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Leveraging Water for Peace: An Evaluation of Hydrological Drought Methodologies

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Abstract: Droughts caused by hydrological processes affect many aspects of society and the economy, including the generation of energy and agriculture. The analysis of hydrological droughts makes planning and managing water resources under climate change easier. However, to achieve a shift in drought management, one must utilize various approaches and techniques that can be applied for both planning mitigation activities and implementing the measures. In this study, I examined the methodologies that allows for the identification of hydrological droughts on a worldwide scale, considering different climate regimes in a consistent manner. The method incorporates the features of the classical variable threshold level method and indices. Furthermore, each evaluated work includes a thorough assessment of current progress, unresolved issues, and future prospects. Improved monitoring and assessment, along with the development of specific plans for areas more likely to be affected, can effectively reduce the long-lasting effects of drought, and strengthen communities and ecosystems.

Keywords: Drought, Hydrological drought, Low flow, Threshold level method, Drought index

1. Introduction

Every year, a significant portion of the world's population, economies, and environment are impacted by the complicated and recurring climatic phenomenon known as drought. Droughts can cause crop failure and food crises in developing nations, where they typically have the worst effects [1]. Drought is a naturally occurring phenomena, characterized by a gradual accumulation of its affects over an extended duration. Drought is defined as a condition of water scarcity caused by inadequate precipitation, which is influenced by meteorological factors such as temperature, precipitation, and humidity [2]. Drought are extreme natural climate phenomena which is characterized by intensity, frequency and duration, manifested by the drastic reduction of precipitation and water reserves for all uses [3]. The increasing of global climate change effects, the current trend is to increase the intensity, duration, and frequency of droughts, leading to climate change towards ultimately desertification.

Researchers with experience in their field are currently engaged in a debate regarding the definition of drought. Several studies have concurred that a lack of rainfall is the primary factor contributing to drought. There has been debate among researchers over the appropriateness of using inadequate moisture content versus deficient precipitation. Drought, as described by Van Loon & Laaha [4], refers to a situation when there is a below-average amount of water available. Drought is typically defined by scholars based on the circumstances in that particular place. The choice of an appropriate drought attribute for a particular drought analysis relies on the hydro-climatic conditions in the specific region, the specific type of drought being examined, the susceptibility of the local environment, the objectives of the study, and the data accessible for evaluating drought conditions. The scarcity or absence of sufficient measurable data regarding the incidence, frequency, and intensity of droughts. Furthermore, there is a deficiency in the availability of adequate and suitable drought evaluation and prediction techniques.

The primary aim of this work is to examine existing data and literature on comprehensive hydrological drought approaches to develop a perspective at the continental, regional, and national levels. This article aims to provide a thorough examination of the evolution of drought definitions throughout time and assess commonly employed drought indices for characterization. This literature review is structured in the following approach: The text includes an abstract and introduction, followed by a section on materials and techniques that outlines the study aims, research questions, and methodology. The sections pertaining to the results and debate have been consolidated into a unified section. Within this section, I initially provide a series of definitions of hydrological drought throughout different

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periods, then followed by the classifications of drought. Furthermore, I proceed to give the drought methodologies categorized accordingly. Furthermore, I provide the equation utilized to compute each index, along with the benefits and limitations associated with each index. Ultimately, the assessment concludes with definitive conclusions.

2. Material

There is a drought categorization system that categorizes droughts into four types based on the characteristics of the water deficit [5]. Based on this categorization, meteorological, hydrological, and agricultural droughts are classified as environmental droughts. These types of droughts are characterized by inadequate levels of precipitation, river flow, groundwater, and soil moisture, respectively. Socio-economic drought, the fourth form of drought, occurs when water resource systems are unable to satisfy water demands. Figure 1 represented the drought propagations.

