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Combined statistical and spatially distributed hydrological model for evaluating future drought indices in Virginia

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A R T I C L E I N F O

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A B S T R A C T

Study region: Virginia, United States.

Study focus: Climate change is expected to impact the intensity and severity of droughts; therefore, it is necessary to simulate future drought conditions using temperature and precipitation projections and hydrological models to derive reliable hydrological variables and drought indices. The objective of this study was to evaluate climate change influences on future drought potential and water resources in five major river basins in Virginia. In this study, the Soil and Water Assessment Tool (SWAT) and Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models were used to compute a Standardized Soil Moisture Index (SSI), a Multivariate Standardized Drought Index (MSDI), and a Modified Palmer Drought Severity Index (MPDSI) for both historic and future periods. The drought conditions were evaluated, and their occurrences were determined at river basin scales.

New hydrological insights for the region: The results of the ensemble mean of SSI indicated that there was an overall increase in agricultural drought occurrences projected in the New (> 1.3 times) and Rappahannock (> 1.13 times) river basins due to increases in evapotranspiration and surface and groundwater flow. However, MSDI and MPDSI exhibited a decrease in projected future drought, despite increases in precipitation, which suggests that it is essential to use hybrid-modeling approaches and to interpret application-specific drought indices that consider both precipitation and temperature changes.

1. Introduction

Drought is one of the most prevalent natural hazards, adversely impacting water resources, the environment, agriculture, and the economy (Sternberg, 2011; Vasiliades and Loukas, 2009). Droughts have been occurring frequently in many parts of the world, and their impacts are being exacerbated by climate change (Dai, 2011). More specifically, global surface temperatures will continue to increase due increases in greenhouse gas emissions (IPCC, 2007; Qin et al., 2014; Pachauri et al., 2014). A warming climate will also lead to an increase in extreme climatic events, such as floods and droughts worldwide (Leonard et al., 2014). Evaluation of future drought incidence is fundamental to water resources management and planning, and this requires investigation of historical droughts and their impacts (Mishra and Singh, 2010 Sehgal et al., 2017).

In recent decades, the frequencies and severities of drought conditions in the United States have increased significantly (Changnon et al., 2000; Karl et al., 2012). Approximately 10% of the total U.S. experienced either severe or extreme droughts at one time during the 20th century (NCDC, 2002). Specifically, droughts can explain 17% of all weather-related disasters that occurred in

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the U.S. between 1980 and 2003 (Ross and Lott, 2003). The western region is currently experiencing one of the most severe droughts the country has never seen, which started in 2012 (Diffenbaugh et al., 2015; Mao et al., 2015). This drought was exacerbated by low winter precipitation and reduced mountain snowpack (Mao et al., 2015), which are both linked to global warming (AghaKouchak et al., 2014; Swain et al., 2014). Furthermore, climate model projections, based on multiple global climate models (GCMs), suggest that drying trends in precipitation, streamflow, and soil moisture can occur over many areas in low- and mid-latitudes due to increasing greenhouse gas (GHG) concentrations (Dai, 2013; Rajsekhar et al., 2015; Kumar et al., 2014; Chen and Sun, 2015; Mishra et al., 2014; Dai, 2011; Wang, 2005; Burke et al., 2006; Sheffield et al., 2012). More specifically, there is a strong tendency for wet areas to get wetter and dry areas to get drier, with a poleward expansion of the subtropical dry zones (Tallaksen and Van Lanen, 2004).

