CROP WATER PRODUCTION FUNCTIONS FOR GRAIN SORGHUM AND WINTER WHEAT

by

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Abstract

Productivity of water-limited cropping systems can be reduced by untimely distribution of water as well as cold and heat stress. The research objective was to develop relationships among weather parameters, water use, and grain productivity to produce production functions to forecast grain yields of grain sorghum and winter wheat in water-limited cropping systems. Algorithms, defined by the Kansas Water Budget (KSWB) model, solve the soil water budget with a daily time step and were implemented using the Matlab computer language. The relationship of grain yield to crop water use, reported in several crop sequence studies conducted in Bushland, TX; Colby, KS and Tribune, KS were compared against KSWB model results using contemporary weather data. The predictive accuracy of the KSWB model was also evaluated in relation to experimental results. Field studies showed that winter wheat had stable grain yields over a wide range of crop water use, while sorghum had a wider range of yields over a smaller distribution of crop water use. The relationship of winter wheat yield to crop water use, simulated by KSWB, was comparable to relationships developed for four of five experimental results, except for one study conducted in Bushland that indicated less crop water productivity. In contrast, for grain sorghum, experimental yield response to an increment of water use was less than that calculated by KSWB for three of five cases; for one study at Colby and Tribune, simulated and experimental yield response to water use were similar. Simulated yield thresholds were consistent with observed yield thresholds for both wheat and sorghum in all but one case, that of wheat in the Bushland study previously mentioned. Factors in addition to crop water use, such as weeds, pests, or disease, may have contributed to these differences. The KSWB model provides a useful analytic framework for distinguishing water supply constraints to grain productivity.

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Acknowledgements

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Dedication

This work is dedicated to my loving wife Erin who gave me confidence, inspiration, and reassurance throughout my graduate school experience.

Chapter 1 - Literature Review

Plant growth is primarily limited by either water or light reception. Primary productivity is the rate at which plants and other organisms produce biomass in an ecosystem. For vegetables, it occurs through the process of photosynthesis, which is a function of several factors, including the ratio of incident photosynthetically active radiation (PAR), the efficiency of radiation absorption by the canopy, and the efficiency of the conversion of absorbed PAR into dry matter (Monteith, 1972). Singer et al. (2011) stated that by quantifying light interception in crop canopies we can gain important information about canopy physiological processes and impacts on microclimate dynamics, which can be used with crop biomass data to calculate radiation use efficiency. This can be used in crop productivity simulation modeling. Light interception is affected by plant population density and alters the plant height. Changes in leaf, shoot, and canopy size determine light absorption and utilization (Mao et al., 2014). Plant growth can be limited by the amount of light received. When the plant absorbs a photon through photosynthesis it is in a high energy state. When that photon is discharged, it goes into a low energy state and emits radiation. This absorption and discharge of light drives the carbon assimilation of the plant, which affects plant growth.

Water-limited plant growth

Dryland crop production in the U.S. central High Plains is frequently limited by precipitation relative to potential evaporation (Farahani et al., 1998). Potential evaporation is the amount of evaporation that would occur if a sufficient water source were available. A dryland cropping system is one where precipitation and not irrigation is used to meet crop water requirements. Desirable traits for crops in dryland cropping systems include a high potential growth rate and an efficient use of available water (Zlatev and Lidon, 2012). Water moves though the soil-plant-atmosphere continuum by different processes, including infiltration, drainage, irrigation, evaporation and soil moisture uptake by plants (Hillel, 1980). Soil evaporation, transpiration of the crop, drainage from the root zone, rainfall, irrigation, and runoff are all determinants of crop water use (Morison et al., 2008). Solar radiation, crop type, temperature, humidity, and wind speed also affect the soil-plant-atmosphere continuum, and it can be difficult to measure such a complex system. The Penman equation was developed in 1948 by Howard Penman in order to calculate evaporative losses. It used daily mean temperature, wind speed, air pressure, water vapor pressure, and solar radiation (Penman, 1948). Potential evapotranspiration and the partitioning of soil evaporation and transpiration are important information for agricultural studies. Evaporation is when liquid water changes phases to a gas and leaves the soil surface, and transpiration is essentially evaporation of water from plant leaves (Allen et al., 1998). Most potential evapotranspiration models were developed in flat areas for agricultural purposes, with potential evaporation and potential transpiration combined (Doorenbos and Kassam, 1979). The Penman-Monteith equation is a modified form of the original Penman equation, and approximates net evapotranspiration with inputs of daily mean temperature, wind speed, relative humidity, and solar radiation (Monteith, 1973). Monteith's addition included vapor pressure deficit, as well as leaves and stomata, in the Penman equation. He also included a measure of stomatal conductance, which is defined as the measure of the rate of passage of carbon dioxide entering or water vapor exiting through the stomata of a leaf. Stomatal conductance is directly related to the boundary layer resistance of the leaf and the water vapor concentration gradient from the leaf to the atmosphere.

Several other equations have been developed to estimate evapotranspiration, many of them requiring fewer variables. The Thornthwaite formula is based mainly on temperature with an adjustment being made for the number of daylight hours (Thornthwaite, 1948). Turc developed an empirical method that calculates potential evapotranspiration over a shorter period of time (Turc, 1961). The Jensen and Haise (1963) equation estimates evapotranspiration from solar radiation and temperature. Priestly and Taylor (1972) developed an equation that required mean daily air temperature, net radiation derived from solar radiation and extraterrestrial radiation, as well as a calibration constant. The Hargreaves-Samani formula required daily maximum and minimum temperatures as well as extraterrestrial radiation (Hargreaves and Samani, 1985). From these formulas it can be seen that there are several methods for calculating evapotranspiration, and which equation to use can depend on several factors from climate region to availability of weather data (Lu et al., 2005).

Vapor pressure deficits also have an effect on plant growth. The vapor pressure deficit is the difference between the pressure exerted by water vapor held in saturated air and the pressure exerted by the water vapor actually held in the air, or in the case of plants, it is the difference between the vapor pressure inside the leaf compared to the vapor pressure of the air at a reference height. As the water vapor deficit increases, the plant needs to draw more water from its roots because the air has greater potential to take the moisture out of the plant. If it is too wet, and the vapor pressure deficit is small, the plant is more susceptible to rot (Seager et al., 2015). Vapor pressure deficit is essentially a combination of temperature and relative humidity. High relative humidity yields a low vapor pressure deficit. A study done by Lobell et al. (2014) associated vapor pressure to drought stress, and found that the sensitivity of maize yields to drought stress has increased, and that agronomic changes today tend to translate improved drought tolerance of plants to higher average yields but not to decreasing drought sensitivity of yields.

Crop coefficients present the relationship between the evapotranspiration of a certain crop and that of a reference crop. They vary with the crop, its stage of growth, growing season, and weather conditions (Ko et al., 2009). The reference evapotranspiration is defined by Doorenbos and Pruitt (1977) as the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977). Alfalfa has also been used as a reference crop in place of green grass cover. Crop coefficient values for most agricultural crops increase from a minimum value at planting to a maximum value at about full canopy cover, then it tends to decline at a point after a full cover is reached in the crop season (Imran et al., 2014).

Soil water deficit effects

Deficits in soil water can decrease primary productivity (Arneth et al., 1998). In order to evaluate the capacity of the available water in the soil profile, it is important to know the upper and lower limits in the plant root zone. Agricultural crop species cause only minor differences in that lower limit, and accurate evaluation of available soil water is vital in order to develop the best water management for crop production in dry regions (Ratliff et al., 1983). During the growing season, water stress, or limited water availability during crucial development stages, can occur, limiting crop yield formation (Osakabe et al., 2014). It is important to be aware of the yield components for the crop in order to identify the stage that could be most damaging for yield formation. Grain sorghum yield components include seeds per head, heads per acre, and seed size/test weight. Wheat yield components include kernel size, kernels per spikelet, spikelets per head, tillers (heads) per plant, and plants per acre. For both wheat and sorghum, water stress can be most damaging during the flowering (or pollination) stage, though it can still be damaging at any stage (Brouwer et al., 1989). Both are fairly drought resistant, which helps them deal with water stress. One study by Hosseini and Hassabi (2011) found that in addition, water deficit stress reduces harvest index due to reduced economic and biological yield.

The water use-yield relationship is important one and provides the expected yield for a given level of water use. It has been reported as a linear relationship for winter wheat in several studies, including Hunsaker and Bucks (1987), Steiner et al (1985), and Musick and Porter (1990). Yield response to water use decreases north to south in the Great Plains, primarily because of the increasingly greater evaporative demand of the atmosphere as latitude decreases (Musick et al., 1994). Yields have been compared with available soil water at planting (ASW_p) and water supply (in season precipitation (ISP) plus ASW_p) in order to see this relationship. A 19-year study done in Montana with winter wheat by Brown and Carlson (1990) found that the slope of grain yield vs. water supply was 129 kg ha^{-1} cm^{-1} compared with a slope from a study in Tribune, KS done by Stone and Schlegel (2006) of 100 kg ha^{-1} cm^{-1}. Winter wheat grain yield response to water stored in soil at planting was 113, 106, 72, 70, 65, and 51 kg ha^{-1} cm^{-1} in plots at Huntley, MT; North Platte, NE; Colby, Garden City, and Hays, KS; and Woodward, OK, respectively (Johnson, 1964). Nielsen et al (2002) found that with dryland winter wheat in Colorado, grain yield was influenced by interaction between ASW_p and precipitation. Yield response to increasing ASW_p was greater with wetter precipitation conditions. Nielsen et al. (2002) also found a wheat yield slope of 95 kg ha^{-1} cm^{-1} of ASW_p with data from Garden City, KS (Norwood, 2000). Crop-water production relationships are altered by variations in soil and climate and have not been well defined for most crops in most areas (Ayer and Hoyt, 1981). As we understand and use crop-water production relationships, we can draw conclusions on optimal water application and the benefits we can achieve from managing water efficiently (Barrett and Skogerboe, 1980).

Soil water balance

The soil water balance measures the change in water storage in the soil profile. It was calculated using a water balance equation:

$$SW_E = SW_B + P_N + I_N - E - D_P \quad [\ 1\ ]$$

where SW_E is the total soil water in the profile at the end of the day (mm), SW_B is the total soil water in the profile at the beginning of the day (mm), P_N is the net precipitation (mm), I_N is the net irrigation (mm), E is the evaporation (from both plant and soil surfaces) in mm, and D_P is the profile drainage in mm (Stone et al., 2008). This is a very simplified form of the equation, and the processes going on are much more complex. It can also be difficult to accurately measure each of these terms. For example, one method to measure soil water contents is by using electromagnetic soil water sensors that work in plastic access tubes. Assuming a soil depth of 3 meters and a bias error of 0.02 m^3m^{-3} there would be an error of 60 mm in the profile water content (Evett et al., 2012).

The effective precipitation (EPR) is the amount of precipitation received by the soil after runoff has been removed, as the runoff does not infiltrate into the soil. A major factor in this is precipitation intensity, or the amount of precipitation received in a given amount of time. As the precipitation increases in intensity it will eventually exceed the soil infiltration capacity. When this happens, there will be more runoff than with a smaller precipitation rate, even if the soil was dry. The infiltration is a complex process influenced by the hydraulic properties of the soil profile, the precipitation intensity, and the water content distribution with depth (Assouline et al., 2007). Time-to-ponding refers to the ability to accurately estimate when initial ponding occurs, or when water has pooled on the soil surface and runoff occurs. As the precipitation falls and infiltrates into the soil it follows preferential flow paths. A preferential flow path is a term that describes the process where water follows favored routes and bypasses other parts of the soil (Luxmoore, 1991). As the water moves through these preferential flow paths, it redistributes itself through the soil.

Soil water surface evaporation occurs through three stages: the energy-limiting rate, the energy- and transport-limiting rate, and the transport-limiting rate. In the first stage, the rate of evaporation is only limited by the potential ET rate, or the rate it would evaporate if there was unlimited water availability (Saxton et al., 1974). In the second stage, upward movement and evaporation from a wet soil is still rapid, but occurs at a decreasing rate as the soil dries out. In the third stage the soil is mostly dried out and water movement becomes very restricted. Here the soil controls the evaporation rate, as the water will evaporate as soon as the soil allows it to reach the surface.

Transpiration and soil water depletion below the surface vary greatly depending on crop type. Crops that have roots that reach farther into the soil profile tend to be more drought tolerant and more suitable for dryland conditions (Jafaar et al., 1993). Crops with shorter growing seasons and rooting depths can leave greater amounts of soil water below the root zone (Merrill et al., 2003). Water uptake by roots is a complex physiological process as it is dependent on the amount of water in the profile as well as the distribution of the root system. Research suggests that the roots are the weakest link for the transport of water throughout a plant (Jackson et al., 2000). As the water moves into the plant canopy and is transpired, the rate of transpiration can be calculated throughout the canopy. Canopy conductance is a function of the distribution of radiation in the plant canopy, and by definition it is the ratio of daily water use to the daily mean vapor pressure deficit. Higher levels of radiation on the surface of a plant increases the rate of transpiration.

The soil water balance and deficits in soil water can be modeled using different types of computer simulations. One example of simulation model is physically-based using the Richards' equation. The Richards' equation is used to represent the movement of water in unsaturated soils (Richards, 1931). It is a nonlinear partial differential equation, and can be difficult to approximate since it does not have a closed-form analytical solution. It uses hydraulic conductivity, pressure head, and water content at different times and elevations in order to simulate water flow. These models are very complex and the numerical solutions of the Richards' equation have been criticized for being computationally expensive and unpredictable (Short et al., 1995). One commonly used physically-based model is the Root Zone Water Quality Model (RZWQM). This model is an integrated physical, biological, and chemical process model that simulates plant growth and movement of water, nutrients, and pesticides in runoff and percolate within agricultural management systems. It is one-dimensional, continuous, and is designed to respond to agricultural management practices including planting, harvesting, tillage, pesticide, manure and chemical nutrient applications, and irrigation events (Hebson and DeCoursey, 1987). Another model commonly used to simulate biophysical processes in agricultural systems is the Agricultural Production Systems Simulator (APSIM). It is structured around plant, soil, and management modules that include a diverse range of crops, pastures and trees, soil processes including water balance, soil pH, erosion, and others (Holzworth et al., 2014).

