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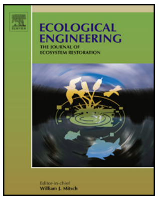

Defining drought in the context of stream health

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ABSTRACT

Droughts affect many sectors, such as agriculture, economic, social, human health, and ecosystems. Many drought indices have been developed; yet, none of them quantifies the impacts of drought on stream health. The purpose of this study is to define a new drought index capable of assessing fish vulnerability. To accomplish this, a hydrological model, called the Soil and Water Assessment Tool (SWAT), and the Regional-scale Habitat Suitability model were integrated in order to understand the state of drought within 13,831 stream segments within the Saginaw Bay Watershed. The ReliefF algorithm was used as the variable selection method, and partial least squared regression was used to develop two sets of predictor models capable of determining current and future drought severities. Forty-seven different climate scenarios were used to investigate drought model predictability of future climate scenarios. The results indicated that the best drought model has a high capability for predicting future drought conditions with R^2 values ranging from 0.86 to 0.89. In general, the majority of reaches (94%) will experience higher drought probability under future climate scenarios compared to current conditions. The procedure introduced in this study is transferable to other watersheds with regional standards for environmental flow to measure the impacts of drought on stream health.

1. Introduction

Droughts are temporary events that can occur almost in all climatic zones and are related to the reduction in received precipitation during a period of time (Wilhite et al., 2014; Mishra and Singh, 2010). Drought ultimately impacts both surface and groundwater resources (Mishra and Singh, 2010). Droughts rank first, among all the natural hazards that affect the human well-being (Wilhite, 2000; Mishra and Singh, 2010); and they are the most costly natural disasters of the world (Wilhite, 2000; Keyantash and Dracup, 2002). Globally, droughts cause an average of \$6–\$8 billion in damages annually (Wilhite, 2000; Keyantash and Dracup, 2002). Therefore, it is important to predict the timing and extent of droughts to help with development of mitigation strategies.

Drought is typically classified as either meteorological, hydrological, agricultural, or ecological drought (Wilhite and Glantz, 1985; American Meteorological Society, 1997; Mcmahon and Finlayson, 2003; Sheffield and Wood, 2011). Moreover, for each type of drought several drought indices have been developed. Meteorological droughts occur when there is a significant deviation from the mean precipitation in a region (Mishra and Singh, 2010; Sheffield and Wood, 2011). The Standardized Precipitation Index (McKee et al., 1993, 1995; Mishra and Desai, 2005a,b; Cancelliere et al., 2007; Mishra et al., 2007; Mishra and Singh, 2009) and Percent of Normal (Hayes, 2006; Sheffield and Wood, 2011; Zargar et al., 2011) are examples of commonly used meteorological drought indices. Hydrological droughts refer to a period of deficiency in the supply of water (both surface and subsurface water) (Panu and Sharma, 2002; Mishra and Singh, 2010; Sheffield and Wood, 2011). Streamflow, lake/reservoir levels, and groundwater levels are the parameters that are used to define hydrological drought (Mishra and Singh, 2010; Sheffield and Wood, 2011). Common hydrological drought indices are the Palmer Hydrological Drought Index (Palmer, 1965; Heim, 2000; Keyantash and Dracup, 2002; Mishra and Singh, 2010; Zargar et al., 2011), the Baseflow Index (The institute of Hydrology, 1980; Gustard et al., 1992; Zaidman et al., 2001; Tallaksen and Van Lanen, 2004; Sheffield and Wood, 2011), and the Surface Water Supply Index (Shafer and Dezman,1982; Heim, 2002; Hayes, 2006; Mishra and Singh, 2010; Sheffield and Wood, 2011). Agricultural droughts are defined as a period of soil

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moisture deficiency, which reduces moisture supply for vegetation and crop yield (Panu and Sharma, 2002; Sheffield and Wood, 2011). This type of drought is driven by meteorological and hydrological droughts (Sheffield and Wood, 2011). Several drought indices have been used to study agricultural drought including the Palmer Drought Severity Index (Alley, 1984; Rao and Padmanabhan, 1984; Johnson and Kohne, 1993; Kim and Valdes, 2003; Dai et al., 2004; Özger et al., 2009) and the Crop Moisture Index (Palmer, 1968; Hayes, 2006; Mishra and Singh, 2010; Sheffield and Wood, 2011). These indices use a combination of hydrometeorological variables such as precipitation, soil moisture, and temperature to analyze agricultural drought (Mishra and Singh, 2010). Ecological drought indices measure the impacts of drought on ecosystems (Sheffield and Wood, 2011); yet, few indices have been developed to quantify these impacts. Examples include the Normalized Difference Vegetation Index that is generally used to monitor the health of a canopy (Rouse et al., 1974; Singh et al., 2003; Kogan, 2005) and Vegetation Condition Index (Kogan, 1995; Singh et al., 2003; Quiring and Ganesh, 2010; Wardlow et al., 2012).

