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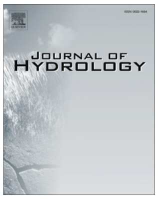

Anatomy of a local-scale drought: Application of assimilated remote sensing products, crop model, and statistical methods to an agricultural drought study

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SUMMARY

Drought is of global concern for society but it originates as a local problem. It has a significant impact on water quantity and quality and influences food, water, and energy security. The consequences of drought vary in space and time, from the local scale (e.g. county level) to regional scale (e.g. state or country level) to global scale. Within the regional scale, there are multiple socio-economic impacts (i.e., agriculture, drinking water supply, and stream health) occurring individually or in combination at local scales, either in clusters or scattered. Even though the application of aggregated drought information at the regional level has been useful in drought management, the latter can be further improved by evaluating the structure and evolution of a drought at the local scale. This study addresses a local-scale agricultural drought anatomy in Story County in Iowa, USA. This complex problem was evaluated using assimilated AMSR-E soil moisture and MODIS-LAI data into a crop model to generate surface and sub-surface drought indices to explore the anatomy of an agricultural drought. Quantification of moisture supply in the root zone remains a gray area in research community, this challenge can be partly overcome by incorporating assimilation of soil moisture and leaf area index into crop modeling framework for agricultural drought quantification, as it performs better in simulating crop yield. It was noted that the persistence of subsurface droughts is in general higher than surface droughts, which can potentially improve forecast accuracy. It was found that both surface and subsurface droughts have an impact on crop yields, albeit with different magnitudes, however, the total water available in the soil profile seemed to have a greater impact on the yield. Further, agricultural drought should not be treated equal for all crops, and it should be calculated based on the root zone depth rather than a fixed soil layer depth. We envisaged that the results of this study will enhance our understanding of agricultural droughts in different parts of the world.

1. Introduction

There is a continuous rise in water demand in many parts of the world in order to satisfy the needs of growing population, rising agricultural demand, and increasing energy and industrial sectors (Mishra and Singh, 2010; Singh et al., 2014). These growing water demands are further challenged by the impact of droughts. Drought propagates through water resources systems in virtually all climatic zones, as it is driven by the stochastic nature of hydroclimatic variables.

Based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013), the atmospheric temperature measurements show an estimated warming of 0.85 degree Celsius since 1880 and each of the last three decades has been

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successively warmer at the Earth's surface than any preceding decade. It is anticipated that future global warming and climate change will have impact on average precipitation, evaporation, and runoff, that happen to be controlling factors for different types of droughts. Drought is well considered to be a global concern, since about half of the earth's terrestrial surfaces are susceptible (Kogan, 1997), and it had the greatest detrimental impact among all natural hazards during the 20th century (Bruce, 1994; Obasi, 1994).

Meteorological records indicated that major droughts have been observed in all continents, affecting large areas in Europe, Africa, Asia, Australia, South America, Central America, and North America (Mishra and Singh, 2010). A number of drought studies have been carried out to investigate drought characteristics using data from multiple sources at the global scale (Sheffield and Wood, 2007; Dai, 2010; Vicente-Serrano et al., 2010; Van Lanen et al., 2013; Wada et al., 2013), national and regional scales (Rajsekhar et al., 2014; Hao and Aghakouchak, 2014; Zhang et al., 2014; Houborg et al., 2012; Li et al., 2012; Wang et al., 2011), and river basin levels (Tallaksen et al., 2009; Mishra and Singh, 2009; Madadgar and Moradkhani, 2013; Van Loon et al., 2014; Zhang et al., 2012).

Over the past several decades, there has been a significant improvement in the development of drought indices to quantify drought events, each with its own strengths and weaknesses (Mishra and Singh, 2010). The commonly used indices are: Palmer Drought Severity Index (PDSI; Palmer, 1965), Crop Moisture Index (CMI; Palmer, 1968), Bhalme and Mooly Drought Index (BMDI; Bhalme and Mooley, 1980), Surface Water Supply Index (SWSI; Shafer and Dezman, 1982), Standardized Precipitation Index (SPI; McKee et al., 1993), Reclamation Drought Index (RDI; Weghorst, 1996), Soil Moisture Drought Index (SMDI; Hollinger et al., 1993), Vegetation Condition Index (VCI; Liu and Kogan, 1996), and Drought Monitor (Svoboda et al., 2002). Comprehensive reviews of drought indices can be found in Heim (2002) and Mishra and Singh (2010). However, the challenge still remains for deriving drought indices because of the uncertainty due to scaling issues to capture detailed information instead of aggregated information within spatial units. In a real-world scenario, it is often noticed that within the regional scale, there are multiple socio-economic impacts (i.e., agriculture, drinking water supply, ecosystem health, hydropower, waste disposal, and stream health) occurring at local scales individually or in combination, either located in clusters or scattered. Therefore, to reduce the socio-economic impacts of a drought, the anatomy of drought needs to be understood at a local scale for near real-time drought management.

