

# Developing Multiple Indicators and Triggers for Drought Plans

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**Abstract:** Drought plans depend on indicators and triggers to characterize drought conditions and guide drought responses. Yet indicators and triggers often suffer from deficiencies, such as temporal and spatial inconsistency, statistical incomparability, and operational indeterminacy. Further, even though indicators and triggers are vital to drought hazard reduction, they are often selected and used arbitrarily, undermining the potential value of drought plans. Addressing these concerns, this paper provides a process and analytic methods for the development, analysis, and evaluation of indicators and triggers. In addition, this paper details their application to Georgia's first state drought plan. Results are transferable to other drought plans, offering scientific justification, operational relevancy, and guidance for drought mitigation and response.

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## Introduction

Drought is a creeping and costly disaster. It develops insidiously, and can inflict billions of dollars of damage throughout the United States in a single drought year (NOAA 2004). Even though the literature offers more than 150 definitions of drought (Wilhite and Glantz 1985), a consistent theme emerges: drought occurs when supplies cannot meet demands. Another theme is that a sound drought plan can reduce drought losses.

To improve drought mitigation and response, water agencies across the United States have been developing and using drought plans. The effectiveness of a drought plan depends on its indicators and triggers. Indicators are variables for characterizing drought conditions, and triggers are specific values of indicators for activating drought responses.

Despite their importance, indicators and triggers are chronically weak parts of drought plans, often lacking scientific justification and operational relevancy. Further, virtually no prior work exists on methodologies for developing and using multiple indicators and triggers. Instead, indicators and triggers are often chosen and combined in an ad hoc way, which can compromise the validity and value of a drought plan. In addition to questionable methods, the question of evaluation remains. For instance, how is it possible to determine which types and combinations of indicators and triggers are "best?"

This paper addresses these questions and needs, providing an overall process and specific methodologies for developing indicators and triggers, for implementing them in a drought plan, and for evaluating their effectiveness. This process was applied over a 4 year period (2000–2003) to the development of the first State Drought Plan for Georgia, and involved more than 100 stakeholders across the state and expert panels. This research and application provides contributions in three main areas: a generalizable approach for developing multiple indicators and triggers; a set of analytic methods for implementing them in operational drought planning; and empirical results from evaluating their performance.

## Criteria for Multiple Indicators and Triggers in Drought Plans

Drought plans are documents that guide decision making before, during, and after a drought. They typically contain the following components: drought categories, drought indicators, drought triggers, and drought responses (AWWA 1992; Shepherd 1998).

Briefly defined, indicators are variables to characterize the magnitude, duration, severity, and spatial extent of drought. Indicators are typically based on hydrologic, meteorologic, or water supply and demand variables, such as streamflow, soil moisture, precipitation, snowpack, groundwater levels, and reservoir storage. Drought triggers, which are threshold values of indicators, determine the timing and level of drought responses associated with drought categories. Drought categories, or levels, typically use nomenclature such as "mild, moderate, severe, extreme drought," or "level 1, level 2, level 3 drought." Drought responses include both strategic longer-term actions, usually implemented before a drought (such as water pricing policies), and tactical shorter-term actions, usually implemented during a drought (such as water use restrictions). Thus, together, indicators and triggers form the linchpin of a drought plan, linking drought conditions with drought responses.

A systematic review of all state drought plans and interviews with drought officials, conducted by the writers, led to the iden-

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tification of criteria that are important for indicators and triggers in a drought plan (Steinemann et al. 2005). The criteria emerged from recognition of both strengths and limitations in existing plans. Accordingly, criteria and considerations for indicators and triggers are discussed below.

### Temporal and Spatial Consistency

Indicators and triggers need to reflect both temporal and spatial variability. For instance, “monthly total precipitation of 5 cm” could imply dry conditions in early spring but wet conditions in late summer; dry conditions for a mountainous area but wet conditions for a desert area. This problem also appears in standard drought indicators. For example, the category of “extreme drought” for the Palmer Drought Severity Index (PDSI) refers to values  $\leq -4.00$  (Palmer 1965; Karl 1986). Yet this category has varying probability of occurrences, depending on time and location; for instance, less than 1% in January in the Pacific Northwest, and more than 10% in July in the Midwest (Karl et al. 1987; Guttman et al. 1992).

### Temporal and Spatial Specificity

Indicators and triggers also need to specify their temporal and spatial scales, along with their actual values. Yet indicators and triggers in drought plans are often vague, such as simply an indicator of “precipitation” or a trigger of “below 25th percentile.” Instead, consider an example of fully specified indicator/trigger: “SPI-6 less than  $-1.5$  for two consecutive months in Climate Division 1 would invoke Level 2 drought in Counties A, B, and C.” (The indicator SPI-6, 6 month Standardized Precipitation Index represents the precipitation anomaly for a prior 6 month period.) Here, the temporal scale for the indicator is the prior 6 months, the spatial scale for the indicator is Climate Division 1, the trigger value is  $-1.5$ , the temporal scale for the trigger is 2 consecutive months, and the spatial scale for the trigger responses is Counties A, B, and C.

### Statistical Consistency among Triggers

A common problem is that triggers are not statistically consistent with each other nor with the drought categories they represent. As an example, consider drought categories of “mild, moderate, severe, extreme” with probabilities of occurrence of 35, 20, 10, and 5%, respectively. Now consider precipitation triggers of 4, 3, 2, and 1 cm for each of those four drought categories. Those precipitation values may have little statistical relevance to those categories; that is, a monthly precipitation value of 4 cm may not have a probability of occurrence of 35%. Moreover, the value of 4 cm could have varying probabilities of occurrence depending on time and location.

These inconsistencies are compounded with multiple indicators. Continuing the example, suppose precipitation triggers of 4, 3, 2, and 1 cm were used together with reservoir level triggers of 100, 90, 80, and 70 m for each of the four drought categories, respectively. The precipitation and reservoir triggers associated with each category may differ in frequency, which could confuse management responses. Moreover, their frequencies may be inconsistent with the drought categories themselves. For instance, the frequencies of precipitation of 4 cm and reservoir level of 100 m might differ from each other, and from the “mild drought” frequency of 35%, especially over all time periods and regions.