Capacitance-type models use a simple form of the Richards' equation and are process-based. They do not use water potentials and conductivity terms in the solution to the Richards' equation. The CERES model is one type of these models. It helps identify relationships between yield-limiting factors, management, and environment (Graeff et al., 2012). Based on management information such as cultivar, planting, fertilization, plant protection, and harvest, as well as soil and weather information, the model computes the daily rate of plant growth with a final estimation of yield and biomass (Graeff et al., 2012). The CERES model is implemented in DSSAT (Decision Support System for Agrotechnology Transfer), a modeling system used around the world to estimate crop growth.

Analytical solutions are often used to check the accuracy of numerical schemes. Transfer function models are a time-series modeling technique. They are often used because using the Richards' equation is often too computationally and data intensive. Transfer models use the "black box" approach, meaning in a time series analysis they measure what goes into the system and what goes out of the system. They make the assumption that the percolation of effective infiltration more closely approximates a linear process as variations in moisture content below the root zone decrease (O'Reilly, 2004).

The role of simulation models in understanding the processes in the soil-plant-atmosphere system has increased significantly over the years in terms of applications. Simulated crop growth is connected to water use (Rosenthal et al., 1987). It is useful to compare simple models with more complex ones, because if the simpler model can sufficiently simulate the processes, it could be a good alternative to a data-intensive complex simulation model (Ines et al., 2001). These models have the potential to explore solutions to water management problems. They also assist in strategic planning to help farmers or companies make the best use of their water (Graeff et al., 2012). Geographic Information System (GIS) also uses soil water balance data and can compare the results spatially instead of as just point measurements in order to analyze soil water deficits in a region. While all models have various degrees of success in application, they all have their weaknesses and fail under certain circumstances. Model developers should point out the limitations of their models and the ranges of their applications (Ma and Schaffer, 2001). As soil water balance models continue to be developed and modified we can gain a clearer understanding of the most important factors in the soil water balance in order to simplify complex simulation models that are easier to understand for the user but still can accurately model the system.

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Chapter 2 - Journal Article

Introduction

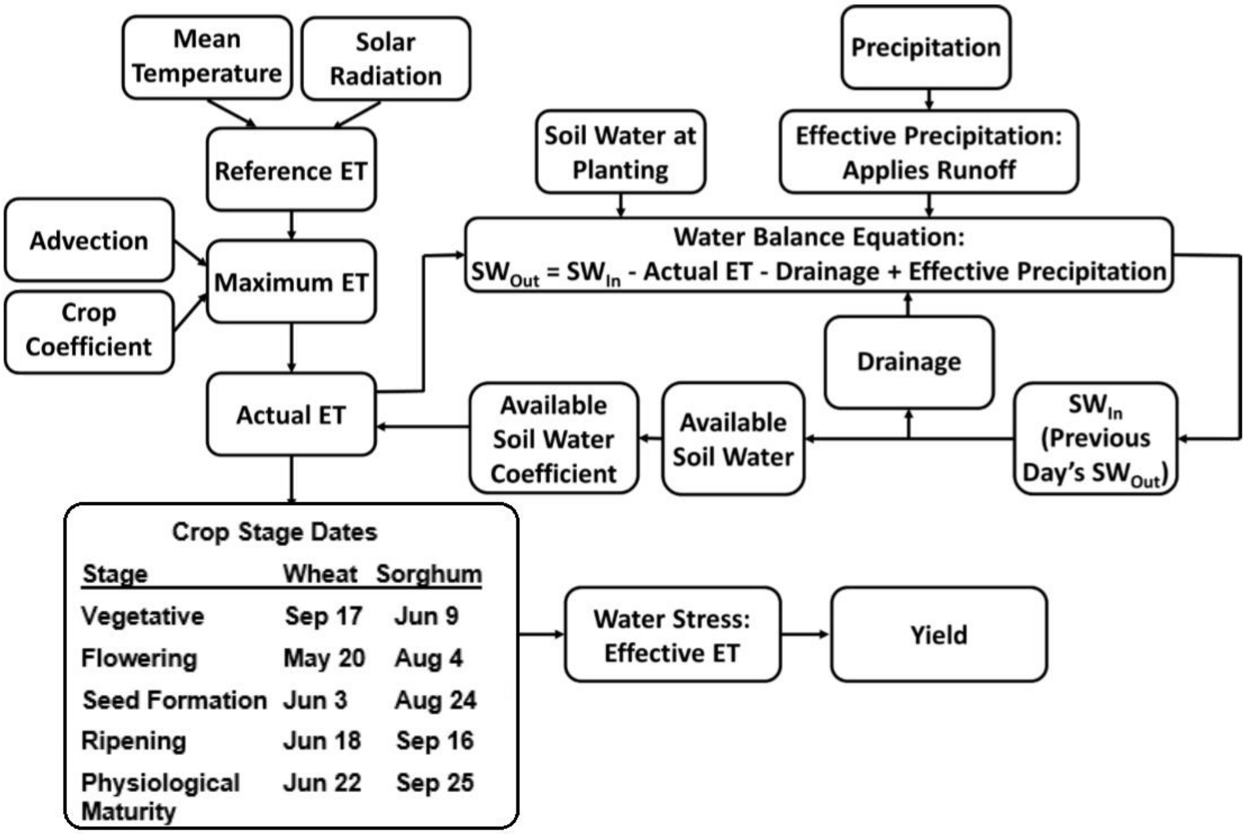
Productivity of water-limited cropping systems in the High Plains can be reduced by many factors. Grain yields for dryland crop production in the semi-arid Great Plains of the United States can be unpredictable because of the irregular nature of growing season precipitation (Nielson et al 2010). Water deficits can affect productivity both at specific growing periods throughout the crop season and in the overall total supply of water (Brown 1959, Passioura 2006). Generally, the timing of water supply has a larger effect on grain yield than total water supply for many crops (Maman et al 2003). Weeds, disease, pests, and weather damage can destroy crops and limit productivity as well. Climate change could also contribute to crop productivity, given improvements in heat and water resources and rising atmospheric CO_2 concentrations (Tao and Zhang 2013). The frequency of years when temperatures exceed the thresholds for damage during critical growth stages is likely to increase for some crops and regions (Hatfield et al 2013). Stone and Schlegel (2006) found in a study done in western Kansas that grain yields increased with both available soil water at emergence (221 kg ha^{-1} cm^{-1} available soil water) and in-season precipitation (164 kg ha^{-1} cm^{-1} in-season precipitation). They found similar yield responses for winter wheat (98 kg ha^{-1} cm^{-1} available soil water and 83 kg ha^{-1} cm^{-1} in-season precipitation). In the same study, 63% of grain sorghum and 70% of wheat variations in grain yield were explained by variations in available soil water at emergence and in-season precipitation. Because of the high input costs for production, farmers can benefit from a tool that will help them assess the risks associated with dryland crop production (Nielson et al 2010).

Grain sorghum and winter wheat are the primary dryland crops in the semiarid regions of the High Plains (USDA Cen. Agric., 2012). The precipitation pattern of a region influences the cropping sequence used in order to maximize the use of rainfall received (Sherrod et al 2014). Both crops are important in the High Plains region due to their drought resistance and ability to produce under limited precipitation. Dryland production is regaining its importance in this region as irrigated crop production decreases with groundwater depletion (Steward et al 2013). Diverse (more crop types) and intensive (more crops in a period of time) cropping systems have the potential to improve crop production without increasing inputs (Tanaka et al 2005). For example, a study done by Mohammad et al (2012) found that wheat grain yield was significantly higher in wheat-summer legume-wheat and wheat-fallow-wheat than in a wheat-summer cereal-wheat rotation. Peterson et al (1996) found that the most direct and practical solution to improving the efficient use of precipitation may be to include a summer crop following winter wheat that would make better use of summer precipitation. They also found that dryland cropping systems with more diverse crops and less fallow per unit time may be one strategy to make more efficient use of precipitation lost to evaporation during fallow.

While there are multiple environmental variables controlling crop yield, comparing actual yield with an expected one can still be revealing (Passioura 2006). Models can be used to calculate an estimated yield based on a water balance equation. It can be challenging to understand the interactions of changing climatic parameters because of the interactions among temperature and precipitation on plant growth and development (Hatfield et al 2013). Crop species respond differently to the timing of rainfall and need to be evaluated separately (Sherrod et al 2014). Water use-yield relationships are the foundation for efficient water management (Siahpoosh et al 2012). These relationships can be developed by simulating the field water balance, including simulated drainage for each location (Stone et al 2011). Mathews and Brown (1938) related crop yield to water use for winter wheat in the southern Great Plains and reported that for each millimeter of crop water use there was wheat productivity of 5.19 kg ha^{-1} with a yield threshold (the level of water use where yield response begins) of 187 mm. A similar study was done by Aiken et al. (2013) in Colby, KS that reported wheat productivity of 9.97 kg ha^{-1} and a yield threshold of 110 mm. The difficulty in measuring the components of the soil water balance prompts the use of simulation models to investigate the processes involved (Lascano 1991). Models investigate separate parts of the system and can be used as a tool to investigate solutions to problems that in agriculture are normally site-specific (Lascano 1991). Models are simplified representations of a complex system and do not include every environmental factor that can influence yield, but they can still be useful in order to observe and understand relationships between water use and grain productivity. The Kansas Water Budget (KSWB) solves the soil water balance and calculates actual evapotranspiration, drainage, and crop water use and uses crop production functions to calculate yield (Kahn et al 1996). The objective of this study was to evaluate the predictive accuracy of the KSWB for crop water use and grain productivity of grain sorghum and winter wheat, grown in a range of crop sequences.

Methods

The predictive accuracy of a modified form of the KSWB model is evaluated through two variables: crop water use and yield. Each of these values was calculated for grain sorghum and winter wheat using different sites, years, and crop rotations. Modeled crop water use data from three sites: Bushland, TX; Colby, KS, and Tribune, KS, were compared with experimental water use data for each crop. The same comparison was done with modeled yield data in order to determine how closely modeled and experimental data were related. Crop water use and yield were then combined into a functional relationship showing yield in response to an increment of water use, where yield was the dependent variable and water use was the independent variable. This function was used to find the yield threshold, which is the level of water use where yield response begins.



Stage	Wheat	Sorghum
Vegetative	Sep 17	Jun 9
Flowering	May 20	Aug 4
Seed Formation	Jun 3	Aug 24
Ripening	Jun 18	Sep 16
Physiological Maturity	Jun 22	Sep 25

Figure 1: Kansas Water Budget Flowchart. SW denotes soil water and ET is the evapotranspiration

The KSWB model (Kahn et al., 1996) solves the water balance with a daily time step. In order to calculate the daily total water content of the soil profile it is necessary to include a water balance equation:

$$SW_i = SW_{i-1} - ET_{a_{i-1}} - DR_{i-1} + EPR_{i-1} \quad [\,2\,]$$

where i is the day of the year and $i\text{-}1$ is the previous day of the year, SW is the total soil water in the profile (mm), ET_a is the daily actual evapotranspiration taken out of the profile (mm), DR is the daily amount of drainage coming out of the bottom of the profile, and EPR is the effective precipitation (mm), which is daily precipitation after taking out runoff. For this implementation of the KSWB the first day of the soil water balance was initialized as the total soil water at planting as provided in the experimental data. If data were not provided, such as when the first year was a noncrop period, a value of 60% of available soil water was used. The model assumes stubble mulch tillage as the tillage treatment. A flowchart depicting the procedure of the KSWB model is shown in Figure 1.

Yields are calculated using crop production functions, which include an effective ET term. Effective ET is used to represent a crop under water stress. A crop's source of water comes from the soil, and if there is not sufficient water to meet a specific crop's water requirement, water stress develops in the plant which has a negative effect on crop growth and yield. Water stress does not have the same effect on the crop at every stage of the crop's growth. To account for this, weighting factors were assigned to each growth period. Weighting factors are different for each growth period of a crop depending on the sensitivity of the growth period to water stress. They relate yield with actual ET relative to maximum ET. The KSWB model divides the crop growing season into four growth periods: vegetative, flowering, seed formation, and ripening. The effective ET is a sum of the weighted ET values for each of the four growth periods.

Effective Precipitation

Effective precipitation was calculated on a daily basis in order to account for runoff:

$$EPR = P(1 - RF) \quad [\,3\,]$$

where P is precipitation (mm) and RF is the runoff fraction from the equation

$$RF = 0.106 + (0.000062 * AP^2) \quad [\,4\,]$$

for the Tribune and Colby soils which are part of soil hydrologic group BC and the equation

$$RF = 0.157 + (0.000072 * AP^2) \quad [\,5\,]$$

for the Bushland soil which is part of soil hydrologic group C. In these equations, AP as the total annual precipitation in inches. This RF value was developed with corn as the base crop. To adjust for grain sorghum, 0.01 is added to the base value, and for winter wheat, 0.10 is subtracted from the base value in order to account for crop type.

The KSWB was modified to simulate multi-year crop sequences. The user initiates a simulation run by selecting a location, cropping sequence (continuous wheat - CW, continuous sorghum - CS, wheat-fallow - WF, wheat-sorghum-fallow - WSF, wheat-wheat-sorghum-fallow - WWSF, or wheat-sorghum-sorghum-fallow - WSSF), the starting year of the simulation (year of first harvest), and the number of years to run the simulation. Weather data are compiled from the first day of the first crop phase to the last day of the last crop phase so that each day the model runs the correct weather data will be used. The total soil water at planting in the soil profile will be inputted for the first crop at the beginning of the chosen sequence in millimeters. At the start of each crop or noncrop phase, it will run the water balance till the end of the phase, then switch to the next phase while changing the necessary parameters and carrying over the water balance. When it reaches the end of the final phase, the model will start over again at the first harvest year and run the simulation again with the second crop in the crop sequence, if applicable. The user will input the soil water at planting for that crop. If that is a noncrop period (fallow in wheat-sorghum-fallow rotation), then the user can enter a 0 which will put in a default value of 60% of available soil water in the profile. The simulation will run until there is a harvest for each of the years specified by the user.

Field Studies – Experimental Data

Simulation results from KSWB model runs were compared with experimental data from three locations. For each location, crop water use (CWU) was calculated as

$$CWU = SW_i - SW_f + P \quad [\ 6\ ]$$

where SW_i is soil water at planting (mm), SW_f is soil water at physiological maturity (mm), and P is in-season precipitation (mm).

