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Drought Indices In Decision-Making Process of Drought Management

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DROUGHT INDICES IN DECISION-MAKING PROCESS OF DROUGHT MANAGEMENT

by

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ABSTRACT

Drought indices are one of the most important elements of an effective drought monitoring and early warning system. They help to characterize drought and guide appropriate responses to reduce drought impacts. Drought indicators are more useful than raw data in decision-making process, even though each index has specific use and limited by its strengths and weaknesses. The literature review showed the evaluation of drought conditions by decision-makers as an important issue, but so far no research has been done to understand how decision-makers use diverse and often conflicting values of drought indices to make drought declarations. This research studies how drought declarations by decision-makers relate to drought indices to measure past two droughts in South Carolina.

The South Carolina Drought Response Committee (DRC), the state's major drought decision-making body, evaluates climate data and seven drought indices to issue drought status declarations for each county of the state. The case of South Carolina's drought management program is beneficial because the state has one of the largest number of drought indicators among other state-level programs in the nation.

My research determines similarities and differences in measures of drought between the DRC and multiple drought indices, such as Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), Z-index, Standardized Precipitation Index (SPI), Crop Moisture Index (CMI), Keetch-Byrum Drought Index (KBDI) and the U.S. Drought Monitor (USDM). Nine years of monthly values of each

index are compared with the DRC declarations in evaluating drought onset, duration, severity and recovery.

The results show that a cumulative approach is more useful in measuring drought conditions rather than one or two indices. The DRC measures drought onset 3-4 months later than the majority of indices. The drought duration of the DRC for overall study period is similar to most drought indices and longer in comparison to drought indices within two drought periods 2000-2002 and 2007-2008. The severity measured by the DRC typically has more moderate months than other indices. The DRC consistently identifies drought recovery after drought indices and tends to agree with drought indices in measuring drought recovery more often than in measuring drought onset.

This research aims to benefit the decision-making process for drought and water managers, government officials, and stakeholders, as it informs drought assessment in the use of major drought indices. This research is an assessment of drought indicators for policy purposes and can be used in advisement for drought triggers in other regions of the country and the world. Effective use of drought indices in decision-making process enhances proactive drought management policies (risk management approaches) and helps to reduce drought impacts with an ultimate goal of creating drought resilient societies.

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List of Abbreviations

CMI .... Crop Moisture Index

DDIT .... Dynamic Drought Index Tool

DMA .... Drought Management Area

DRC .... South Carolina Drought Response Committee

FAO .... Food Agricultural Organization

HMNDI .... High-level Meeting on National Drought Policy

IPCC .... Intergovernmental Panel on Climate Change

KBDI .... Keetch-Byram Drought Index

NDMC .... National Drought Mitigation Center

NDP .... National Drought Policy

NOAA .... National Oceanic and Atmospheric Administration

PDI .... Palmer Drought Index

PDSI .... Palmer Drought Severity Index

PHDI .... Palmer Hydrological Drought Index

SC DHEC .... South Carolina Department of Health and Environmental Control

SCDA .... South Carolina Department of Agriculture

SCDNR .... South Carolina Department of Natural Resources

SCEMD .... South Carolina Emergency Management Division

SCFC .... South Carolina Forestry Commission

SPI .... Standard Precipitation Index

UNCCD .... United Nations Convention to Combat Desertification

USDA .... U.S. Department of Agriculture

USDM.. U.S. Drought Monitor

WMO .... World Meteorological Organization

CHAPTER 1

INTRODUCTION

Drought distresses large areas, lasts for long periods of time and affects most climates. Droughts are expected to increase in frequency and severity, which will have serious impacts on the economic, social and environmental sectors of effected populations of virtually all nations (IPCC 2012). In order to reduce drought impacts it is important to avoid most commonly used reactive (crisis management) and promote proactive (risk management) approach (Wilhite 2000). The World Meteorological Organization (WMO), the Food and Agriculture Organization of the United Nations (FAO), the United Nation Convention to Combat Desertification (UNCCD) and other United Nations agencies have promoted the establishment of national drought policies (NDP) with an ultimate goal to create drought resilient societies (WMO and UNCCD 2012). One of the essential elements of NDP is the implementation of proactive drought management systems including effective monitoring and early warning systems to deliver timely information to decision makers of all levels.

As one of the most important parts of a proactive drought management system, drought indicators characterize drought conditions and help to guide appropriate responses to reduce impacts (Steinemann and Cavalcanti 2006). Drought indicators, including indices, are used to assess and measure drought. Even though a drought index value is more useful than raw data for decision-making, indicators and triggers often suffer from deficiencies, such as temporal and spatial inconsistencies, statistical

incomparability, and operational indeterminacy (Steinemann 2003).

