Simulating agricultural water stress using a grid-based daily soil water balance model—application to Illinois, USA

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ABSTRACT

Recently, climate change has emerged as an issue that affects many aspects of society. Because changes in water resources have a direct impact on the growth of crops and the ecosystem, water management is an increasingly important challenge nationwide in the USA. Output from a soil water balance model can be used as an input to an agricultural productivity model or a vegetation model, which would be used to identify the need for measures to address drought. In this study, a daily soil water model was developed based on a grid analysis of the spatial distribution of water stress. As a test case, the model was applied to Illinois State, USA, where various field observation data as well as digital maps were available to the public. Inputs to the model can be divided largely into soil, climate, and crop data, and their various coordinate systems and spatial resolutions were adjusted to match. Data on soil attributes were obtained from Soil Survey Geographic Database Soil maps by the USDA Natural Resources Conservation Service. Climate data were compiled for 2001–2012 and daily precipitation and reference evapotranspiration from the Penman-Monteith method were spatially interpolated. Several water balance indices were developed to quantify the degree of water stress. The results showed that the water stress conditions in Illinois were bad in 2002, 2005, 2007 and 2011, with the most severe water shortage in 2005. This model could be applied to agricultural water stress evaluation over any scale, from local to global.

Keywords: Soil water balance, Water stress, Illinois.

1. INTRODUCTION

Climate change is threatening sustainable agriculture by destabilizing the supply and demand of water. In particular, grain prices will surge because of reduced production if the uncertainty in the supply of the agricultural water increases in granaries of the world such as America, China, or Russia. The Agricultural Outlook 2011–2020, published jointly by the OECD (Organization for Economic Cooperation and Development) and FAO (Food and Agriculture Organization), predicts that prices for agricultural

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commodities will fall in the short term but increase over the next decade to average 20–30% higher in real terms compared to the values for the 2001–2010 period. Recently, international grain prices surged because of severe droughts in the United States and Russia. Meteorological disasters such as drought or floods are becoming increasingly frequent and intense, so accurate analysis and evaluation for changes in agricultural water is required urgently. Agricultural water management may include prediction of crop yields or identifying the need for measures to address drought by securing a stable water supply or rationing water use. Output from a soil water balance model can be used as an input to an agricultural productivity model or a vegetation model. A precedent study was announced in IPCC (Intergovernmental Panel on Climate Change) fourth report, in which the agricultural water supply and crop’s water demand were compared in order to examine their adaptability to climate change (Cohen and Neale, 2003; Neilson et al., 2004). In addition, various studies analyzing water stress and water use efficiency of crops are currently underway (Alderdasi & Neilsen, 2001; Yuan et al., 2004; Liu et al, 2007; Pereira et al., 2012).
This study aims to examine the dependence of crop water stress on the agricultural water balance as crop water stress becomes more important for stable grain production. A grid-based water balance model was developed to simulate daily soil moisture, and was then applied to Illinois, US. At this location, various field observation data as well as digital maps were open to the public. Crop water stress indices were proposed by considering crop water supply and demand. Their temporal and spatial distribution were also examined.

2. DATA AND METHODS

2.1 Methods

The crop water stress index is a valuable tool for monitoring and quantifying water stress. It is determined from the quantitative balance between crop water consumption and water resource availability in terms of agricultural water balance. As such, a new water balance model was developed using two modules: simulation of water requirements and calculation of hydrologically effective runoff. All processes were designed to be conducted over a grid in order to make the process applicable on a global scale.

2.1.1 A grid-based soil water balance model

A soil water simulation model was formulated to simulate daily water balance (Eqs. 1–2). The readily available moisture was set to 50% of total available moisture. For this model, effective rainfall (ER) is rainfall during the growing season minus that occurring after soil saturation or irrigation.

$$AM(t) = AM(t-1) + PR(t) - AET(t) \quad (1)$$

$$ER(t) = PR(t) - RO(t) \quad (2)$$

where, AM(t) is the total available soil moisture (mm) at time t; PR(t) is the precipitation (mm/day) at time t in cases of more than 5.0 mm/day; and AET(t) is actual crop evapotranspiration (mm/day) at time t calculated by multiplying the Penman-Monteith reference evapotranspiration by the crop coefficient (Table 1).

Table 1. Crop coefficients by growth stages for the Penman-Monteith reference evapotranspiration (Allen et al, 1998; Alderfasi & Nielsen, 2001; Texas Agrilife Extension Service)

Growth stage		Initial (31 / 21 days)*	Developing (30 days)	Mid-season (41 days)	Late-season (31 / 21 days)
Crop coefficients	Corn	0.30	Linear interpolation	1.15	0.40
	Bean	0.40	Linear interpolation	1.15	0.35

*(for Corn / for Bean)

2.1.2 A simple runoff model

This study examined a simplified runoff model using a curve number (CN) method, which could be applied regardless of the analysis extent or scale. The daily surface runoff, that is, the quantity of potentially available water, is successively derived from water balance equations as follows (Eq. 3-6).

$$S_t = S_{t-1} + P_t - Q_t - ET_t \qquad (3)$$

$$S'_t = S_{t-1} + P_t \qquad (4)$$

$$Q_t = \left[\tanh\left(\frac{S'_t}{S_{max}}\right)\right]^m \cdot S'_t \qquad (5)$$

$$CN = \frac{25,400}{S+254} \longrightarrow S = \frac{25,400}{CN} - 254 \qquad (6)$$

where, S is storage; P is precipitation; Q is runoff flow corresponding to a hyperbolic tangent function; ET is evapotranspiration; and S_{max} is the maximum storage capacity determined by the CN method (Eq. 5).