Table 1: Experimental data for all studies. Crop Sequences: CW - Continuous Wheat, CS - Continuous Sorghum, WF - Wheat-Fallow, WSF - Wheat-Sorghum-Fallow, WWSF - Wheat-Wheat-Sorghum-Fallow, and WSSF - Wheat-Sorghum-Sorghum-Fallow. Tillage: SM - Stubble Mulch, NT - No-Till, RT - Reduced Tillage, ST - Sweep Tillage.

Study Citation	Location	Crop Sequences	Duration	Soil Depth (m)	Tillage Practices
Jones and Popham, 1997	Bushland, TX	CW, CS, WF, WSF	1984-1993	1.8	SM, NT
Schlegel et al., 2002	Tribune, KS	CW, WWSF, WSSF	1996-2000	1.8	CW and sorghum - NT, wheat following sorghum - RT
Aiken et al., 2013	Colby, KS	WSF	2002-2008	1.8	NT
Aiken (Unpublished)	Colby, KS	WSF	2007-2014	2.4	ST
Baumhardt and Jones, 2002	Bushland, TX	WSF	1990-1995	1.8	SM, NT
Moroke et al., 2011	Bushland, TX	CS	2000-2001	2.4	SM, NT

Table 1 shows the experimental data for all studies. The soil type for Bushland was a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) at the USDA-ARS

Conservation and Production Research Laboratory in Bushland. The soil type for Colby was a Keith silt loam (fine-silty, mixed, superactive, mesic Aridic Argiustoll) at the Northwest Extension-Research Center in Colby. The soil type for Tribune was a Richfield silt loam (fine, smectitic, mesic Aridic Argiustoll) at the Southwest Research-Extension Center near Triune. The crop water use and yield values using stubble mulch tillage were taken from the experimental data. Tables 2 and 3 show starting and ending dates (planting and physiological maturity dates) for each crop and for each of the individual studies.

Table 2: Starting and ending dates for wheat crop for experiments and for Kansas Water Budget model

Wheat			
Reference	**Location**	**Planting Date**	**Physiological Maturity Date**
Jones and Popham 1997	Bushland	Late Sep, Early Oct	Late June, Early July
Baumhardt and Jones 2002	Bushland	Late Sep, Early Oct	Early July
Aiken et al 2013 Aiken Unpublished	Colby	Sep 17 to Oct 20	June 18 to July 3
Schlegel et al 2002	Tribune	September	Late June, Early July
KSWB	-	September 17	June 22

Table 3: Starting and ending dates for sorghum crop for experiments and for Kansas Water Budget model

Sorghum			
Reference	**Location**	**Planting Date**	**Physiological Maturity Date**
Jones and Popham 1997	Bushland	Early to Mid-June	Late Oct, Early Nov
Baumhardt and Jones 2002	Bushland	Mid to late June	Late Oct, Early Nov
Moroke et al 2011	Bushland	May 31 to June 6	Sep 28 to Oct 18
Aiken et al 2013 Aiken Unpublished	Colby	May 16 to June 6	Sep 20 to Nov 7
Schlegel et al 2002	Tribune	Late May, Early June	October
KSWB	-	June 9	September 25

Performance Measures

Simple linear least square regression models were developed and used to relate modeled results to experimental data for crop water use and yield for each crop at each location with a level of significance of 0.05. Observed values were the independent variable, and were plotted on the horizontal axis. Modeled values were the dependent variable, and were plotted on the vertical axis. A t-test using standard error and n-1 degrees of freedom was used to test slope and intercept against a slope of one and an intercept of zero.

The Nash-Sutcliffe (NS) model was used to assess the predictive power of each model for both crop water use and yield. It evaluated the deviation of observations from model predictions relative to deviations of observed values from their mean:

$$NS = 1 - \frac{\sum(Observed - Modeled)^2}{\sum(Observed - Mean(Observed))^2} \qquad [\ 7\ ]$$

Observed values are those from the experimental data, and modeled values are those from the KSWB model. If the NS coefficient is zero, then the model predictions are as accurate as the mean of the observed data. If it is less than zero, the observed mean is a better predictor than the model (or the residual variance is larger than the data variance). The closer the coefficient is to one, the more accurate the model.

Crop water use and yield data were also plotted together for both observed and modeled results for each crop at each location. Crop water use was the independent variable and was plotted on the horizontal axis, and yield was the dependent variable and was plotted on the vertical axis. Plots of the CWU-yield relationship were made for both modeled and observed values and were compared, both wheat and sorghum. Tests for linearity were done using a simple least squares regression model. The level of significance was 0.05 and coefficients of determination (R^2) values were calculated to determine how well the linear model fit the data. Root mean square error (RMSE) was calculated to measure the model accuracy. A t-test was calculated to compare slope of the observed CWU-yield relationship with that of the pooled modeled CWU-relationship for each study to determine if the two slopes were significantly different. The following formula from Cohen et al. (2003) was implemented in Excel to calculate the t-value:

$$t = \frac{b_1 - b_2}{\sqrt{s_{b_1}^2 + s_{b_1}^2}}, df = n_1 + n_2 - 4 \qquad [\ 8\ ]$$

where t is the t-value, b_1 and b_2 are the slopes of the two regression lines, s_{b1} and s_{b2} are the standard errors of the two regression lines, df is the degrees of freedom, and n_1 and n_2 are the sample sizes for the two lines. When the observed t-value is greater than a corresponding t-value, at the 0.05 significance level, we reject the null hypothesis that there is no difference between the slopes.

Results

This section is divided into two parts: results of the performance measures for winter wheat and those of grain sorghum. In each section are the performance measures for crop water use, yield, and the yield-crop water use relationship, comparing observed and modeled results.

Winter Wheat

Simulation results were compared against field observations of water use and yield for each set of field studies. Regressing modeled wheat crop water use with observed (Fig. 2, Table 4) resulted in a linear relationship in four of the five cases (AIK Unp, B&J 2002, J&P 1997, and SCH 2002), as well as the two cases of pooled results (one case with all the data and one case with all data except J&P 1997). B&J 2002 and SCH 2002 had predictive skill using the Nash-Sutcliffe method, meaning they had a value greater than zero. Both sets of pooled results also had predictive skill. In three of five cases, and both sets of pooled results, predictive accuracy had a negative bias in slope which was offset by a positive bias in intercept. Predicted crop water use was generally equal to or greater than observed water use. Predictive accuracy (RMSE = 57.3 mm, restricted pooled results) declined when the J&P study was included in pooled results.

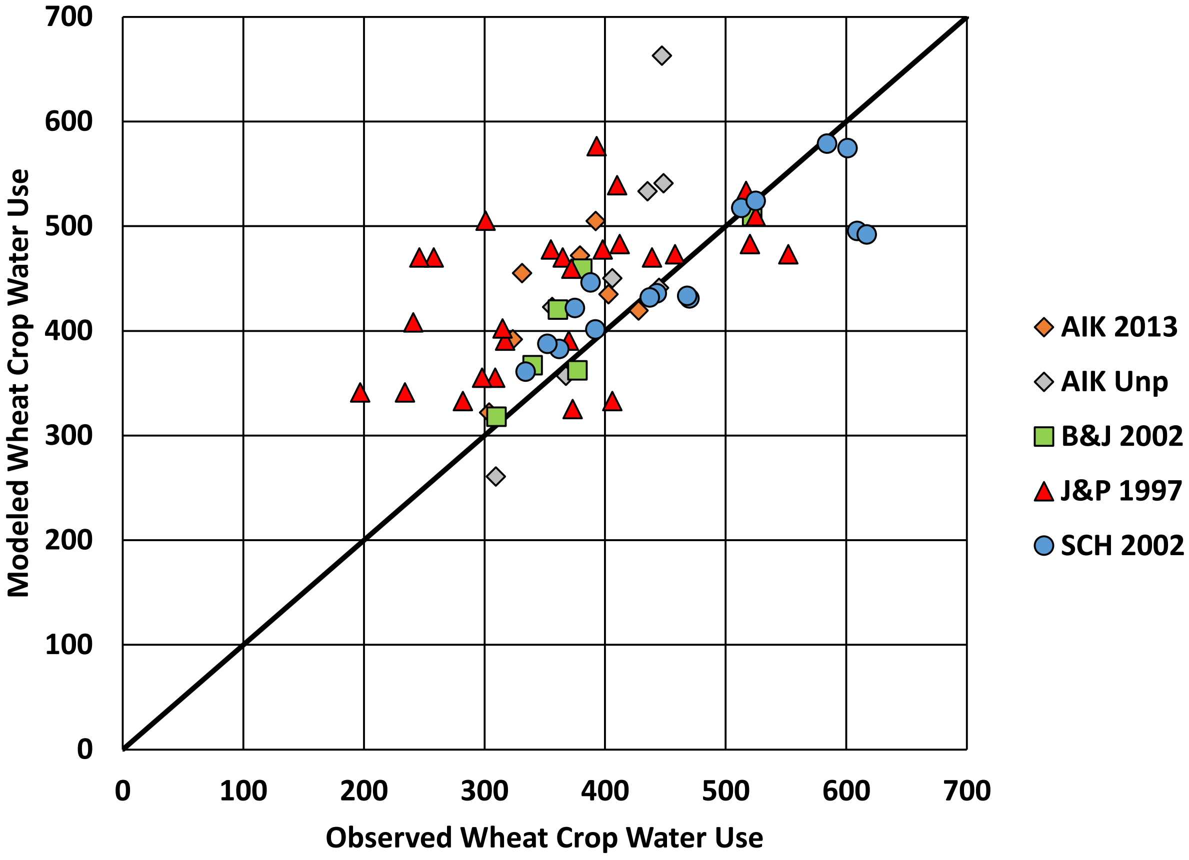


Figure 2: The predictive accuracy for Kansas Water Budget (KSWB) simulation for crop water use (mm) is presented in relation to field observations of water use for winter wheat; studies were conducted in Bushland, TX (J&P 1997, B&J 2002), Tribune, KS (SCH 2002) and Colby, KS (AIK 2013 and AIK Unp).

Table 4: Performance measures for crop water use of winter wheat, where modeled crop water use from the Kansas Water Budget was regressed on observed.[1]

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.734	160	0.328	0.1793‡	53.4	-2.32
AIK Unp	8	2.01	-349	0.730	0.0069	68.9	-2.88
B&J 2002	6	0.826	90.7	0.739	0.0281	40.3	0.598
J&P 1997	27	0.398*	293†	0.228	0.0047	62.7	-0.382
SCH 2002	16	0.595*	180†	0.771	<0.0001	32.8	0.720
Pooled	64	0.499*	244†	0.375	<0.0001	61.0	0.103
Pooled – No J&P 1997	37	0.659*	167†	0.505	<0.0001	57.3	0.378

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[1] * - Slope different from one at a significance level of 0.05.

† - Intercept different from zero at a significance level of 0.05.

‡ - Did not pass the test for linearity (from p-value).

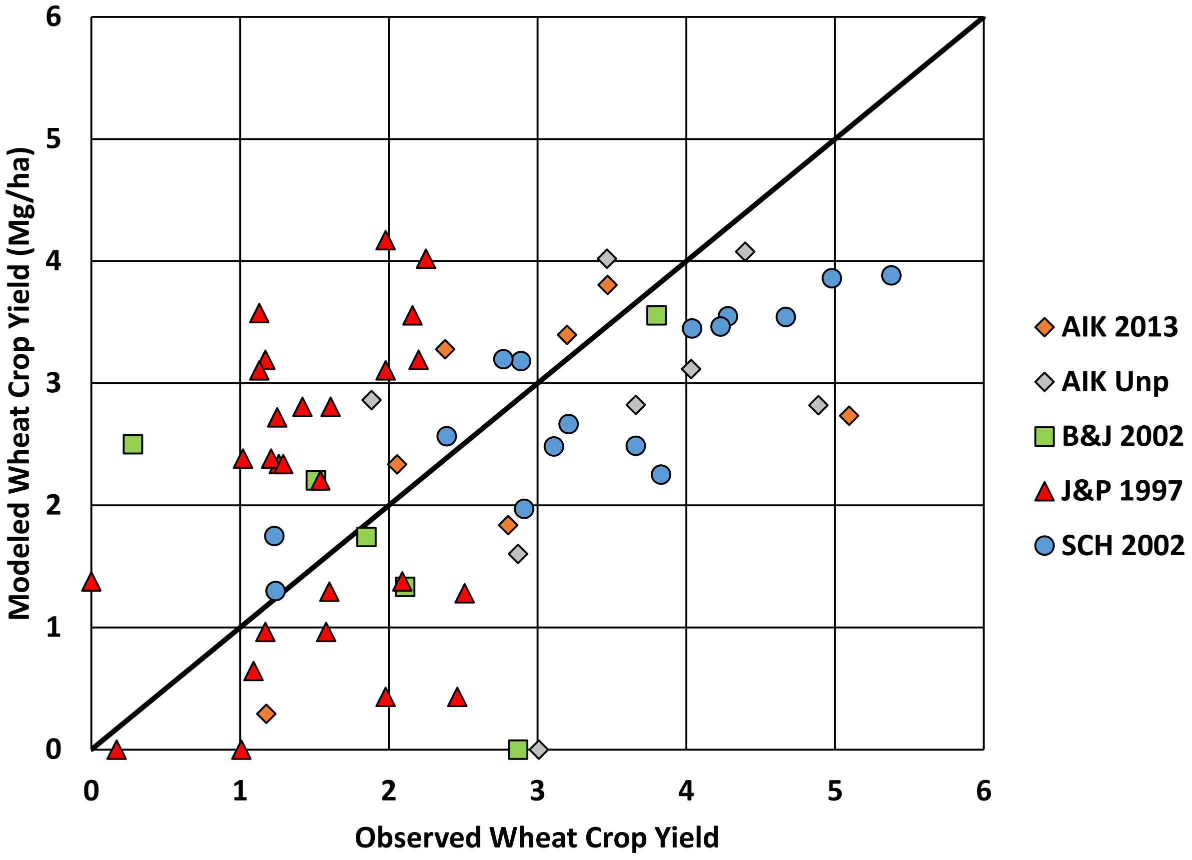

Figure 3: The predictive accuracy for Kansas Water Budget (KSWB) simulation for crop yield (Mg/ha) is presented in relation to field observations of crop yield for winter wheat; studies were conducted in Bushland, TX (J&P 1997, B&J 2002), Tribune, KS (SCH 2002) and Colby, KS (AIK 2013 and AIK Unp).