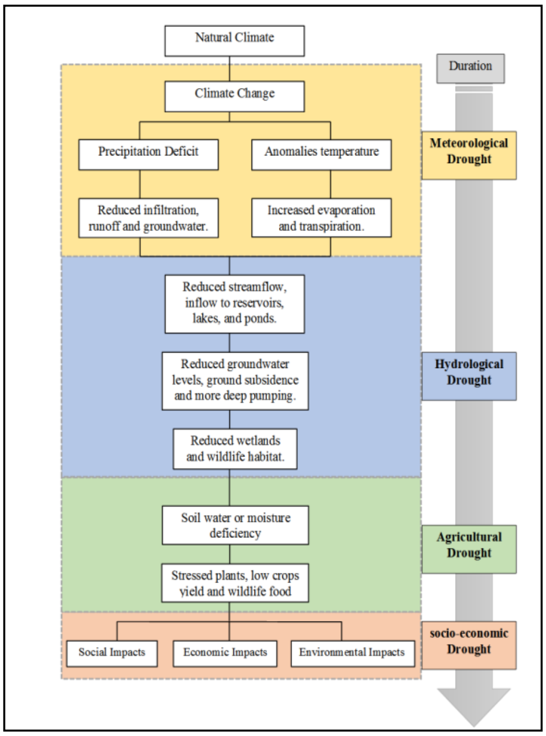

Fig. 1 - Propagation classification of drought

Over the past two decades, there has been extensive analysis of the characteristics of hydrological droughts. Furthermore, accurately identifying a drought event throughout time is challenging and heavily reliant on the chosen methodology. Furthermore, the frequency of drought incidence continues to be a crucial determinant. Lastly, the spatial coverage of a drought event, while valuable for meteorological droughts, is irrelevant for hydrological droughts as water managers are solely concerned with streamflow at a limited number of locations. It is evident that streamflow at these specific points offers a comprehensive assessment of runoff distribution across the area. Hydrologic drought indices consolidate extensive data on precipitation, snow accumulation, river discharge, soil moisture, and other water supply and availability variables to form a coherent overview. In terms of managing water resources, it is crucial to establish the baseline flow levels and metrics for measuring the severity of drought. Multiple indices exist to quantify the extent to which precipitation or stream flow during a specific time period has diverged from known historical norms.

3. Methodology

3.1 Hydrological Drought Assessment Using Threshold Method

The low flow characteristics is to quantify droughts according to their magnitude and are useful for understanding the hydrological regime of a river. However, to understand drought processes and impacts, it is necessary to identify the drought characteristics based on streamflow below a certain threshold level [6]. The threshold level method is the most frequently applied quantitative method to identify drought characteristics from time series variables. This method allows for deriving a time series for each drought event and then characterizing each drought by its time of occurrence, duration, and deficit volume (severity) [3]. The threshold level method is a commonly employed approach for quantitatively analyzing the deficit characteristics of hydrological drought. This method relies on evaluating the onset and termination of the drought by utilizing a defined threshold level in the time series of discharges. The threshold value, also known as level (Qx), separates the values in a time series into two groups: those below the threshold and those above it. Periods with values below the specified threshold are classified as periods of hydrological drought.

Nevertheless, there is no definitive threshold level that is more desirable than another, and the choice of a certain threshold level remains a subjective determination. In the developed dataset, fixed thresholds at annual timescales, and variable thresholds taken at seasonal and monthly timescales are used to derive the deficit duration and severity indicators [7]. A flow duration curve (FDC) is a highly useful technique for illustrating the entire spectrum of river discharges, encompassing both low flow conditions and flood occurrences. The relationship being referred to is the correlation between a specific discharge value and the percentage of time that this discharge is equaled or surpassed. It may also be described as the connection between the frequency and magnitude of streamflow discharges. FDC can serve as a method for calibrating rainfall-runoff models by comparing simulated flow-time data for various development scenarios [8].