1.1. Importance of local-scale drought studies

With the advancement in technology (e.g., remote sensing, climate forecasts), significant improvement is made in drought identification, monitoring, and with reasonable accuracy in forecasting (Mishra and Singh, 2010) at a regional to global scale by aggregating hydroclimatic fluxes as well as land surface characteristics. However, drought management can be improved by understanding and quantifying the triggering variables at a local scale. The local-scale drought analysis can partly overcome large amounts of uncertainties due to scale issues, model parameter, data quality, non-availability of socio-economic information, missing micro-scale climate, and catchment information. The local-scale drought is a subset of regional- or global-scale drought, that needs special attention to improve water management. For example, drought varies with space and time within a river basin (Mishra and Singh, 2009); and there are specific sub-basins where drought is frequent, that needs local-scale treatment to improve water management within the watershed. Similarly, agricultural drought is mainly driven by stochastic and heterogeneous soil moisture, that poses a challenge to generate subsurface drought (soil moisture) information. However, with recent development of Soil Moisture Active and Passive (SMAP) mission products, it is expected that the robustness of agricultural drought monitoring and forecasting information will improve. Our focus in this study is limited to local-scale agricultural drought analysis to improve agricultural water management.

1.1.1. Application to agricultural drought

Different crops are grown in different parts of the world, regions, and even within the same watershed. When compared with that of other types of drought, agricultural drought quantification is not as straightforward due to several reasons, for example, crop water requirements are different for different crops, which make it complex to quantify drought appropriately. Here, crop water requirement is defined as the amount of water needed by the crop to grow optimally and to compensate for the loss through evapotranspiration. Given a drought situation, different crops will behave differently, which means the drought for one type of crop may not represent the same condition for other types of crop (i.e., drought for crop may not be a drought condition for another crop). The agricultural drought will differ between crops because of two major factors (demand and supply), that are discussed in the following section:

1.1.1.1. Crop water demand. The agricultural drought index should be represented by the crop water availability during the growing season, that varies among crops and seasons. This is governed by several factors (FAO; http://www.fao.org/docrep/s2022e/s2022e07.htm):

(a) *Climate factors*: Comparatively higher crop water needs are found in areas that are hot, dry, windy, and sunny. Climate factors also influence the duration of the total growing period and the various growth stages.
(b) *Crop type*: Higher leaf area (example: maize) will be able to transpire and, thus, use more water than the reference grass crop.
(c) *Growth type*: Crops that are fully developed will require more water than those at growth stages.
(d) *Total growing period*: This is an important variable, as it mostly depends on local circumstances (e.g. local crop varieties). The growing periods largely differ, depending on the type of crops, for example, sugarcane (270–365 days), maize grain (125–180 days), cotton (180–195 days), and sunflower (125–130 days). The total growing period (T) also determines crop growth stages, that include initial stage (0.1 T), crop development stage (0.7–0.8 T), and mild to late season stage (0.1–0.2 T);
(e) *Crop water needs*: This information needs to be collected at local scale, as it is driven by several factors (a–d). For example, maize needs 500–800 mm of water, sunflower needs 600–1000 mm of water, whereas sugarcane needs 1500–2500 mm of water.
(f) *Drought resistance*: Some of the crops are more sensitivity to drought in comparison to others, for example, crops with low sensitivity (cotton), medium to high sensitivity (maize), and high sensitivity (potato and sugarcane).

1.1.1.2. Crop water supply. The water is supplied to crops by the soil moisture available in the root zone. Therefore, to quantify an agricultural drought index, the relationship between water extraction and root zone needs to be understood. In general, more water is extracted from the top layer in comparison to the bottom layers.