Table 5: Performance measures for winter wheat yields, where modeled crop yields from the Kansas Water Budget were regressed on observed.[2]

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.559	0.915	0.337	0.1715‡	1.06	0.0946
AIK Unp	8	0.535	0.777	0.146	0.3508‡	1.33	-1.84
B&J 2002	6	0.0159	1.86	0.000255	0.9760‡	1.34	-0.989
J&P 1997	27	0.501	1.35†	0.0624	0.209‡	1.22	-4.02
SCH 2002	16	0.552*	0.960†	0.717	<0.0001	0.430	0.432
Pooled	64	0.417*	1.37†	0.217	0.00011	1.04	0.0298
Pooled – No J&P 1997	37	0.491*	1.06†	0.316	0.00030	0.898	0.0242

Modeled wheat yields regressed on observed (Fig. 3, Table 5) resulted in a linear relationship in one of five cases, as well as for the pooled results of all cases. The predicted yields in this case, as well as the pooled results exhibited negative bias in slope and offsetting positive bias in intercept. AIK 2013 and SCH 2002 were the two cases that had predictive skill, as well as both sets of pooled results. Predictive accuracy (excluding J&P) was 0.90 Mg ha^{-1}.

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[2] * - Slope different from one at a significance level of 0.05.

† - Intercept different from zero at a significance level of 0.05.

‡ - Did not pass the test for linearity (from p-value).

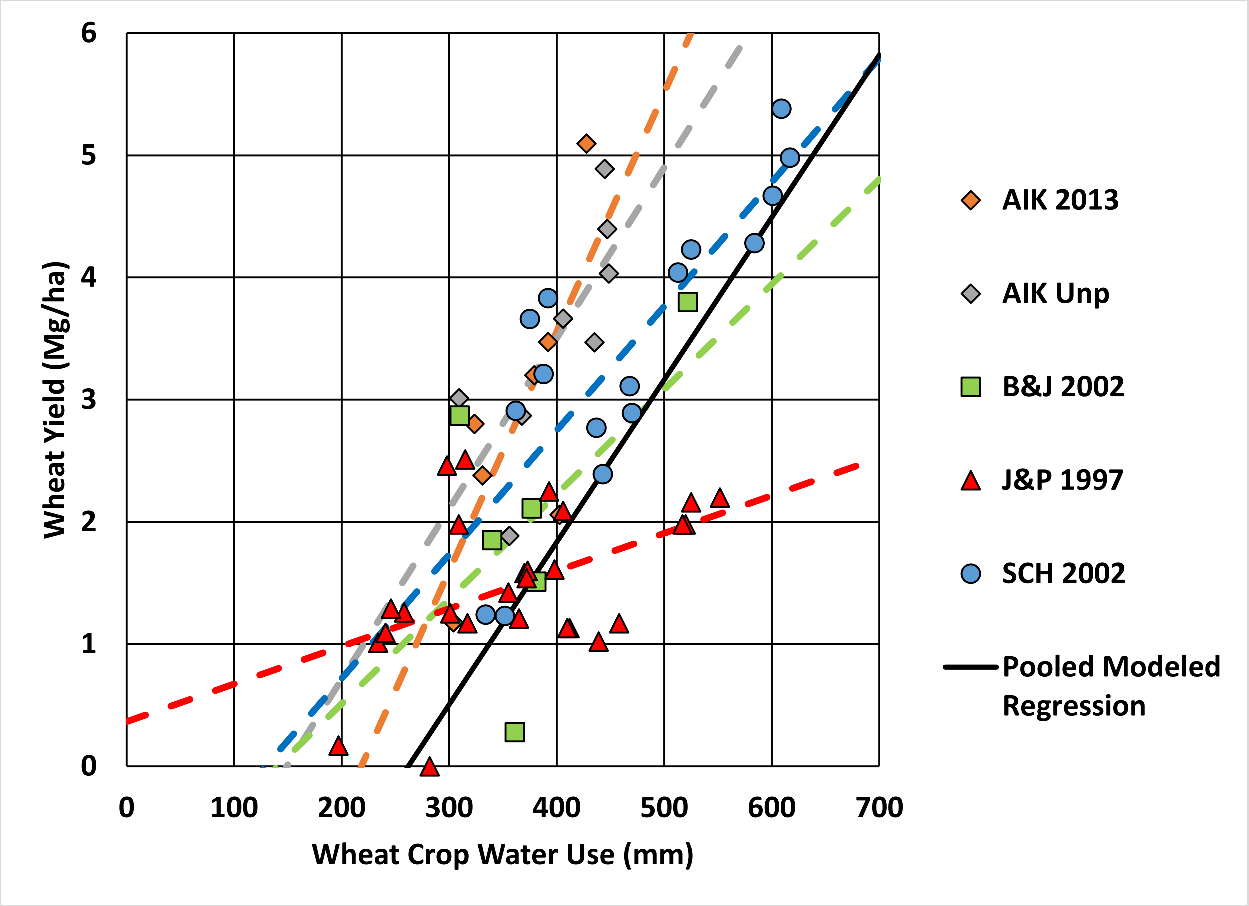

Figure 4: Crop yield (Mg/ha) is presented in relation to crop water use (mm) for winter wheat; the solid black line represents modeled yields from all studies regressed on modeled water use, the symbols represent observed yield and crop water use, and the dashed lines represent observed yield regressed on observed water use. Studies were conducted in Bushland, TX (J&P 1997, B&J 2002, MOR 2011), Tribune, KS (SCH 2002) and Colby, KS (AIK 2013 and AIK Unp).

Table 6: Performance measures for observed wheat yields regressed on observed wheat crop water use, where n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.[3]

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	19.6	-4280	0.538	0.0606†	0.921	218
AIK Unp	8	14.0	-2080	0.590	0.0260	0.655	149
B&J 2002	6	8.58	-1210	0.276	0.2843†	1.14	141
J&P 1997	27	3.08*	365	0.230	0.0114	0.552	-118
SCH 2002	16	10.2	-1310	0.686	<0.0001	0.695	129
Pooled	64	8.71	-1020	0.399	<0.0001	1.01	117
Pooled – No J&P 1997	37	10.0	-1090	0.503	<0.0001	0.876	109

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[3] * - Differed significantly from the pooled modeled regression.

† - Did not pass the test for linearity (from p-value).

Table 7: Performance measures for modeled wheat yields regressed on modeled wheat crop water use, where n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins or where the regression line intercepts the x-axis.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	19.6	-5860	0.956	0.0001	0.274	299
AIK Unp	8	9.99	-1920	0.850	0.0011	0.556	192
B&J 2002	6	15.8	-4540	0.872	0.0064	0.478	287
J&P 1997	27	15.6	-4740	0.832	<0.0001	0.518	304
SCH 2002	16	9.95	-1700	0.712	<0.0001	0.434	171
Pooled	64	13.3	-3500	0.770	<0.0001	0.561	263
Pooled – No J&P 1997	37	11.8	-2660	0.788	<0.0001	0.500	225

Observed yield thresholds for the yield-crop water use relationship for wheat (Table 6) ranged between 129 and 218 mm (excluding the J&P case, with an unrealistic negative value for yield threshold). Corresponding observed slopes of the relationship were between 8.6 and 19.6 kg ha^{-1} mm^{-1}. Three of the five cases and both of the pooled cases were found to be linear. No differences were detected between observed slopes and slope of the restricted pooled results for four of the five cases. The modeled yield threshold was numerically greater than the observed yield threshold. Figure 4 shows a solid black line representing pooled modeled yield regressed on pooled modeled water use, the symbols representing observed yield and crop water use, and the dashed lines representing regression of observed yield regressed on observed water use, all for winter wheat.

The modeled yield thresholds for the yield-crop water use relationship for wheat (Table 7) ranged between 171 and 304 mm. Modeled slopes of the same relationship ranged between 9.95 and 19.6 kg ha^{-1} mm^{-1}. All cases were found to be linear.

Grain Sorghum

In two of the five cases of sorghum crop water use, as well as the pooled results, there was a linear relationship (AIK Unp and B&J 2002/MOR 2011) when the modeled values were regressed on observed values (Fig. 5, Table 8),. The model had predictive skill in these two cases, as well as in both sets of the pooled results. No bias was detected in one linear case; a negative bias in slope was observed in the other linear case. Pooled results exhibited offsetting negative bias in slope and positive bias in intercept.

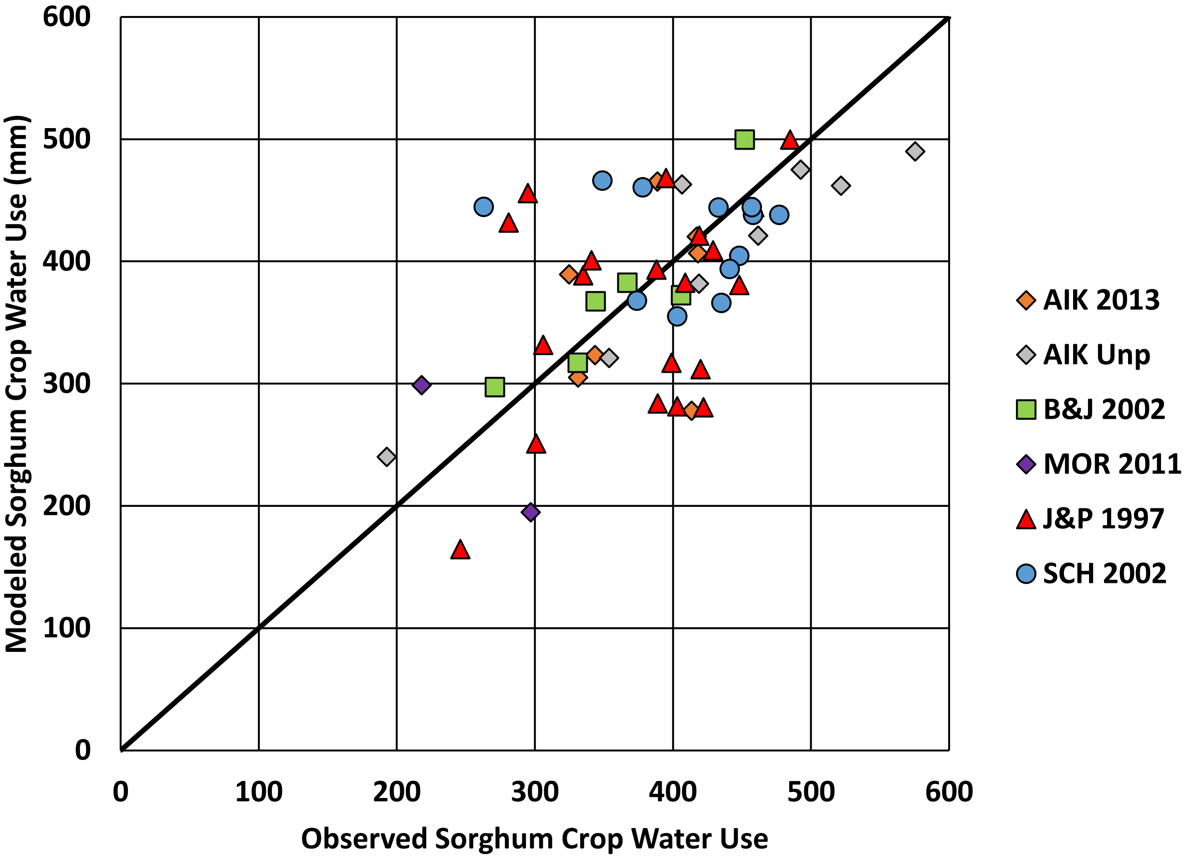

Figure 5: The predictive accuracy for Kansas Water Budget (KSWB) simulation for crop water use (mm) is presented in relation to field observations of water use for grain sorghum; studies were conducted in Bushland, TX (J&P 1997, B&J 2002, MOR 2011), Tribune, KS (SCH 2002) and Colby, KS (AIK 2013 and AIK Unp).

Table 8: Performance measures for crop water use of grain sorghum, where modeled crop water use from the Kansas Water Budget was regressed on observed. [4]

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.448	201	0.0761	0.5493‡	72.2	-1.77
AIK Unp	8	0.688*	112	0.857	0.0010	35.8	0.787
B&J 2002 and MOR 2011	8	0.915	33.9	0.603	0.0234	59.9	0.435
J&P 1997	20	0.496	177	0.147	0.0950‡	80.3	-0.725
SCH 2002	12	-0.109*	463.2†	0.0282	0.6020‡	40.6	-0.662
Pooled	55	0.584*	154†	0.322	<0.0001	65.0	0.101
Pooled – No J&P 1997	35	0.605*	152†	0.446	<0.0001	56.0	0.389

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[4] * - slope different from one at a significance level of 0.05.

† - intercept different from zero at a significance level of 0.05.

‡ - Did not pass the test for linearity (from p-value).

