research plot data.

Methods

Results from a field study with corn, conducted from 2005 through 2008, were compared with results from the KSWB. Weather data, precipitation events, and irrigation events from the field study were used as inputs to the KSWB. Field measurements of soil water during the growing season, growing season evapotranspiration, and grain yields were compared with results from the KSWB.

Field Study

A field study, described by Klocke et al. (2003), was conducted at Kansas State University's Southwest Research and Extension Center located near Garden City, Kansas (38°01'06.20"N, 100°49'199.95"W). Corn (*Zea mays* L.) was grown in a five-year rotation of corn-corn-wheat-grain sorghum-sunflower. Each crop in the rotation was grown during all years of the study. The crops were planted in rotation during 2004, but the antecedent soil water following the 2003 crop year was the same across irrigation treatments; therefore, data from years 2005 through 2008 were used from this study. A linear-move sprinkler irrigation system delivered water to six irrigation treatments, replicated four times, and water was applied only during the growing season. The irrigation system coefficient of uniformity (CU) was determined to be 80.2%. Each plot was 13.7 m wide and 27.4 m long. Each irrigation treatment was in the same plot location from year to year so the antecedent soil water from each treatment carried over to the next year. Net irrigation (25 mm) was the same for all irrigation events, but the irrigation frequency was from 4.5 to 14 days across irrigation treatments to obtain a water application differential among the treatments. The irrigation frequency variable simulated irrigation supply constrained from 5.5 to 1.8 mm d^{-1}. Total soil water (TSW) was measured bi-weekly during the growing season to a depth of 1.8 m in 0.3-m increments with the neutron attenuation method (Evett and Steiner, 1995). Precipitation was measured in four rain gages, one at each corner of the study area. No runoff was observed in the plots that were managed with no-till methods; therefore, the measured rainfall was considered to be effective. Drainage was calculated using a field calibrated Wilcox-type drainage equation (Miller and Aarstad, 1972), where drainage was a function of TSW. Crop evapotranspiration, designated as ETc for the field study, was calculated for each time period between soil water measurements using a water balance of effective precipitation, net irrigation, drainage, and the change in soil water. The soil was formed on upland plains in calcareous loess that is deep and well drained. The soil type was a Ulysses silt loam with an available water capacity of 180 mm m^{-1} between field capacity (34% volumetric) and permanent wilting (16% volumetric). Cultural practices, including hybrid selection, no-till planting techniques, fertilizer applications, and weed control, were not limiting to crop production.

Description of the Kansas Water Budget

The Kansas Water Budget (KSWB) was developed to predict grain yields for rainfed, deficit irrigated, and fully irrigated crops in western Kansas (fig. 1). It was executed daily to calculate the effective ET (ETe) during the growing season that was linearly related to yield with a regionally developed yield-ETe relationship for corn:

$$Y = 0.044(ETe) - 12.1 \tag{1}$$

where

Y = corn grain yield (Mg ha^{-1})

ETe = effective growing season evapotranspiration (mm).

ETe was the amount of water that was effectively used by the crop to produce yield and was calculated using methods adapted from Doorenbos and Kassam (1986). ETe was derived in four steps: (1) reference ET (ETr) was calculated with daily weather factors; (2) maximum ET for a non-stressed crop (ETm) was calculated from ETr and a crop coefficient (Kc); (3) actual ET (ETa) was calculated from ETa and soil water stress coefficients.(Ks); and (4) ETe was calculated from the ratio of ETa to ETm and yield response weighting factors for each of the four segments of the growing season [designated as Ky by Doorenbos and Kassam (1986)]. ETa in the KSWB was equivalent to ETc in the field study because ETa was updated daily from a soil water balance. ETa was used to refer to the KSWB and ETc was used to refer to the field measurements. ETr was calculated daily with the method proposed by Jensen and Haise (1963):