**Table 1.** Incomparability among Some Standard Drought Indicators

Drought indicator	Indicator values	Drought category	Cumulative frequency (%)
SPI	0 to $-0.99$	Mild	16–50
	$-1.00$ to $-1.49$	Moderate	6.8–15.9
	$-1.50$ to $-1.99$	Severe	2.3–6.7
	$-2.00$ or less	Extreme	$<2.3$
PDSI	0.00 to $-1.49$	Near normal	28–50
	$-1.50$ to $-2.99$	Mild–moderate	11–27
	$-3.00$ to $-3.99$	Severe	5–10
	$-4.00$ or less	Extreme	$\leq 4$
SWSI	$-2.00$ to 0.00	Mild	26–50
	$-3.00$ to $-2.00$	Moderate	14–26
	$-4.00$ to $-3.00$	Severe	2–14
	below $-4.00$	Extreme	$<2$

Note: SPI=Standardized Precipitation Index; PDSI=Palmer Drought Severity Index; and SWSI=Surface Water Supply Index.

### Statistical Consistency among Categories

Drought categories for standard indicators also lack statistical consistency (see Table 1). For instance, the category of extreme drought occurs less than 4% of the time for the Palmer Drought Severity Index, considering all months and climate divisions in the United States (Karl 1986). But extreme drought occurs less than 2.3% of the time for the Standardized Precipitation Index (SPI) (McKee et al. 1993), and less than 2% of the time for the Surface Water Supply Index (SWSI) (Garen 1993). The indicator values themselves are also incomparable: A value of  $-1.5$  corresponds to a probability of occurrence of 27% on the PDSI scale, 6.7% on the SPI scale, and 32% on the SWSI scale.

Even when indicator scales are statistically consistent, their values and relationships to drought categories may be difficult to interpret. For instance, a PDSI value of  $-1.5$  may have little intuitive or hydrologic meaning to decision makers. Moreover, a given indicator increment may not correspond to a given probability increment. For example, the values of the Standardized Precipitation Index are based on the statistical Z score, implying that a value of  $-1.5$  represents the same probability of occurrence (6.7%), regardless of location or time. But the indicator has different probability differentials for equal index differentials. For instance, the probability differential between an SPI of  $-1.0$  and  $-1.5$  is 9.1% (defining moderate drought), and between an SPI of  $-1.5$  and  $-2.0$  is 4.4% (defining extreme drought), even though both categories represent an index differential of 0.5. The point is that indicator scales should be easy to understand, justify, and use.

### Drought Progressing and Drought Receding

Drought categories and responses are invoked as drought progresses and revoked as drought recedes. Thus, triggers should specify conditions both for getting into and getting out of a drought, and at each level of a drought plan. Further, the triggers for drought progressing and receding can be different, depending on management goals. For instance, a water agency may want to implement water use restrictions as soon as drought conditions start developing, but wait to lift restrictions until conditions have definitively recovered.

## Systematic Approach for Combining Indicators and Triggers

Because drought has many definitions, multiple indicators and triggers can be useful for representing drought conditions. The process of combining indicators and triggers can be considered in two ways.

The first is when several indicators are synthesized into one overall indicator. For instance, the SWSI combines information on precipitation, snowpack, streamflows, and reservoir storage. Although an overall indicator may provide ease of implementation, its scientific bases can be tenuous, such as the rationale for weights ascribed to the individual indicators in the overall indicator.

The second is when several indicators are used for operational drought management. For instance, suppose that a drought plan is based on three indicators/triggers: reservoir storage, precipitation, and streamflow. The question becomes: When is a drought level implemented? Is it when one of the three triggers are met, two of the three, or all three? Is it the most severe condition of the triggers, or a majority of the triggers? Or is there some other process? Thus, a problem arises because multiple indicators and triggers are often specified in a drought plan, but without a systematic method for combining, using, and evaluating them.

## Developing, Analyzing, and Evaluating Indicators and Triggers

This section details the process and methods for designing indicators and triggers, and their application to the first drought management plan for the state of Georgia. The state recently emerged from one of the most severe droughts on record (1998–2002), prompting increased concern about growing demands for limited supplies. Prior to this study, the state's approach to drought planning was to require local utilities to develop drought plans as part of their water withdrawal permit application. Yet an evaluation of these local plans (Shepherd 1998) found that most had technical and methodological deficiencies that limited their effectiveness. For instance, most plans lacked consistent drought levels and triggers for drought responses.

Recognizing the limitations of these local plans, and the need for a more comprehensive and rigorous approach, the state embarked on the development of a statewide drought plan, directed by the lead writer, and involving a group of state and local water officials and agency representatives (called the Georgia Drought Planning Committee or "Committee"), and more than 100 stakeholders in the state. The writers developed the indicators and triggers for the plan, through an interactive and iterative process, as detailed in the following section. This section will provide both the general methods and the specific application.

### Indicator and Trigger Development, Analysis, and Evaluation Process

Development of indicator and triggers:

1. Define scale and scope of analysis;
2. Develop drought indicators;
3. Establish drought plan levels and triggering scale; and
4. Develop triggering objectives.

Analysis of indicators and triggers:

5. Transform indicators to triggering scale and levels;
6. Calculate multiperiod indicators;

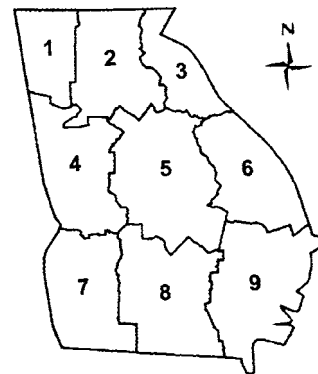


Fig. 1. Georgia's climate divisions

7. Calculate individual and multiple triggering sequences; and
8. Calculate final drought sequences.

Evaluation of indicators and triggers:

9. Elicit expert assessments;
10. Compare final drought sequences with expert assessments;
11. Refine final drought sequences and iterate evaluation process; and
12. Select final indicators and triggers for drought plan.