The Flow Duration Curve (FDC) is created by rearranging the time series values of flow in descending order, assigning these values to different intervals, and then counting the number of occurrences inside each interval. The cumulative class frequencies are subsequently computed and presented as a proportion of the total number of time steps throughout the recording period. Ultimately, the minimum value of each discharge category range is graphed in relation to the percentage points. FDC can be derived from streamflow data at several time resolutions, including annual, monthly, or daily intervals [7]. Flow duration curves (FDCs) derived from daily flow time series offer the most comprehensive approach to analyzing the duration properties of a river. Curves can also be created using alternative time intervals, such as m-day or m-month average flow time series. In this scenario, before the construction of the FDC, a method called moving average is employed to create a new time series of flows that are averaged over a period of m days or m months. This is done using the existing daily or monthly data that is initially available [3].

The determination of the threshold level (Q0) for hydrological drought study and assessment can vary depending on the specific goal and methodologies employed [6]. The threshold level is often determined based on the low flow indices. One approach is to determine it by calculating its percentile within the flow time curve. The percentiles most frequently utilized span from the 70th percentile to the 90th percentile. In arid regions, percentile values below Q70 are frequently utilized for intermittent rivers and streams [9]. The deficiency characteristics are determined by analyzing the time series values of a measured parameter in the hydrological cycle that fall below a specified threshold level. The deficit characteristics of hydrological drought primarily rely on analyzing the duration of the deficit period and assessing the magnitude of the deficit. The deficit period is defined as the duration of time during which the discharge falls below the Q90 cutoff level or when there is insufficient water volume during these days. The threshold level method is a fundamental approach for determining the features of a deficit [10].

Threshold values are selected to encompass the spectrum of frequently employed. Q90 and Q70 are utilized to designate perennial streams. Based on the experience form previous studies [11] threshold levels in the range between Q90 and Q70 for perennial streams are considered reasonable also for an extreme value analysis of droughts. Flow duration curves are created for intermittent rivers, which experience extended periods without water lasting several months. These curves are based solely on discharge values that are not zero, and the threshold level is determined as the Q70 value. Additionally, certain authors employ multiple variations of threshold values. Aside from a constant level that remains consistent throughout the year, there are also varying threshold values based on seasons, months, and N-day intervals. When a defined threshold level type is used, the percentiles are generated from a selected annual period over an extended duration.

A 90th percentile (Q90) was designed for the examination of low flows [11]. This percentile indicates the discharge value that was exceeded for 90% of the observed period in the time series of observed discharges. The computation of percentiles for low flows is a well-accepted and commonly used method in various areas of water management, including drinking water supply, hydroelectric power design, irrigation planning, determination of minimum discharges for treated rivers, and surface water withdrawals. When constructing numerous flow duration curves on a single chart, it becomes possible to analyze and assess variations in the water runoff from multiple profiles within a single catchment or across multiple catchments [12].

3.2 Limitation of Threshold Method

The threshold level approach can be used to assess three categories of drought: meteorological, soil moisture, and hydrological drought. Variable comparison is necessary for researching drought propagation. Consequently, research on the spread of drought often use the threshold level approach [4]. Another advantage of the threshold level method is that it stays as close to the original time series as possible [6][13]. A limitation of the threshold level method is the absence of standardized drought classes. Therefore, in global drought studies, standardization is necessary to minimize disparities between climatic types and facilitate comparability. Moreover, it is inevitable to make subjective decisions, such as determining the appropriate threshold level to utilize.

This is analogous to the options available for selecting a distribution when computing standardized indices. Another drawback of the threshold level method for global analysis arises in arid regions with temporary rivers. This is due to long periods with almost no precipitation and natural zero flow, resulting in a threshold level of zero [7]. In arid regions, it is better suitable to employ a zero-streamflow day or zero-streamflow month technique, which calculates the consecutive days with precipitation below 1 mm, rather than using the threshold level method [14]. A group of academics has devised a novel approach to assess streamflow drought on a broad scale by combining the threshold level method.