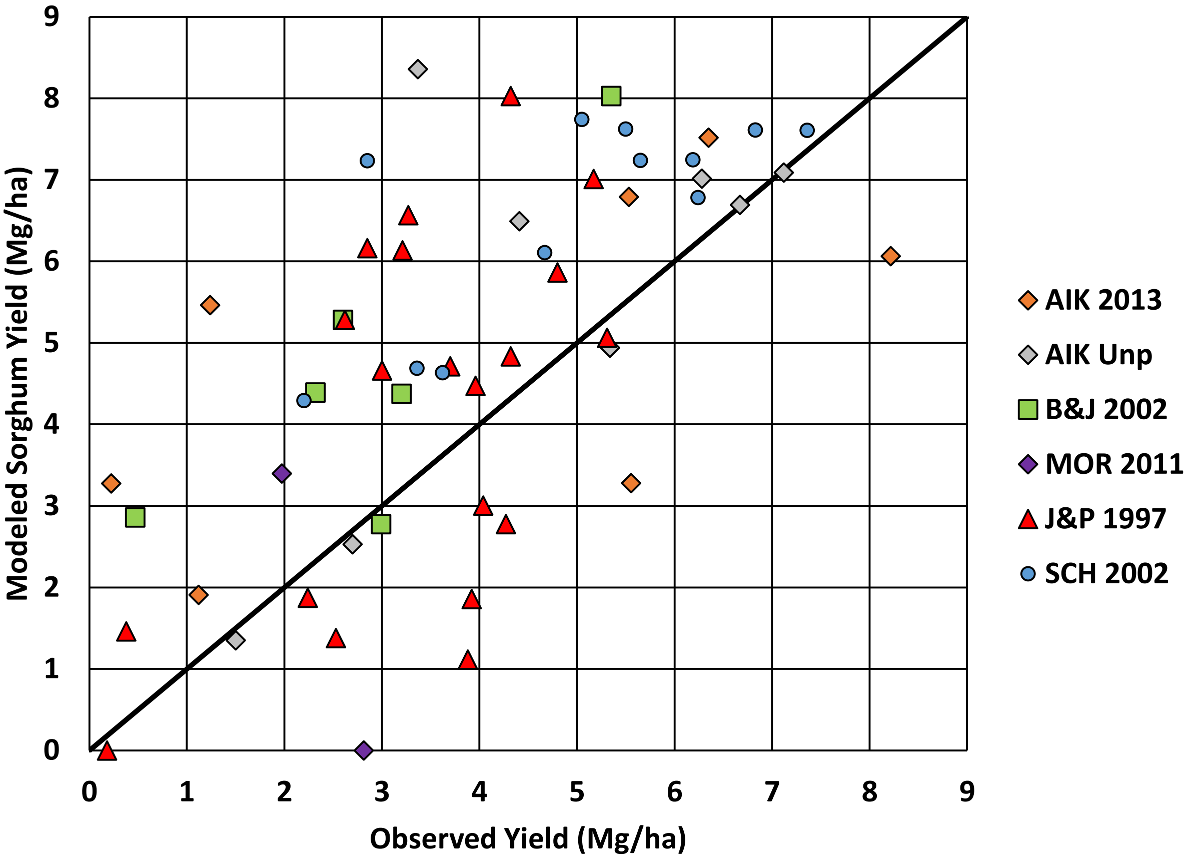

Figure 6: The predictive accuracy for Kansas Water Budget (KSWB) simulation for crop yield (Mg/ha) is presented in relation to field observations of crop yield for grain sorghum; studies were conducted in Bushland, TX (J&P 1997, B&J 2002, MOR 2011), Tribune, KS (SCH 2002) and Colby, KS (AIK 2013 and AIK Unp).

Table 9: Performance measures for grain sorghum yields, where modeled crop yields from the Kansas Water Budget were regressed on observed.[5]

Study	n	Slope	Intercept	R^2	P - value	RMSE	Nash-Sutcliffe
AIK 2013	7	0.423*	3.19†	0.396	0.1301‡	1.78	0.304
AIK Unp	8	0.814	1.76	0.456	0.0663‡	1.95	-0.0437
B&J 2002 and MOR 2011	8	0.980	1.23	0.336	0.1319‡	2.03	-1.74
J&P 1997	20	0.932	0.946	0.311	0.0106	1.94	-1.22
SCH 2002	12	0.582*	3.68†	0.538	0.0066	0.930	-0.510
Pooled	55	0.770	1.92†	0.423	<0.0001	1.74	-0.148
Pooled – No J&P 1997	35	0.690*	2.49†	0.464	<0.0001	1.62	0.0329

Regarding modeled sorghum yields regressed on observed yields (Fig. 6, Table 9), two of five cases (J&P 1997 and SCH 2002) and both sets of pooled results exhibited a linear relationship. A negative bias in slope was offset by a positive bias in intercept for this case and both pooled results. One case had predictive skill (AIK 2013), as well as the restricted pooled results. Three of the five cases and one of the pooled cases had slopes that were not different from one and three of the five cases and none of the pooled cases had intercepts that were not different from zero at a significance level of 0.05.

Observed yield thresholds for the yield-crop water use relationship for sorghum (Fig. 7, Table 11) ranged between 89 and 275 mm, excluding the case of J&P. Corresponding slopes

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[5] * - slope different from one at a significance level of 0.05.

† - intercept different from zero at a significance level of 0.05.

‡ - Did not pass the test for linearity (from p-value).

ranged from 13.8 to 39.5 kg ha^{-1} mm^{-1}. Three of the five cases and both of the pooled cases were found to be linear. Three of the cases, AIK Unp, B&J 2002/MOR 2011, and J&P 1997 had slopes that differed from that of the pooled modeled regression. Figure 7 shows a solid black line representing pooled modeled yield regressed on pooled modeled water use, the symbols representing observed yield and crop water use, and the dashed lines representing regression of observed yield regressed on observed water use, all for grain sorghum.

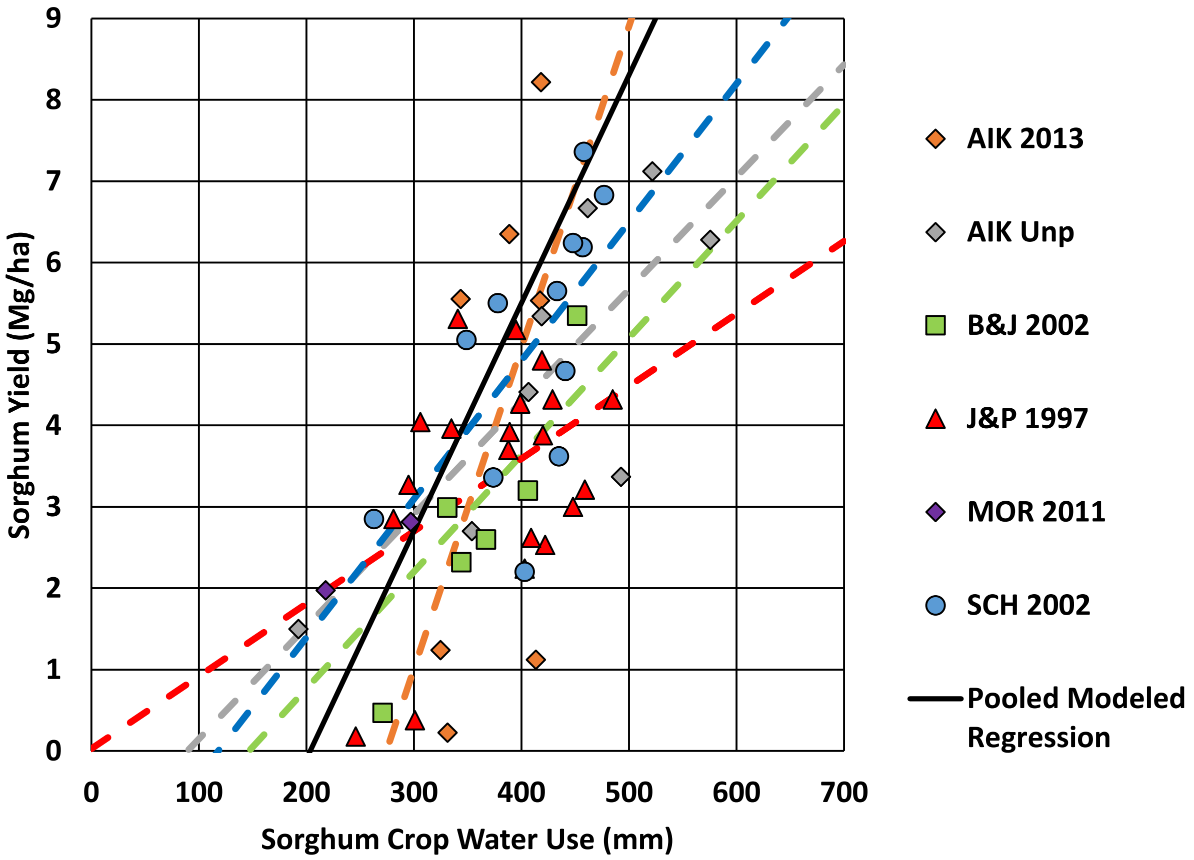

Figure 7: Crop yield (Mg/ha) is presented in relation to crop water use (mm) for grain sorghum; the solid black line represents modeled yields from all studies regressed on modeled water use, the symbols represent observed yield and crop water use, and the dashed lines represent observed yield regressed on observed water use. Studies were conducted in Bushland, TX (J&P 1997, B&J 2002, MOR 2011), Tribune, KS (SCH 2002) and Colby, KS (AIK 2013 and AIK Unp).

Table 10: Performance measures for observed sorghum yields regressed on observed sorghum crop water use, where n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.[6]

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	39.5	-10800	0.287	0.2155†	2.88	275
AIK Unp	8	13.8*	-1230	0.645	0.0164	1.30	89.4
B&J 2002 and MOR 2011	8	14.4*	-2110	0.618	0.0206	0.910	147
J&P 1997	20	8.91*	25.6	0.184	0.0594†	1.26	-2.88
SCH 2002	12	17.0	-2010	0.392	0.0294	1.34	118
Pooled	55	15.5	-2090	0.377	<0.0001	1.53	135
Pooled – No J&P 1997	35	17.5	-2640	0.447	<0.0001	1.62	151

---

[6] * - Differed significantly from the pooled modeled regression.

† - Did not pass the test for linearity (from p-value).

Table 11: Performance measures for modeled sorghum yields regressed on modeled sorghum crop water use, where n is the sample size, the p-value is for a test of linearity at a significance level of 0.05, and the yield threshold is the level of water use where yield response begins, or where the regression line intercepts the x-axis.

Study	n	Slope (kg ha^{-1} mm^{-1})	Intercept (kg ha^{-1})	R^2	P - value	RMSE	Yield Threshold (mm)
AIK 2013	7	30.3	-6300	0.984	<0.0001	0.287	208
AIK Unp	8	26.8	-5350	0.927	0.0001	0.713	200
B&J 2002 and MOR 2011	8	25.9	-5700	0.977	<0.0001	0.379	191
J&P 1997	20	26.1	-5410	0.944	<0.0001	0.553	207
SCH 2002	12	32.0	-6830	0.927	<0.0001	0.369	213
Pooled	55	28.0	-5720	0.929	<0.0001	0.612	204
Pooled – No J&P 1997	35	28.5	-5670	0.944	<0.0001	0.520	199

The modeled yield thresholds for the yield-crop water use relationship for sorghum (Fig. 7, Table 11) ranged between 191 and 213 mm. The modeled slopes were very similar as well, ranging between 25.9 and 32.0 kg ha^{-1} mm^{-1}. All cases were found to be linear.

For both wheat and grain sorghum, the precision of the yield-water use relationship was greater for modeled results (RMSE = 0.50 and 0.52 kg ha^{-1} mm^{-1}, respectively) than the relationship derived from observations (RMSE = 0.88 and 1.62 kg ha^{-1} mm^{-1}, respectively).

Discussion

Analysis of pooled results are differentiated with respect to the J&P 1997 study; either excluding or including the results of this long-term field study. Review of predictive accuracy for individual studies and pooled studies support this approach. Results of the earlier Bushland study

(J&P 1997) appear to differ from the later Bushland study (B&J 2002), especially in slopes and yield thresholds of the yield-water use relationship, for both crops. The later study had greater slopes and yield thresholds than the earlier study in both wheat and sorghum, based on experimental results. In contrast, the modeled results were very similar for the two studies, indicating similarity of conditions considered by the model. Because of the predictive skill of KSWB for results of both the B&J 2002 and J&P 1997 studies, for wheat and sorghum crop water use indicates the KSWB model can be successfully applied in the Bushland, TX region. There are some possible reasons for the differences between the J&P 1997 and B&J 2002 studies. One reason may be due to the difference in sample size. The J&P 1997 study had many more observations with a variety of crop sequences compared to the later Bushland study. Another may be that because the J&P 1997 study began earlier than the B&J 2002 study, improvements in crop production technology may have occurred that were beyond the scope of the KSWB model.

The KSWB model had similar predictive accuracy for crop water use of wheat and grain sorghum, considering RMSE, Nash-Sutcliff, and the coefficient of determination for the restricted pooled results. Similarly, the predictive accuracy for yield was similar for both crops, though accuracy was substantially reduced and the Nash-Sutcliff criteria for predictive skill was not met. Therefore, it is remarkable to observe the performance of KSWB in replicating the yield-water relationship for both wheat and grain sorghum.

The relationship of wheat yield to water use simulated by the KSWB was similar to the relationships developed for four of the five field studies. Both the slopes and yield thresholds for the five cases analyzed for this study were similar to those reported in Mathews and Brown (1938) and Aiken et al. (2013), with the exception of J&P 1997. However, the magnitude of the yield thresholds of each of five studies was numerically less than that derived from the pooled simulated results, indicating that yield response to water use began with less water than calculated by the model. This suggests KSWB systematically underestimates wheat productivity, in response to water use.

In contrast, the sorghum yield response to water use relationship simulated by the KSWB (pooled modeled regression) differed from that of three studies—particularly the slope of the yield response to an increment of water use. Simulated sorghum yield thresholds were consistent with observed yield thresholds for four of five locations. Experimental yield response to an increment of water use was substantially less—approximately half—that calculated by the KSWB for four of the five studies. This result indicates that the model predicted a much higher yield response to water than was observed. This also indicates a substantial gap between actual and potential sorghum yields.

Regional trends

Most of the slopes of the yield to water use relationship (experimental, but not modeled results) were smaller in Bushland than in Tribune or Colby for both wheat and sorghum. One possible reason for this is that Bushland has higher temperatures on average, as well as higher precipitation. Growing seasons with higher temperatures can cause a decrease crop yields and also a decrease in the slope of the yield-water use relationship because of the heat stress. Another reason is that the start and end dates for the crop seasons at each of the sites are not the same day as they are in the model. Start dates for each season are not always on the same day so a date range is given. Many factors, such as timing of precipitation, influence when planting begins. For example, in Bushland the planting dates for wheat could be anywhere between late September and early October, but for Colby the planting date could be as late as October 20th. For sorghum, harvest dates could be as early as September 20 (Colby) or as late as early November (Bushland). There is some uncertainty in the model on this point, because if the model has a shorter growing season than the study, the precipitation during the growing season is not the same, especially if there were large precipitation events after the model growing season ended but before the end of the growing season of the study.

