2010

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A SOIL WATER CLIMATOLOGY FOR KANSAS

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ABSTRACT—Regional climate models suggest that summers in the Great Plains may become increasingly dry during this century, raising concern about the availability of water resources for irrigation and municipal water supplies. While the models predict drier conditions across the region, the impact of climate change on water availability at the local scale will depend largely upon the soils and their ability to store water during dry periods. This study presents a soil water climatology for Kansas using a climatic water balance approach. Monthly observations of temperature and precipitation for the period 1950–2006 are used to calculate climatologies of actual evapotranspiration, soil water utilization and recharge, and runoff at the soil unit level. Results indicate that actual evapotranspiration rates are small across the state during the winter and spring, reaching a maximum during summer. Soil water utilization is greatest during summer in eastern Kansas; soil water recharge is greatest in the spring in central Kansas and during the fall in eastern Kansas. Soil moisture surplus (runoff) is most pronounced in eastern Kansas during spring and early summer, and soil water shortages (deficit) are common year-round in western Kansas and in soils with low field capacities during the summer months.

Key Words: climatic balance, Great Plains, hydroclimatology, Kansas, soil water

INTRODUCTION

Soil water is an important component of the hydrologic cycle, particularly in climates where the available precipitation is insufficient to meet the needs of plants. In addition, the variation in soil water content throughout the year plays a critical role in determining the amount of water that supplies rivers and streams, resulting in periods of abundant streamflow when the soils are saturated and reduced streamflow when soils are unsaturated. Variations in climate also impact the soil water hydrology and related hydroclimatic conditions. Of particular concern are periods of precipitation extremes, during which soils may become waterlogged or desiccated for extended periods of time, resulting in significant negative impacts for agriculture. Moreover, regional climate models predict drier summers during the next 100 years (Solomon et al. 2007), suggesting the need to better understand the spatial variability of soil water climatology in order to plan for the availability of water resources for urban and rural areas alike.

In the Great Plains, the localized nature of summer precipitation is often unable to balance high evapotranspiration rates, and as such, plants rely on the soil to provide the additional water necessary to maintain optimal growth. The amount of water stored in the soil is a function of a variety of soil characteristics, including structure, texture, composition, layer thickness, and so on, and the spatial variability of soil water is related not only to spatial patterns of precipitation and evaporation but also to the spatial variation of soil characteristics.

The purpose of this study is to create a soil water climatology for Kansas at the soil unit level. Several global and regional soil water climatologies have been produced...
by others (Willmott et al. 1985; Mintz and Serafini 1992; Porporato et al. 2004), but given the scale of analyses, the use of individual soil units is problematic, because researchers often parameterize or estimate soil characteristics rather than use the observed soil conditions. In this study, a monthly soil water climatology is calculated at the soil unit level, thereby taking into account the spatial variability of the individual soil characteristics.

The climatic water balance provides a mechanism to determine the impact of precipitation and evapotranspiration on the availability of water at the local scale (Thornthwaite and Mather 1955). Using a budgeting approach, the water balance tracks the amount of precipitation, evapotranspiration, and the movement of water within the soil to determine the overall hydroclimatic variability throughout the year (Mather 1978; Legates and Mather 1992). In particular, the water balance readily identifies periods of water surplus, water deficit, and changes in soil water storage. The water balance approach has been used in a variety of applications, including climate classification (Thornthwaite 1948; Wilmott and Feddema 1992; Feddema 2005), analysis of hydrologic variability (Yeh et al. 1998; Cayan and Georgakakos 1995; Wolock and McCabe 1999; Daly and Porporato 2006; Garbrecht et al. 2004), land-cover and land-use planning (Giambelluca et al. 1996; Mahmood and Hubbard 2004), and climate change (Valdes et al. 1994; Porporato et al. 2004). This study presents the monthly climatologies of the standard water balance parameters for Kansas using observed temperature and precipitation for the period 1940–2006 as a means of understanding the annual cycle of hydrologic surplus and deficit.

**DATA AND METHOD**

Monthly observations of surface temperature and precipitation for the period 1900–2006 were obtained from the National Climatic Data Center (dataset TD3220.) Stations were selected based on spatial coverage, and only those stations with complete records were used (Fig. 1.) In order to provide adequate spatial coverage using complete climate data observations, the final period of record used for the study was 1950–2006.

Soils data for 1,242 individual soil units for Kansas were obtained from the U.S. General Soil Map (STATS-GO) from the Natural Resources Conservation Service, USDA (Fig. 2). Soil water storage limits (field capacity) were calculated for each individual soil unit using the average water-holding capacities at the bottom and top of each soil layer, from which the total field capacity for the

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**Figure 1. Kansas climate stations used in the analysis. Source: National Climatic Data Center, NOAA.**

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soil unit was calculated by summing the depth-weighted water-holding capacities for all layers within the soil profile.