### Define Scale and Scope of Analysis

One of the first decisions was to determine the scale of analysis for evaluating drought in the state. Several alternatives were investigated: climate divisions (CDs), river basins, political jurisdictions (such as counties), or critical water use regions within the state (such as the Atlanta region). The Committee decided to evaluate drought according to its nine climate divisions (Fig. 1). Primary reasons were the availability of geophysical data according to CD, and the correspondence between CDs and critical drought regions in the state. For instance, the Atlanta region (major urban area reliant on surface water) was represented by Georgia CDs 2 and 4; the Flint River Basin (major agricultural area reliant on groundwater) was represented by Georgia CDs 4 and 7.

### Develop Drought Indicators

Another fundamental decision concerned the indicators to characterize drought conditions in the state. In a first phase, through a series of large group meetings, the stakeholders in the drought planning process generated a list of more than 100 candidate indicators, then narrowed that list to about 50 indicators, representing the various water uses (municipal, industrial, energy, tourism, recreation, agriculture, water quality, flora, and fauna). Then, through several meetings, the Committee refined and narrowed the list of indicators to four key variables: precipitation, groundwater, reservoir storage, and streamflows.

In this process, the Committee considered the extent to which the indicator represented critical impacts, primary drought vulnerabilities, water supplies and demands, and types of drought affecting the area. Also considered were the availability, historic record, and validity of data for the indicator. Indicators were eliminated, for a certain region, if they did not meet these criteria. For instance, the PDSI was deemed unsuitable as an indicator for managed water systems because it omits reservoir storage. Reservoir storage, in turn, was deemed unsuitable as an indicator for agricultural areas that rely primarily on ground water for irrigation. In

**Table 2.** Drought Plan Levels According to Percentile Thresholds

Drought level	Percentile range (%)
0	0.35–0.50
1	0.20–0.35
2	0.10–0.20
3	0.05–0.10
4	0.00–0.05

other words, different indicators were used for representing different types of drought conditions in different parts of the state.

For the final indicators, the Committee developed a list of four precipitation indicators (SPI-3, 6, 9, 12), 13 (unregulated) streamflows, four reservoirs, and 11 groundwater wells. These indicators were used to represent drought conditions according to climate division. This means, for instance, that 36 precipitation indicators were initially developed, one for each of the nine Climate Divisions and the four SPIs. In the end, not all indicators would be used for all CDs, but a full set was developed for the purposes of analysis and evaluation.

### **Establish Drought Plan Levels and Triggering Scale**

Drought plan levels were established on the basis of percentiles representing probabilities of occurrence. This framework based on percentiles offers a consistent basis for associating triggers with drought levels, and for comparing and combining multiple indicators and triggers (Steinemann 2003). Also, the state found the percentile approach to be quantitatively and intuitively appealing, and straightforward to implement. Another approach would have been acceptable, such as drought plan levels based on impacts. That approach would recognize that, for instance, a 35th percentile of streamflow could cause different impacts, depending on the resource. However, in this case, trying to associate levels with an explicit assessment of impacts proved to be analytically intractable. Instead, the state considered impacts through the selection of indicators (representing vulnerable areas and sectors) and the selection of triggers (representing management responses to mitigate impacts), as discussed later in the paper.

The levels of drought were defined according to threshold probabilities,  $\tau_k$  ( $k=1, \dots, s$ ), that represent cumulative probabilities,  $F(x_k)$ , of a particular drought indicator variable, such that

$$\tau_k = F(x_k) = \Pr\{X \leq x_k\} \quad (1)$$

where  $X$ =random value of the drought indicator;  $s$ =number of categories; and  $x_k$ =value of the drought indicator corresponding to the threshold probability for category  $k$ . The upper bound of a category is established by  $\tau_k$ , and the lower bound by  $\tau_{k-1}$ .

These threshold probabilities were used to define trigger values, as determined by the Committee, for the categories of an indicator. The state of Georgia drought plan used four categories

$$\{\tau_1, \dots, \tau_4\} = \{0.35, 0.20, 0.10, 0.05\} \quad (2)$$

Here, drought level increases with increasing values of  $k$ , with  $k=1, 2, 3, 4$ , representing mild, moderate, severe, and extreme drought, respectively. Indicator data are then transformed to a scale based on percentiles, with each trigger corresponding to the particular drought level as defined by threshold probabilities (see Table 2).

### **Develop Triggering Objectives**

Drought indicators vary according to their frequency, duration, persistence, and transition among drought levels (Steinemann 2003). For instance, some indicators may reflect shorter-term anomalies and provide early warnings of drought, yet be more susceptible to false alarms and more oscillatory among drought levels. Other indicators may reflect longer-term anomalies and provide more stable and persistent assessments of drought, yet be slower to detect developing drought conditions. Thus, decisions needed to be made about the desired behavior of indicators and triggers, which would affect how and when drought responses would be invoked. Accordingly, the Committee developed performance objectives for indicators and triggers.

For drought progressing (going into a drought), indicators needed to be able to provide advance warning while minimizing false alarms; that is, to be able to detect incipient drought conditions yet provide some assurance that drought conditions were progressing (becoming more severe) before implementing restrictions.

For drought receding (getting out of a drought), indicators needed to be conservative (assuming more severe drought conditions) while avoiding prolonged restrictions; that is, to be able to provide assurance that drought conditions were receding (becoming less severe), and recovering long term, before lifting restrictions or rescinding responses.

For during a drought, indicators needed to provide stability and smooth transitions among drought levels; that is, to remain in a certain drought level without frequent jumping between and over different drought levels in the middle of a drought.