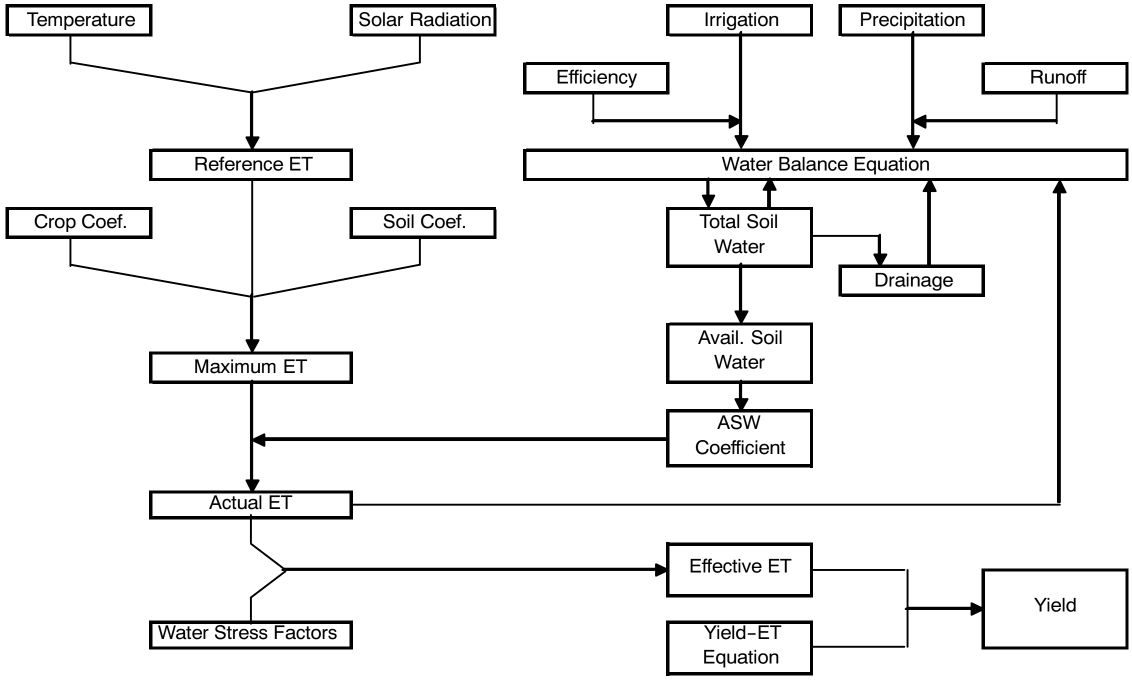


Figure 1. Flow chart for the Kansas water budget.

$$\text{ETr} = (0.078 + 0.0252(\text{MAT})(\text{RAD})) / (2.493 - (0.00214(\text{MAT}))) \qquad (2)$$

where

ETr = reference ET (mm)

MAT = mean of daily maximum and minimum air temperature (°C)

RAD = average daily solar radiation (MJ m^{-2}).

ETr was increased when daily maximum air temperature was more than 33°C to account for advective energy. This correction added 5% to ETr for every degree above 33°C but the maximum correction was 25%. ETm was calculated daily from ETr with bare-soil water coefficients (Kbs) during the non-growing season and crop coefficients (Kc) during the growing season (Doorenbos and Pruitt, 1977; Wright, 1982):

$$\text{ETm} = (\text{Kbs or Kc})\text{ETr} \qquad (3)$$

ETm values assumed that the crop was not stressed by soil water content, atmospheric conditions, weeds, disease, or lack of nutrients. ETa was calculated during the growing season from ETm with soil water stress coefficients (Ks):

$$\text{ETa} = \text{ETm}(\text{Ks}) \qquad (4)$$

The soil Ks values were calculated from the function reported by Jensen et al. (1971):

$$\text{Ks} = (\log(\text{ASW} + 1))/\log(101) \qquad (5)$$

where ASW was volumetric available soil water (%).

Figure 2 shows an example of ETr, ETm, and ETa, as calculated by the KSWB. The difference between ETr and ETm are the effects of Kbs or Kc. The difference between ETm and ETa, especially during the last half of the growing season, shows the effects of Ks.

