Addressing monitoring needs for drought management

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Abstract: Persistent drought and increased water demand require that comprehensive drought planning, based on accurate drought indicators, guide future water resource management. Yet, drought indicators are often the weakest components of drought plans because drought affects different sectors at different time scales, making it difficult to define and measure. Utilizing the Carolinas Dynamic Drought Index Tool (DDIT) this research evaluates the spatial and temporal distribution of drought intensity and frequency as detected by South Carolina's state drought indicators and the recently defined Federal Energy Regulatory Commission's (FERC) Low Inflow Protocol (LIP) indicators for the Catawba-Wateree.

Indicator discrepancies were identified and several major recommendations emerge from the research. First, statistical inconsistencies exist between the drought classes defined by the S.C. Drought Response Act regulations; these can be resolved by transforming the indicators from raw values to percentiles. Second, discrepancies in drought detection based on the LIP indicators were most acute during the drought recovery phase for the Catawba-Wateree River Basin LIP, which is dependent on a recovery of all indicators to initiate a stage downgrade. Recommendations include shortening the streamflow average and utilizing a basin average U.S. Drought Monitor designation rather than maximum value. The addition of a recovery condition based on storage recovery should also be considered.

The research connects indicators based on scientific justification with operational relevancy by evaluating water systems' and power company's vulnerability to drought, their understanding of drought indicators, and their identification of indicator characteristics that provide the most effective drought response. The research results can be used to improve planning and coordination within and between levels of government and water users to help reduce society's vulnerabilities to drought and ensure sustainable water to meet growing demands.

Introduction

Designating indicators to measure drought intensity, and triggers to activate response improves drought mitigation. However, decision makers typically rely on multiple triggers without realizing their spatial and temporal inconsistencies. Drought monitoring tools need to accommodate the diverse requirements of users from different sectors, managing drought across a range of different spatial jurisdictions.

Over the last decade, as South Carolina endured two record multi-year droughts, it became clear that the sustainability of the state's water resources could no longer be taken for granted. The droughts brought about changes in how the state's water resources are managed and reinforced the need for improved coordination and planning. The persistent drought and increased water demand required that comprehensive drought planning, based on accurate drought indicators, guide future water resource management.

This research evaluates the spatial and temporal distribution of drought intensity and frequency as detected by South Carolina's state drought indicators and the recently defined Federal Energy Regulatory Commission's (FERC) Low Inflow Protocol indicators for the Catawba-Wateree Basin. The research provides scientific and operational information to consider in evaluating whether changes should be made to the drought indicators listed in the South Carolina Drought Response Act regulations, and those recently implemented in the FERC Low Inflow Protocol (LIP) for the Catawba-Wateree river basin.

Background

Like many states, the evolution of South Carolina's drought planning has occurred through trial and error in response to increasing drought impacts. South Carolina first recognized the need to formalize a drought plan by passing the South Carolina Drought Response Act in 1985 (South Carolina Drought Response Act, 1985). This act was amended in 2000 to implement guidelines set forth in the 1998 State Water Plan. South Carolina is unique in dealing with drought management through legislation and its associated regulations (Knutson and Hayes, 2001).

While South Carolina's drought response program is proactive in having state and local level drought indicators, many are being developed without scientific justification (Mizzell, 2008). One of the research goals is to determine whether statistical inconsistencies exist among state-defined drought indicators and categories. The S.C. Drought Response Committee relies primarily on seven drought indicators defined in the S.C. Drought Response Act's supporting regulations (Table 1) to declare four levels of drought: incipient, moderate, severe, and extreme. South Carolina uses seven indicators because droughts can be characterized in many different ways (Wilhite and Glantz, 1985) and no single indicator serves as an adequate national standard to characterize drought.

The incorporation of drought planning in the Federal Energy Regulatory Commission's hydropower relicensing over the past decade has resulted in additional improvements to South Carolina's drought response. The evolution of the drought plans, or Low Inflow Protocol, in the Catawba-Wateree river basin was an important step toward the recognition of drought mitigation during this federal-mandated process. However, the LIPs were new to the relicensing process for the two basins and the identification of drought indicators and trigger points presented challenges to the licensee (Duke Energy) and the stakeholders. The local drought indicators used by Duke Energy are presented in Table 2.

In summary, the process of planning for drought has evolved at all levels over the past few decades. Despite this, detecting drought and its impacts continues to present a daunting task. Single indicators often prove to be inadequate in detecting the onset, duration and recovery from drought especially for diverse sectors. Additional challenges occur when users combine multiple indicators in drought management plans without understanding the spatial and temporal consistency and the direct relevance of the indicators in meeting their needs.