Overall, drought indicators needed to provide ease of calculation, understanding, and implementation. The triggers needed to assist decision making and provide scientific justification for invoking or revoking a certain level of the drought plan. Yet decision makers retained the final authority on the drought level and responses to declare.

### **Transform Indicators to Triggering Scale and Levels**

The next step was to develop a triggering system that would provide a statistically consistent framework for combining, comparing, and evaluating multiple indicators. To accomplish this, all indicators were converted to a scale based on percentiles. Then, drought levels were associated with different percentile thresholds. Other approaches could have been used, such as relating triggers to impacts rather than percentiles. In the end, the percentile approach was selected because of ease of implementation (and difficulties determining quantitative links between triggers and impacts mitigated), and because the indicators were already being monitored and evaluated according to frequencies, so the triggering framework was consistent with current operations. Also, as a national example, the U.S. drought monitor (Hayes et al. 2005) uses indicators based on percentiles.

For precipitation, the SPI-3, 6, 9 and 12 were used as indicators. The SPI is a standardized anomaly, equivalent to the statistical Z score, representing the precipitation deficit for a specific time scale, such as 3, 6, 9, or 12 months, relative to climatology (McKee et al. 1993). The SPI values were calculated by fitting a gamma distribution to a long-term record of precipitation (107 years, 1895–2001) provided by the Western Regional Climatic Center. From there, using an equiprobability transformation (Panofsky and Brier 1958), the percentile on the gamma

distribution was linked to the percentile on the standard cumulative normal distribution. The percentiles on the standard normal distribution correspond to the statistical Z score, which is the SPI value.

For streamflows, long-term records of monthly mean unregulated streamflows, provided by the U.S. Geological Survey (USGS), were converted to a scale based on percentiles by developing empirical cumulative distribution functions (ECDFs). In this approach for ECDFs, historical monthly mean data for each streamflow gauge were stratified by month. Then, the data within the 12 sets of long-term records, one set for each month, were ranked from the lowest flow to the highest flow. Estimators of the percentiles,  $p(x)$ , were then calculated according to ranking algorithm

$$p(x) = i/(n + 1) \quad (3)$$

where  $x$ =data value;  $x_i$  ( $i=1, \dots, n$ );  $i$ =rank of the order statistic; and  $n$ =number of data values.

For reservoirs, the long-term records of monthly mean reservoir levels were also stratified according to month. Then for each reservoir, each month's record was converted to percentiles by developing ECDFs, in a similar approach as for streamflows. For groundwater, percentiles were calculated from probability of exceedance (POE) data, which provide the monthly value exceeded  $p\%$  of the time, at 5% intervals for monthly means for each well. POE data were used because they were detrended and recommended by the U.S. Geological Survey for calculating the indicators. The POE data were then compared with the monthly mean data for each well in order to calculate, through interpolation and extrapolation, percentile levels for each month for each well. The drought trigger level for the groundwater wells was based on a majority criterion; the level affecting at least five out of nine wells.

Drought indicator data were obtained from several sources, including the U.S. Army Corps of Engineers, the U.S. Geological Survey, the Western Regional Climatic Center, and the National Center for Data Collection. The data were processed by the writers, and used by the Georgia Environmental Protection Division for monitoring and plan implementation.

With drought indicator data transformed to percentiles, triggers were determined, where each monthly datum corresponds to a specific percentile and drought level (Levels 0, 1, 2, 3, and 4) for each month (Table 2).

### Calculate Multiperiod Indicators

In this next step, indicators based on single time periods were converted to indicators for multiple and sequential time periods, herein called "multiperiod indicators." The multiperiod indicators were important to meet performance objectives: to provide more stable and less oscillatory drought triggers, especially in the middle of a drought, to minimize possible false alarms, and to reduce the risk of missing a lagged or persistent drought signal.

Multiperiod indicators were calculated for consecutive indicator periods, with each period 1 month ahead of the previous period, and with nomenclature as follows: indicator name (such as "SPI-6"), number of sequential indicator periods (such as 1, 2, 3, or 4, in parentheses), drought level (least severe among the indicator periods for drought progressing, and most severe among the indicator periods for drought receding), and the month associated with the last indicator period.

**Table 3. Drought Levels Associated with SPI-3 and SPI-6 for One, Two, Three, and Four Consecutive Periods for Georgia's Climate Division 3**

CD	June 1998	July 1998	August 1998	September 1998	October 1998	November 1998	December 1998	January 1999	February 1999	March 1999	April 1999	May 1999	June 1999	July 1999	August 1999	September 1999	October 1999	November 1999	December 1999	January 2000	February 2000	March 2000	April 2000	May 2000	June 2000	July 2000	August 2000	September 2000	October 2000	November 2000	December 2000				
SPI-3(1)	—	2	3	3	1	0	1	0	1	2	2	2	2	—	0	3	—	—	—	—	0	2	1	2	2	3	4	1	0	1	0	2			
SPI-3(2)	—	—	2	3	1	1	1	1	1	1	2	2	2	0	0	0	0	—	—	—	0	0	1	1	2	2	3	3	1	1	1	1	1		
SPI-3(3)	—	—	—	2	2	1	1	1	1	1	1	2	2	2	0	0	0	—	—	—	—	—	0	1	1	2	2	2	1	1	1	1	1	1	
SPI-3(4)	—	—	—	—	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	2	2	2	2	1	1	1	1	
SPI-6(1)	—	—	—	0	2	3	3	1	1	2	2	2	1	2	2	1	—	—	—	—	0	0	0	2	3	3	4	3	2	4	1	1	2	2	
SPI-6(2)	—	—	—	—	0	2	3	3	1	1	2	2	2	2	2	2	1	—	—	—	0	0	0	0	2	3	3	3	3	3	3	3	3	3	2
SPI-6(3)	—	—	—	—	—	0	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	0	0	0	2	3	3	3	3	3	3	3	3	3
SPI-6(4)	—	—	—	—	—	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	3	3	3	3	3	3	3

For instance, referring to Table 3, the multiperiod indicator “SPI-6(2)—Level 1—March 1999” means that the SPI-6 was in Level 1 or more severe (for drought progressing) for two sequential 6 month time periods (ending with February 1999 and March 1999). Similarly, “SPI-6(2)—Level 2—September 1999” means that the SPI-6 was in Level 2 drought or less severe (for drought receding) for two sequential 6 month time periods (ending with August 1999 and September 1999).