The hydroclimatic variability for Kansas was modeled using a soil water balance model originally developed by Thornthwaite (Thornthwaite 1948). The model uses the following equation to account for the gain, loss, and storage of water within the soil column based upon the balance between runoff ($R$), precipitation ($P$), actual evapotranspiration ($AET$) and changes in soil water storage over time ($\Delta w/\Delta t$):

$$R = P - AET - \Delta w/\Delta t$$

where $AET = E + T$

Actual evapotranspiration ($AET$) is defined as the sum of evaporation of soil water ($E$) and transpiration from the local vegetation ($T$). In the model, $AET$ is calculated as the difference between precipitation and potential evapotranspiration plus changes in soil water storage; it is assumed that the actual evapotranspiration cannot exceed the potential evapotranspiration, defined as the maximum evaporation possible given adequate water conditions.

The specific model used in this study was developed by McCabe and Markstrom (2007). In this model, precipitation as both rain and snow is estimated from the monthly total precipitation and mean monthly temperature (Fig. 3). Monthly potential evapotranspiration ($PET$) is calculated using the Hamon equation:

$$PET_{Hamon} = 13.97dD^2W_t$$

where $PET_{Hamon}$ is potential evapotranspiration, $d$ is number of days per month, $D$ is mean monthly hours of daylight, and $W_t$ is the saturated water vapor density (Hamon 1961). Use of the Hamon equation provides estimates of $PET$ derived from the mean monthly temperature and the latitude of the climate station as the source data.

The model was initialized by setting the total soil water content to zero and then running the model using monthly observations of temperature and precipitation for the period 1940–1950. This was done to ensure that all soil units had reached field capacity, and that soil storage values accurately accounted for the movement of water within the soil profile as well as contributing to runoff. A check of all soil units indicated that field capacity had been achieved at least once prior to 1950. The model was then run using monthly time steps for the period 1950–2006 to obtain monthly calculations of $PET$, $AET$, soil water storage, soil water deficit, and soil water surplus.
(runoff). Monthly average values were then calculated for the period of record to provide the monthly soil water climatologies. As the model uses a monthly time step, it is possible that water infiltration to the root zone may be overestimated, as runoff may be underestimated. However, from a climatological perspective the monthly data provide an acceptable representation of hydroclimatic variability.

In order to validate the model, extensive time series of observations of evapotranspiration and soil water conditions are not readily available. As such, observations of stream discharge were compared to model estimates of runoff as a means of validating the performance of the model. Observations of annual stream discharge were obtained from the USGS Water Data for the Nation dataset for stream gauging stations located in close proximity to the climate stations used in the study. Of the available gauging stations, six stations were identified with continuous monthly observations for the period 1950–2006 (Fig. 4; Table 1).

The annual time series of stream discharge and the annual series of modeled runoff were subjected to a logarithmic transformation and then standardized (zero mean, unit variance). The annual discharge series were then averaged to produce a single time series of annual stream discharge variability that was then compared to

Figure 3. Thornthwaite Water Balance Model (after McCabe and Markstrom 2007).
the average modeled runoff series. The two series were subjected to a least squares regression analysis, the results of which indicate that the model accurately replicates nearly 80% of the annual stream discharge variability (Fig. 5).

A plot of the two series demonstrates that the model does an acceptable job in predicting the majority of annual stream discharge, with the exception of extremely dry years such as the mid-1950s and early 1990s (Fig. 6).

RESULTS

The field capacity of the soil serves as an important indicator of soil water storage potential and varies as a function of soil characteristics such as soil texture, horizon thickness, and depth to parent material. Figure 7 shows the various physiographic regions in Kansas (Kansas Geological Survey 1997) and the spatial variability of field capacity is presented in Figure 8. Soils with reduced field capacities coincide with the Arkansas River Lowlands, Red Hills, Chautauqua Hills, the western Osage Cuestas, and the eastern Flint Hills. Moderate field capacities occur throughout the Wellington-McPherson Lowlands, the western Flint Hills, and the western Glaciated Region. The majority of the High Plains, Smoky Hills, Cherokee Lowlands, as well as the eastern halves of the Glaciated Region and Osage Cuestas, are characterized by high field capacities.

The monthly total precipitation climatology is presented in Figures 9A and 9B. The longitudinal gradient is evident during all months of the year. Winter (DJF) is the driest season; during the months of December and February, precipitation in the western half of the state is approximately 50% of that which falls to the east. January, the driest month, exhibits precipitation totals of less that 20 mm for all portions of the state with the exception of the southeast. The longitudinal gradient becomes increasingly pronounced with the onset of spring (MAM) and throughout the summer (JJA). Maximum precipitation occurs in the eastern third of the state during June,
with drier conditions becoming more apparent in western Kansas in August. Precipitation continues to decrease during the fall (SON), with the areas of reduced precipitation migrating from the west to the east.