Methodology

The purpose of this research is to determine which drought indicators are most effective in enhancing South Carolina's state and local drought mitigation policies. This was accomplished through two research objectives.

1. Determine the statistical consistency among state indicators and drought categories.

The first objective evaluates the correlation between state-level drought indicators (Table 1) used by the S.C. Drought Response Committee for official drought stage determination. The frequency of occurrence within each threshold trigger level will reveal any inconsistencies between indicators and serve to better understand the duration and probability of drought occurrence. If the indicators are consistent they should have similar frequencies. This evaluation will compare statistical properties of probability distributions using the two-way chi-square test. The primary data source for this analysis was the Carolinas Dynamic Drought Index Tool (DDIT) (Carbone et al., 2008; Rhee, 2007).

Percent frequency distributions of each monthly state drought indicator were calculated for the period 1951-2005. The highest U.S. Drought Monitor (DM) drought level for each county was extracted from a database provided by the National Drought Mitigation Center for the period 2000–2005. The interpolated indicator data were spatially averaged by county for all variables, excluding streamflow and groundwater. Streamflow and groundwater drought levels are based on percent frequency of occurrence and therefore are consistent spatially. Three counties, Oconee, Florence, and Charleston, were selected for analysis to represent different geographic regions in South Carolina.

The chi-square test was used to estimate the independence of the drought indicators categorized by drought occurrence (extreme/severe, moderate, incipient, and normal). The DM frequency of occurrence for 2000 – 2005 was extrapolated to represent drought frequencies for the period from 1951-2008. However, the values are not representative of drought conditions throughout the period of record since severe drought was common from 2000-2005. The null hypothesis for the chi-square test is that no difference exists between the indicators.

2. Identify inconsistencies between multiple indicators used in local drought plans.

Frequency distributions were computed to determine probabilities of drought occurrence for local drought indicators used in the Catawba-Wateree Low Inflow Protocol (Table 2). Specifically, the research will determine whether drought detection in the Catawba-Wateree river basin can be improved by revising the current indicators. Criteria for changing the LIP indicators identified by the Catawba-Wateree Drought Management Advisory Group were used to evaluate indicator performance. These criteria include that the LIP

Table 1. State level indicators designated by regulation.

Drought Indicator	Incipient	Moderate	Severe	Extreme
Palmer Drought Severity Index	-0.50 to -1.49	-1.50 to -2.99	-3.00 to -3.99	< -4.00
Standardized Precipitation Index	0.00 to -0.99	-1.00 to -1.49	-1.50 to -1.99	< -2.00
U.S. Drought Monitor	DO	D1	D2	>=D3
Crop Moisture Index	0.00 to -1.49	-1.50 to -2.99	-3.00 to -3.99	<-4.00

Table 2. Local-level drought indicators for Duke Energy.

System Name	Source	Stage 0[1]	Stage 1[1]	Stage 2[1]	Stage 3[1]	Stage 4[1]
Duke Energy	11 Catawba Wateree Lakes	Storage index (SI) based on combination storage in all lakes. Ratio of Remaining Useable Storage to Total Usable Storage (TSI)				
		90% TSI < SI < 100% TSI	75% TSI < SI <= 90% TSI	57% TSI < SI <= 75% TSI	42% TSI < SI <= 57% TSI	SI <= 42% TSI
	U.S DM	U.S. Drought Monitor Three-Month Numeric Average				

indicators and stages accurately reflect hydrologic conditions, don’t change too quickly, reflect seasonal variability, use storage conservatively, the calculations are easily understood and the public’s perception of drought is consistent with hydrologic conditions. The primary data source for this analysis was the DDIT, U.S Drought Monitor, and other data sources such as lake storage and streamflow received from Duke Power.

Results

State Indicator Results

Figure 1 displays the frequency plot of the indicators for Florence County showing inconsistencies between the occurrence frequency for most stages of drought. The inconsistencies between most indicators are greatest from no drought to moderate and less for severe and extreme drought. The frequency of occurrence in extreme drought is consistent between all indicators (< 2%) except for the DM and streamflow. Based on the range of levels defined in the S.C. Drought Response Act’s supporting regulations for streamflow, extreme drought will occur more often than severe, moderate, or incipient droughts. For all other indicators, extreme drought occurs the least often, as expected based on the highest severity level and defined ranges. The DM is generally inconsistent with other indicators for each level of drought especially extreme. It has only been in existence since 2000 a period when South Carolina experienced extended periods of severe and extreme droughts.

