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A Review of Some Indices used for Drought Studies

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Abstract

Droughts are serious extreme events that have adverse effects on the physical environment and water resource systems in both developed and developing countries. Consequently, there is need for adequate measures for responding to and mitigating various impacts arising from drought occurrence. The design and implementation of drought mitigation and response strategies requires an understanding of the various indices that are used to examine drought both at single site and in an area. In the case of water resources management during critical drought periods for instance, a means of objectively identifying drought events in terms time and duration of occurrence, magnitude and severity is required. This is possible only using various indices to characterize drought. In this paper, some of the key drought indices are reviewed and their strengths and weaknesses identified.

Keywords: drought, index, severity, mitigation

1. Introduction

Drought is a serious extreme hydrological hazard that has afflicted most societies in both developing and developed countries in the past and will continue to do so in the future. Its widespread and frequent occurrence and increased severity worldwide has underscored the vulnerability of both the developed and developing countries to the hazard resulting in unprecedented socio-economic and environmental impacts. In many parts of the world, drought is a recurrent disaster and often the precursor of famine and is indeed the single most important factor limiting agricultural and livestock production in most countries.

It is perceived in many different ways and therefore can be defined in various ways depending on the discipline. Consequently, there are various drought types including meteorological, hydrological, agricultural or socio-economic but generally it occurs as a result of the failure of expected rains, which leads to various effects in the physical environment and on human activities. While some drought definitions are directly related to physical considerations, others have been expressed in terms of societal impacts. Due to its recurrent nature in most regions of the world, there is concern among the scientific and research community on the inability of governments and other actors to effectively and timely respond to its occurrence and ameliorate its associated impacts. Effective management of drought requires an adequate knowledge and understanding of the various ways of characterizing its occurrence. This is possible from the indices available to analyse the different drought types in the different sectors of development.

In the water sector for instance, planning for short-term response to drought occurrence requires water authorities to put water restriction policies in place to be implemented during drought episodes. In the absence of proper indices to characterize drought, restrictions on water use may be imposed in an ad hoc manner and so a staged response plan is needed based on values of a particular drought index to allow for sustainable management of water supply during critical periods of drought occurrence (Srikanthan & Stewart 1992). In this paper, the commonly available drought indices are examined for their suitability to determine periods of drought occurrence for purposes of planning of water and other environmental resources. The indices are used to provide a clear and comprehensive picture of drought occurrence in a given area and require various types of data such as rainfall, stream flow and other water supply indicators. They are far more useful than raw data for decision-making.

2. Drought Indices

Standard definitions of drought refer to the occurrence of water within the hydrological cycle and include various types depending on the discipline. A drought index is one that gives a quantitative estimate of drought severity. Its development should involve the selection of the nature of water deficit to be studied, the averaging period to be considered, the truncation level to be applied to separate drought from the remainder of the time series and the method of regionalization (Dracup *et al.*, 1980 and Oladipo, 1985). Consequently, available indices may be grouped into meteorological, agricultural and hydrological and include the Decile Index, Percent of Normal Standardized Precipitation Index, Palmer Drought Severity Index, Crop Moisture Index, Surface Water Supply Index, the Reclamation Drought Index and the Bhalme and Mooley Drought Index.

2.1 Deciles Index

The Deciles Index, DI index groups monthly precipitation occurrences into deciles. The index provides an accurate statistical measurement of precipitation with long climatic data records required for accurate calculations of the index. The index, developed by Gibbs and Maher (1967), avoided some of the weaknesses within the "percent of normal" approach and divided the distribution of occurrences over a long-term precipitation record into tenths of the distribution. They called each of these categories a decile with the first decile representing the rainfall amount not exceeded by the lowest 10% of the precipitation occurrences. The second decile is the precipitation amount not exceeded by the lowest 20% of occurrences. These deciles continue until the rainfall amount identified by the tenth decile is the largest precipitation amount within the long-term record. By definition, the fifth decile is the median, and it is the precipitation amount not exceeded by 50% of the occurrences over the period of record.

The deciles are grouped into five classifications namely; deciles 1-2 lowest 20% much below; normal deciles 3-4 next lowest; 20% below normal deciles 5-6; middle 20% near normal deciles 7-8; next highest 20% above normal deciles 9-10; highest 20% much above normal. The decile method is relatively simple to calculate and requires less data and fewer assumptions than the Palmer Drought Severity Index (Smith *et al.*, 1993). In this system, farmers and ranchers can only request government assistance if the drought is shown to be an event that occurs only once in 20-25 years (deciles 1 and 2 over a 100-year record) and has lasted longer than 12 months (White and O'Meagher, 1995). This provides a uniform drought classification, which unlike a system based on the percent of normal precipitation, assists authorities to determine appropriate drought responses. One disadvantage of the decile system is that a long climatological record is needed to calculate the deciles accurately.