There is no universal drought indicator measuring all types of drought effectively (Heim 2002). Numerous specialized indices have been proposed to measure drought in different ways. Extensive listings of drought indices are available (WMO 1975a,b; Hayes 1999; Heim 2002). Some studies explore the effectiveness of drought indices to measure drought on a global scale (Vicente-Serrano et al. 2012) and other rank drought indices in terms of usefulness for the assessment of drought severity (Keyantash, and Dracup 2002). No studies have been found that compare drought indices to the evaluations by drought management committees in drought management programs.

South Carolina stands out as an example of a proactive state drought management program that uses multiple drought indicators to monitor drought. South Carolina has one of the largest number of drought indicators among drought management plans adopted on state levels in the nation. The South Carolina Drought Response Committee (DRC), the state's major drought decision-making body, consults drought indices as outlined in the Drought Response Act (Act) (S.C. Code Ann. §49-23-10 to 100, 1976) and supporting regulations. The DRC evaluates seven drought indicators to declare drought status updates. The Act advises the Committee to use multiple drought indices, such as Palmer Drought Index (PDI, Palmer 1965) (which includes Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI) and Z-index), Standardized Precipitation Index (SPI; McKee et al. 1993), Crop Moisture Index (CMI; Palmer 1968), Keetch-Byrum Drought Index (KBDI; Keetch and Byrum 1968) and the U.S. Drought Monitor (USDM; Svoboda 2000).

This research takes a closer look at the work of the DRC and compares the DRC's

drought status declarations to values of drought indices. Since drought indices are often inconsistent with one another, it is a challenge for decision-makers and drought managers to deliver a comprehensive evaluation of drought conditions. This research aims to investigate the relationship between DRC drought status declarations and drought indices in measuring drought.

The **research objective** is to understand how the information from different drought indices relates to the DRC drought status declarations by considering four measures: drought onset, duration, severity and recovery. The **goal** for the research is to compare drought indices with the decisions of the DRC to find similarities and differences between them. The goal directly leads to the following **research question**: How do drought indices relate to the DRC drought status declarations?

The overarching hypothesis is the Act's implementation through the work of the DRC in drought alert phases is not consistent with any single index as measured by correspondence with onset, duration, severity and recovery. This major hypothesis leads to four sub-hypotheses:

1. The DRC drought alert phases lag behind drought indices entering drought.
2. The DRC drought alert phases and drought indices identify different durations when measuring drought.
3. The DRC drought alert phases indicate different levels of drought severity than drought indices.
4. The DRC alert phases lag behind drought indices in drought recovery.

The research evaluates drought indices and the DRC drought alert phases in measuring past droughts during a nine-year period 2000 – 2008 on a monthly scale for

five South Carolina regions: Charleston County, Edgefield County, Florence County, Oconee County and Richland County. The research investigates the relationship between the DRC drought measurements and drought indices to identify patterns in order to with a goal to enhance drought monitoring and management strategies.

This thesis is organized in six chapters: introduction, literature review, background, methodology, results with discussion and conclusion. Chapter 1 is an introduction to the subject of the research, states the hypothesis and research questions. Chapter 2 reviews relevant literature on drought indicators and previous work in finding better drought indices to inform drought decision-making process. Chapter 3 provides background and context of past drought in the region. Chapter 4 presents the study area and methodology of the research along with data limitations. The results and discussion of relevant findings of the research are presented in the Chapter 5. The concluding Chapter 6 summarizes key findings and provides broader applications and suggestions for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Drought

This chapter introduces key concepts in drought studies and drought monitoring and early warning system. Section two discusses the development of the South Carolina drought management program, and the following sections review relevant literature to understand main strengths and weaknesses of drought indicators. The conclusion of this chapter highlights a need to understand how values of drought indices relate to the drought decision-makers' evaluations and while putting this study in context of previous research.

Drought is a naturally reoccurring climatic variability. With a changing climate, droughts are likely to become more severe and occur more often. Drought, in contrast to aridity, affects almost all climates in the world (WMO 2006). There is no universal definition of drought (Heim 2002), however, a common theme in defining drought is a deficit in normal precipitation for a region over a period of time sufficient to cause impacts.

Impacts are the primary ways to measure drought severity. Based on impacts, the WMO defines four major drought types: **meteorological, agricultural, hydrological,** and **socio-economic** (Figure 2.1). All droughts originate from a deficiency of precipitation and begin as meteorological drought. Other types of drought and their impacts cascade from meteorological drought to other types (WMO 2006). All types of

drought have distinctive characteristics that vary across different locations, climate types, populations and economic vulnerabilities.