A chi-square test was used to estimate the independence of the drought indicators categorized by drought occurrence (extreme/severe, moderate, incipient, and normal). The null hypothesis was rejected for most of the indicator comparisons, which indicates statistically significant differences exist between the indicators. The difference between the KBDI and groundwater indices was not statistically significant; however, there is no relationship in the indicator computation. The KBDI was developed to detect forest-fire potential. Groundwater is a trigger used to detect longer-term hydrologic droughts.

Local Drought Indicator Results

Table 3 shows the inconsistencies in the percent frequency of occurrence between Duke’s LIP indicators for the period 2000-2008. Duke began voluntarily following the LIP in 2006, but to extend the period of analysis the dataset was expanded to 2000. The storage indicator never reached Stage 4 and only one percent of the time reached Stage 3. Whereas, streamflow reached Stage 4, 15.5 percent, and Stage 3, 19.6 percent. The DM reached Stage 4, 5.2 percent, and Stage 3, 14.4 percent of

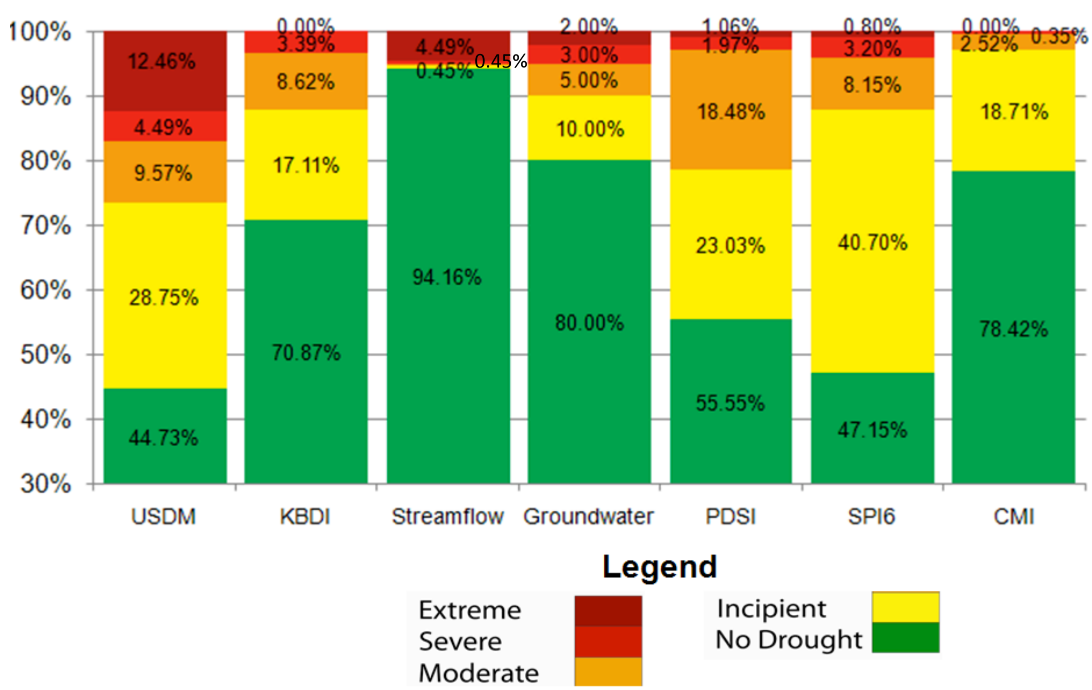

Figure 1. Frequency of drought class severity measured by different State indices, Florence County.

the time. The difference in percent occurrence between the indicators for Stage 1 is less. The 4.1 percent occurrence of Stage 0 drought by streamflow is inconsistent with the other indicators and can, in part, be attributed to the smaller range of possible values defined in the LIP. The fewer occurrences of drought in general, and especially the lower occurrences of the higher drought levels by the storage indicator, are consistent with Duke's planning. According to their LIP, after Stage 0 the storage indicator must reach a higher level before the official stage is upgraded. Streamflow and the DM cannot trigger an upgrade beyond Stage 0 without confirmation by the storage indicator that the level of drought has increased. The higher frequencies of streamflow and DM, however, do impact the stages during recovery. Groundwater levels are also considered during recovery and all gages must return to a lower stage to downgrade.