2.2 Percent of Normal

The percent of normal, PN is a simple calculation suited to the needs of weather forecasters and general audiences. The index is calculated by dividing actual precipitation by normal precipitation typically considered to be a 30-year mean and multiplying by 100% and this can be calculated for a variety of time scales but usually these time scales range from a single month to a group of months representing a particular season, to an annual or water year. It is quite effective for comparing a single region or season. The percent of normal precipitation is one of the simplest measurements of rainfall for a location and analyses using the percent of normal are very effective when used for a single region or a single season. Some of the disadvantages of this index include the fact it can easily be misunderstood, since "normal" is a mathematical term that does not necessarily correspond with what you should expect the weather and percent of normal is also easily misunderstood and gives different indications of conditions, depending on the location and season.

Besides, the mean precipitation is often not the same as the median precipitation, which is the value exceeded by 50% of the precipitation occurrences in a long-term climate record. This is because precipitation on monthly or seasonal scales does not have a normal distribution whereas use of the percent of normal comparison implies a normal distribution where the mean and median are considered the same. Use of this index therefore makes it difficult to link a value of a departure with a specific impact occurring as a result of the departure, inhibiting attempts to mitigate the risks of drought based on the departures from normal and form a plan of response (Willeke *et al*. 1994).

2.3 Standardized Precipitation Index

The Standardized Precipitation Index, SPI is an index based on the probability of precipitation for any time scale and is used by many drought planners due to its versatility. The advantages of the index include the fact that it can be computed for different time scales, can provide early warning of drought, help assess drought severity and is simpler compared to the Palmer index. It was developed on the basis that precipitation deficit has different impacts on ground water, reservoir storage, soil moisture and stream flow (McKee *et al*. 1993). The index was designed to quantify the precipitation deficit for multiple time scales that reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale, while ground water, stream flow and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee *et al*. (1993) originally calculated the SPI for 3-, 6-, 12-, 24-, and 48-month time scales.

The calculation of the index for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards & McKee 1997). Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. Since the index is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. A drought event occurs any time the SPI is continuously negative and has intensity of -1.0 or less whilst it ends when the SPI becomes positive.

Table 1. Standardized precipitation index classification criteria

Value	Condition
≥ 2.0	extremely wet
1.5 –1.99	very wet
1.0 – 1.49	moderately wet
-0.99 - 0.99	near normal
-1.0 - -1.49	moderately dry
-1.5 - -1.99	severely dry
≤ -2.0	extremely dry

Each drought event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues. The accumulated magnitude of drought (or drought magnitude) obtained by the positive sum of the SPI for all the months within a drought event. Because the SPI is standardized, these percentages are expected from a normal distribution of the SPI such that the 2.3% of SPI values within the extreme drought category is a percentage that is typically expected for an extreme event (Wilhite 1995). This standardization allows the SPI to determine the rarity of drought occurrence, as well as the probability of the precipitation necessary to end the drought episode (McKee *et al*. 1993). The criteria as to when wet or drought conditions begin using the SPI index is shown in Table 1 (McKee *et al*. 1995).

2.4 Palmer Drought Severity Index

The Palmer drought severity index, PDSI is a soil moisture algorithm calibrated for relatively homogeneous regions and is used extensively to trigger drought relief programs. Some of the limitations of the index include the fact that the Palmer values may lag emerging droughts by several months; is less well-suited for mountainous land or areas of frequent climatic extremes; is complex and has an unspecified, built-in time scale that can be misleading. It was developed by Palmer in 1965 to measure the departure of the moisture supply based on the supply-and-demand concept of the water balance equation, taking into account more than just the precipitation deficit at specific locations with the objective of providing measurements of standardized moisture conditions to enable comparisons of moisture conditions to be made between locations and between months (Palmer 1965). The index is a meteorological drought index and responds to weather conditions that have been abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by the PDSI ends without taking into account both shorter- and longer-term hydrologic impacts such as stream flow, lake and reservoir levels (Karl & Knight 1985). The classification criterion for this type of index is as shown in Table 2.

Table 2. Palmer Index Classification Criteria

Value	Condition
≥ 4.0	extremely wet
3.0 – 3.99	very wet
2.0 – 2.49	moderately wet
1.0 - 1.99	slightly wet
0.5 – 0.99	insipient wet spell
0.49 - -4.9	near normal
-0.5 - -0.99	insipient dry spell
-1.0 - -1.99	mild drought
-2.0 - -2.99	moderate drought
-3.0 - -3.99	severe drought
≤ -4.0	extreme drought