ETa, calculated with equation 4, was updated daily with the soil water content from a water balance:

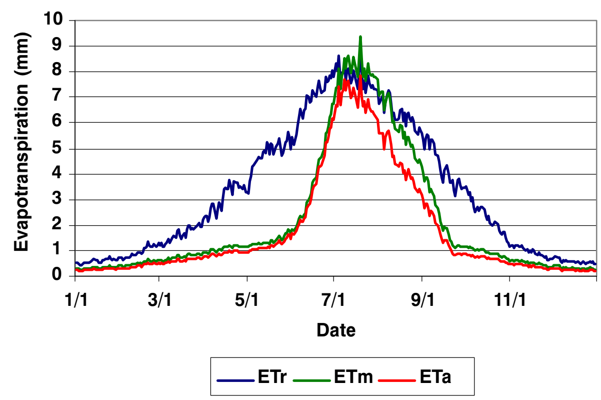


Figure 2. Example of reference ET (ETr), maximum ET (ETm), and actual ET (ETa) from an execution of the Kansas water budget.

$$TSW_t = TSW_y + P_y + I_y - D_y - ETa_y \qquad (6)$$

where TSW_t was total soil water to a depth of 1.8 m at the beginning of today; TSW_y was total soil water at the beginning of yesterday; P_y was precipitation that infiltrated into the soil yesterday, I_y was the irrigation that infiltrated into the soil yesterday; D_y was water that drained from the 1.8-m depth of soil yesterday; and ETa_y was the water extracted from the soil yesterday. Ks was calculated from TSW (eq. 5) and transferred for the calculation of the next day's ETa. Daily drainage was calculated using the Wilcox method as described by Miller and Aarstad (1972). Daily drainage for Ulysses silt loam soil (Stone et al., 1987) was:

$$D_P = 42.7(\text{TSW}/729)^{18.06} \qquad (7)$$

where

TSW = total soil water (volumetric) in the 1.8-m profile (mm).

ETe was calculated from a ratio of ETa to ETm and weighting factors (WF) that accounted for the crop's sensitivity to water stress during each of four growth periods: vegetative, flowering, seed formation, and ripening. The weighting factors were 36 for vegetative, 33 for flowering, 25 for seed formation, and 6 for ripening. Considering the amount of ETm in each growth period, the weighting factors represented 14%, 53%, 18%, and 15% of the relative yield response weighting for the growth periods of vegetative, flowering, seed formation, and ripening, respectively. The growing season ETe was calculated by:

$$WETF = (ETa/ETm)WF \quad (8)$$

where

WETF = the weighted ET factor for each growth period calculated by using the sum of ETa and ETm, and the weighting factor (WF) for each growth period.

$$ETe = (Sum\ WETF/100)ETm \quad (9)$$

where ETm is the total growing season no-stressed evapotranspiration.

RESULTS

PRECIPITATION AND HAIL EVENTS DURING THE FIELD STUDY YEARS

Precipitation data (table 1) were tabulated by month during the growing season (May through September), January through April, and October through December. On an annual basis precipitation was above average during 2006 and below average during 2005, 2007, and 2008. Precipitation also was summed from the previous non-growing season (October through April) through the growing season (May through September). The 2006-2007 non-growing season precipitation was nearly twice the average, and the other years were below average. Growing season precipitation was below average except during 2006 (5% above average). Cropping season precipitation, from the previous October through the end of the growing season, included the total precipitation that impacted the crop. Cropping season precipitation was well above average during 2006-2007, near average during 2004-2005 and 2005-2006, and well below average during 2007-2008.

The field plots received hail events on 4 July 2005, 11 July 2006, and 20 June 2008 (Currie and Klocke, 2008). Maximum leaf area index (LAI) across water treatments in 2007 (no hail) was 4.1, while LAI was 2.9 in 2005, 3.2 in 2006, and 2.5 in 2008. All hail events occurred before tassel emergence.

SOIL WATER DATA FROM FIELD STUDY AND KSWB

TSW in the top 1.8 m of soil, calculated daily with the KSWB from 1 January 2005 through 31 December 2008, was plotted for irrigation treatment 1 with 5.5-mm d^{-1} system capacity (figs. 3a and 3b); treatment 4 with 3.0-mm d^{-1} system capacity (figs. 3c and 3); and treatment 6 with 1.8-mm d^{-1} system capacity (figs. 3e and 3f). Soil water data were collected from field measurements on discrete days during the growing seasons and were averaged over the four replications. These data, plotted with ± 1 standard deviation error bars, were superimposed on the KSWB simulation results. Field measurements of TSW matched well with KSWB predictions except for treatment 1 during the 2006 cropping season, which was the wettest of the four years. Data from the field measurements showed that soil water contents can vary from point to point across four replications of the field study, yet the averages of the four replications did match well with the KSWB simulations.