3.3 Hydrological Drought Assessment Using Indices

Hydrologists have endeavored to create efficient indices for the purpose of characterizing hydrological droughts [15]. These indicators are based on hydrological variables or the likelihood of drought and have been widely utilized in many global geographical areas. Most hydrological drought indices primarily rely on stream flows. Drought indices and definitions that rely exclusively on flow or reservoir storage are typically intended for managing reservoirs and are rarely employed as indicators for drought relief or for monitoring drought across large areas. While no single main index is universally superior to the others, certain indexes are more suitable for specific purposes than others.

Utilizing drought indices is the most straightforward approach to monitor drought conditions, as they offer a quantifiable means of identifying the start and conclusion of a drought event. This is due to the fact that the index value serves as an indicator of the extent of drought severity [15]. Over the years, various drought indices have been created to accurately describe hydrological droughts. Drought indices are essential instruments for monitoring and evaluating drought conditions and serve as the foundation for making water resources management decisions during drought events [16]. Four frequently used indicators for monitoring surface water are the Streamflow Drought Index (SDI), Standardized Streamflow Index (SSFI), Standardized Reservoir Supply Index (SRSI) and Standardized Water-level Index (SWI).

3.4 Streamflow Drought Index (SDI)

The streamflow drought index (SDI) was developed recently by Nalbantis [17] is a very simple and effective index for hydrological droughts. SDI using instead of flow rates in m3/s, allows monitoring of the hydrological droughts' duration, severity and frequency and drought forecast in due time. Unlike many other sophisticated indices that need extensive data and complex calculations, the Streamflow Drought Index (SDI) was designed to be a straightforward and efficient measure for assessing hydrological droughts. Positive SDI values reflect wet conditions while negative values indicate a hydrological drought. Based on the SDI, five states of hydrological drought are defined which are denoted by an integer number ranging from 0 (non-drought) to 4 (extreme drought). The Streamflow Drought Index (SDI) successfully captures the hydrological drought conditions and the performance of the index is validated based on both the historic drought archives and results from other drought indices [18].

3.5 Standardized Streamflow Index (SSFI)

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Modarres [19] first introduced SSFI in 2007 and specifically, SSFI for a specific period was defined as the variation in streamflow from the average to the standard deviation. Constructed utilizing monthly streamflow data and the normalization techniques associated with Standardised Precipitation Index (SPI). The calculation can be performed for both actual and anticipated data, offering insight into times of high and low flow that are linked to drought and flood events.

3.6 Standardized Reservoir Supply Index (SRSI)

Created by Gusyev [20] in Japan, this method serves as a systematic approach for analyzing reservoir data during periods of drought. Resembling SPI, the monthly data is utilized to calculate a probability distribution function of reservoir storage data. This function offers insights into the water supply for a certain region or basin, ranging from -3 (very dry) to +3 (very wet).

3.7 Standardized Water-level Index (SWI)

Established by Bhuiyan [21] at the Indian Institute of Technology, India, as a method to evaluate deficiencies in groundwater recharge. It utilizes well data to examine the influence of drought on the replenishment of groundwater, serving as a hydrology-based drought indicator. Interpolation allows for the estimation of values between given data points. Table 1 showed the comparison of each index for hydrological drought.