The multiperiod indicators were calculated according to the following equations:

IF  $\{D_{(1)i}, D_{(1)i-1}, \dots, D_{(1)i-(n-1)}\} \geq D_{(n)i-1}$ , going to an equal or more severe drought level from  $D_{(n)i-1}$  to  $D_{(n)i}$ , then

$$D_{(n)i} = \text{least value among } \{D_{(1)i}, D_{(1)i-1}, \dots, D_{(1)i-(n-1)}\} \quad (4)$$

IF  $\{D_{(1)i}, D_{(1)i-1}, \dots, D_{(1)i-(n-1)}\} \leq D_{(n)i-1}$ , going to an equal or less severe drought level from  $D_{(n)i-1}$  to  $D_{(n)i}$ , then

$$D_{(n)i} = \text{greatest value among } \{D_{(1)i}, D_{(1)i-1}, \dots, D_{(1)i-(n-1)}\} \quad (5)$$

IF at least one among  $\{D_{(1)i}, D_{(1)i-1}, \dots, D_{(1)i-(n-1)}\} \geq D_{(n)i-1}$  and at least one among  $\{D_{(1)i}, D_{(1)i-1}, \dots, D_{(1)i-(n-1)}\} \leq D_{(n)i-1}$ , going from  $D_{(n)i-1}$  to  $D_{(n)i}$ , then

$$D_{(n)i} = D_{(n)i-1} \quad (6)$$

where  $D$ =drought level of the indicator;  $n$ =number of indicator time periods; and  $i$ =current indicator period analyzed.

Multiperiod indicators were calculated for precipitation, streamflows, reservoir levels, and groundwater indicators, and for one, two, three, and four consecutive indicator periods. More consecutive periods could have been examined; however, the Committee felt that four would be more than sufficient to dampen month-to-month oscillations in drought levels. The precipitation indicator (the SPI) had four indicators associated with each month, corresponding to SPI-3, SPI-6, SPI-9, and SPI-12, and then four multiperiod indicators associated with each one of those four monthly indicators, resulting in 16 SPI indicators for each month. Note that there is a distinction between the number of months for each single-period SPI indicator (3, 6, 9, and 12 month anomalies) and the number of sequences for each multiperiod SPI indicator (one, two, three, and four sequences). For instance, the single-period “SPI-3, March 1999” means that 3 consecutive months of data (January, February, and March 1999) were used to calculate the indicator. The multiperiod “SPI-3(2), March 1999” represents the SPI-3 for February 1999 and the SPI-3 for March 1999. Also note that the SPI-3(2) is not equivalent to the SPI-6(1), and so forth. The SPI-6(1) for March 1999 would be the level associated with the 6 month precipitation anomaly, with March 1999 as the last month, whereas the SPI-3(2) for March 1999 would be the multiperiod indicator just described. This can be shown in Table 3, which represents the SPI-3 and SPI-6 for 1, 2, 3, and 4 consecutive months for CD 3. We now examine how drought levels can be calculated using multiperiod triggers.

First, consider the case in which drought progresses. Refer to Table 3 and note the value of SPI-6(4) from December 1998 (Level 0) to January 1999 (Level 1). In this case, the levels of SPI-6(1) for January 1999, December 1998, November 1998, and October 1998 (SPI-6(1) are greater than the SPI-6(4) level for December 1998. So SPI-6(4) for January 1999 is the least among those four SPI-6(1) levels, which is Level 1.

Next, consider the case in which drought recedes. Refer again to Table 3 and note the value of SPI-6(2) from January 1999 (Level 3) to February 1999 (Level 1). In this case, levels of SPI-6(1) for February 1999 (Level 1) and January 1999 (Level 1) are less than the SPI-6(2) level for January 1999 (Level 3). So SPI-6(2) for February 1999 is the greatest among those two SPI-6(1) levels, which is Level 1.

Finally, consider the case in which drought may be neither progressing nor receding. From Table 3, note the value of SPI-6(4) from October 2000 (Level 3) to November 2000 (Level 3). In this case, levels of the SPI-6(1) for November 2000, October 2000, September 2000, and August 2000 are both greater than and less than the SPI-6(4) level for October 2000, which is Level 3. Therefore, the level of SPI-6(4) for November 2000 is maintained at Level 3.

### Calculate Individual and Multiple Triggering Sequences

For each CD, the set of indicators and their associated multiperiod indicators enabled the generation of “triggering sequences.” A triggering sequence represents the drought level that would have been associated with each indicator for each month. Using CD 3 as an example, Table 3 presents some multiperiod indicators and their triggering sequences, and Table 4 presents all the indicators and their associated triggering sequences. A blank cell means that the value of the indicator was above the 50th percentile, so it was not considered a drought level. More than 500 individual and multiple triggering sequences (for all CDs in Georgia) were developed in this process. These triggering sequences were then combined to generate “final drought sequences” as detailed in the next section.

### Calculate Final Drought Sequences

A central analytic challenge was the development and evaluation of alternative processes for combining multiple trigger sequences into a single, final drought sequence on which to make decisions. The goal was to develop a systematic and scientifically justifiable approach for determining the final drought level among sets of combinations of individual indicator levels of precipitation, streamflows, reservoirs, and groundwater.

To accomplish this, the triggering sequences were combined and evaluated according to three methodologies: (1) most severe drought level (MSDL); (2) majority of drought levels (MODL); (3) IN triggers and OUT triggers (IN/OUT).