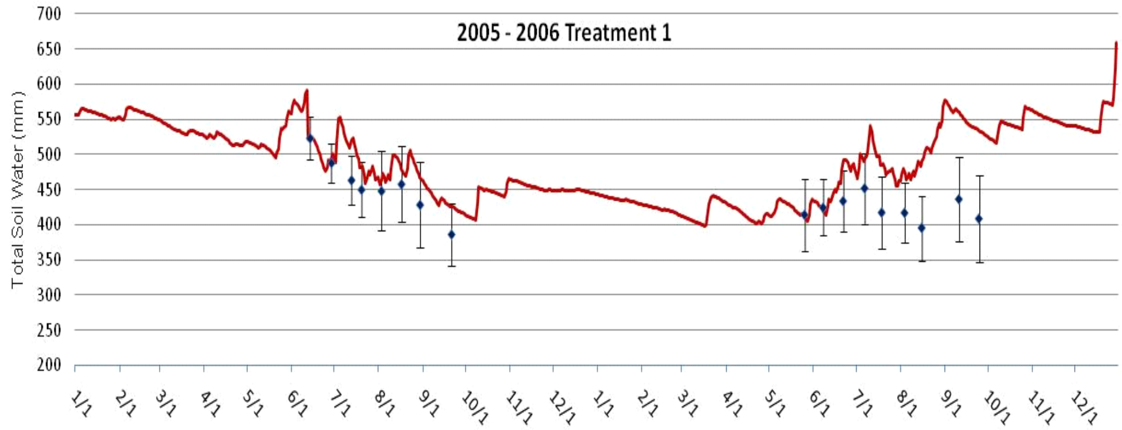
YIELD-ET AND YIELD-IRRIGATION FROM FIELD STUDY AND KSWB

Relative grain yields for deficit irrigation treatments 2 through 6 were calculated as a percentage of the full irrigation treatment 1 yield for each year. Soil water stress factors were included in the KSWB, but many other factors influenced field yields among the years, including the hail events. The KSWB does not consider all of these other factors; therefore, actual yields were scaled with the maximum yields for that year to reduce the influence of environmental factors from year to year. Relative yields from treatments 2 through 6 of the field study versus the KSWB were plotted for 2005 through 2008 in figure 4. A linear regression of relative yields revealed that, as relative yields decreased with less irrigation, KSWB under predicted field yields. Perhaps the differences between conventional (tilled soils) used for calibrating the KSWB and no-tillage management used in the field study can explain this trend. Others have compared conventional tillage with not-till and have reported a similar trend (Lamm et al., 2009). Comparison of ETc and ETa (fig. 5) also showed divergence as irrigation decreased.

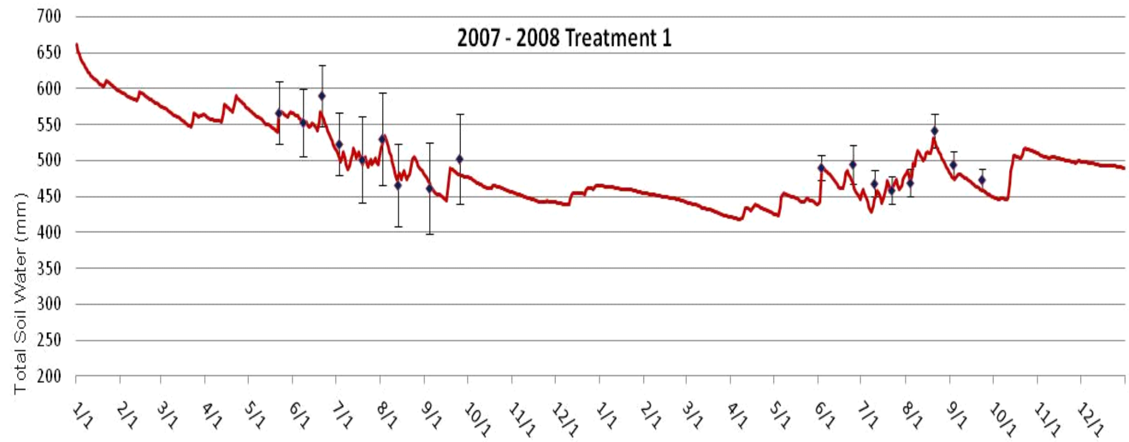
Table 1. Precipitation (mm) at Garden City, Kansas.