When looking at the modeled results for the yield to water use relationship most of the points fall on the same line and have very small dispersion, especially in sorghum but also for wheat. The KSWB yield formation algorithm calculates yield as a weighted average of crop water use—with stress factors comprising the weighting factors. If there is no stress, weighting factors will have no effect, and yield-water use relationship will be a straight line. The smaller coefficient of determination for the simulated yield-water use relationship, for wheat, suggests a greater role of stress factors in wheat yield calculation for wheat. The dispersion of observed data points about the yield-water use relationships of wheat and sorghum are substantially greater than for the modeled relationship, as indicated by the smaller coefficient of determination for the observed relationship. This suggests that factors other than water may be limiting yield responses. The model accounts for some of the stress factors such as water and temperature effects on evaporative demand, but there are many factors other than these that contribute to or harm yields. Weeds, pests, diseases, tillage, and fertility, as well as other management practices, could all be potential factors limiting yields in the experimental results; factors which are explicitly beyond the scope of the KSWB model. One of the sources of uncertainty in the model is that the actual planting and physiological maturity dates for each of the field studies differ from the model assumptions. Other sources include the uncertainty of hydraulic properties and that the soil profile was treated as a block of homogenous soil instead of being broken up into layers, each with different properties.

While this study analyzed a number of different cropping sequences of wheat and sorghum, these sequences were not compared with each other. Although this analysis could be useful, it was not undertaken in this work. For example, Aiken et al. (2013) found that replacing an uncropped fallow period with an oilseed crop can reduce grain yield response of continuous wheat by 31%. A study done by Mohammad et al (2012) found that wheat grain yield was significantly higher in wheat-summer legume-wheat and wheat-fallow-wheat than in a wheat-summer cereal-wheat rotation. Peterson et al (1996) found that the most direct and practical solution to improving the efficient use of precipitation may be to include a summer crop in the following winter wheat that would make better use of summer precipitation.

Conclusion

The KSWB model demonstrated predictive skill for crop water use, but not yield of grain sorghum and winter wheat. The simulated yield-water use relationship was consistent with that of four of five field studies of wheat and two of five field studies of sorghum. Simulated yield response of wheat to water use indicates the actual yield threshold of water use may be smaller than simulated, but observed yield response to subsequent water use is similar to that which was simulation. In contrast, the simulated yield threshold for grain sorghum appears similar to the simulated value, but actual yield response to subsequent water use is approximately half the potential value. The KSWB provides a useful analytic framework for distinguishing water supply constraints to grain productivity.

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Appendix A - Matlab Code

User_Input.m

```
% Obtains user-input to specify batch run conditions, simulating water
% balance and corresponding yields of wheat and grain sorghum in multi-year
crop sequences

% Functions:
% User specified conditions include site, crop sequence, initial year and
duration of simulation period
% User also specifies location of weather data in computer files
% Initializes site parameters and control arrays used in establishing
individual water balance, and subsequent water use and yield runs
% Establishes control matrix used to specify sequence of simulation
% Calls specific routines in order required for specified sequence

% Clears main window and variables
clear all;
clc;

% Define constants for control array
% Format: [1 2 3 4]
% 1 = crop(1=wheat, 2=sorghum, 3=fallow)
% 2 = planting start DOY
% 3 = harvest end DOY
% 4 = 1=crop dates in 2 separate years, 2=crop dates in same year
% w = wheat, s = sorghum, nc_ww = noncrop between wheat phases, nc_fw =
noncrop between fallow and wheat phases (for wheat-fallow rotation), nc_ws =
noncrop between wheat and sorghum phases, nc_sw = noncrop between sorghum and
wheat phases, nc_ss = noncrop between sorghum phases
CA_w =[1 260 173 1];
CA_s =[2 160 268 0];
CA_nc_ww = [0 174 259 0];
CA_nc_fw = [0 174 259 1];
CA_nc_ws = [0 174 159 1];
CA_nc_sw = [0 269 259 1];
CA_nc_ss = [0 269 159 1];

% Control matrices corresponding to crop sequences
% 9/25/15 Added versions of control matrices corresponding to each phase of
crop sequence
CM_w = [CA_w; CA_nc_ww];
CM_s = [CA_s; CA_nc_ss];
CM_wf = [CA_w; CA_nc_fw];
CM_fw = [CA_nc_fw; CA_w];
CM_wsf = [CA_w; CA_nc_ws; CA_s; CA_nc_sw];
CM_sfw = [CA_s; CA_nc_sw; CA_w; CA_nc_ws];
CM_fws = [CA_nc_sw; CA_w; CA_nc_ws; CA_s];
CM_wwsf = [CA_w; CA_nc_ww; CA_w; CA_nc_ws; CA_s; CA_nc_sw];
CM_wsfw = [CA_w; CA_nc_ws; CA_s; CA_nc_sw; CA_w; CA_nc_ww];
CM_sfww = [CA_s; CA_nc_sw; CA_w; CA_nc_ww; CA_w; CA_nc_ws];
CM_fwws = [CA_nc_sw; CA_w; CA_nc_ww; CA_w; CA_nc_ws; CA_s];
CM_wssf = [CA_w; CA_nc_ws; CA_s; CA_nc_ss; CA_s; CA_nc_sw];
```

```
CM_ssfw = [CA_s; CA_nc_ss; CA_s; CA_nc_sw; CA_w; CA_nc_ws];
CM_sfws = [CA_s; CA_nc_sw; CA_w; CA_nc_ws; CA_s; CA_nc_ss];
CM_fwss = [CA_nc_sw; CA_w; CA_nc_ws; CA_s; CA_nc_ss; CA_s];

% Sinfo.param (3 x 6) available water and drainage coefficients for each
location
%Bushland
Bush_sw_max = 732;     % Max W allowed (upper limit)(mm)
Bush_ulaw = 640;       % Upper limit of AW (mm)
Bush_llaw = 347;       % Lower limit of AW (mm)
Bush_dr_a = 20.5;      % Coefficient a in drainage equation dW/dt = a(W/b)^c
(p 38)
Bush_dr_b = 680;       % Coefficient b in drainage equation dW/dt = a(W/b)^c
(p 38)
Bush_dr_c = 34.11;     % Coefficient c in drainage equation dW/dt = a(W/b)^c
(p 38)

%Colby
Col_sw_max = 766;     % Max W allowed (upper limit)(mm)
Col_ulaw = 660;       % Upper limit of AW (mm)
Col_llaw = 313;       % Lower limit of AW (mm)
Col_dr_a = 32.2;      % Coefficient a in drainage equation dW/dt = a(W/b)^c (p
38)
Col_dr_b = 715;       % Coefficient b in drainage equation dW/dt = a(W/b)^c (p
38)
Col_dr_c = 23.17;     % Coefficient c in drainage equation dW/dt = a(W/b)^c (p
38)

%Tribune
Trib_sw_max = 787;     % Max W allowed (upper limit)(mm)
Trib_ulaw = 650;       % Upper limit of AW (mm)
Trib_llaw = 290;       % Lower limit of AW (mm)
Trib_dr_a = 42.7;      % Coefficient a in drainage equation dW/dt = a(W/b)^c
(p 38)
Trib_dr_b = 729;       % Coefficient b in drainage equation dW/dt = a(W/b)^c
(p 38)
Trib_dr_c = 18.06;     % Coefficient c in drainage equation dW/dt = a(W/b)^c
(p 38)

% Soil parameters matrix layout
%               SW Max  Upper AW  Lower AW  DR a  DR b    DR c
% Bushland   1x1 vector
% Colby
% Tribune

Sinfo.param = [Bush_sw_max Bush_ulaw Bush_llaw Bush_dr_a Bush_dr_b Bush_dr_c;
Col_sw_max Col_ulaw Col_llaw Col_dr_a Col_dr_b Col_dr_c; Trib_sw_max
Trib_ulaw Trib_llaw Trib_dr_a Trib_dr_b Trib_dr_c];

% Import the crop coefficient data from file for leap year and non-leap year
dxx1 = '~\Kxx.xlsx';
dxx2 = '~\Kxx_ly.xlsx';
% Imports raw data files from Excel
kxx1 = xlsread(dxx1);
kxx2 = xlsread(dxx2);

% Ask the user to select a site
```

```
site = input('Experimental site is Bushland [1], Colby [2], Tribune [3]');

% Ask the user which crop sequence
seq = input('Crop sequence is WW [1], SS [2], WF [3], WSF [4], WWSF [5], WSSF
[6]');

% Receive data from weather function
% wd_iyear = first year of weather data requested by user
% wd_dur = number of years of weather data requested by user
% dx2 = weather files found for dates specified by user
% APP = annual precipitation for each of the requested years in three
columns:
% 1: the given year
% 2: annual precipitation using 8/1 - 7/31 convention (wheat)
% 3: annual precipitation using 1/1 - 12/31 convention (sorghum)
[wd_iyear, wd_dur, dx2, APP] = Weather_in();

yrdur=wd_dur;
% Initialize first harvest year.
year = wd_iyear;
% Establish control matrices for each phase of crop sequences
if seq ==1
    CM_ph=CM_w; ph = 1;
elseif seq ==2
    CM_ph=CM_s; ph = 1;
elseif seq ==3
    CM_ph=[CM_wf; CM_fw]; ph = 2;
elseif seq==4
    CM_ph=[CM_wsf; CM_sfw; CM_fws]; ph = 3;
elseif seq==5
    CM_ph=[CM_wwsf; CM_wsfw; CM_sfww; CM_fwws]; ph = 4;
elseif seq==6
    CM_ph=[CM_wssf; CM_ssfw; CM_sfws; CM_fwss]; ph = 4;
end;
% Determine number of phases for selected crop sequence
% ph=numel(CM_ph);
m=0;
for h=1:ph
    CM=CM_ph;
    year = wd_iyear;
    % Determine number of arrays in control matrix
    NumArr=numel(CM)/(ph*4);
    % Ask user for the available soil water at planting using each year and
phase
    SW_start = input(['What was available soil water at planting in '
num2str(year) ' for phase ' num2str(h) '(mm)? (Enter 0 if unknown)']);
    % If available soil water at planting is unknown:
    if SW_start == 0
        % Initialize soil water (aka SWO) at 60% of available water capacity
        SW_start = 0.6*(Sinfo.param(site,2)-
Sinfo.param(site,3))+Sinfo.param(site,3);
    end
    % Determine cycle length, from selected crop sequence
    cycle_length=0; % Initialize cycle length
    % Determine number of complete cycles from weather records and cycle
length
    % Alert user if there isn't enough weather data
```

```
    for k=1:NumArr
        cycle_length = cycle_length + CM(k,4); % Shows how many years to
complete the user input
    end;
    if yrdur < cycle_length
        disp('Not enough weather data to complete a sequence...aborting.');
        break
    end
    % Floor rounds down to the next integer, this shows the number of
    % cycles that can be done in this number of years.
    cycle_number = floor(yrdur/cycle_length);
    app_year = 1;
    first = 0;
for i=1:cycle_number
    for j=(m*NumArr + 1):(m*NumArr+NumArr)
        % Need to identify jth control array to pass into WB_BC, also, which
annual precipitation value to use for runoff calculation
        % Draws crop, start date, end date, and year span from control matrix
for each crop (or noncrop) run
        crop = CM(j,1);
        start = CM(j,2);
        enddate = CM(j,3);
        span = CM(j,4);
        % Adds span to year if not the first year
        if first > 0
            year = year + span;
        end
        % If the year is after the final year, terminate the program
        if year == wd_iyear+yrdur
            break
        end
        first = 1;

        % Obtain boundary conditions for water balance (WB) for current
control array

        % Inputs: weather data for all years(dx2), crop, start and end dates,
crop coefficient data files (kxx1 and kxx2), current year

        % Outputs: daily maximum ET (mET), daily precipitation (Prep), daily
crop coefficients (kx), weather data between start and end dates of the
crop/noncrop (dx)

        [mET,Prep,kx,dx] = WB_BC(dx2,crop,start,enddate,span,kxx1,kxx2,year);

        % Calculate runoff fraction from appropriate elements of annual
precipitation matrix APP
        if span ==0
            if app_year > wd_dur
                AP_rec = 0;
            else
            AP_rec = APP(app_year,2);
            end
        else
            if app_year > wd_dur
                AP_rec = 0;
            else
```

```
            AP_rec = APP(app_year,3);
            app_year = app_year + 1;
            end
        end
        % Calculates runoff
        if site == 1
            RF_eq = 0.157 + (0.000072*AP_rec*AP_rec);
        else
            RF_eq= 0.106 + (0.000062*AP_rec*AP_rec);
        end
        % Adjusts runoff depending on crop
        if CM(j,1)==1
            RF=RF_eq-0.1;
        elseif CM(j,1)==2
            RF=RF_eq+0.01;
        elseif CM(j>1)==0
            RF=RF_eq+0.03;
        end;

        % Water Balance Equation

        % Inputs: weather data between start and end dates of the
crop/noncrop (dx), soil properties (Sinfo), site, daily crop coefficients
(kx), daily precipitation (Prep), daily maximum ET  (mET), runoff fraction
(RF), soil water at planting (SW_start)

        % Outputs: soil water at harvest (SW_last), daily ending soil water
(SWO), daily initial soil water (SWI), daily drainage (DR), daily
        % available soil water (ASW), daily available soil water coefficient
(Ka), daily actual ET (aET), daily effective precipitation (EPR), error in
soil water or drainage calculations

        [SW_last,SWO,SWI,DR,ASW,Ka,aET,EPR,error] =
WB(dx,Sinfo,site,kx,Prep,mET,RF,SW_start);

        % Calculate CWU and Yield

        % Inputs: daily actual ET (aET), daily maximum ET (mET), daily
effective precipitation (EPR), daily precipitation (Prep), daily drainage
(DR), current year, current crop, soil water at planting (SW_start), soil
water at harvest (SW_last)

        % Outputs: effective ET (eET), sum of actual ET (aET_sum), sum of
maximum ET (ETmax_sum), crop yield - zero if noncrop (Yield), sum of
precipitation, drainage, and effective precipitation during crop/noncrop
period (Prep_sum, DR_sum, EPR_sum), crop water use  (CWU), sum of actual ET
and maximum ET for each of the four growth periods (aET_comp and mET_comp)


[eET,aET_sum,ETmax_sum,Yield,Prep_sum,DR_sum,EPR_sum,CWU,aET_comp,mET_comp] =
WU_Y(aET,mET,EPR,Prep,DR,year,crop,SW_start,SW_last);

        % Place output in matrix
        output(i,1,j)=year;
        output(i,2,j)=crop;
        output(i,3,j)=SW_start;
        output(i,4,j)=SW_last;
```

```
        output(i,5,j)=aET_sum;
        output(i,6,j)=DR_sum;
        output(i,7,j)=Prep_sum;
        output(i,8,j)=EPR_sum;
        output(i,9,j)=CWU;
        output(i,10,j)=eET;
        output(i,11,j)=Yield;
        % Set soil water start in next crop/noncrop to be equal to soil water
value at the end of the previous crop/noncrop
        SW_start=SW_last;
    end
    % Terminate program if the year is later than the user specified
    if year == wd_iyear+yrdur
        break
    end
end

m = m + 1;
end
Arr = yrdur * NumArr;
Reshape = output(:,:);
Output = reshape(output,[11,Arr]);
% Write output to an Excel file
xlswrite('~\Output.xlsx',Output);
```

