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Estimating irrigation water use for maize in the Southeastern USA: A modeling approach

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ABSTRACT

Increased crop production and expansion of irrigated acreage in the southeastern USA have increased agricultural water use during the past two decades. To optimize irrigation water use, it is important to know when to irrigate and how much water should be applied. The objectives of this study were (1) to evaluate the Cropping System Model (CSM)-CERES-Maize model with measured data of the amount of water required for supplemental irrigation and (2) to apply the CSM-CERES-Maize model for estimating irrigation water use for maize in the southeastern USA. The CSM-CERES-Maize model was evaluated for 2000–2004 for five counties that represent the dominant maize production regions in South Georgia. For each county, historical daily weather data, three representative soil profiles, and specific crop management recommendations were used as input for the model. The simulated results were then compared with observed data obtained during the same period. The amount of water required for irrigation for each growing season was simulated for 58 years using historical weather data from 1950 to 2007 for 88 selected counties that corresponded to the most important agricultural production region in Georgia. Both monthly and annual water demand for maize was determined for each county. The total seasonal amount of water required for irrigation across counties and years ranged from 136 to 281 mm, with an average of 227 mm. The irrigation requirements among months varied from 10 to 79 mm, with the highest amount required for May. The results from the evaluation showed that the model was able to simulate the amount of water required for maize irrigation in good agreement with the observed data. This demonstrated the potential application of the CSM-CERES-Maize model as a tool for estimating water demand for irrigation. The estimated water requirements for supplemental irrigation can be used by both policy makers and local farmers for planning the amount of water required for supplemental irrigation as well as for improvements in irrigation management for water conservation.

1. Introduction

One of the main concerns for future irrigated agriculture is if there will be sufficient freshwater to supply the increasing requirements of both agricultural and non-agricultural consumers. Irrigated agriculture is perhaps one of the most important uses of water throughout the world. Almost 70% of the freshwater withdrawals in the world go toward irrigation uses (FAO, 2011). However, irrigation water faces increasing competition from non-agricultural sectors resulting in a global scarcity of freshwater (Faurès et al., 2000; FAO, 2011; Postel, 2001; USGS, 2009).

In the United States, agriculture is a major user of both ground and surface water, accounting for 80% of the national consumptive water use and for over 90% in many western States (USDA, 2004). Historically, ground-water problems have been associated with major urban-industrial withdrawals, but irrigation development has attracted attention due to the measures that have been taken to enable improved management of water resources (Kundell, 2006). Irrigation management is a complex problem in the southeastern USA due to the high spatial and temporal variability of local weather conditions, especially rainfall. Similar to many regions around the world, irrigation in the southeastern USA is mainly supplemental during periods of drought, as rainfall varies during the crop growing season. Although the average annual precipitation is over 1300 mm in the southeastern USA (Nuti and Lamb, 2009; Lamb et al., 2011)

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the use of irrigation in the region has increased because of the uncertainty associated with rainfall distribution and crop stress by drought that potentially can cause a decrease in yield and production, irrigation is used to supplement precipitation during drought periods to sustain profitable crop production (Lamb et al., 2011). Maize is one of the crops that is commonly irrigated in Georgia and other southeastern states. Total acreage under irrigation in the region has grown considerably (Harrison, 2009). Estimates by both the Georgia-National Agricultural Statistics Service and the Cooperative Extension Service indicate that approximately 55% of maize in Georgia is irrigated (Lee, 2007a,b).

The total amount of water required for irrigation and the frequency of application varies as a function of the crop, management, cultivar selection, soil conditions and local weather conditions. Crops differ in their responses to water deficits at different growth stages and the amount of water used is closely associated with final crop biomass and grain yield (Whitty and Chambliss, 2002). The timing and amounts of rainfall during the season, the soil profile, texture, depth and the ability to hold water, as well as the crop water requirements are all factors which influence the need for irrigation.

The decision making process by the producers also plays a key role in determining the final irrigation schedule and the decision of when to apply water and how much water to apply to the each individual field (Rhoads and Yonts, 2000; Guerra et al., 2007). Decisions are dictated by each producer's goal, design criteria, and strategy in combination with the water availability and rainfall. At the same time policy makers are currently evaluating different options to address water demand by agriculture and other sectors. However, they will have to use all tools that are available to address water issues to maximize its effective use, including crop simulation models and associated decision support systems, to make water use as a community resource efficient (Kundell, 2006; Mullen et al., 2009). Georgia's future relies on the sustainable management and protection of the state's limited water supplies. In February 2008, the Georgia General Assembly adopted the Georgia Comprehensive State-wide Water Plan, to "Guide Georgia in managing water resources in a sustainable manner" (EPD, 2009). The Environmental Protection Division of the Georgia Department of Natural Resources has been charged with estimating both current and future water needs by agriculture for the major crops for effective planning. An initial component of this planning process is the estimation of current water use for irrigation and forecasted needs (Hook et al., 2005).