Year	Jan.-Apr.	May	June	July	Aug.	Sept.	Oct.-Dec.	Annual	% of Annual	Oct.-Apr.[a]	May-Sept.[b]	Oct.-Sept.[c]	% of Annual[d]
2005	75	71	80	89	43	24	78	461	92	134	308	442	91
2006	63	64	59	119	65	23	186	579	116	141	330	471	97
2007	149	30	64	42	67	53	42	447	89	335	256	591	122
2008	70	49	79	31	64	18	129	440	88	113	241	353	73
Long term avg.	103	50	86	63	71	43	84	501		172	314	485	
Average 05-08	89	54	70	70	60	29	109	482		181	284	464	
Study/Long term (%)	87	107	81	112	84	68	129	96		105	90	96	

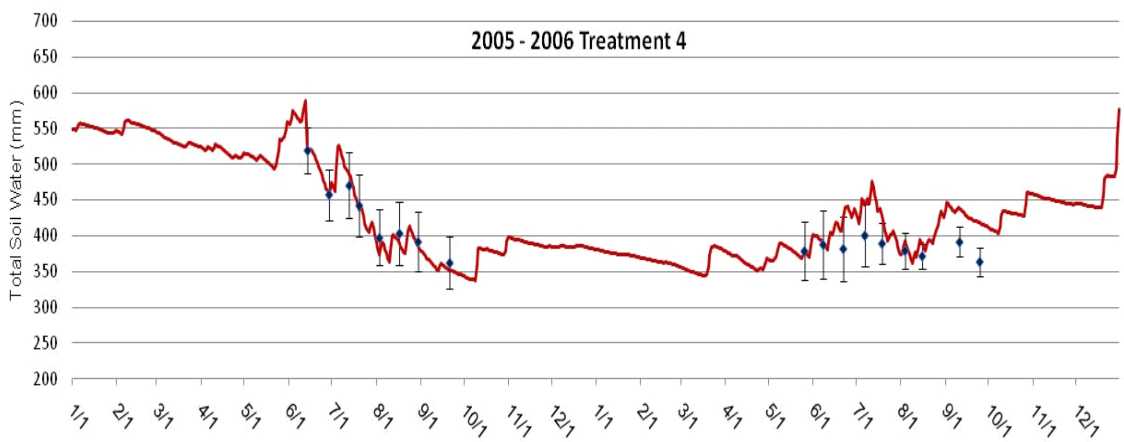
[a] Off-season precipitation from the previous 1 October through the current 30 April.
[b] Growing season precipitation for the current 1 May through 30 September.
[c] Cropping season precipitation total from the previous 1 October through the current 30 September.
[d] Cropping season precipitation total as a percentage of annual long-term average (501 mm).



(a)

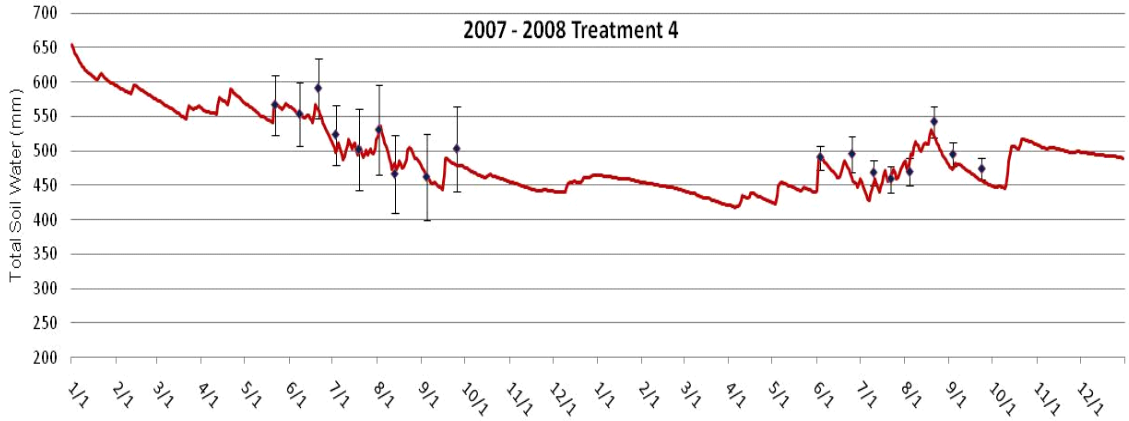


(b)

