Journal of Hydrology 476 (2013) 265–273

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evaluation of drought indices via remotely sensed data with hydrological variables

Minha Choi [a,*], Jennifer M. Jacobs [b], Martha C. Anderson [c], David D. Bosch [d]

[a] Water Resources and Remote Sensing Laboratory, Department of Civil and Environmental Engineering, Hanyang University, Seoul 133-791, Republic of Korea
[b] Environmental Research Group, Department of Civil Engineering, University of New Hampshire, Durham, NH 03824, USA
[c] U.S. Department of Agriculture, Agricultural Research Service, Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA
[d] U.S. Department of Agriculture, Agricultural Research Service, Southeast Watershed Research Laboratory, Tifton, GA 31793, USA

ARTICLE INFO

Article history:
Received 29 May 2012
Received in revised form 17 October 2012
Accepted 26 October 2012
Available online 5 November 2012
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of V. Lakshmi, Associate Editor

Keywords:
Drought
Soil moisture
Streamflow
Evaporative Stress Index (ESI)
Palmer Drought Severity Index (PDSI)
Vegetation Health Index (VHI)

SUMMARY

An intercomparison among standard and remotely sensed drought indices was conducted using streamflow and soil moisture measurements collected in the Little River Experimental Watershed, Georgia, US, during the period from 2000 to 2008. All drought indices exhibited a linear, monotonic association with soil moisture, but there was a non-linear monotonic association between the drought indices and streamflow. Of the indices examined, the Evaporative Stress Index (ESI) showed reasonable performance with about 90% accuracy capturing moderate drought conditions and 80% accuracy capturing severe drought conditions in comparison to observed soil moisture and streamflow. While the ability of the ESI to capture shorter term droughts is equal or superior to the Palmer Drought Severity Index (PDSI) when characterizing droughts based on soil moisture and streamflow thresholds, the accuracy of the ESI was less efficient in the case of severe droughts. A drought index developed from the Advanced Microwave Scanning Radiometer (AMSR-E) soil moisture product showed reasonable correlations with the observed soil moisture and streamflow. However the ESI, Vegetation Health Index (VHI), and PDSI demonstrated greater skill in detecting drought in this study region. Multi-variable linear regression models revealed that the joint use of PDSI and appropriate remote sensing products improved predictions of observed hydrologic variables. Overall, the ESI was identified as a promising drought index for characterizing streamflow and soil moisture anomalies, particularly in regions where precipitation observations are unavailable, sparsely distributed, or biased with respect to regional averages.

1. Introduction

Droughts can lead to serious consequences, with impacts varying with rainfall timing, intensity, and spatial distribution (Kallis, 2008; Wilhite, 2000). While droughts are fundamentally driven by precipitation deficits, drought monitoring data are typically reported and applied via broad impact categories including (1) meteorological drought reflecting anomalies in accumulated precipitation; (2) agricultural drought described as reduced root-zone soil moisture and crop yields; (3) hydrological drought quantified by low stream flow, depleted groundwater, and reservoir levels deficits; and (4) socioeconomic drought characterized by the inability to meet societal water demands.

Among the many drought indices currently produced, some indices are perceived to be more broadly useful and easy to implement, and have had a long history of usage within the drought research community (Mendicino et al., 2008). The Palmer moisture anomaly index (*Z*-Index) and the Palmer Drought Severity Index (PDSI; Palmer, 1965), for example, are routinely reported and widely used to monitor drought in the United States and other countries. These indices are typically calculated from time series measurements of daily precipitation and air temperature, along with estimates of soil moisture storage, recharge, and surface runoff, and are reported at regional scales. Recently, observational data have been used to assess the performance of these drought indices by drought impact category. The results indicate that existing indices are not equally robust for monitoring different aspects of drought (Kallis, 2008).

Satellite remote sensing provides an alternative approach to monitoring drought over large areas. Remote sensing methods differ from most existing methods because they are not precipitation driven, but rather monitor vegetation stress or soil moisture status using diagnostic observations of key land-surface states. As reviewed by Moran (2003), the thermal infrared (TIR) remote sensing approach can provide effective estimates of water stress in many plant ecosystems. The Vegetation Health Index (VHI) uses TIR satellite imagery to monitor the increase in canopy temperature that occurs when plants undergo stress (Kogan, 1997). The Evaporative Stress Index (ESI) described by Anderson et al. (2007a, 2007b,

* Corresponding author. Address: Department of Civil and Environmental Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea. Tel.: +82 2 2220 0324; fax: +82 2 2220 4322.
E-mail address: mchoi@hanyang.ac.kr (M. Choi).

0022-1694/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2012.10.042

2011a) also uses TIR observations via the Atmosphere-Land Exchange Inverse (ALEXI) remote sensing model to quantify anomalies, the ratio of the actual evapotranspiration (AET) to the potential evapotranspiration (PET). This ratio decreases with decreasing plant available soil water. Microwave remote sensing also provides direct observations of near surface soil water stress (Choi et al., 2008).

In contrast to the standard precipitation-driven drought indices, remotely sensed drought indices have a shorter period of record, commensurate with the satellite era. While preliminary research shows promising results, there are limited analyses of the relative value of remotely sensed drought products and intercomparisons have typically been conducted only at large (continental) spatial scales (e.g., Anderson et al., 2007b, 2011a).