The spatial variability of mean actual evapotranspiration is shown in Figures 10A and 10B. As expected, actual evapotranspiration is small throughout the winter months in response to reduced precipitation and lower temperatures. Actual evapotranspiration increases uniformly across Kansas throughout the spring in response to increases in temperature and available water. The highest actual evapotranspiration occurs during the summer months, with July experiencing the greatest rates, particularly in the Smoky Hills, Wellington-McPherson Lowlands, and the Red Hills physiographic provinces. Following this peak occurrence during July, actual evapotranspiration rates decrease throughout the fall and into winter, with slightly higher rates in the eastern half of the state compared to the west, a reflection of the longitudinal precipitation gradient.

Soil water utilization is defined as the amount of water evaporated from the soil during periods when the potential evapotranspiration exceeds precipitation amounts. The monthly climatologies of soil water utilization are presented in Figures 11A and 11B. In summer, water stored in the soil is used in addition to precipitation to balance the potential evapotranspiration values. The greatest amount of soil water use occurs in July in the eastern third of Kansas, particularly in the Osage Cuestas. Soil water utilization is limited (less than 10 mm/month) throughout the non-summer months.

Figures 12A and 12B contain the monthly climatologies of soil water recharge, or the amount of water added to the soil per month when the soil water conditions are below field capacity. Soil water recharge is most prevalent during spring and fall, when sufficient water is available.
from precipitation and when evapotranspiration rates are less severe. In spring, recharge rates are greatest in the Smoky Hills and central Kansas during March and in north-central Kansas during May. During fall, soil water recharge is greatest in eastern Kansas due to the higher precipitation amounts received relative to the rest of the state. Recharge rates are less during winter in response to reduced precipitation and less in summer due to increased temperatures and evapotranspiration.

Periods of runoff and deficit identify months of either a surplus (runoff) or shortfall (deficit) in the soil water balance. Monthly climatologies of runoff are shown in Figures 13A and 13B; monthly climatologies of soil water deficit are presented in Figures 14A and 14B. Runoff occurs following periods of soil water recharge once the soils have reached field capacity, and the longitudinal gradient in runoff is similar to that of precipitation, with the greatest runoff occurring during spring and early summer in the more humid regions of eastern Kansas. Areas of deficit occur throughout the year in the southern and western High Plains and in the Arkansas River Lowlands, and noticeable summer deficits occur in the western Osage Cuestas beginning in June and continuing into October.

**CONCLUSION**

The monthly climatologies produced in this study describe the spatial and temporal variations of the hydro-climatology for Kansas. The longitudinal precipitation gradient is readily apparent beginning in spring and extending through the fall, with the greatest precipitation occurring in eastern Kansas during the summer months. Actual evapotranspiration rates are low across the state during the winter and spring, reaching a maximum during summer, and becoming increasingly less during the...
fall; a weak longitudinal gradient is apparent during spring and again in fall. Soil water utilization is greatest during July in response to high actual evapotranspiration rates and is most pronounced in the eastern half of the state. Soil water recharge occurs during the spring, primarily during the months of March and May in central Kansas and during the fall in eastern Kansas. Soil water surplus (runoff) is most pronounced in eastern Kansas during spring and early summer; insufficient precipitation in western Kansas results in less runoff year-round. Soil water shortages (deficit) are common year-round in the western part of the state in response to less precipitation and increased actual evapotranspiration during the summer, and soils with low field capacities also exhibit deficit conditions during the summer months.

The model used in this study is applicable to rain-fed conditions as the snow hydrology in the model is estimated from monthly temperature conditions. The results of this and similar hydrologic studies provide opportunities to predict the impact of drought years on water availability for crops and to plan for the use of local water resources for irrigation under drought conditions. In addition, the ability to model the hydroclimatic variability at the soil unit level provides an opportunity to assess the impact of climate change on the availability of water resources.

REFERENCES


Figure 9A. Mean monthly precipitation (mm) for January–June, 1950–2006.
Figure 9B. Mean monthly precipitation (mm) for July-December, 1950-2006.
Figure 10A. Mean monthly actual evapotranspiration (mm) for January–June, 1950–2006.
Figure 10B. Mean monthly actual evapotranspiration (mm) for July–December, 1950–2006.
Figure 11A. Mean monthly soil water utilization (mm) for January–June, 1950–2006.
Figure 11B. Mean monthly soil water utilization (mm) for July–December, 1950–2006.
Figure 12A. Mean monthly soil water recharge (mm) for January–June, 1950–2006.
Figure 12B. Mean monthly soil water recharge (mm) for July–December, 1950–2006.
Figure 13A. Mean monthly runoff (mm) for January–June, 1950–2006.
Figure 13B. Mean monthly runoff (mm) for July–December, 1950–2006.
Figure 14A. Mean monthly deficit (mm) for January–June, 1950–2006.
Figure 14B. Mean monthly deficit (mm) for July-December, 1950-2006.