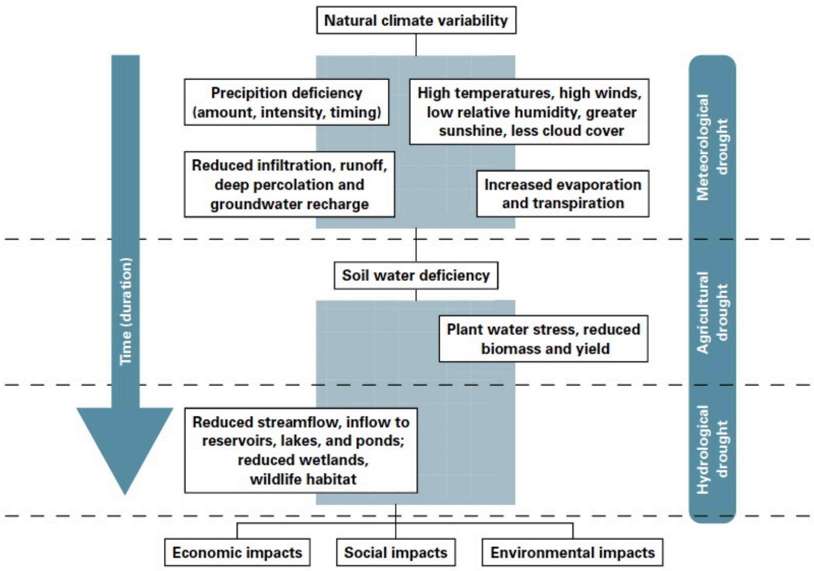


Figure 2.1: Commonly accepted drought types occurrence and impacts sequence. (Source: National Drought Mitigation Center, University of Nebraska-Lincoln, U.S.A.)

The ability of societies to reduce drought effects and build resilience is a grave significant concern on a global level. The WMO and other United Nations agencies promote an implementation of NDP that will provide practical insight into useful, science-based actions to address key drought issues (WMO and UNCCD 2012). Such policies are intended to engender cooperation and coordination at all levels of government in order to increase their capacity to cope with extended periods of water scarcity in the event of a drought (Sivakumar et al. 2011).

In March 2013, the High-level Meeting on National Drought Policy (HMNDP) marked the first globally-coordinated attempt to move towards science-based drought disaster risk reduction. The top-level United Nations conference adopted a declaration encouraging governments to develop and implement national drought policy and issued

detailed scientific and policy guidance on how to achieve this (HMNDP Final Declaration 2013). One of the essential elements of national drought policy is an implementation of an effective and proactive drought management system.

An effective drought monitoring and early warning systems is a way to prevent or reduce drought impacts. An effective drought monitoring system has the ability to deliver an early warning in a case of the drought's onset, successfully measure drought severity and spatial extent, and communicate facts to decision-making groups in a timely manner (Hayes 2011). The development of National programs can be informed by the experiences of regional drought management programs.

2.2 South Carolina Drought Management Program

For several decades, South Carolina has been using proactive drought monitoring and management strategies. In 1982, the state was among the first to formulate a drought management plan and established the Drought Advisory Committee the same year. The Act was enacted in 1985 and amended in 2000. In the amendment, changes were made to set specific numerical values for the indices that define each level of drought. It also established new Drought Management Areas (DMAs) still based on geopolitical sectors and river basins, instead of climate divisions.

The Act established the DRC to address drought related problems and responses. The DRC is composed of statewide and local committee members and includes the following South Carolina agencies: Emergency Management Division of the Office of the Adjutant General (SCEMD), Department of Health and Environmental Control (SCDHEC), Department of Agriculture (SCDA), Forestry Commission (SCFC), and Department of Natural Resources (SCDNR). A committee within one of four DMAs

represents the interests of: counties, municipalities, public service districts, private water suppliers, agriculture, industry, domestic users, regional councils of government, commissions of public works, power generation facilities, special purpose districts and Soil and Water Conservation Districts.

The DRC evaluates drought conditions for each county within DMAs using seven indicators stated in the regulations for the Act and determines if a need for action exists beyond the scope of local government. The DRC meets when needed to evaluate monitored drought conditions and determines drought status by using climatic data and indices outlined in the regulations (Table 2.1). The DRC evaluates drought conditions and characteristics of each drought alert phase: incipient, moderate, severe and extreme. During ongoing drought the statewide committee coordinates planning and response with the appropriate local committee in the impacted DMAs.

Table 2.1: State drought indicators and drought alert phases.