In general, a concept of drought that has received the least attention is ecohydrological aspects of drought that can be summarized as stream health. A healthy stream is an ecosystem that is flourishing, sustainable, resilient to stress, and maintains its societal values over time (Meyer, 1997). Many biological monitoring methods exist to measure the ecological conditions of stream systems. Among these methods, biological indicators are widely used for detecting the presence of point and non-point source pollutants, changes in physical habitat, and the effects of long-term disturbance events on ecosystems (Barbour et al., 1999; Nerbonne and Vondracek, 2001; Flinders et al., 2008). Fish are the most commonly used biological communities for water-quality assessments (Barbour et al., 1999; Flinders et al., 2008; Carlisle et al., 2013). Fish are sources of food for aquatic and terrestrial species, while being primary consumers of macroinvertebrates and algae (Carlisle et al., 2013). This links fish communities to other biotic characteristics of the ecosystem, which allows fish to be representative of the larger picture within the stream system. Furthermore, fish are relatively easy to collect and identify, provide long-term and regional impacts due to their mobility and lifespan, and their environmental requirements are well-known (Karr and Dudley, 1981; Barbour et al., 1999; Carlisle et al., 2013). Additionally, fish assemblages cover a variety of trophic levels such as omnivores, herbivores, insectivores, planktivores, and piscivores, which provides an integrative view of stream environmental health (Karr and Dudley, 1981; Barbour et al., 1999).

Flow is a key driver of stream ecological processes that affect aquatic organism performance, distribution, and abundance (Hart and Finelli, 1999; Bunn and Arthington, 2002). Alteration of flow regimes especially during dry seasons can significantly affect the ecosystem health (Koster et al., 2010; Hamaamin et al., 2013). Drought perturbs stream ecological conditions by altering native biological communities such as fish assemblages (Lake, 2003). Drought can cause reductions and alterations in fish populations and their structure by reducing spawning and recruitment (Lake, 2003). Therefore, it is important to quantify the impacts of drought on stream biota.

In this study, a new drought index is defined in the context of stream health. In general, the majority of drought indices are sensitive to the impacts of drought to human usages including drinking or crop production neglecting other aspects of environmental sustainability such as stream health. Therefore, this study is unique because it uses fish integrity as an indicator to define drought. By coupling the hydrologic model with a regional-scale habitat suitability model, the drought model will be developed capable of identifying drought zones for all streams within the study area. This allows targeting the streams that are more prone to degradation due to extreme climatological conditions allowing mitigation practices to be more effectively deployed.

2. Materials and methodology

2.1. Study area

The study area for this study is the Saginaw Bay Watershed located in the east central region of Michigan's Lower Peninsula; with a total area of 16,122 km^2, its final outlet drains into Lake Huron, Fig. 1. Most of this area is agricultural and forest lands (37% and 37%, respectively), with the agricultural lands dominated by corn and soybean crops. The remaining lands are pasture (9.5%), urban (7.5%), wetlands (8%), and water (1%). The Saginaw Bay Watershed is Michigan's largest 6-digit hydrologic unit code (HUC 040802) and consists of six 8-digit HUC watersheds, the Tittabawassee (HUC 04080201), Pine (HUC 04080202), Shiawassee (HUC 04080203), Flint (HUC 04080204), Cass (HUC 04080205), and Saginaw (HUC 04080206).There are 13,831 stream segments within the Saginaw Bay Watershed with different sizes and temperatures; with the majority of streams being warm water streams (Einheuser et al., 2013). The Saginaw Bay Watershed has been designated as area of concern by the US Environmental Protection Agency due to fish consumption advisories caused by excessive agrochemical utilization and contaminated sediments (USEPA, 2013).

2.2. Modeling process

The goal of the modeling process is to predict drought zones based on stream health. In order to accomplish this goal, a multistep modeling process was developed (Fig. 2). First, the Soil and Water Assessment Tool, a hydrological model, was used to obtain daily streamflow data (1972–2012) for all stream segments in the Saginaw Bay Watershed. The daily streamflow data was used as an input into a regional-scale habitat suitability model in order to assess the impacts of flow fluctuation on fish assemblages. Next, the changes in fish assemblages were translated into drought zones. Knowing drought zones for each stream segment, it was hypothesized that a drought predictive model could be developed using physiographical and climatological variables. Selected variables were then used to accomplish two general goals: (1) develop a drought model capable of determining current drought severity (using ReliefF algorithm) and (2) develop a drought forecast model capable of predicting future drought severity (using time series variables). Finally, the partial least square regression was used to create drought predictive models using the previously selected variables.

2.3. Soil and water assessment tool

In this study, the Soil and Water Assessment Tool (SWAT) was used to simulate daily streamflow data for 13,831 stream segments of the Saginaw Bay watershed. SWAT is a physically based, continuous time model developed by the US Department of Agriculture—Agricultural Research Service (Gassman et al., 2007). In this spatially explicit model, a watershed is delineated into multiple subwatersheds, which are further segmented into hydrologic response units (HRUs) with homogenous land cover, soil, slope, and management practices. This model uses physiographical and climatological characteristics of a region to simulate streamflow, runoff, soil erosion, as well as nutrient, sediment, and pesticide loadings (Gassman et al., 2007; Neitsch et al., 2011).

Different sources were used to obtain the physiographical and climatological data needed to run SWAT model. The National Elevation Dataset (NED) of the US Geological Survey (USGS) with a