Journal of Hydrology 520 (2015) 300–313

Contents lists available at ScienceDirect

Journal of Hydrology

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

# Assessment of global aridity change

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ARTICLE INFO

*Article history:*
Received 31 May 2014
Received in revised form 2 October 2014
Accepted 11 November 2014
Available online 18 November 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

*Keywords:*
Aridity
Climate change
Precipitation
Potential evapotranspiration
Trend
Clustering

## SUMMARY

The growing demand for water and the anticipated impacts of climate change necessitate a more reliable assessment of water availability for proper planning and management. Adequate understanding of the past changes in water resources availability can offer crucial information about potential changes in the future. Aridity is a reliable representation of potential water availability, especially at large scales. The present study investigates the changes in global aridity since 1960. The study considers the UNESCO aridity index, with aridity being represented as a function of its two key drivers: precipitation ($P$) and potential evapotranspiration (PET). First, published literature on changes in trends of $P$, PET, and aridity across the world is surveyed. This is followed by the analysis of trends in the aridity observations over the period 1960–2009. The nonparametric Mann–Kendall test is performed for trend analysis and outcomes investigated for the presence of clusters of trend across different grid cells the analysis is conducted over. The results suggest that arid zones are becoming slightly more humid and vice versa. They also indicate that the trend in aridity changed, or even reversed, around 1980 in most parts of the world. We speculate that the reason for this was the dramatic change (rise) in global temperature around 1980 as per both published literature and the present analysis, which, in turn, caused similar trends for global PET. We also call for additional research to verify, and possibly confirm, the present results.

## 1. Introduction

In recent years, numerous studies have reported compelling evidence on the occurrence of climate change and its impacts on our water resources, environment, health, and society (e.g. Tett et al., 1999; Karl and Trenberth, 2003; IPCC, 2007; Keller, 2008; Kundzewicz et al., 2007; Raghavan et al., 2012). For instance, noticeable changes in temperatures, snowmelt, frequency and magnitude of extreme hydroclimatic events (e.g. floods, droughts), and mean sea levels have been observed in different regions around the world (IPCC, 2007). Projections based on Global Climate Models (GCMs) also indicate further rising of temperatures and negative effects on our water resources and environment over the next century than over any time during the last 10,000 years, thus giving rise to enormous challenges in their planning and management (e.g. Kundzewicz et al., 2008; Sivakumar, 2011a). The effects of climate change have and continue to put additional pressure on our water resources, which have already been significantly exploited to meet our growing water demands due to a combination of factors, including population growth, urbanization, industrialization, improved living standards, and changes in land cover and land use (e.g. Chen et al., 2011; Sivakumar, 2011b; Murray et al., 2012; Singh et al., 2014). In recent decades, development of irrigated agriculture for production of food to support the population growth has also raised the demand for water and created a condition of water stress (e.g. Postel, 1998).

On one hand, based on numerous anthropogenic and biodiversity indicators, nearly 80% of the global population in 2000 resided in high water stress regions (Vörösmarty et al., 2010). On the other hand, shortage of water availability is one of the most important problems constraining vegetation productivity in both direct and indirect ways (Mu et al., 2011). Thus, there is a need to monitor the potential water availability in order to identify and focus management efforts towards regions at risk, especially in the face of climate change and its impacts. Aridity classes are reliable representations of potential water availability at various scales, especially at large scales. They are largely defined by the climatic zones.

Study of the effects of climate variability and change on natural resources is crucial for their planning and management at local, regional, national, and global scales. To this end, there is a need to classify various climatic zones to assess possible shifts that have

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http://dx.doi.org/10.1016/j.jhydrol.2014.11.033
0022-1694/

occurred in the past. Such a classification helps to identify aridity levels for assessment of potential water availability and, hence, for water resources planning and management in various sectors. To this end, a number of studies have attempted to find the aridity trends around the world and, as a result, different aridity indexes have also been proposed and used. The following studies serve as examples of the indexes used in aridity investigations thus far. Oguntunde et al. (2006) have used the Budyko's aridity index to study the aridity trends in the Volta River Basin in West Africa. Costa and Soares (2009) have used the Aridity Intensity Index to identify the aridity trends in the south of Portugal. Zhang et al. (2009) have used the De Martonne aridity index to study the aridity trends in the Pearl River basin in South China, while Huo et al. (2013) have used the Thornthwaite aridity index to identify the aridity trends in northwest China. Croitoru et al. (2013) have used the De Martonne and the Pinna combinative index to study the aridity trends over Romania. Tabari and Aghajanloo (2013) have employed the UNESCO aridity index for an aridity trend analysis in the north and northwest of Iran. Despite these studies and advances, a comprehensive global study to find, compare, and interpret probable aridity trends in each of the aridity zones separately continues to be elusive.