Drought Phase / Index	Incipient	Moderate	Severe	Extreme
PDI (PDSI, PHDI and Z-Index)	-0.50 to -1.49	-1.50 to -2.99	-3.00 to -3.99	≤-4.00
CMI	0.00 to -1.49	-1.50 to -2.99	-3.00 to -3.99	≤-4.00
SPI	0.00 to -0.99	-1.00 to -1.49	-1.50 to -1.99	≤-2.00
KBDI	300 to 399	400 to 499	500 to 699	≥700
USDM	D0	D1	D2	≥D3
Average daily streamflow	111%-120% of the minimum flow for 2 CW*	101%-110% of the minimum flow for 2 CW*	between the minimum flow and 90% of the minimum for 2 CW*	≤ than 90% of the minimum for 2 CW*
Ground Water (Static water level in an aquifer)	between 11 - 20 ft above trigger level for 2 CM**	between 1-10 ft above trigger level for 2 CM**	between the trigger level and 10 ft below for 2 CM**	>than 10 ft below the trigger level for 2 CM**

*CW=consecutive weeks, **CM=consecutive months

South Carolina DRC uses several drought indices since drought can be

characterized in many different ways (Wilhite and Glantz 1985). Drought indices assimilate thousands of bits of data on rainfall, snowpack, streamflow and other water supply indicators into a comprehensible big picture (Hayes, 1999). Drought indicators are designed to measure and evaluate drought conditions and to trigger an appropriate responses to reduce drought impacts (Hrezo et al. 1986; Fisher and Palmer 1997; Steinemann et al. 2005; Palmer et al. 2002; Mizzell 2008). The complexity of drought makes determining drought indicators and triggers complicated. If standard drought indices existed, it would make comparative analysis of droughts more reliable and more comprehensive (Lake 2011). Each indicator has specific characteristics, purpose, spatial and temporal extent. In order to understand the advantages and drawbacks of each indicator, an overview of drought indices used in the work of the DRC is presented in this chapter.

2.3 Overview of Drought Indices

A review of drought indices can be found in several sources including Alley (1984), Wu et al. (2001), Hayes (1999), Heim (2002), Wilhite and Glantz (1985). Heim (2002) references several extensive lists of drought indicators, such as Friedman (1957), Palmer and Denny (1971), World Meteorological Organization (1975a,b, 1985), Hasemeier (1977), Wilhite and Hoffman (1980), Wilhite and Wood (1983), NOAA (1989) and lists Frick et al. (1990) as an additional references for indices developed for regional studies. This review highlights basics uses, advantages and disadvantages of drought indices used by the South Carolina DRC.

2.3.1 Palmer Drought Severity Index

As it is established by the Act, the DRC consults the PDI as a drought indictor when drought status updates are declared. The PDI refers collectively to three indices: PDSI, the PHDI, and the Z Index (Heim 2002). The DRC uses the same trigger levels for these indices (Table 2.1). These three indices are all measured on the same scale and considered individually by the DRC.

In 1965 W.C Palmer developed the PDSI, one of the most widely used drought indicators. It is a good index for meteorological and agricultural drought. This index allows the comparison of droughts with different time and spatial scales. It is a soil moisture drought index that works well with large areas of uniform topography. Table 2.2 lists categories of the PDI that range from wet conditions in positive values and dry conditions in negative values.

Table 2.2: Palmer Drought Index classes (Source: Palmer 1965).

Palmer Drought Classes			
≥ 4.0	Extremely wet	-0.5 to -0.99	Incipient dry spell
3.0 to 3.99	Very wet	-1.0 to -1.99	Mild drought
2.0 to 2.99	Moderately wet	-2.0 to -2.99	Moderate drought
1.0 to 1.99	Slightly wet	-3.0 to -3.99	Severe drought
0.5 to 0.99	Incipient wet spell	≤-4.0	Extreme drought
0.49 to -0.49		Near normal	

The main advantages of this index as suggested by Alley (1984) are: it measures the abnormality of recent weather for a region; it places current conditions in historical perspective; and it provides spatial and temporal representations of historical droughts. Alley (1984), Karl and Knight (1985) and McKee et al. (1993) discuss the limitations of the PDSI: it doesn’t take into account streamflow, lake and reservoir levels, and other

longer-term hydrologic impacts; it does not present accurate results in winter and spring due to the effects of frozen ground and snow; it tends to underestimate runoff conditions.

2.3.2 Palmer Hydrological Drought Index

The PHDI was developed by W.C. Palmer and very similar to the PDSI since it is derived as an additional term of the PDSI calculation. The PHDI is a method to calculate hydrological droughts based on precipitation and evaporation. It quantifies the long-term cumulative impact from hydrological drought and wet conditions, which more accurately reflect groundwater conditions, reservoir levels, etc. (Heim 2002). The PHDI is a slow changing response for drought and usually changes even more slowly than the PDSI.