During the last 30 years, crop modeling has been shown to be a valuable tool that can be used for a diverse range of applications in many countries (Hook, 1994; Garrison et al., 1999; Ruíz-Nogueira et al., 2001; López-Cedrón et al., 2008). However, most of these applications have focused on yield predictions based on alternate crop management practices for a range of different environments (Tsuji et al., 1998; Hoogenboom, 2000; Jones et al., 2003). In addition to yield predictions, crop simulation models can also be used with determining resource use such as the consumption of water by supplemental irrigation and to determine optimum irrigation management strategies (Guerra et al., 2005; Hook, 1994; Maxrobert and Savage, 1998; Nijbroek et al., 2003).

The Decision Support System for Agrotechnology Transfer (DSSAT version 4.5) is a comprehensive system tool that facilitates the evaluation and application of crop models for a range of agricultural and environmental uses, such as yield and water use predictions (Tsuji et al., 1994; Jones et al., 2003; Hoogenboom et al., 2004, 2010). One of the main models of DSSAT includes the Cropping System Model (CSM)-CERES-Maize for the simulation of maize growth, development and yield (Jones and Kiniry, 1986; Ritchie et al., 1998; Jones et al., 2003). The CSM-CERES-Maize model has been evaluated extensively for simulating growth and yield for soil and weather conditions and management practices representing the southeastern USA. Studies conducted by Hook (1994) and Persson et al. (2009a,b) showed that the model predicted yield very for local conditions in the state of Georgia (Hook, 1994). In addition to predicting yield, CSM-CERES-Maize can be used as a tool for on-farm irrigation scheduling, using long-term and multi-year simulations. The CSM model has been applied widely for different environments and management practices, including irrigation, and has shown to provide good predictions under irrigated conditions (Kiniry and Bockholt, 1998; Tsuji et al., 1998; Jones et al., 2003; Panda et al., 2004).

The CSM-CERES-Maize model simulates growth and development throughout the growing season starting at planting until final harvest. It includes detailed routines for simulating the soil and plant water and nitrogen dynamics. The model operates on a daily time step; the inputs required include daily weather data, crop management practices, and soil surface and soil profile parameters. The soil water balance of the CSM-CERES-Maize model is determined on a daily basis as a function of precipitation, irrigation, transpiration, soil evaporation, runoff, and drainage from the bottom of the profile. Soil water content is simulated for a one-dimensional soil profile based on fixed computational layers or the original soil horizons distributed into numerous layers with depth increments specified by the user (Ritchie and Godwin, 1989; Ritchie et al., 1998). Once the model has been evaluated for an environment, it can be used as a valuable tool for evaluating alternative crop management strategies (Hook, 1994; Boote et al., 1996, 2010; López-Cedrón et al., 2008; Tsuji et al., 1998).There are several causes for the variability in water requirement by maize. This includes soil type, which can vary even within a small area of cultivation and even within a field, rainfall, which also varies both spatially and temporally, crop management, including variety or cultivar, plant density, fertilization and planting date, which can vary among cycles. Several studies have been conducted on crop water requirements for maize based on its growth and development, in terms of amount and timing of application, but none that include both the interaction of environmental conditions and irrigation management practices. From 1999 to 2002 a study was conducted to monitor water use for supplemental irrigation across the state of Georgia for over 600 locations (Thomas et al., 2003; Hook et al., 2004, 2005). Although this study provided good results, it was limited with respect to developing strategies for policy making due to the fact that complete were only available for three years. The overall goal of this study was to determine water requirements for supplemental irrigation during periods of drought following the mandate expressed by the state of Georgia through its first Comprehensive Georgia State-wide Water Management Plan. The specific objectives include (1) to evaluate the performance of CSM-CERES-Maize simulation model for predicting water use for irrigation and (2) to apply the CSM-CERES-Maize model for estimating irrigation water use for maize in the southeastern USA in order to develop strategies for water use planning.

2. Materials and methods

2.1. Site selection and observed data

Five of the top producing counties for maize in Georgia were selected. These include the counties of Baker, Miller, Mitchell, Seminole and Terrell which are located in the major irrigated region of Georgia (USDA-NASS, 2007; CES 2009). Data obtained from the Agricultural Water Pumping project (AWP), which was a program designed to determine agricultural water use by irrigation for the major crops across the entire state of Georgia and conducted during 2000–2004 (Thomas et al., 2003; Hook et al., 2004, 2005) were