As of now, to assess aridity, the UNESCO aridity index (UNESCO, 1979) is most widely used. The UNESCO aridity index (AI) is based on the ratio of annual precipitation ($P$) to potential evapotranspiration (PET). Precipitation and PET are two important components of the hydrologic cycle. Precipitation is a very difficult process both to observe and to simulate. Precipitation is generated through complex interactions of dynamic atmospheric convergence, advection, and lifting mechanisms, as well as surface conditions that relate to moisture availability and thermal stability, and, therefore, shows a high degree of variability. Evapotranspiration (ET) is one of the most important climatic parameters and has an important role in energy control and mass exchange between the atmosphere and terrestrial ecosystems. Potential evapotranspiration, a key input to hydrologic models, is generally considered to be the maximum rate of evaporation from vegetation-covered land surfaces when water is freely available and evaporation rate is primarily determined by meteorologic controls (Zhou et al., 2008). Since evapotranspiration is affected by different climatic factors (see Yang and Yang, 2012 for some details), such as temperature ($T$), sunshine, atmospheric humidity, wind, surface albedo, and soil moisture, assessment of PET is a complicated and challenging task, although its variability is significantly lower than that of precipitation.

Generally, since the UNESCO aridity index can provide a reliable assessment of water balance by considering aridity as a balance between precipitation (as input) and PET (as output), it can be argued that use of this index is better for assessment of the available humidity than an index that is based only on precipitation. Therefore, in the present study, aridity is described as a function of two parameters: precipitation and potential evapotranspiration. To validate this approach, a systematic two-step procedure is followed: (1) analysis of $P$, PET, and aridity trends based on a review of published literature; and (2) analysis of $P$, PET, and aridity trends based on global data observed during 1960–2009. The nonparametric Mann–Kendall test (Kendall, 1975) is used for analysis, and both spatial and temporal aspects of aridity time series are addressed. Following this, the agglomerative hierarchical clustering approach is employed to assess whether the trends that are observed can be classified into different groups or they are homogeneously dispersed across the world and over time. Finally, to interpret the aridity trends, a correlation analysis between aridity and major climatic parameters is also carried out.

The rest of this paper is organized as follows. In Section 2, particular emphasis is placed on the contribution of precipitation and potential evapotranspiration to aridity trends based on published literature. Section 3 describes the data and methods used in this study. Section 4 presents the results, with particular attention laid on aridity trends using actual observations and their temporal variability by cluster analysis. A detailed discussion of these results is presented in Section 5, and a set of conclusions is drawn in Section 6.

## 2. Background

### 2.1. Aridity indexes

Aridity has been defined by various indicators. In 1900, the first quantitative climate classification system, which included two important climatic parameters, temperature and precipitation, was introduced by Köppen (Köppen, 1900; Larson and Lohrengel, 2011). This climate classification system, called the 'Köppen's classification' was based on the principle that plants integrate several climatic elements (Sparovek et al., 2007). This classification utilizes near-surface temperature and precipitation to represent climatic regimes, thus detecting climatic shifts associated with the primary climatic components (Köppen, 1931). The Köppen climate classification is often used to assess changes over climatologically consistent spatial zones (Diaz and Eischeid, 2007; Roderfeld et al., 2008) and defines arid and semi-arid zones as two of its prominent classes. In the 1920s, the De Martonne aridity index (I ar-DM) was developed (De Martonne, 1926). This index is calculated based on the mean annual values of precipitation ($P$) and temperature ($T$). Unlike the Köppen classification, the De Martonne aridity index expresses the aridity as a function of time, thus allowing assessment of change.

Since then, many other, and more complex, aridity indexes have been introduced, especially based on reference evapotranspiration ($ET_o$). There are also several formulae, as appropriate, to calculate aridity indexes, such as those adopted by UNESCO (UNESCO, 1979) and UNEP (UNEP, 1992): aridity index = precipitation (mm)/potential evapotranspiration (mm). However, when these new indexes were first introduced, there was no suitable standard method to calculate $ET_o$. The Penman method (Penman, 1948) was internationally recognized as a basis for this in the late 20th century. The Penman–Monteith method is a variant of the Penman method, and is recommended by FAO (Allen et al., 1994).

The methods introduced by UNESCO (1979) and UNEP (1992) are widely used for classification of different types of climate. These numerical methods use quantitative values for classifying the climatic zone boundaries. In the current study, to map the climate at the global scale, UNESCO's climate classification is used. Based on this classification, there are five main climatic classes: hyper-arid, arid, semi-arid, sub-humid, and humid. The UNESCO aridity index assesses potential water availability by considering five climatic parameters: temperature, precipitation, wind speed, sunshine hours, and relative humidity. Temperature, radiation, and water availability are the main abiotic controls of ecosystem primary production in various regions of the world (Boisvenue

**Table 1**
Aridity index (AI) classification system based on UNESCO (1979) and UNEP (1992) methods.

| Zone | UNESCO (1979) $P$/PET Penman method | UNEP (1992) $P$/PET Thornthwaite method |
|---|---|---|
| Hyper-arid | AI < 0.03 | AI < 0.05 |
| Arid | 0.03 < AI < 0.20 | 0.05 < AI < 0.20 |
| Semi-arid | 0.20 < AI < 0.50 | 0.20 < AI < 0.50 |
| Sub-humid | 0.50 < AI < 0.75 | 0.50 < AI < 0.65 |
| Humid | 0.75 < AI | 0.65 < AI |