2.3.3 Palmer Z-Index

The Palmer Z-index shows short-term soil moisture droughts and wetness with the soil moisture anomaly on a monthly scale. The Z-index has the same advantages and disadvantages as the PDSI (Hayes 1999). However, the Z-index responds faster to changes in soil moisture values. This index, in comparison to other analyzed indicators, has a higher frequency of indicating a drought and indicates short duration droughts more often.

2.3.4 Standard Precipitation Index

The SPI Standard (or Standardized) Precipitation Index is a meteorological drought index that was developed by McKee et al. (1993) and designed to quantify precipitation deficits for multiple time scales. Soil moisture conditions respond to precipitation anomalies on a relatively short scale, while ground water, streamflow, and reservoir storage reflect the longer- term precipitation anomalies (Hayes 1999). The SPI calculation for any location is based on the long-term (at least thirty years) precipitation

record for a desired period. Its standardization allows the SPI to determine the frequency of a current level of drought, as well as the probability of precipitation necessary to end the current drought (McKee et al. 1993). For these reasons, McKee et al. (1993) originally calculated the SPI for 3-, 6-, 12-, 24-, and 48-month time scales. The use of different timescales allows the effects of a precipitation deficit on different water resource components (groundwater, reservoir storage, soil moisture, streamflow) to be assessed. The index ranges from negative to positive values and measures dry and wet conditions (Table 2.3).

Table 2.3: Standard Precipitation Index categories (Source: McKee et al. 1993).

SPI Values	
≥2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-.99 to .99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤-2	Extremely dry

The SPI can provide early warning of drought and its severity because it can specify drought conditions for each location and is well suited for risk management. The advantages of this index are that the longer timescale are sometimes used as an approximation of streamflow and groundwater droughts (Hayes 1999). The disadvantages of the index are the need for a long time series of observed data and the possibility of trends in precipitation during this period (Hayes 1999). The Lincoln Declaration on Drought Indices, the result of WMO's the Inter-Regional Workshop on Indices and Early Warning Systems for Drought, recommends the SPI for widespread use in countries to track meteorological drought (Hayes et al. 2011).

2.3.5 Crop Moisture Index

In 1968 W.C. Palmer developed the CMI as a short-term soil moisture drought index to monitor week-to-week crop conditions (Table 2.4). It is not intended to assess long-term droughts. This index related to the Palmer Z-index, which is calculated similarly. It is based on the mean temperature and total precipitation for each week within a climate division, as well as the CMI value from the previous week (Hayes 1999).

Table 2.4: Crop Moisture Index classes (Source: Palmer 1968).

CMI Classes	
≥3.0	Excessive wet, some fields flooded
2.0 to 2.99	Too wet, standing water in some fields
1.0 to 1.99	Prospects good, but fields too wet
0.0 to 0.99	Moisture adequate for immediate needs
0.0 to -0.99	Conditions improved but need more rain
-1.00 to -1.99	Prospects improved but still only fair
-2.00 to -2.99	Drought eased, but more rain needed
≤-3.0	Situation still serious, rain badly needed

The CMI responds rapidly to changing conditions. It is suited for summer drought predictions and can only be used during growing season. It can detect drought sooner than the PHSI and the PHDI. The CMI's rapid response to changing short-term conditions may provide misleading information about long-term conditions (Hayes 1999).

2.3.6 Keetch-Byram Drought Index

J. Keetch and G. Byram in 1968 developed the KBDI for use by fire control managers. The KBDI is a measure of meteorological drought. The daily index uses precipitation and soil moisture analyzed in a water budget model. The index increases for each day without rain (see Table 2.5) and decreases when it rains. Drought is not by itself a prerequisite for wildfires. Other weather factors, such as wind, temperature, relative

humidity and atmospheric stability, play a major role in determining the actual fire danger.

Table 2.5: Keetch-Byram Drought Index categories (Source: Melton 1998).

KBDI	Class
0 to 150	Upper soil and duff layer are very wet during this stage and do not contribute to the fire very much.
150 to 300	Pine and hardwood stumps can ignite in this stage but the fire hardly goes below ground. Snags may cause escaped fires but can be controlled by standard control tactics. More attention is needed when the KBDI levels are close to 300.
300 to 500	Fire intensity at this stage increases significantly. If the KBDI exceeds 350, all the planned winter and spring understory fire should be canceled.
500 to 700	In this stage, fire behavior tends to become unpredictable and more urban interface type fire starts to occur. Summer site preparation burns should be canceled. Severe wind condition aggravates the fire.
≥700	Urban interface fires become a major cause of wildfires. Every burning activity should be prohibited until the KBDI levels go down below 500.