The goal of this study is to quantify differences among standard and remotely sensed drought indices at smaller spatial scales, and to investigate their relationships with observed indicators of agricultural and hydrological droughts. The Little River Experimental Watershed (LREW) in Georgia, US was selected for this analysis because it has a network of soil moisture and streamflow observations at scales comparable to those used in drought reporting. Additionally, the LREW was at the center of the devastating 2007 southeastern US drought. In this study, the PDSI, VHI, and ESI drought indices, along with microwave retrievals of soil moisture, are analyzed within the 2000–2008 historical time period. This study's objectives are to quantify the indices' ability to track observed streamflow and soil moisture anomalies and to identify moderate and severe droughts. In addition, an intercomparison of the drought indices for the period 2003–2007, when all datasets were concomitantly available, is conducted to determine the extent to which the indices add unique information.

2. Study area and observational data

The LREW (334 km^2) is located in the western headwaters of the Suwannee River basin within the state of Georgia (Bosch and Sheridan, 2007). The watershed has been managed by the USDA-ARS Southeast Watershed Research Lab (SEWRL) to collect hydrologic and climatic data since 1967 (Bosch et al., 2007a). Land use is predominantly row-crop agriculture (40%), pasture (18%), evergreen forest (36%), and wetlands and residential (6%). The main crops are rainfed cotton and peanuts with typical growing seasons from May to October (Bosch et al., 2006). The climate is humid with average annual rainfall of 1160 mm. The soils are mostly sandy and well-drained at the surface and have relatively high permeability (Miller and White, 1998).

In the watershed, streamflow and soil moisture was measured within a 334 km^2 drainage area (Fig. 1). Streamflow was continuously monitored at eight sites during the study period (2000–2008) using a Virginia V notch weir (Bosch et al., 2007b). Increasing the control elevation sometimes renders ponding upstream for the control structure due to low gradient streams in the watershed (Bosch et al., 2007b). This type of weir is generally less sensitive to submerged flow conditions because of application over a wide range of flow conditions. Due to these problematic conditions, special calibrations for the rating curve were applied in this study (Bosch et al., 2007b). Streamflow computed via these calibrated curves was aggregated to the watershed scale for comparison to the drought indices.

Soil moisture observations were obtained from in situ measurement networks deployed within the watershed. Soil moisture was measured at 29 sites and at three depths (50, 200, and 300 mm) using Stevens–Vitel Hydra probes (Stevens Water Monitoring Systems, Inc.). These probes measure the average dielectric constant using a 6 cm length tine (Cosh et al., 2005). A general calibration method for mineral soils was used to compute volumetric soil moisture contents from the measured voltage and typically 2% of volumetric soil moisture error was known (Choi et al., 2008; Cosh et al., 2005). Because most soil moisture network sites were much drier than the regional mean soil moisture contents (Bosch et al., 2006), our study uses the four time-stable locations (RG50, RG32, RG67, and RG16) in each EASE-Grid identified by Choi et al. (2008). These four time stable locations are shown in Fig. 1. The soil moisture observations from these locations were spatially averaged to match the spatial extent of the drought indices for the watershed. Soil moisture measurements from the network sites were also depth-averaged and compared directly to the drought indices.

3. Methodology

For this study, four indicators were used as regional drought metrics: the PDSI, the VHI, the ESI, and the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) soil moisture product. A brief description of each drought metric appears below.

3.1. Palmer Drought Severity Index (PDSI)

The PDSI is one of the original drought indices developed for the US (Palmer, 1965). It is a cumulative drought index which computes soil water storage using a simple two-layer soil water balance equation driven by precipitation data. Monthly precipitation is used to determine the Z index (moisture anomaly index). The Z indices are computed for each month from the precipitation difference (d) between actual precipitation and the climatically appropriate for existing conditions (CAFEC) precipitation. To obtain multi-month cumulative drought assessments, the Z indices are accumulated over time to form the PDSI using a recursive relationship:

$$\begin{aligned} \mathrm{PDSI} &= 0.897\mathrm{PDSI}_{i-1} + \frac{1}{3}Z_i \\ Z_i &= K_i d_i \end{aligned} \tag{1}$$

where i is the dry spell of the ith month and K_i is a weighting factor. The contribution from the previous PDSI and current month's Z index was determined empirically by Palmer using a set of drought events of specified severity and duration that were recorded in central Iowa and western Kansas (Palmer, 1965). Due to strong weighting of PDSI$_{i-1}$ compared to Z_i, the index has been shown to have a relatively long memory of antecedent moisture conditions and therefore it is less effective with short term droughts. The main inputs to estimate the PDSI are air temperature, precipitation, and soil water capacity maps. PDSI estimates PET by the temperature-based Thornthwaite (1948) method. The PDSI has been widely used to trigger designation of agricultural and hydrological droughts. In this study, the PDSI data were obtained from the archive generated at the climatic division scale by the National Climate Data Center (http://www1.ncdc.noaa.gov/pub/data/cirs/).

3.2. Vegetation Health Index (VHI)

The remote sensing-based Vegetation Health Index (VHI), developed from Advanced Very High Resolution Radiometer (AVHRR) imagery, has been widely used in global drought monitoring because of the large area coverage afforded by this polar orbiting system (Kogan, 1997). The VHI is a weighted average of two sub-indices derived from AVHRR data: (1) the Vegetation Condition Index (VCI; Karnieli et al., 2010; Kogan, 1997, 2002), computed from Normalized Difference Vegetation Index [NDVI;