2.1.3 Water stress indices

A number of studies have evaluated crop water stress, and different indices have been proposed (Jackson et al., 1981; Jackson, 1982; Jun et al., 2011). In this study, two water stress indices based on soil water balance are proposed: CWSR (Crop Water Satisfaction Ratio), and REIC (Rainfall Effectiveness Index for Crop).

$$CWSR = \frac{\sum SRO}{\sum CWC} \qquad (7)$$

$$REIC = \frac{\sum ER}{\sum CWC} \quad (8)$$

where SRO is the amount of surface runoff (mm/yr), and CWC is the annual consumptive use by crops (mm/yr) (equal to AET).

2.2 Data collection and pre-processing

The test area was Illinois State, USA, the center of the Corn Belt. Daily climate data, including temperature, relative humidity, wind speed, solar radiation, and precipitation, from 2001 to 2011 were collected from the Illinois State Water Survey, and daily reference evapotranspiration was calculated by the Penman–Monteith method. In addition, two types of digital maps—SSURGO soil maps of USDA NRCS and CDL (Crop Data Layer) crop maps of USDA—were employed. Crop coefficients by growth stage were referenced from FAO Irrigation & Drainage Paper No.56 and other existing research reports (Alderfasi & Nielsen, 2001; Texas Agrilife Extension Service). Root depth and cultivation calendar for two target crops, corn and bean, were established by using FAO and USDA guidelines (Dwyer et al., 1988; Rhodes, 1991; Bauder & Schneekloth, 2006; National Agricultural Statistics Service). All collected data had the same coordinate system and were interpolated in a 250-m grid unit.

3. RESULTS

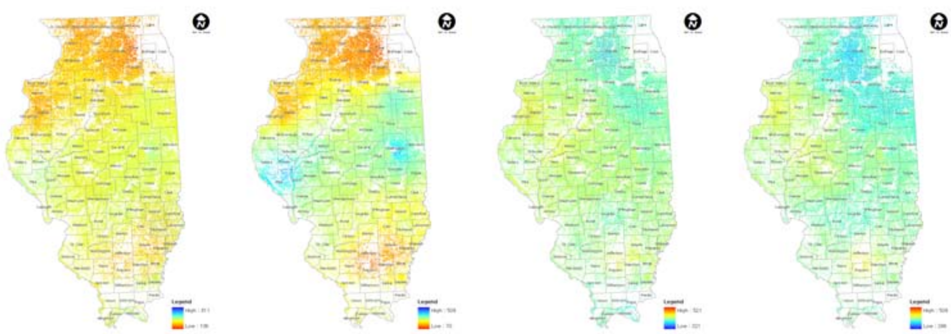
3.1 Change in soil water balance from 2001 to 2011

Daily soil water balance was simulated for corn and soybean on the 250-m grid, and then each element of the water balance was aggregated into county units. Results indicated comparatively bad conditions in 2002, 2005, 2007, and 2011 (Table 2). In particular, 2005 had more severe water stress compared to previous years (Figures 1 and 2). The annual precipitation in 2005 for corn-growing areas, 223.5 mm/yr, was about 56% less than the average from 2001 to 2011. Effective rainfall was about 68% lower, and actual crop evapotranspiration was about 7% higher. As a result, irrigation requirements increased in 2005.

Table 2. Results of daily soil water balance simulation from 2001 to 2011

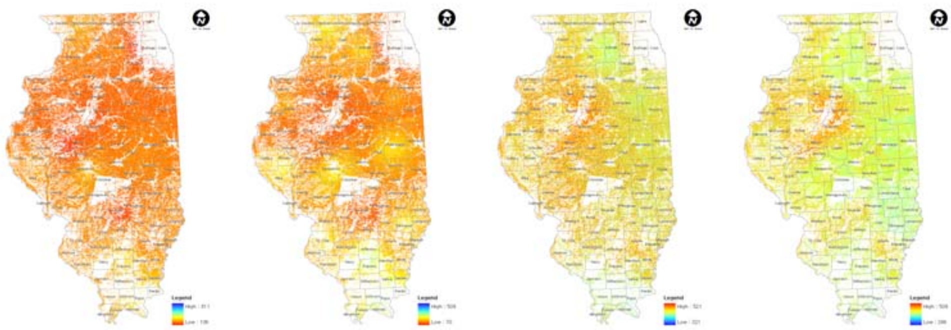
Year	Precipitation (PR)		Effective Rainfall (ER)		Consumptive use by crops (CO)		Irrigation Requirements (IR)	
	Corn	Bean	Corn	Bean	Corn	Bean	Corn	Bean
2001	362.5	322.7	229.8	205.2	436.7	386.8	388.1	342.9
2002	410.2	256.7	199.2	180.9	452.7	410.4	411.1	375.0