#### Most Severe Drought Level

For the MSDL approach, the final drought level was based on the most severe condition for each month among a set of indicators. The MSDL calculation is as follows

$$D_i = \text{greatest value among } \{I_{i1}, I_{i2}, I_{i3}, \dots, I_{in}\} \quad (7)$$

where  $D$ =final drought level;  $I$ =indicator drought level, with the number of indicators ranging from 1 to  $n$ ; and  $i$ =month analyzed.

As an example, assume that the Georgia’s CD 3 is being evaluated according to the MSDL approach (refer to Table 4). The final drought level for March 1999 would be Level 4 because it was the most severe level among the indicators (SPI-9, in this case).

#### Majority of Drought Levels

The MODL is the drought level at which 50% or more of the indicators are equally or more severe. In this application, the

**Table 4. Triggering Sequences for Georgia's Climate Division 3**

Indicators CD 3	June 1998	July 1998	August 1998	September 1998	October 1998	November 1998	December 1998	January 1999	February 1999	March 1999	April 1999	May 1999	June 1999	July 1999	August 1999	September 1999	October 1999	November 1999	December 1999	January 2000	February 2000
SPI-3	—	2	3	3	1	0	1	0	1	2	2	2	—	0	0	3	—	—	—	0	2
SPI-6	—	—	0	0	2	3	3	1	1	2	2	2	1	2	2	1	—	—	1	0	0
SPI-9	—	—	—	—	—	1	1	2	3	4	3	2	1	2	2	2	1	1	1	0	1
SPI-12	—	—	—	—	—	—	—	—	1	2	3	4	3	2	2	2	1	1	1	1	2
Lake Hartwell	—	0	0	0	0	1	0	0	0	1	2	2	1	1	2	1	1	1	1	1	2
Clark Hill Lake	—	—	—	—	—	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1
Broad River near Bell	—	—	—	0	—	0	1	1	—	3	1	2	1	1	3	3	0	1	2	1	2
Chattahoochee River near Cornelia	—	1	1	2	2	2	2	1	0	2	2	2	2	1	4	4	—	0	1	1	3

drought levels under comparison represented each group of indicators (such as precipitation), instead of the individual indicators themselves (such as the SPI-6). Each indicator group was given the same weight in the analysis, although the evaluation could also be performed with weights ascribed to each group or each individual indicator in the grouping.

The MODL calculation is as follows

$$D_i = \text{drought level at which 50 \% or more of the indicator group levels}\{G_{pi}, G_{si}, G_{gi}, G_{ri}\} \text{ are equally or more severe than the level associated with month } i \tag{8}$$

where  $D$ =final drought level;  $G$ =indicator group analyzed;  $p, s, g, r$ , respectively=precipitation, streamflow, groundwater, and reservoirs; and  $i$ =month analyzed.

The MODL was calculated in two ways: (1) using the MODL to determine the drought level within each group and (2) using the MSDL to determine the drought level within each group. Then, MODL was used for the final drought level among the groups. Refer to Table 4, for March 1999. For (1), the MODL within each group, for precipitation, reservoirs, and streamflows, is Level 2, Level 1, and Level 2, respectively. (For instance, precipitation is Level 2 because three out of four indicators were as severe as or more severe than Level 2.) Then, the MODL among the groups is Level 2. For (2), the MSDL within each group, for precipitation, reservoirs, and streamflows, is Level 4, Level 1, and Level 3, respectively. Then, the MODL among the groups is Level 3.

**IN Triggers and OUT Triggers**

The IN/OUT methodology considers both triggers IN (drought progressing) and triggers OUT (drought receding). The IN trigger is used to move from a less severe to a more severe drought level. The OUT trigger is used to move from a more severe level to a less severe level. Given triggering goals presented earlier, the criteria for IN and OUT triggers differ: IN seeks early action in invoking drought restrictions, whereas OUT seeks more conservative (later) action in revoking drought restrictions. For this case, the state developed the following criteria:

For IN: when any one of the triggers for any one of the CDs is at a more severe level for at least 2 consecutive months. For OUT: when all of the triggers for that CD are at a less severe level for at least 4 consecutive months. The first OUT trigger would be the IN trigger, followed by all other trigger for that CD. This is because, after testing various algorithms for IN and OUT triggers, it was determined that the first in the sequence of OUT triggers needed to be the same as the IN trigger. Otherwise, the current drought level could be inconsistent—it could prescribe both moving into and out of a particular drought level at the same time. For example, if the SPI-6 were the first to trigger Level 1, then the SPI-6 would be considered as the IN trigger, and it would serve as the first OUT trigger, meaning that the SPI-6 would need to recover by at least one level, then the other triggers would need to recover by at least one level, before revoking that drought level for that CD.

The calculation of IN and OUT triggers is as follows

$$\text{IF } I_i \geq D_{i-1} \text{ then } D_i = I_i \tag{9}$$

$$\text{IF } I_i < D_{i-1} \text{ then } \tag{10}$$

$$D_i = \text{greatest value among } \{O_{(1)i}, O_{(2)i}, \dots, O_{(n)i}\},$$

$$\text{IF } \{O_{(i)i}, O_{(2)i}, \dots, O_{(n)i}\} < D_{i-1}$$

OR

$$D_i = D_{i-1}, \text{ IF at least one among } \{O_{(i)i}, O_{(2)i}, \dots, O_{(n)i}\} \geq D_{i-1}$$

where  $I$ =IN trigger drought level;  $O$ =OUT trigger drought level;  $D$ =final drought level;  $i$ =month; and  $(n)$ =series of OUT triggers (from 1 to  $n$  triggers considered as OUT triggers).

Table 5 provides an example of an IN and OUT trigger calculation. Here, SPI-6 (2) was considered as the IN trigger while OUT triggers would be SPI-6 (2) followed by the rest of the indicators, in any order. In this example, the final drought level for July 2000–November 2000 is Level 3 because drought is progressing and the IN trigger, SPI-6 (2), is at Level 3 or more severe for 2 consecutive months. Then, in December 2000, the IN trigger goes to Level 2; however, the final drought level is governed not only by the IN trigger but also by the OUT triggers, of which five are at Level 2 and two are at Level 3. Therefore, the final drought level is still Level 3 for December 2000.