2.3.7 U.S. Drought Monitor

The USDM was developed by US agencies within National Oceanic and Atmospheric Administration and the U.S. Department of Agricultural with the NDMC in 1999. The USDM is a drought-monitoring tool that consolidates and centralizes drought-monitoring activities. The weekly outputs depict drought severity and spatial extent, along with a drought type.

The USDM incorporates the PDSI, the SPI, the Percentage of Normal Precipitation, the Soil Moisture Model Percentiles, the Daily Streamflow Percentiles and the Satellite Vegetation Health Index, along with some ancillary indicators such as the KBDI, snowpack conditions, reservoir levels, groundwater levels, USDA reported the crop status, direct soil moisture measurements, and others (Svoboda 2000). The USDM

maps are based on many objective inputs, but each week an author reviews the maps and adjusts them manually to reflect real-world conditions as reported by numerous experts throughout the country in five drought types (Table 2.6) (Svoboda 2000).

Table 2.6: U.S. Drought Monitor drought intensity categories (Source: Svoboda 2000).

USDM categories	
D0	Abnormally dry
D1	Moderate drought
D2	Severe drought
D3	Extreme drought
D4	Exceptional drought

One of the main advantages of the USDM is that it is a consensus product reflecting the collective best judgment of many experts based on several indicators. A limitation of the USDM lies in its attempt to show drought at several temporal scales (from short-term drought to long-term drought) on one map product (Heim 2002). The USDM uses an integrated approach and relies on the analyses of several key indices and ancillary indicators to create a drought status maps. It is important to mention that the USDM is designed to help in the identification of the drought extent and severity and does not intend to replace any local or state information or declare drought emergencies and warnings (Svoboda 2000).

The Table 2.7 summarizes relative strengths and weaknesses of drought indices. It is important to mention that drought indicators have different temporal variability. Even though most drought indices are calculated on a monthly scale, the CMI and the USDM are calculated weekly and the KBDI daily. The weakly drought indicators respond to wet and dry spells more frequently and can measure strengthening drought conditions faster, than slow-changing indices, such as PDSI and PHDI.

Table 2.7: Overview of major drought indices.

Drought Index	Who and When	Strengths	Weaknesses
PDSI Monthly	1965 by W.C Palmer	Soil moisture index and good indicator for meteorological and agricultural drought; Places current conditions in historical perspective; Provides spatial and temporal representations of historical droughts	Does not take into account streamflow, lake and reservoir levels, and other longer-term hydrologic impacts; Not accurate results in winter and spring due to the effects of frozen ground and snow; Tends to underestimate runoff conditions
PHDI Monthly	1965 by W.C Palmer	Quantifies the long-term cumulative impact, more accurately reflects groundwater conditions, reservoir levels, etc.	Slow response to drought and usually changes even more slowly than the PDSI
Z-Index Monthly	1965 by W.C Palmer	Same advantages and disadvantages as the PDSI	Responds faster to changes in soil moisture values. Drought is declared more often with shorter duration of the drought spells
SPI Monthly	1993 by McKee et al.	Longer timescale sometimes used as an approximation of streamflow and groundwater droughts	Need for a long time series of observed data and the possibility of trends in precipitation during this period
CMI Weekly	1968 by W.C. Palmer	CMI responds rapidly to changing conditions, can detect drought sooner than the PDSI and the PHDI; Suited for summer drought prediction	Can only be used in the growing season; Not intended to assess long-term droughts
USDM Weekly	1999 US agencies	Reflecting the collective best judgment of many experts based on several indicators	Show drought at several temporal scales (from short-term drought to long-term drought) on one map product.
KBDI Daily	1968 by J. Keech and G. Byram	Forest fire potential assessment for forest fires	Not precise in detecting drought, because more than just deficiency of

			precipitation influences forest fires

A wide range of available drought indices have their own advantages and disadvantages, calculated on different time scales, effective for specific locations (PDSI for areas with uniform topography) or during specific periods (CMI for growing period). No single indicator or index can represent the diversity and complexity of drought effects (Hayes et al. 2005; Mizzell 2008) and that is why it is useful to use multiple indicators when monitoring drought conditions to deliver appropriate drought response and to reduce the impacts (Botterill and Hayes 2012).