2003	403.8	297.5	249.5	228.2	438.9	399.9	393.4	362.3
2004	392.8	329.3	241.3	221.0	398.9	358.7	352.1	317.3
2005	223.5	193.7	167.8	148.5	480.5	431.3	440.3	392.3
2006	303.0	257.6	210.1	193.8	446.6	408.0	400.3	364.2
2007	310.3	284.6	228.5	210.5	469.7	421.8	416.4	373.6
2008	470.1	395.2	297.8	276.3	443.6	401.6	378.7	342.5
2009	493.7	394.3	310.0	276.7	409.6	368.3	339.6	304.0
2010	562.9	458.4	340.4	306.4	465.8	426.0	378.1	348.2
2011	452.1	400.0	252.2	214.1	476.4	432.0	403.6	368.8



(a) Precipitation (b) Effective rainfall (c) Consumptive use (d) Water requirement

Figure 1. Water balance simulations for 2003



(a) Precipitation (b) Effective rainfall (c) Consumptive use (d) Water requirement

Figure 2. Water balance simulations for 2005

3.2 Change in water stress indices from 2001 to 2011

CWSR and REIC were designed to express spatiotemporal changes in crop water stress. The higher the index value, the less is the crop water stress. The two indices were able to confirm the low value of the 2005, and the severe water stress was estimated. Figure

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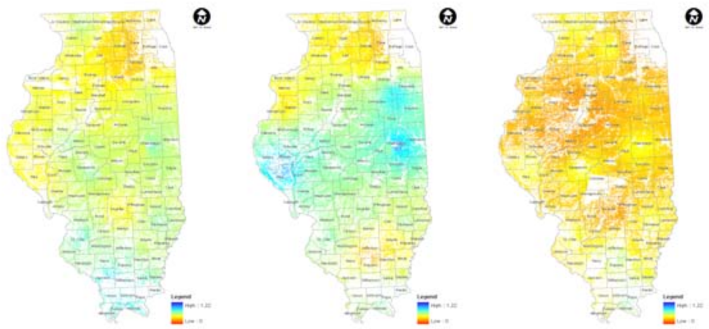
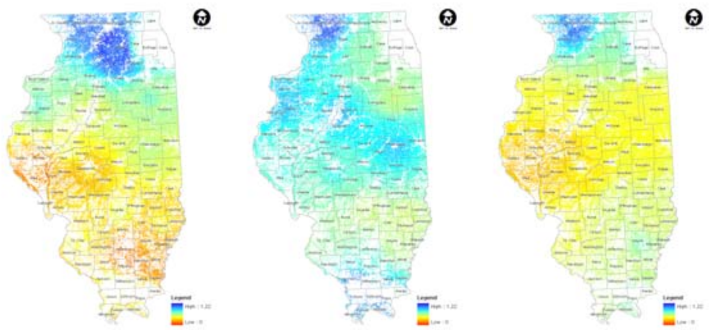
3 shows that REIC was higher in 2003 than in 2005 as a result of high rainfall and less actual crop evapotranspiration. Table 3 summarizes the average value of each index for 102 counties, with both indices showing the highest value in Stephenson County for 2001 to 2011.



(a) 2001 (b) 2003 (c) 2005



(d) 2007 (e) 2009 (f) 2011

Figure 3. REIC during the period from 2001 to 2011.

Table 3. CWSR and REIC derived daily soil water balance simulation from 2001 to 2011

Year	Crop Water Satisfaction Ratio (CWSR)		Rainfall Effectiveness Index for Crop (REIC)	
	Corn	Bean	Corn	Bean
2001	0.22	0.23	0.52	0.53
2002	0.46	0.25	0.44	0.44
2003	0.37	0.26	0.57	0.57
2004	0.34	0.33	0.60	0.61
2005	0.10	0.09	0.35	0.35
2006	0.25	0.23	0.47	0.48

2007	0.20	0.21	0.50	0.51
2008	0.37	0.34	0.67	0.69
2009	0.59	0.45	0.76	0.75
2010	0.52	0.46	0.73	0.72
2011	0.49	0.42	0.53	0.50

4. SUMMARY AND DISCUSSION

This study proposed a grid-based, simple, soil–water balance model for evaluating water stress. Preliminarily two indices (CWSI and REIC) were calculated for the state of Illinois, USA, using three main environmental variables: CWC, ER, and SRO. The results showed that conditions were bad in 2002, 2005, 2007, and 2011, with the most severe water shortage having occurred in 2005. The annual average of the CWSR from 2001 to 2011 is 0.35 for corn and 0.30 for soybean. Corn and soybean had the same REIC value of 0.56. During the drought year of 2005, CWSR was 0.09 for corn and 0.10 for soybean. The approach adopted in this study is still being investigated, and further work will be carried out: development and integration of further water stress indices, advancement of user interface for model operation, and modification for global-scale application.

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