### Elicit Expert Assessments

More than 500 triggering sequences were developed, through the process detailed above, using different combinations of indicators and different combination methodologies. The next challenge was determining which indicators and triggers were “best,” by judging the performance of the sequences.

To assess this, the following questions were investigated, among others: Which indicators, triggers, and combinations of them, would have produced a drought level (triggering) sequence that would have most appropriately reflected drought conditions in each area and sector? Knowing what we know now, which levels should have declared and when? In other words, what drought level, for each month, each CD, and each sector, would have produced the best overall management and impact mitigation of the drought?

To determine the most suitable indicators, triggers, and combination methodology, a retrospective assessment process was conducted with six individuals who were regarded as experts on state drought conditions during the period 1997–2001. These experts included state water managers, state environmental agency officials, and agricultural, urban, and environmental water managers. Specifically, they were asked to designate the drought level for each month during that period, and for each of four sectors that represented major water users and drought vulnerabilities: large municipal and industrial, small municipal and industrial, agricultural, and environmental.

The experts were asked to conduct this retrospective assessment for each climate division and for the state as a whole. This process resulted in 9,000 drought level assessments, total: one for each month, each of 5 years, each CD (plus the entire state), each sector (small/large municipal and industrial, agricultural, and environmental), from five of the six experts. Note, however, that the number of discrete assessments was reduced considerably because experts often ascribed the same drought level to sets of months, CDs, and sectors. The sixth expert, along with the lead writer, led the process. Each expert was asked to provide an assessment independently, without consulting others or the indicator/trigger sequences, but they could refer to their own notes and data. Then, after each expert provided their assessment, the results were synthesized through a Delphi process, involving

**Table 5. Drought Level Calculation Using IN Trigger and OUT Trigger Methodology (CD-3)**

CD 3	July 1998	August 1998	September 1998	October 1998	November 1998	December 1998	January 1999	February 1999	March 1999	April 1999	May 1999	June 1999	July 1999	August 1999	September 1999	October 1999	November 1999	December 1999	January 2000	February 2000	March 2000	April 2000	May 2000	June 2000	July 2000	August 2000	September 2000	October 2000	November 2000	December 2000										
(a) IN triggers																																								
SPI-6 (2)	—	—	0	0	2	3	3	1	1	2	2	2	2	2	2	2	1	—	—	0	0	0	0	2	3	3	3	3	3	3	3	3	3	3	3	2				
(b) OUT triggers																																								
SPI-6 (2)	—	—	0	0	2	3	3	1	1	2	2	2	2	2	2	2	1	—	—	0	0	0	0	2	3	3	3	3	3	3	3	3	3	3	3	3	2			
SPI-9 (3)	—	—	—	—	—	—	1	1	2	3	3	3	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	2	3	3	3	3	3	3	3	3	3	3		
SPI-12 (4)	—	—	—	—	—	—	—	—	—	—	1	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	
Hartwell (4)	—	—	—	—	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
Clark Hill (4)	—	—	—	—	—	—	—	—	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Broad (4)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Chattahoochee (4)	—	—	—	—	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
(c) Final drought level																																								
—	—	—	0	0	2	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

**Table 6.** Final Indicators Selected for Georgia State Drought Plan

Climate division	Drought indicators			
	SPIs	Reservoirs	Streamflows	Groundwater
1	SPI-3, SPI-6, SPI-12	Lake Allatoona	Chattooga River at Summerville	—
2	SPI-3, SPI-6, SPI-12	Lake Lanier Lake Allatoona	Etowah River at Canton Chattahoochee River near Dahlonega	—
3	SPI-3, SPI-6, SPI-12	Lake Hartwell Clark Hill	Broad River near Bell Chattahoochee River near Cornelia	—
4	SPI-3, SPI-6, SPI-12	—	Flint River at Montezuma	—
5	SPI-3, SPI-6, SPI-12	—	Oconee River at Dublin Ocmulgee River at Macon	2 U.S. Geological Survey wells
6	SPI-3, SPI-6, SPI-12	Lake Hartwell Clark Hill	Ogeechee River near Eden	—
7	SPI-3, SPI-6, SPI-12	—	Spring Creek near Iron City Ichawaynochaway Creek at Milford	9 U.S. Geological Survey wells
8	SPI-3, SPI-6, SPI-12	—	Alapaha River at Statenville	—
9	SPI-3, SPI-6, SPI-12	—	Satilla River at Atkinson	—

iterations to discuss the responses, converging in a consensus that represented the experts' combined knowledge and heuristics. The results of these expert assessments were used in the next step.

### **Compare Final Drought Sequences with Expert Assessments**

The 500+ final drought sequences, developed from the earlier steps, were then compared to experts' retrospective assessments of drought conditions during 1997–2001. Analytic techniques included a bivariate Pearson correlation, and a Delphi process of review with the team of experts. While the broader group of stakeholders was involved in identifying indicators and triggers, the decisions on the final drought sequences were conducted with the Committee designated by the state officials. Through the process of developing and comparing triggers sequences with the retrospective assessment, the Committee identified the most promising indicators and triggers for each CD, narrowing down more than 500 combinations to approximately 100 combinations, as well as the most promising methodologies.

### **Refine Final Drought Sequences and Iterate Evaluation Process**

The process of refining drought sequences and generating new drought sequences involved approximately 10 full iterations (going back to the first phase of the process) and 40 partial iterations (going back to the second phase of the process) with the water managers and other experts, before arriving at the final set of drought triggers. In some cases, the iteration process started back at step one, to develop new drought indicators, such as new wells or streamflow locations (full iteration). In most cases, though, the process started back at step five, to generate new trigger sequences, which were then evaluated by experts and re-refined (partial iteration). After the expert evaluation of triggering sequences, the most promising indicators and their sequences were retained or refined, and new indicators and sequences were developed. Then a set of additional triggering sequences and combinations of them were developed. Experts again evaluated this new set of sequences. From there, the most promising sequences were determined, more were generated, and the process of generating sequences and evaluating them was repeated.