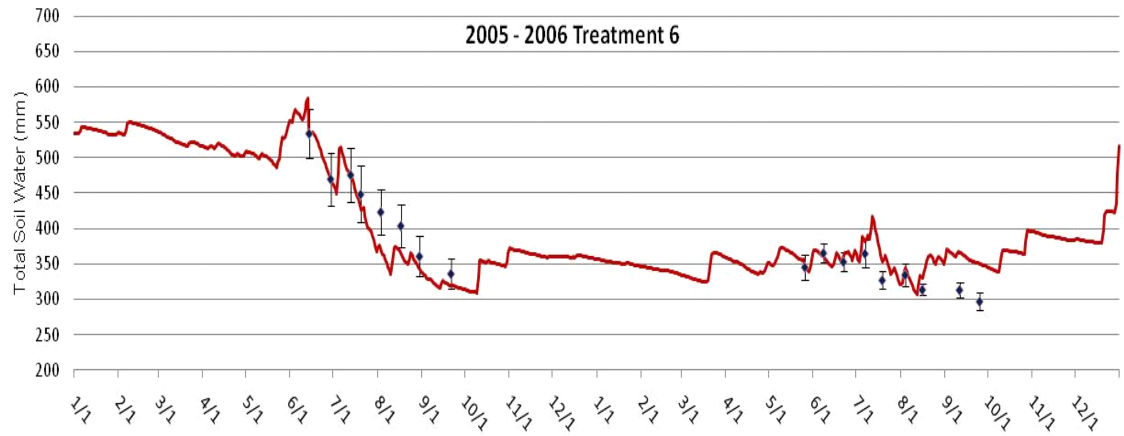


(c)

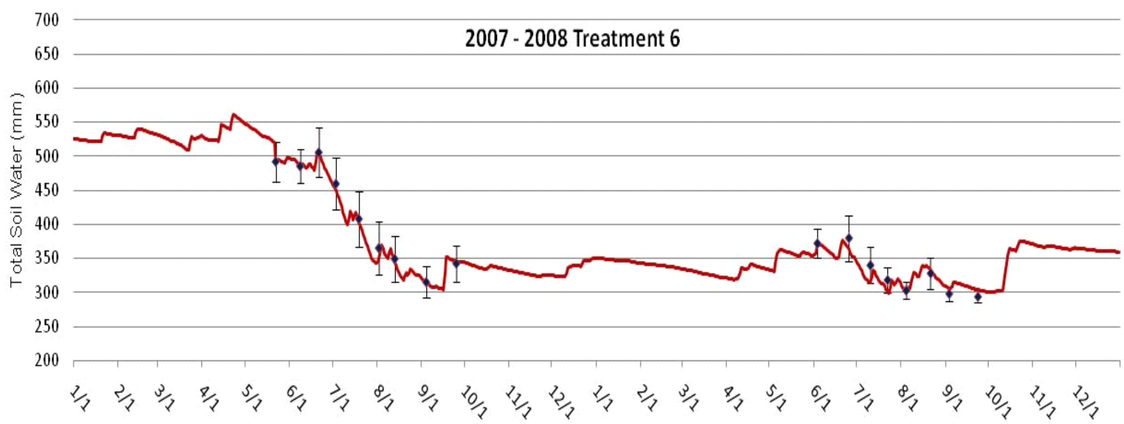
Figure 3. Total soil water for irrigation treatments 1-6 from 2005-2008 (solid line from KSWB and discrete points from field measurements with ±1 standard deviation error bars).



(d)



(e)



(f)

Figure 3 (con't). Total soil water for irrigation treatments 1-6 from 2005-2008 (solid line from KSWB and discrete points from field measurements with ±1 standard deviation error bars).