Previous research was focused on identifying the most suitable drought index to measure drought. Vicente-Serrano et al. (2012) compared drought indicators ability to measure drought on a global scale. Keyantash and Dracupu (2002) ranked drought indices in terms of usefulness of drought severity assessment. The Lincoln Declaration on Drought Indices aimed to develop standards for drought indices and guidelines for a drought early warning system. The declaration was a result of the Interregional Workshop on Indices and Early Warning Systems of Drought, sponsored by the WMO, other UN agencies with NDMS, NOAA, and other prominent organizations. The workshop came to the consensus that the Standardized Precipitation Index (SPI) should be used to characterize the meteorological droughts around the world. As for agricultural and hydrological drought, no specific index was selected for each of these drought types (Hayes et al. 2011). The document emphasized the need for coordination between data monitoring agencies to facilitate effective decision-making.

While drought monitoring system is a “cornerstone” of effective drought management (Wilhite and Buchanan-Smith 2005) and information provided by drought indices is essential for risk management, it is important to be aware of strengths and weaknesses of each drought index when evaluating drought conditions, especially for drought decision-makers, who often don’t know about specifics of each index (Steinemann and Cavalcanti 2006; Mizzell 2008).

The literature review showed the evaluation of drought conditions by decision-makers is an important issue, but so far no research has been done to understand how decision-makers use diverse, and often conflicting values of drought indices to make drought declarations. This research studies how drought declarations of decision-makers relate to drought indices to measure past drought events in South Carolina.

CHAPTER 3

BACKGROUND

3.1 Drought in South Carolina

This background chapter reviews the 1998-2002 and 2007-2008 drought events in historical perspective. South Carolina is vulnerable to drought and droughts are frequent in the history of the state. Figure 3.1 illustrates frequencies and durations of droughts and wet spells as measured by the PDSI for the South Carolina for a period 1900-2012. Positive numbers indicate wet conditions and negative numbers correspond to dry spells and droughts. The figure shows that the state experienced droughts of different severity and duration every decade for the presented period.

The PDSI indicates that the state is in incipient drought conditions every two to three years. During the 1900-2012 period, there are two to three drought spells of moderate severity (PDSI=-2) per decade, severe and extreme droughts (PDSI=-3 to -4<) are even less frequent. The PDSI reaches and exceeds extreme status (the -4 value) only ten times for the presented 113-year period. The state experienced the PDSI extreme drought conditions six times in decades 1900-1970 and four times since 1970.

The most prominent drought events were at the end of the 1920s through the first half of the 1930s, the drought of the 1950-1957, 1980-1982, 1998-2002, 207-2008 and the most recent drought that started in 2010. Some droughts lasted for a year, while other lasted almost a decade. The drought of the 1950s lasted for seven years with no relief and had devastating effects on the state. However, the following two decades had abundant

rainfall and the PDSI did not exceed the incipient drought level.

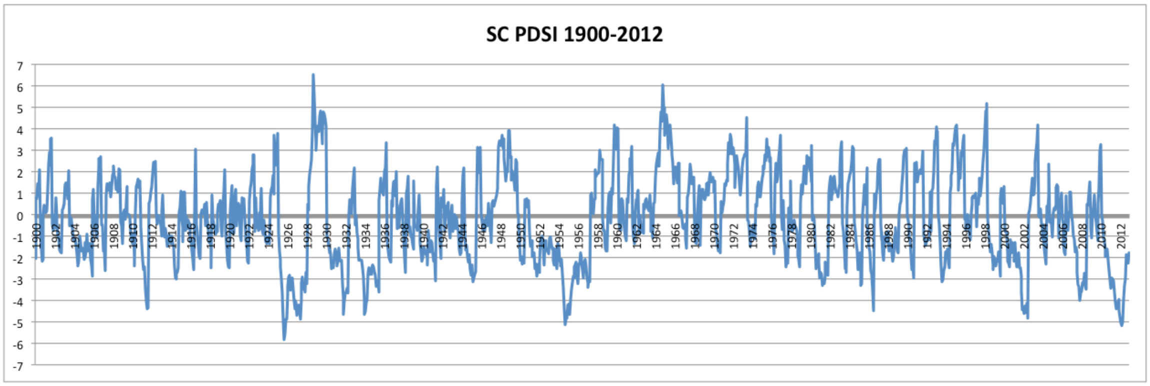


Figure 3.1: South Carolina drought measured by monthly PDSI 1990-2012.

The PDSI is one of many drought indices that the DRC consults when issues drought status declarations. The DRC's drought status declarations are archived on the SCDRC web site[1]. More information on the SCDNR DRC archive is available in methodology chapter section 4.1.1. Figure 3.2 reconstructs the DRC declarations for all South Carolina Counties from press releases in the archive. These status maps put the past two droughts in historical perspective and show spatial extent of those droughts in relation to drought severity.