The PDSI is calculated using precipitation and temperature data, as well as the local available water content of the soil. From the inputs, all the basic terms of the water balance equation can be determined, including evapo-transpiration, soil recharge, and runoff and moisture loss from the surface layer. However, human impacts on the water balance, such as irrigation, are not considered. Complete descriptions of the equations can be found in Palmer (1965) and Alley (1984). The index was developed to include the duration of a drought also known as a wet spell such that an abnormally wet month in the middle of a long-term drought should not have a major effect on the index or that a series of months with near-normal precipitation following a serious drought should not mean that the drought is over. It is important to note that the index is a hydrological one known as the Palmer Hydrological Drought Index (PHDI) since it is based on moisture inflow (precipitation), outflow, and storage, and does not take into account the long-term trend (Karl and Knight, 1985). A modified method of computing the PDSI has been described and used by Heddinghaus & Sabol (1991) such that the modified PDSI differs from the PDSI during transition periods between dry and wet spells.

The Palmer Index varies roughly between -6.0 and +6.0. Palmer arbitrarily selected the classification scale of moisture conditions based on his original study areas in some states of the USA (Palmer 1965). The Palmer Index is typically calculated on a monthly basis and is popular and widely used for a variety of applications. The index's popularity and wide application in drought monitoring may be attributed to the fact that it provides decision makers with a measurement of the abnormality of recent weather for a region; an opportunity to place current conditions in historical perspective; and spatial and temporal representations of historical droughts (Alley 1984). The index is most effective measuring impacts sensitive to soil moisture conditions, such as agriculture; is useful as a drought monitoring tool and has been used to trigger actions associated with drought contingency plans (Willeke *et al*. 1994).

The Palmer Index has considerable limitations in its application. These limitations have been extensively described by Alley (1984) and Karl & Knight (1985) and include the following.

- The values quantifying the intensity of drought and signalling the beginning and end of a drought or wet spell were arbitrarily selected and have little scientific meaning.
- The index is sensitive to the available water content of a soil type and so its application for a Climate Division may be too general.
- The two soil layers within the water balance computations are simplified and may not be accurately representative for a location.
- Other aspects of precipitation such as snowfall, snow cover, and frozen ground are not included in the index and since all precipitation is treated as rain, the timing of PDSI or PHDI values may be inaccurate in regions where snow occurs during the winter and spring seasons.
- The natural lag between when precipitation falls and the resulting runoff is not considered. In addition, no runoff is allowed to take place in the model until the water capacity of the surface and subsurface soil layers is full, leading to an underestimation of runoff.
- Potential evapo-transpiration is estimated using the Thornthwaite method which although it is widely accepted, it is still only an approximation.

Other notable limitations of the index include the fact that it does not accurately represent the hydrological impacts resulting from longer droughts since the index is designed for agriculture. Besides, it does not do well in regions of extreme rainfall or runoff variability and the "extreme" and "severe" drought classifications do occur with a greater frequency in some parts than in others (Smith *et al*. 1993; Willeke *et al.* 1994; McKee *et al*. 1995 and Kogan 1995). Because of such reasons, the index is limited in accuracy when comparing the intensity of droughts between two regions thus making drought planning responses much more difficult and cumbersome.

2.5 Crop Moisture Index

The crop moisture index, CMI is a Palmer derivative developed by Palmer (1968) from procedures within the calculation of the PDSI and reflects moisture supply in the short term across major crop- producing regions. It is not intended to assess long-term droughts. Some of its advantages include the fact that it identifies potential agricultural droughts. The index uses a meteorological approach to monitor weekly crop conditions. The difference between the two indices is that whereas the PDSI monitors long-term meteorological wet and dry spells, the CMI was designed to evaluate short-term moisture conditions across major crop producing regions. It is based on the mean temperature and total precipitation for each week within a Climate Division together with the CMI value from the previous week. The CMI responds rapidly to changing conditions, and it is weighted by location and time so that maps, which commonly display the weekly CMI, can be used to compare moisture conditions at different locations.

The index suffers several shortcomings including the fact that it is not a good long-term drought-monitoring tool since it is designed to monitor short-term moisture conditions affecting a developing crop. Besides, the index's rapid response to changing short-term conditions may provide misleading information about long-term conditions. For instance, a beneficial rainfall during a drought may allow the CMI value to indicate adequate moisture conditions, while the long-term drought at that location persists. Another characteristic of the CMI that limits its use as a long-term drought-monitoring tool is that the index typically begins and ends each growing season near zero. This limitation prevents the index from being used to monitor moisture conditions outside the general growing season, especially in droughts that extend over several years. The CMI also may not be applicable during seed germination at the beginning of a specific crop's growing season.