Yields have been found to be a linear relationship with crop evapotranspiration, which was consistent with results from field data and the KSWB (fig. 6). The linear regression of ETc and relative yields from the field study were very similar to the linear regression of ETe and relative yields from KSWB. Furthermore, both equations had comparable predictive power. There were small differences between the slopes and intercepts for field and KSWB relationships between relative yields and ETc or ETe. Quadratic regressions of net irrigation with relative yield by irrigation treatments over years from field results tended to deviate from KSWB results as irrigation decreased (fig. 7). Relative yields from field data may have greater than KSWB results because the field was in no-till management and the KSWB was calibrated with historical data from conventionally managed research plots. This result is consistent with results described earlier.

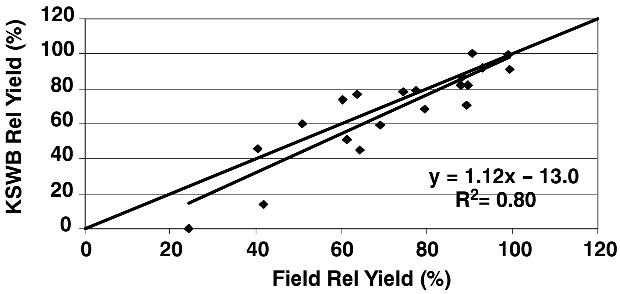


Figure 4. Relative grain yields from the field study and the KSWB.

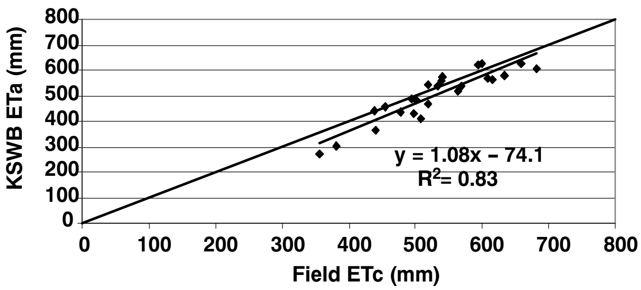


Figure 5. ETc from field study and ETa from KSWB.

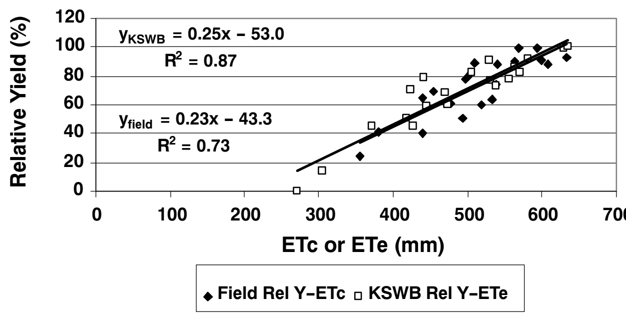


Figure 6. Relative yield vs. ETc from the field or ETe from the KSWB.

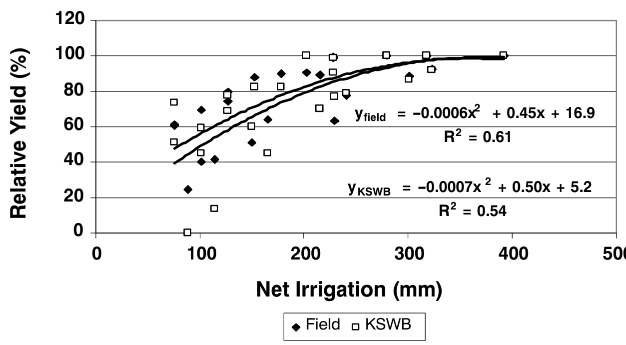


Figure 7. Relative yield over years vs. net irrigation from field data and the KSWB.