Weather_in.m

```
function [wd_iyear, wd_dur, dx2, APP] = Weather_in_9_29_15()
% Weather_in provides internal access to external weather data
% Provides for user-selected path, base name and extension for
annual weather data files;
% Creates annual data matrices corresponding to daily weather records
% Calculates annual precipitation (1/1 - 12/31 and 8/1 - 7/31 conventions);

close all
clc

% Find directory
dfltfldr='~'; %Where the weather data is, default for user interface
folder=uigetdir (dfltfldr,'select a folder'); %User chooses where the weather
data will be found

% Load annual weather data files
% Code derived from P Coyne, Calib_gui data_calib or ima_read files

ext='.xlsx';

% Displays message if no files are in the directory
if folder==0
    disp('No folder selected...aborting.');
    return
end
% User selects an image file from the default or specified directory
```

```
if isempty(ext)==1;
    filespec=folder;
else
    filespec=[folder '\*' ext];
end;
d=dir(filespec);
if isempty(d)==1
    disp('No data files in the selected folder...aborting.');
    return;
else
    % If .xlsx files in directory, display the directory content:
    fprintf(1,'\n');
    % Base name input by user for desired weather file (BUSH = Bushland,
    % COLBY = Colby, TRIB = Tribune)
    wd_base = input('Base name weather data files (without year nor suffix):
','s');
end;

% User input of start year and number of years for weather data files
wd_iyear=input('Initial year of weather data (four digit): '); %ex: 1995
wd_dur=input('Number of years of continuous weather data: ');
wd_prioryear = wd_iyear-1; % Finds year previous to first harvest year for
wheat calculations
wd_year=wd_iyear;

wdn=''; % Character array can change for any input

% Combines user inputs to give file name for weather data for year prior to
initial harvest year
wdn{1}=strcat(folder,'\',wd_base,'_',num2str(wd_prioryear),ext);

for i=2:wd_dur+1
    wdn{i}=strcat(folder,'\',wd_base,'_',num2str(wd_year),ext);
    % 2D character array ([wd_dur] x [# of characters in string])
    wd_year=wd_year+1; % Year increments as it should
end;

dx = '';

for i=1:wd_dur+1
    dx{i} = xlsread(wdn{i}); % Makes nested array with weather data for a
year in each cell
end


[r c]=size(dx);
dxtmp = nan(366,6,c);
for i=1:c
    tmp = dx{1,i};
     dxtmp(1:size(tmp,1),:,i) = tmp;
end
dxtmp = permute(dxtmp, [1 3 2]);
% Creates weather data file with daily weather data for each year requested
by the user
dx2 = reshape(dxtmp, [size(dxtmp,1)*size(dxtmp,2), size(dxtmp,3)]);
clear dx dxtmp
tmp = squeeze(dx2(:,1));
```

```
dx2(isnan(tmp),:)=[];  clear tmp


% Calculate AP
% APP = annual precipitation for each of the requested years in three
columns:
% 1: the given year
% 2: annual precipitation using 8/1 - 7/31 convention (wheat)
% 3: annual precipitation using 1/1 - 12/31 convention (sorghum)
Is = nan(wd_dur,1); Ie=Is; AP_S=Is; AP=Is; Is_s=Is; Ie_s=Is;
APP=nan(wd_dur,3);
pyear=wd_prioryear;
for j=1:wd_dur %goes from first year to last year of the simulated weather
date, e.g. year 1 to year 4
    leaptest = mod(pyear,4); %Test if year is leap year
    if leaptest == 0 %Leap year test says this year is a leap year
        Is_s(j) = find(dx2(:,1) ==pyear & dx2(:,2) == 214); % This year is a
leap year
        Ie_s(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 212); % This year is
not
        AP_S(j) = sum(dx2(Is_s(j):Ie_s(j),5)); % Sum of precipitation column
from these start to end points, Aug 1 to July 31
        Is(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 1);
        Ie(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 365);
        AP(j) = sum(dx2(Is(j):Ie(j),5));
    elseif leaptest == 3 %Test says this year isn't a leap year but next year
is
        Is_s(j) = find(dx2(:,1) ==pyear & dx2(:,2) == 213); % This isn't a
leap year
        Ie_s(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 213); % This is a
leap year
        Is(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 1);
        Ie(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 366);
        AP_S(j) = sum(dx2(Is_s(j):Ie_s(j),5)); % Precipitation sum
        AP(j) = sum(dx2(Is(j):Ie(j),5));
    else
        Is_s(j) = find(dx2(:,1) ==pyear & dx2(:,2) == 213); % This isn't a
leap year
        Ie_s(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 212); % This isn't
either
        AP_S(j) = sum(dx2(Is_s(j):Ie_s(j),5)); % Precipitation sum
        Is(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 1);
        Ie(j) = find(dx2(:,1) ==pyear+1 & dx2(:,2) == 365);
        AP(j) = sum(dx2(Is(j):Ie(j),5)); % Precipitation sum
    end
    APP(j,1)=pyear+1;
    APP(j,2)=AP(j);
    APP(j,3)=AP_S(j);
    pyear=pyear+1;
end
end
```

WB_BC.m

```
function [mET,Prep,kx,dx] = WB_BC(dx2,crop,start,enddate,span,kxx1,kxx2,year)
```

```
% Obtain boundary conditions for water balance (WB) for current control array

% Inputs: weather data for all years(dx2), crop, start and end dates, crop
% coefficient data files (kxx1 and kxx2), current year

% Outputs: daily maximum ET (mET), daily precipitation (Prep),
% daily crop coefficients (kx), weather data between start and end
% dates of the crop/noncrop (dx)

%Functions:
%Acquires daily weather data for the specified crop/non-crop interval
%Computes maximum ET according to modified Jensen-Haise
%Prepares output file appropriate for the WB routine

% Acquisition of correct crop coefficient values
% Wheat
if crop == 1
    if mod (year,4)>0 % Not a leap year
        if span==1 % Spans 2 years
            % Concatenate overwinter period
            kx1_a = kxx1(start:end,3);
            kx1_b = kxx1(1:enddate,3);
            kx = [kx1_a;kx1_b];
        else % All in same year
            kx = kxx1(start:enddate,3);
        end;
    else %Leap year
        if span == 1 % Spans 2 years
            % Concatenate overwinter period
            kx2_a = kxx2(start:end,3);
            kx2_b = kxx2(1:enddate+1,3);
            kx = [kx2_a;kx2_b];
        else % All in same year
            kx = kxx2(start:enddate+1,3);
        end;
    end;
% Sorghum
elseif crop == 2
    if mod (year,4)>0 % Not a leap year
            kx = kxx1(start:enddate,4);
    else % Leap year
            kx = kxx2(start:enddate+1,4);
    end;
% Noncrop
else
    if mod (year,4)>0 % Not a leap year
        if span==1 % Spans 2 years
            % Concatenate overwinter period
            kx3_a = kxx1(start:end,2);
            kx3_b = kxx1(1:enddate,2);
            kx = [kx3_a;kx3_b];
        else
            kx = kxx1(start:enddate,2);
        end;
    else % Leap year
        if span==1 % Spans 2 years
```

```
            % Concatenate overwinter period
            kx4_a = kxx2(start:end,2);
            kx4_b = kxx2(1:enddate+1,2);
            kx = [kx4_a;kx4_b];
        else
            kx = kxx2(start:enddate+1,2);
        end;
    end;
end
% Put in a system so it would recognize if the previous crop was
% wheat or sorghum for the noncrop phase so it would know which noncrop
% element to use.
% Separating out weather data for calculation using start and end dates
    leaptest = mod(year,4); % Test if year is leap year
    yearm1 = year-1;
    if leaptest == 0 && span == 0 % Leap year & all in one year
        first_day = find(dx2(:,1) == year & dx2(:,2) == start+1);
        last_day = find(dx2(:,1) == year & dx2(:,2) == enddate+1);
        dx = dx2(first_day:last_day,:);
    elseif leaptest == 0 && span == 1 % Leap year & in 2 years
        first_day = find(dx2(:,1) == yearm1 & dx2(:,2) == start);
        last_day = find(dx2(:,1) == year & dx2(:,2) == enddate+1);
        dx = dx2(first_day:last_day,:);
    elseif leaptest == 1 && span == 1 % Previous year was leap year, spans 2
years
        first_day = find(dx2(:,1) == yearm1 & dx2(:,2) == start+1);
        last_day = find(dx2(:,1) == year & dx2(:,2) == enddate);
        dx = dx2(first_day:last_day,:);
    elseif leaptest == 1 | leaptest == 2 | leaptest == 3 && span == 0 % Not a
leap year, all in one year
        first_day = find(dx2(:,1) == year & dx2(:,2) == start);
        last_day = find(dx2(:,1) == year & dx2(:,2) == enddate);
        dx = dx2(first_day:last_day,:);
    elseif leaptest == 2 | leaptest == 3 && span == 1 % Not a leap year or
previous year not a leap year, spans 2 years
        first_day = find(dx2(:,1) == yearm1 & dx2(:,2) == start);
        last_day = find(dx2(:,1) == year & dx2(:,2) == enddate);
        dx = dx2(first_day:last_day,:);
    end
nd = size(dx,1);

% Compute maximum ET for entire weather data matrix

% Unit conversion
dx(:,[3 4]) = (dx(:,[3 4])-32)/1.8; % Converts MaxF and MinF to degrees C
dx(:,5) = dx(:,5)*25.4; % Converts precipitation from inches to mm

% Reference ET
Tx = dx(:,3); Tn = dx(:,4); % Assign MaxC to Tx and MinC to Tn
Tx(Tx<0) = 0; % Prevents MaxC from going below zero
Tn(Tn<0) = 0; % Prevents MinC from going below zero
Prep = dx(:,5); Rs = dx(:,6); % Assigns precipitation to Prep and solar
radiation to Rs
Ta = (Tx+Tn)/2; % Calculates mean temperature in C using min T and max T
L = 2.493 - 0.00214*Ta; % Calculates latent heat of vaporization (cal cm-2)
```

```
ETr = ((0.078+0.0252*Ta(:)).*Rs(:))./L(:); % Uses Amos et al conversion of
Jensen and Haise (1963) and Wright (1982) to calculate reference ET (mm d-1)

% Maximum ET
Adv = nan(nd,1); % Assigns an empty NaN matrix to Adv, size is length of
imported data X 1, Adv is dimensionless advection term
Txsh = 33; % Gives threshold value in degrees C for maximum temperature
Adv(Tx<=Txsh) = 0; % Assigns 0 value to Adv matrix on all days where MaxC is
less than the threshold (33 C)
Adv(Tx>Txsh) = (Tx(Tx>Txsh)-Txsh)*0.05; % Increases Adv by 0.05 for each day
for every degree over the threshold
Adv(Adv>=0.25) = 0.25; % Sets 0.25 as the maximum threshold for Adv
mET = ((1+Adv(:)).*ETr(:)); % Calculates maximum ET in mm using Adv and ETr
(p 69)
end
```

WB.m

```
function [SW_last,SWO,SWI,DR,ASW,Ka,aET,EPR,error] =
WB(dx,Sinfo,site,kx,Prep,mET,RF,SW_start)
% Objective:
% Calculate soil water budget for wheat, sorghum or non-crop time intervals
% Functions
% Calculates soil water balance (KSWB, Stone et al., 2006) for
% any of three locations and any of six crop/non-crop sequences involving
% wheat and grain sorghum
% Corresponding to weather data file (dx) water balance will run
    % Site: 1=Bushland, 2=Colby, 3=Tribune
    % Crop: 0=Noncrop, 1=Wheat, 2=Grain Sorghum

% Inputs: weather data between start and end dates of the
% crop/noncrop (dx), soil properties (Sinfo), site, daily crop
% coefficients (kx), daily precipitation (Prep), daily maximum ET
% (mET), runoff fraction (RF), soil water at planting (SW_start)

% Outputs: soil water at harvest (SW_last), daily ending soil water
% (SWO), daily initial soil water (SWI), daily drainage (DR), daily
% available soil water (ASW), daily available soil water coefficient
% (Ka), daily actual ET (aET), daily effective precipitation (EPR),
% error in soil water or drainage calculations

nd = length(dx);
SWI = nan(nd,1); DR = SWI; EPR = SWI; ASW = SWI; Ka = SWI; aET = SWI; SWO =
SWI; error = SWI; % Creates empty matrices of NaN with size length of number
of days X 1
dr_max=50.8; % Upper limit to daily drainage
SWI(1)=SW_start; % Sets soil water for first day of water balance
for i=1:nd
    USW_error=0; LSW_error=0;dr_error=0;% Reset error flags for SW and
drainage
    % Drainage
```

```
    DR(i) = 
Sinfo.param(site,4)*(SWI(i)/Sinfo.param(site,5))^Sinfo.param(site,6); % 
Drainage equation estimated using Wilcox technique (p 83)
    if DR(i) > dr_max; DR(i) = dr_max; dr_error =1;end %
    % Effective Precipitation
    EPR(i) = Prep(i)*(1-RF); % Calculates effective precipitation by applying 
runoff fraction to precipitation
    % Available Soil Water
    ASW(i) = 100*(SWI(i) - Sinfo.param(site,3))/(Sinfo.param(site,2) - 
Sinfo.param(site,3));   % Calculates available soil water as a percentage (p 
70)
    if ASW(i) < 0; ASW(i) = 0; end % Sets ASW lower limit to 0
    if ASW(i) >100; ASW(i) = 100; end % Sets ASW upper limit to 100
    % Available Soil Water limiting Coefficient (Ka)
    Ka(i) = (log10(ASW(i)+1))/log10(101); % Calculates available soil water 
coefficient using Jensen et al (1971) equation (p 70)
    if Ka(i) <0.02; Ka(i) = 0.02; end % Sets lower limit to 0.02
    if Ka(i) >1.0; Ka(i) = 1; end % Sets upper limit to 1
    % Actual ET
    aET(i) = Ka(i) * mET(i) * kx(i,1); % Actual ET calculation (aET is equal 
to max ET at 100% ASW) (p 70)
    % Soil Water Out
    SWO(i) = EPR(i) + SWI(i) - DR(i) - aET(i); % Calculates end of day soil 
water content by adding effective precipitation and previous day water 
content and subtracting drainage and actual ET
    if SWO(i) > Sinfo.param(site,1); SWO(i) = Sinfo.param(site,1); 
USW_error=1;end % Sets upper limit to soil water content
    if SWO(i) < Sinfo.param(site,3); SWO(i) = Sinfo.param(site,3); 
LSW_error=1;end % Sets lower limit to soil water content
    error=[USW_error LSW_error dr_error];
    if i ~= nd;
        SWI(i+1) = SWO(i); % Sets soil water in of the next day to equal soil 
water out of the current day
    end
end
if isempty(dx) == 1
    SW_last = 0;
else
    SW_last = SWO(nd); % Sets the final soil water value to SW_last
end
end
```