2.6 The Surface Water Supply Index

This index, abbreviated by SWSI was developed by Shafer & Dezman (1982) and is designed to complement the Palmer index and makes use of stream flow, precipitation and reservoir storage as data inputs. It represents water supply conditions unique to a basin and has the disadvantage that changing a data collection station or water management requires that new algorithms be calculated, and the index is unique to each basin, which limits inter basin comparisons. Since the Palmer Index is basically a soil moisture algorithm calibrated for relatively homogeneous regions and is not designed for large topographic variations across a region and does not account for snow accumulation and subsequent runoff, the SWSI was designed to be an indicator of surface water conditions. The index incorporates both hydrological and climatological features into a single index value resembling the Palmer Index. The index values can be standardized to allow comparisons between basins.

The data requirements for the index include snow-pack, stream flow, precipitation, and reservoir storage and since it is season dependent, the index is computed with only the snow-pack, precipitation and reservoir storage in the winter whilst during the summer season; stream flow replaces snow-pack as a component within the SWSI equation. The SWSI for a particular basin is determined according to the following procedure.

(i) Monthly data are collected and summed for all the precipitation stations, reservoirs, and snow-pack or stream flow measuring stations over the basin. Each summed component is normalized using a frequency analysis gathered from a long-term data set.

(ii) The probability of non-exceedence (that is, the probability that subsequent sums of that component will not be greater than the current sum) is determined for each component based on the frequency analysis. This allows comparisons of the probabilities to be made between the components. Each component has a weight assigned to it depending on its typical contribution to the surface water within that basin, and

(iii) The weighted components in (ii) are summed to determine a SWSI value representing the entire basin.

Like the Palmer Index, the SWSI is centred on zero and has a range between -4.2 and +4.2. One of its advantages is that it is simple to calculate and gives a representative measurement of surface water supplies across a basin. Several characteristics of the SWSI limit its application. Because the SWSI calculation is unique to each basin or region, it is difficult to compare SWSI values between basins or regions (Doesken *et al*. 1991). It is difficult to maintain a homogeneous time series of the index since within a particular basin or region, discontinuing any station means that new stations need to be added to the system and new frequency distributions need to be determined for that component. In addition, if changes in water management within a basin such as flow diversions or construction of new projects like reservoirs do occur, then the entire SWSI algorithm for that basin needs to be redeveloped to account for changes in the weight of each component. Extreme events also cause a problem if the events are beyond the historical time series, and the index will need to be re-evaluated to include these events within the frequency distribution of a basin component (Heddinghaus & Sabol 1991).

2.7 Reclamation Drought Index

The Reclamation drought index, RDI just like the SWSI, is calculated at the river basin level, and makes use of temperature, precipitation, snow-pack, stream flow and reservoir levels as data input and has the advantage that by including a temperature component, it also accounts for evaporation. The index was developed by the Bureau of Reclamation in the USA, as a trigger to release drought emergency relief funds and has recently been used as a tool to define drought severity and duration, and to predict the onset and end of periods of drought.

The index is limited in its use for inter basin comparisons as it is unique to each river basin. The classifications for the index are given in Table 3. Just like the SWSI, the RDI is calculated at a river basin level, and incorporates the supply components of precipitation, snow pack, and stream flow and reservoir levels. However, it differs from the SWSI in that it builds a temperature-based demand component and a duration component into the index. The RDI is adaptable to each particular region and its main strength lies in its ability to account for both climate and water supply factors. The RDI values and severity designations are similar to the SPI, PDSI, and SWSI.

Table 3. Reclamation Drought Index Classification Criteria

Value	Condition
≥ 4.0	extremely wet
1.5 – 4.0	moderately wet
1.0 – 1.5	normal to mild wetness
0.0 – -1.5	normal to mild drought
-1.5 - -4.0	moderate drought
≤ -4.0	extremely drought

2.8 Bhalme and Mooley Drought Index

This index was developed by Bhalme & Mooley (1980) and is based on the four months of monsoon rainfall in India. To use this type of index, a moisture index is first defined as the percentage of departure of monthly rainfall from the long term mean weighted by the reciprocal of the coefficient of variation and then an appropriate drought index derived from the moisture index to account for the duration factor of abnormal moisture deficiency with the monthly index values generally ranging from –4 to +4 in which the descriptive terms used to characterise the weather being similar to those of Palmer.

3. Conclusion

In conclusion, it should be noted that various indices for different drought types are available and that different indices have strengths and weaknesses and that not a single index is superior to the rest in all circumstances but some indices may be better suited than others for certain applications. The Palmer Drought Severity Index, for instance, is widely to determine when to grant emergency drought assistance, but the Palmer is better when working with large areas of uniform topography. For other areas with mountainous terrain and with complex regional hydrological and microclimates, the index can be supplemented with other indices such as the Surface Water Supply Index. Sometimes it may be necessary to combine indices in a study to be able to comprehensively deal with the drought hazard. The indices should, however, not be based on identical data. The choice of an index depends on the purpose of a study and for water supply planning and management for instance, the SWSI is the most suitable and only index that is used since it takes into account the various components of a water supply system and is generally used together with the PDSI.

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