### **Select Final Indicators and Triggers for Drought Plan**

Through this process of generating and evaluating drought indicators and triggers, the final set of indicators was selected for the state drought plan (see Table 6). Findings and lessons include the following:

In the most severe drought level method, once indicator values were calculated for each month, it used the most severe drought level among them as the final drought level. Even though this method was straightforward, it had some drawbacks. First, the MSDL triggering sequences were typically more severe than the experts' evaluations of drought conditions. Second, the final drought condition could depend on the value of just a single indicator for just 1 month, which may not reflect overall conditions. Finally, the MSDL approach exhibited significant oscillation among drought levels, which could present difficulties for implementation and public acceptance.

In the majority of drought levels method, the majority criterion was based on categorical indicators, such as precipitation, groundwater, streamflow, and reservoirs. Categorical indicator values were calculated by either MODL or MSDL. The MSDL was more severe than MODL, and increased the influence of individual indicators on the final drought level. Overall, the MODL method, using MSDL within each category, provided better correlation with the retrospective assessments while avoiding problems of relying on single indicators, yet it still exhibited oscillation among drought levels.

The IN/OUT triggers method is more complex than the first two, yet it had the advantage of allowing adaptation of the sequence according to the region and type of drought. For example, an agricultural area dependent on seasonal precipitation could have the SPI-3 or SPI-6 as the IN trigger; an area dependent on reservoirs could have the reservoir indicators as the IN trigger, and so forth. Moreover, this methodology allowed the use of more than one IN trigger and OUT trigger, and these could correspond to indicators for early detection (for IN) and remaining drought impacts (for OUT).

More specifically, comparing the SPIs as IN triggers, the sequences with SPI-6 (2) demonstrated the highest correlation with the retrospective assessments. The SPI-6 appeared to be more stable than SPI-3, and tended to detect longer-term drought conditions earlier than the SPI-9 and SPI-12. The SPI-6 (2) also

detected longer-term drought conditions earlier than the SPI-6 (3) and SPI-6 (4), yet was not as oscillatory as the SPI-6 (1). Other IN triggers that performed well included reservoirs (2), streamflow (2), and groundwater (2), depending on their relative importance for the region.

Comparing the SPIs as OUT triggers, the SPI-12 was the most conservative of the indicators; that is, it remained in more severe levels of drought longer. Among the SPI-12s, the SPI-12 (2) and SPI-12 (3) were less erratic than the SPI-12 (1), and they detected severe levels of drought earlier than the SPI-12 (4). However, the sequences using SPI-12 (4) as the OUT trigger exhibited stronger correlations with the retrospective assessment. Moreover, the sequences that included not only the SPI-12 (4) as the OUT trigger, but also reservoirs (4), streamflows (4), and groundwater (4), when applicable, provided a more conservative approach for the final drought level and the highest correlations with the retrospective assessments. Also, by using streamflows, reservoirs, and groundwater indicators with four consecutive periods as the OUT triggers, the final drought level and its corresponding responses takes into account the time required for many hydrologic processes to start to recover before revoking a drought condition.

The multiperiod indicators exhibited a pattern of increasing persistence as the number of consecutive periods increased. Multiperiod triggers, with fewer consecutive periods (such as 1 and 2), tended to detect drought conditions earlier, and multiperiod triggers with higher consecutive periods (such as 3 and 4), tended to be more conservative recovering from severe drought levels. Note that other approaches for developing triggers are possible (see, e.g., Palmer et al. 2002), and other methods of combining multiple triggers could be devised.

The IN/OUT methodology was the one that exhibited the strongest correlation with the expert assessments for all Georgia's nine climate divisions. In addition, it exhibited less oscillation among drought levels than the other methods, reduced the risk of overdependence on a single indicator (as with the MSDL methodology), also reduced the risk of missing an early warning signal (as with the MODL methodology), allowed a conservative approach to drought receding, and permitted the use of multiple triggers and multiperiod triggers, for IN and OUT. This methodology was the one selected for the Georgia drought plan.

The Georgia drought plan was formally adopted on March 26, 2003, and the indicators and triggers are being implemented as follows. The state routinely monitors and evaluates the drought indicators specified in the drought plan, according to each of the nine climate divisions. If any one of the indicators in any one or more of the nine climate divisions reaches or passes a given drought level for 2 or more consecutive months, a preliminary evaluation by state officials is conducted. If this evaluation indicates the possible need for a drought response declaration for that climate division, and for all or part of the relevant hydrologic regions in and adjacent to that climate division, the Georgia Environmental Protection Division Director and the drought committee will make a determination of the appropriate level of response. Before decreasing the level of drought response, all of the indicators in that climate division need to be in a more favorable condition for at least 4 consecutive months. Recent work with the state has included the consideration of climate forecast information for drought management, and using such forecasts as prospective drought indicators.

## Conclusions

Drought plans often rely on multiple indicators and triggers, yet the indicator scales and trigger levels often have little statistical or operational meaning. Methods for combining them in a useful and consistent way are also lacking. As a result, indicators and triggers have caused implementation difficulties for drought plans.

This paper presents an approach and a set of analytic methods for developing indicators and triggers with statistical consistency, for combining them and implementing them for drought mitigation and response, and for using historic data and expert heuristics to evaluate their performance and select ones that would be most effective for drought management.

In addition to these technical evaluations, an important criterion is decision-making value. Indicators and triggers should be straightforward to understand and implement, based on data that are available, sound, and justifiable, and related to impact mitigations and responses. Further, indicators and triggers should be viewed as one of several inputs to drought decision making, as a supplement to human expertise and other quantitative and qualitative information about drought conditions.

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