WU_Y.m

```
function 
[eET,aET_sum,ETmax_sum,Yield,Prep_sum,DR_sum,EPR_sum,CWU,aET_comp,mET_comp] = 
WU_Y(aET,mET,EPR,Prep,DR,year,crop,SW_start,SW_last)
% Calculates effective water use and yield
%   Water use in four development stages are considered; weighting
%   functions are implemented using the ratio of actual to maximum ET;
%   yield is a first order linear function of effective water use,
%   calculated as sum of weighted components; weights correspond to impacts
%   of stage-dependent water deficits on yield formation.
```

```
% Inputs: daily actual ET (aET), daily maximum ET (mET), daily
% effective precipitation (EPR), daily precipitation (Prep), daily
% drainage (DR), current year, current crop, soil water at planting
% (SW_start), soil water at harvest (SW_last)

% Outputs: effective ET (eET), sum of actual ET (aET_sum), sum of
% maximum ET (ETmax_sum), crop yield - zero if noncrop (Yield), sum
% of precipitation, drainage, and effective precipitation during
% crop/noncrop period (Prep_sum, DR_sum, EPR_sum), crop water use
% (CWU), sum of actual ET and maximum ET for each of the four
% growth periods (aET_comp and mET_comp)

% Summations
EPR_sum = sum(EPR);
aET_sum = sum(aET);
ETmax_sum = sum(mET);
DR_sum = sum(DR);
Prep_sum = sum(Prep);
CWU = SW_start - SW_last + Prep_sum;
if SW_last == 0
    CWU = 0;
end

if crop == 0
    eET = 0;
    Yield = 0;
    aET_comp = 0;
    mET_comp = 0;
else
    % Days from planting to end of vegetative, flowering, yield formation,
ripening development stages
    if (mod(year,4))>0;
        Dstage_ww = [245 259 274 278]; % Wheat: non-leap year
        else Dstage_ww = [246 260 275 279];% Wheat: leap year
    end
    Dstage_gs = [56 76 99 108];% Grain Sorghum: all years

    % Weighting factors for yield impact of relative water use during four
development stages
    wET_ww = [49 31 19 1]; % Wheat
    wET_gs = [44 39 14 3]; % Grain Sorghum
    if crop==1;
        Dstage = Dstage_ww;
        wET = wET_ww;
    else
        Dstage = Dstage_gs;
        wET = wET_gs;
    end

    % Yield coefficients: Intercept and slope of yield regression in bu/A and
inches
    YregWW = [-60.5 6.02]; % Wheat @ 12.5% moisture
    YregGS = [-84.4 12.18]; % Grain Sorghum @ 12.5% moisture
    Yreg = [YregWW; YregGS];

    % Actual ET
```

```
    aETveg = sum(aET(1:Dstage(1))); % Calculates cumulative actual ET for
vegetative period
    aETfl = sum(aET(Dstage(1)+1:Dstage(2))); % Calculates cumulative actual
ET for flowering period
    aETform = sum(aET(Dstage(2)+1:Dstage(3))); % Calculates cumulative actual
ET for yield formation period
    aETrip = sum(aET(Dstage(3)+1:Dstage(4))); % Calculates cumulative actual
ET for ripening period
    sum_aET = aETveg + aETfl + aETform + aETrip;
    aET_comp = [aETveg aETfl aETform aETrip sum_aET];

    % Maximum ET
    mETveg = sum(mET(1:Dstage(1))); % Calculates cumulative max ET for
vegetative period
    mETfl = sum(mET(Dstage(1)+1:Dstage(2))); % Calculates cumulative max ET
for flowering period
    mETform = sum(mET(Dstage(2)+1:Dstage(3))); % Calculates cumulative max ET
for yield formation period
    mETrip = sum(mET(Dstage(3)+1:Dstage(4))); % Calculates cumulative max ET
for ripening period
    sum_mET = mETveg + mETfl + mETform + mETrip;
    mET_comp = [mETveg mETfl mETform mETrip sum_mET];

    % Weighted ET
    wETveg = wET(1)*aETveg/mETveg;
    wETfl = wET(2)*aETfl/mETfl;
    wETform = wET(3)*aETform/mETform;
    wETrip = wET(4)*aETrip/mETrip;

    % Effective ET
    eET = (1/25.4)*sum_mET*(wETveg + wETfl + wETform + wETrip)/100; %
Calculates effective ET for wheat in mm and converts to inches (p 72)

    % Yield calculation
    Yield = Yreg(crop,1)+Yreg(crop,2)*eET; % Calculates wheat yield in
bushels/acre at 12.5% moisture
    if Yield < 0
        Yield = 0;
    end
end
end
```

Appendix B - Crop Coefficients and Soil Factors

Crop Coefficients

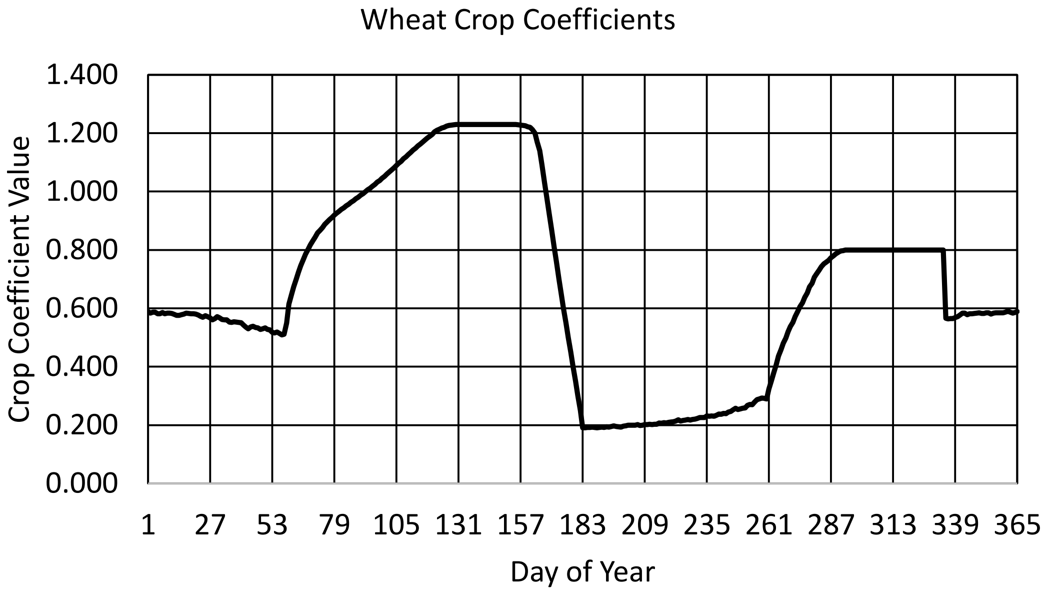

Figure 8: Crop coefficients for winter wheat

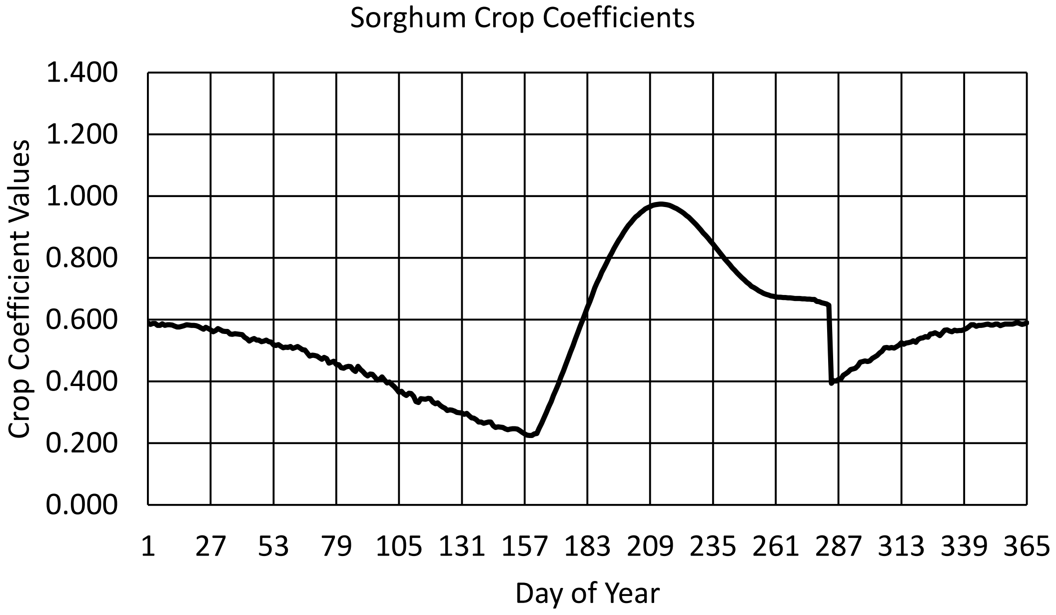

Figure 9: Crop coefficients for grain sorghum

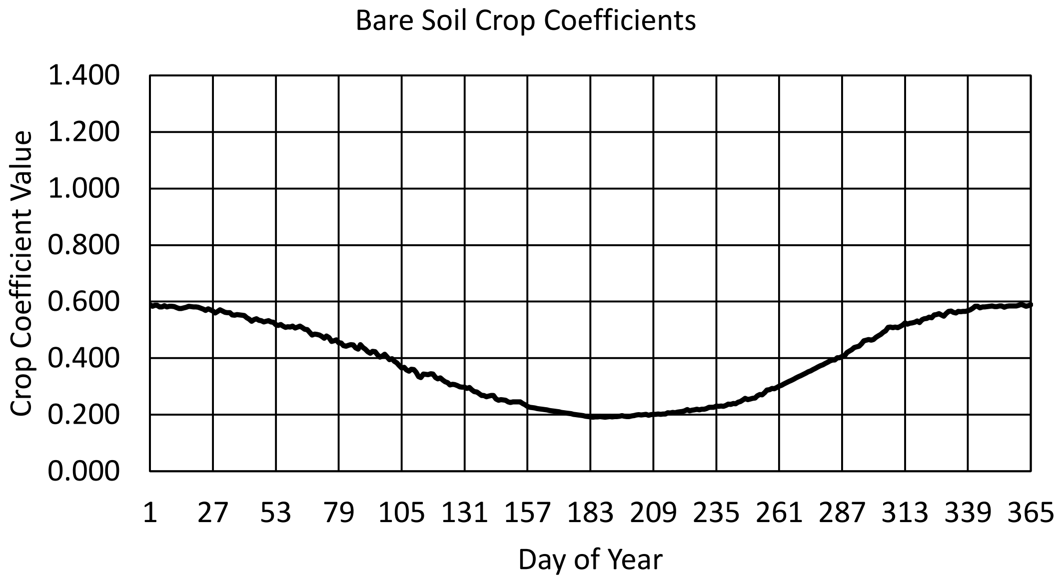

Figure 10: Crop coefficients for bare soil

Soil Factors

Table 12: Soil factors for each site

Study	Location	Maximum water allowed in the profile (mm)	Upper limit of available water (mm)	Lower limit of available water (mm)	Available Water Capacity (mm)	Drainage Equation
Baumhardt and Jones, 2002	Bushland	732	640	347	293	$20.5 * \left(\frac{SWI}{680}\right)^{34.11}$
Jones and Popham, 1997	Bushland	732	640	347	293	$20.5 * \left(\frac{SWI}{680}\right)^{34.11}$
Moroke et al., 2011	Bushland	732	640	347	293	$20.5 * \left(\frac{SWI}{680}\right)^{34.11}$
Aiken et al., 2013	Colby	766	660	313	347	$32.2 * \left(\frac{SWI}{715}\right)^{23.17}$
Aiken (Unpublished)	Colby	766	660	313	347	$32.2 * \left(\frac{SWI}{715}\right)^{23.17}$
Schlegel et al., 2002	Tribune	787	650	290	360	$42.7 * \left(\frac{SWI}{729}\right)^{18.06}$

Table 13: Runoff equation for each site

Study	Location	Soil Type	Soil Hydrologic Group	Runoff Equation
Baumhardt and Jones, 2002	Bushland	Pullman clay loam	C	$RF = 0.157 + (0.000072 * AP^2)$
Jones and Popham, 1997	Bushland			
Moroke et al., 2011	Bushland			
Aiken et al., 2013	Colby	Keith silt loam	BC	$RF = 0.106 + (0.000062 * AP^2)$
Aiken (Unpublished)	Colby			
Schlegel et al., 2002	Tribune	Richfield silt loam		