Applications of the KSWB

KSWB is a tool that can be the basis for deficit irrigation management decisions and economic analysis of irrigation practices. Multiple executions of the KSWB can produce yield irrigation relationships that are the basis of many planning decisions. Yield response to irrigation can be coupled with crop production costs to find optimum irrigation strategies when water supplies reduce irrigation and maximum yields cannot be achieved. An example of a decision tool that relies on yield-irrigation relationships from the KSWB is the Crop Water Allocator (CWA) (Kansas State University, 2006; Klocke et al., 2006). The premise of the CWA is that a finite amount of irrigation from a common irrigation source can be divided among crops in a rotation. It answers two questions on the basis of maximum net economic returns: (1) what is the best to worst crop rotation and (2) how much of the available water supply should be allocated to each crop in a rotation. This is a multi-year planning decision because crop rotations are usually fixed for a number of years. In this case, long-term average yield-irrigation relationships for each crop are needed to predict potential crop yield from each irrigation amount (Stone et al., 2006). Multiple executions of KSWB have been used to generate the yield-irrigation relationships. When relative yields, averaged over years from the 4-year field study at Garden City, Kansas, were superimposed onto the KSWB output the results were almost identical (fig. 8). The good correspondence between the two yield-irrigation relationships is validation for use of the KSWB for long-term management decisions.

A second decision tool, the Crop Yield Predictor (CYP) (Kansas State University, 2010), assists users in making irrigation scheduling decisions prior to or during a given growing season, based on economic return. The CYP predicts crop yield potential and net economic return from alternative irrigation schedules. In this mode, irrigation schedules are predetermined in contrast with traditional irrigation schedules, which are determined from real-time irrigation needs and short-term predictions of weather factors. When water supplies are limited the irrigator needs to predict the capabilities of the irrigation system to provide the optimum schedule of irrigation. In this case the important questions to be answered by the CYP for optimum economic returns are: (1) will pre-season irrigation be justified; (2) when should irrigation be started during the growing season, and (3) when should irrigation cease. Multiple executions of the KSWB with trial irrigation schedules (dates and amounts of irrigation events) give yield predictions and net economic returns for each scenario.

Summary

The Kansas Water Budget (KSWB) was developed for western Kansas to calculate crop yield from a regionally

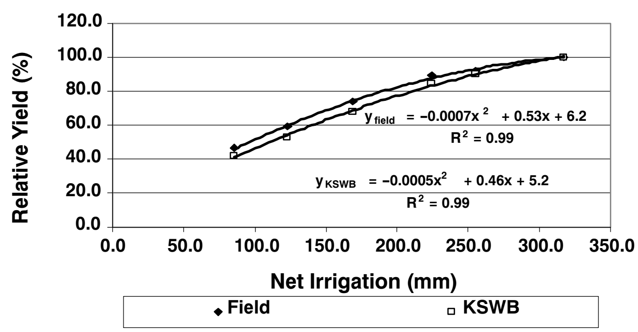


Figure 8. Yield-irrigation relationship averaged over the four years of the field study.

calibrated yield-ET relationship. Effective ETe, calculated by the KSWB, was the water consumed by the crop with consideration of crop's sensitivity to water stress. ETe was derived from daily reference ET (ETr), daily crop coefficients (Kc), daily soil water stress factors (Ks), and crop stress factors. A daily water balance was calculated to update daily Ks coefficients. The calculated ETe was substituted into the calibrated yield-ET relationship to calculate crop yield.

Bi-weekly soil water contents during the growing season and grain yields were measured in a 4-year field study that included six irrigation treatments ranging from irrigation to meet full crop needs to five levels of deficit irrigation. Crop ET (ETc) was calculated from a bi-weekly water balance of net irrigation, effective precipitation, drainage, and the change in soil water content. Weather factors, precipitation events, and irrigation events during the field study were used as inputs to the KSWB. Field and simulated crop yields from the five deficit irrigation treatments were converted to relative yields, which were percentages of fully irrigated yields each year. Average soil water contents from field data on discrete days compared well with KSWB results, but field soil water contents varied among irrigation treatment replications. Relative crop yields and crop ET (ETc) compared well with KSWB results for the fully irrigated treatment, but the KSWB results tended to underestimate field results as irrigation declined. These differences may be attributed to calibrations of the KSWB with historical data from conventional (tilled) management but the field study was managed with no-till techniques. Field and KSWB yield-ET relationship results were almost identical. KSWB results have been used for irrigation planning and management decision tools to find optimum results based on economic returns from multiple crop rotations and irrigation scheduling scenarios.

Acknowledgements

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