To identify and understand specific characteristics of regional drought, spatio-temporal observations of hydrological variables, such as runoff, soil moisture, and evapotranspiration (ET), are needed (Mo, 2008). Furthermore, satellite remote-sensing data can also provide essential information for identifying drought conditions with high spatio-temporal resolution (Wang et al., 2016). Specifically, they can provide insights into how human activities and land processes respond to drought conditions (Mu et al., 2012; Svoboda et al., 2002). However, since long-term and fine-resolution observations are sparse, large-scale hydrological models are used to simulate the land surface water and energy fluxes as well as hydrological variables, such as soil moisture, ET, and runoff, which are subsequently used to assess historic and future drought characteristics under climate change scenarios (Lakshmi et al., 2004; Mishra et al., 2010; Wang et al., 2011). For example, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is an effective method to simulate and quantify the impact of climate change on the hydrological cycle and on drought conditions (Wu and Johnston, 2007; Jha et al., 2004). Furthermore, SWAT has been successfully applied to simulate water quantity over a wide range of scales and environmental conditions (Schuol et al., 2008) and to evaluate various types of drought, including meteorological, agricultural, and hydrological drought (Wang et al., 2011). It is possible that hydrological models can be the basis for evaluating drought conditions through the development of multiple drought indices, mitigation, and management strategies (Narasimhan and Srinivasan, 2005).

In recent decades, several drought indices have been developed to quantify meteorological, agricultural, and hydrological droughts. Generally, drought indices are computed to define drought and the related parameters, such as intensity, duration, and severity (Mishra and Singh, 2010). Drought indices are useful for drought detection (Niemeyer, 2008), assessing the onset and recovery (Tsakiris et al., 2007), declaring drought levels (intensity or severity), evaluating droughts (Niemeyer, 2008), drought forecasting, and future drought projection. For instance, the Standardized Precipitation Index (SPI) was proposed and used as a meteorological drought-monitoring tool (McKee et al., 1993). It is one of the most popular indices for quantifying meteorological drought (Zargar et al., 2011; Mishra and Singh, 2009). SPI is based on long-term precipitation records by transforming the cumulative probability of precipitation over a specific time period. These data are fit to a particular probability distribution (e.g., Gamma distribution), which is then transformed into a normal distribution with an SPI mean value of zero (McKee et al., 1993; Edwards, 1997). The framework of SPI computation serves as the basis for Standardized Soil Moisture Index (SSI; Hao and AghaKouchak, 2013) applied to monitor agricultural drought, which uses soil moisture as an input. Furthermore, SPI finds its application in quantifying future drought projections (Loukas et al., 2008; Liu et al., 2013). Generally, the mean value of the precipitation total is set to zero, values above zero indicate wet conditions, and values below zero indicate dry conditions (Table 1). Another popular drought metric is the Palmer Drought Severity Index (PDSI; Palmer, 1965); however, several shortcomings of PDSI have been documented (Alley, 1984), which have led to alternative indices.

Despite all of these efforts, one of the key problems that exist today in identifying droughts is the need for a single hydrological or meteorological indicator, which is lacking due to the inherent difficulty in obtaining many variables over large areas. This compromises the development of reliable risk assessment and drought management plans (Hao and AghaKouchak, 2013). To address these limitations, a Multivariate Standardized Drought Index (MSDI), based on multiple hydroclimatic variables, was developed and applied to quantify past droughts in the United States (Hao and AghaKouchak, 2013, 2014).

By employing large-scale hydrological models and multiple drought indices, numerous studies have investigated future droughts and the impacts of climate change on droughts in the southwestern and central United States (Hoerling and Eischeid, 2007; Gutzler and Robbins, 2011; Seager et al., 2007; Strzepek et al., 2010). Even though severe and significant droughts have affected the southeastern U.S. in recent decades (Wilhite and Hayes, 1998; Changnon et al., 2000; VDEM, 2013), there are few studies available that provide future drought projections based on high-resolution and physically based hydrological models, multiple drought indices, and climate change projections for this region. For instance, several regions in Virginia have experienced extreme drought as recent as 2007 or 2012, but these droughts were not fully understood due to the lack of comprehensive data and the difficulty in evaluating

Table 1
Classification of SPI, SSI, and MSDI values (McKee et al., 1993).

SPI values	Drought category
2.0 and above	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.0 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
−2.0 or more	Extreme drought