Table 3. Percent frequency of drought for Duke's LIP indicators, April 2000 – April 2008

Drought Level	Storage	Streamflow	DM
	4/00-4/08		
Stage 4	0.00 %	15.5 %	5.2 %
Stage 3	1.0 %	19.6 %	14.4 %
Stage 2	7.3 %	10.3 %	16.5 %
Stage 1	15.5 %	10.3 %	15.5 %
Stage 0	21.6 %	4.1 %	16.5 %
No Drought	54.6 %	40.1 %	31.9 %

Due to the streamflow, DM, and groundwater, the official LIP operated under a Stage 3 declaration from October 2007 until February 2009. The storage indicator returned to normal elevation in February 2008. This caused concern by some water users in the basin since Stage 3 requires mandatory water restrictions. The complaint was that the lakes had been at normal elevation for many months making it difficult to justify the Stage 3 water restrictions. The indicator analysis shows that the 6-month streamflow, DM, and groundwater held the declaration at Stage 3.

The chi-square test was used to estimate the independence of the Duke LIP drought indicators categorized by drought occurrence (Stage 2-Stage 4, Stage 1, Stage 0, and No Drought). The null hypothesis was rejected between all the indicators indicating there are statistically significant differences between the storage index, streamflow, and the DM.

Conclusions

The backbone of the drought planning process is the identification of drought indicators that link the drought conditions to the responses. Determining the drought indicators and triggers, however, is no easy task given the complexity of drought. This research enhanced South Carolina's drought response by evaluating the spatial and temporal distribution of drought intensity and frequency as indicated by South Carolina's state indicators and the recently defined FERC Low Inflow Protocol (LIP) indicators for the Catawba-Wateree basin.

The analysis identified significant discrepancies between the state indicators detection of drought. Several state indicators suggest South Carolina is in some level of drought 40 to 50 percent of the time while others show drought impacting the state only 20 percent of the time. Based on the streamflow triggers, the state's streams are in drought generally less than 10 percent of the time. The inconsistencies among many of the indicators can be attributed to the inconsistencies in the drought level ranges defined by the S.C. Drought Response Act's regulations. These inconsistencies create confusion for the S.C. Drought Response Committee and S.C. water users. The S.C. Drought Response Committee should consider revising the trigger levels. The research confirmed recommendations by Steinemann (2005) that transforming indicators to percentiles is a viable solution for using multiple and often statistically inconsistent indicators. The triggers could be based on percentiles rather than raw indicator values. The decision maker can relate triggers to the concept of return periods or probabilities of occurrence and the trigger values associated with each drought level would be consistent.

The evolution and implementation of the drought plans or LIP in the Catawba-Wateree FERC license demonstrated the need for additional research on drought indicator validation. The LIPs were new to the relicensing process and the identification of drought indicators and trigger points presented challenges to the licensee (Duke Energy) and the stakeholders. This research shows discrepancies between the LIP indicators especially during the drought recovery phase since the LIP can not be downgraded until all indicators reflect a lower drought stage. Suggestions based on this research include shortening the 6-month streamflow average and revising the DM to better reflect an average designation rather than the highest in the basin. Remove groundwater as an official indicator until additional gages are added and further data analysis conducted. Since the storage elevation is a key indicator for determining water availability in the LIP river basin, adding a recovery condition based solely on storage should be investigated. The recovery from the LIP should consider both a slow recovery where all indicators must reach a lower level before the stage is lowered to a more rapid recovery that accounts for the storage recovering to a certain elevation for a user-determined time period. Stakeholders and system operators in the Yadkin-Pee Dee Basin confirm that the two additional recovery criteria based on storage in Alcoa/Progress Energy's LIP provided a more accurate representation of the drought's true impact on their system and compensated for the inconsistency in their other indicators.

These suggested changes should primarily meet the Catawba Wateree Drought Management Group's criteria for changing the LIP indicators by better reflecting the hydrologic conditions in the basin, more closely aligning the public's perception of drought to the true hydrologic conditions while keeping the indicator calculations relatively simple and conservatively maintaining storage. Duke has decided to evaluate similar changes to the LIP based on recommendation from the Catawba Wateree Drought Management Group. Even though there has been concern over the indicators, the drought response in the basin should be used as a model for building consensus among drought plans. Numerous water systems, agencies and stakeholders from two states, and the power company worked together to develop a drought plan that has been implemented and enforced by the majority of the water systems in the basin. The protocol includes a mechanism for making future enhancements and the overall basin-wide drought response has been successful.

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