Table 1 - Comparison of hydrological drought indices

Index	Input parameters	Applications	Strengths	Weaknesses	Reference
Streamflow Drought Index (SDI).	Streamflow data.	This tool is employed to monitor and detect drought occurrences based on a specific measuring device, which may or may not accurately reflect broader water basins.	The index is readily accessible and user-friendly. Allowance is made for the absence of data, and the accuracy of the results increases with the length of the streamflow record.	A single input (streamflow) fails to consider managerial choices, and intervals of zero flow can distort the outcomes.	[15]
Standardized Streamflow Index (SSFI).	Streamflow data.	Monitoring of hydrological conditions at multiple timescales.	An input variable that permits the absence of data simplifies usability.	Exclusively considers the streamflow in the context of drought monitoring, without examining any other factors.	[19]
Standardized Reservoir Supply Index (SRSI).	Reservoir inflows and volumes.	Considers the overall amount of water coming in and being stored in a certain reservoir system and offers data for managers of municipal water supply and local irrigation providers.	Computationally simple, as it emulates SPI calculations by utilizing a conventional gamma distribution for the probability distribution function.	Does not consider alterations resulting from reservoir management and losses resulting from evaporation.	[20] [22]
Standardized Water-level Index (SWI).	Groundwater well levels.	Intended for regions characterized by regular periods of reduced water flow in major rivers and streams throughout specific seasons.	The influence of drought on groundwater is a crucial element in agricultural and municipal water supply.	Only considers groundwater and the interpolation between data points may not accurately represent the broader region or climate conditions.	[23]

3.8 Limitation of Hydrological Drought Indices Method

The limitation using indices is that a reference period must be chosen, which can cause difficulties under multi-decadal climate variability. The sensitivity of drought indices to the chosen reference period is substantial, comparable to the sensitivity of drought trend analysis to the selection of periods. Given that there exist standardized indices with comparable calculation methods for all variables related to the terrestrial hydrological cycle, these indices can serve as a valuable tool in studying the spread of droughts. This is particularly important when comparing droughts in various parts of the hydrological cycle. An additional constraint arises when the estimated values over extended temporal periods are occasionally employed as an estimation of hydrological drought [24]. Hydrological indices are not suggested in other research since they just focus on hydrological factors and fail to account for all relevant propagation processes.

4. Conclusion

Future advancements in drought characterization and monitoring must acknowledge that drought indexes may not always accurately represent the true risk of water scarcity in a specific region. To properly evaluate the risk of water shortage, it is crucial to also consider the reliability of the water supply systems. There is a need for improvement in the utilization of targeted indicators that are specifically chosen for the water supply system being studied, in order to accurately capture the unique characteristics of the system.

The indicators must consider both the dependability of the source (groundwater, river flows, reservoirs) and the susceptibility of the demand (municipal, agriculture, environment). Anticipated advancements in the future will focus on determining the optimal spatial scale for drought monitoring. In several countries, establishing a national drought monitoring center is seen as a practical way to connect meteorological and hydrological services that collect data. However, in other countries, it is necessary to have a specific set of indicators within the river basin or administrative boundaries, such as a basin authority or region. This is particularly important when the monitoring is focused on assessing the risk of water scarcity in the primary sources of the water supply system.

The future will see a growing focus on the ability to predict droughts on a seasonal basis. This is because such predictions have the potential to significantly decrease the uncertainties associated with managing droughts. Significant gains in this field can be anticipated when progress is achieved in comprehending global atmospheric circulation and its impacts on smaller scales, such as regional or basin levels [25]. Global climate indexes can enhance the reliability of drought forecasts in this setting.

The findings of this study highlight the pressing necessity for prompt and synchronized actions to tackle the rising problem of droughts resulting from climate change. To alleviate the extensive impacts of drought and enhance the resilience of communities and ecosystems, it is feasible to enhance monitoring and evaluation techniques while implementing customized measures in susceptible locations. It is imperative that prompt and concerted efforts be made to address the growing problem of droughts brought on by climate change, since the implications of this study highlight the urgent necessity for such measures. It is possible to lessen the far-reaching effects of drought and to construct communities and ecosystems that are more resilient if monitoring and evaluation methods are improved, and if targeted solutions are implemented in regions that are particularly vulnerable. This review focuses on the latest indices and methodologies employed in designing drought indices. We examine their advantages and disadvantages, as well as identify significant areas of research that have not been addressed. We also discussed potential sources of data sets and modelling techniques that will aid in the use of drought indices on a broader geographical scale, as well as at a more localized level.

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