As Figure 3.1 shows, South Carolina has had a number of droughts and this study evaluates the two most recent drought periods. Other droughts have difference emergences (fast vs. slow, hot vs. cold drought). The research is a case study of the two droughts that have occurred since the Act was amended in 2000 and the drought information became accessible on-line (see section 4.1). During the study period (2000-2008), South Carolina experienced two droughts 1998-2002 (slow emerging drought) and 2007-2008 (fast emerging drought), each of them different in duration, severity and

[1] http://www.dnr.sc.gov/climate/sco/Drought/drought_press_release.php

extent. The 1998-2002 drought lasted longer and affected the entire state, while 2007-2008 drought had a shorter duration and was most prominent across the western part of the state. Drought events vary based on climatology of drought and physiographic features of affected area.

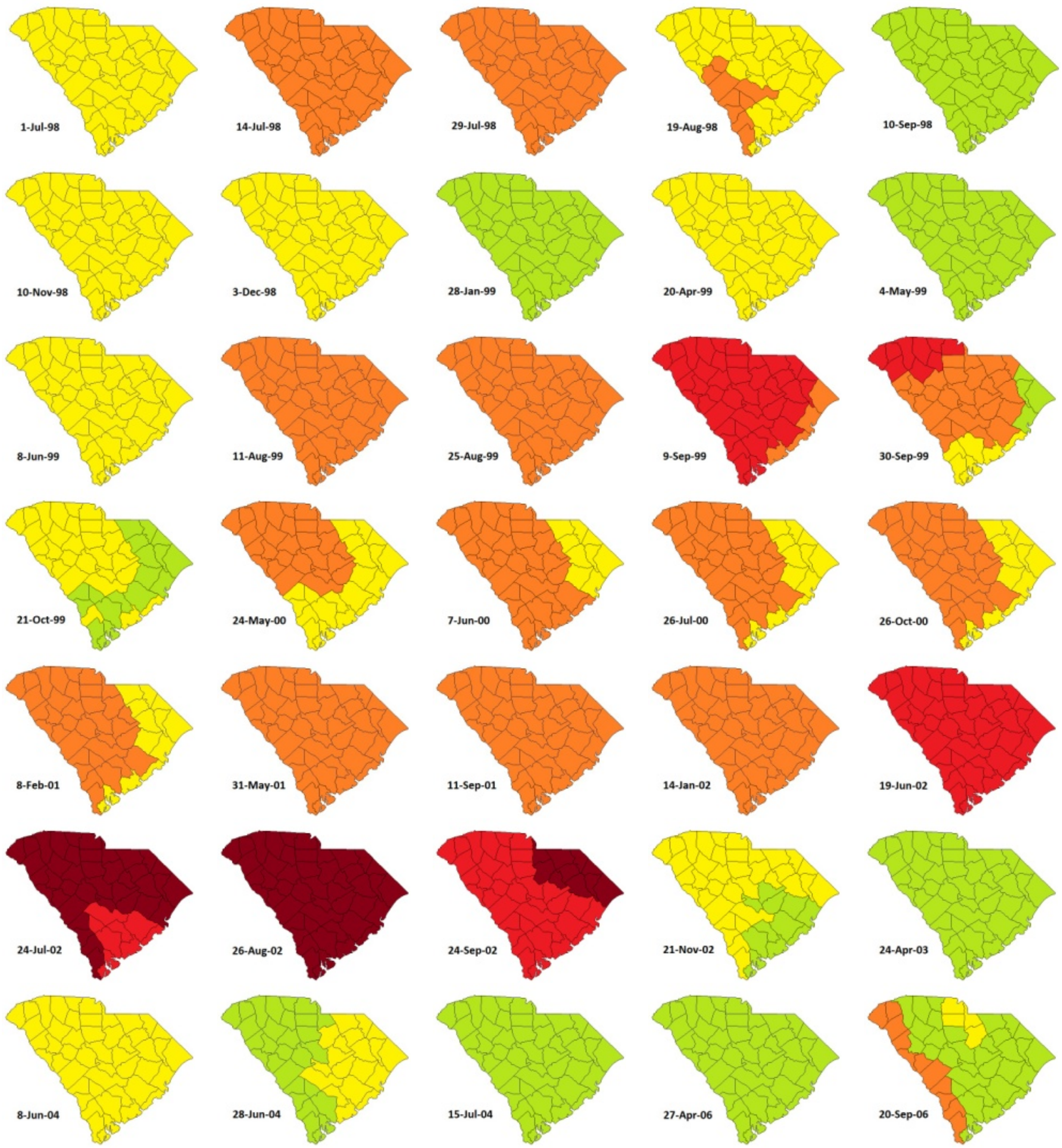


Figure 3.2: Drought status declarations as measured by the DRC (cont. next page).

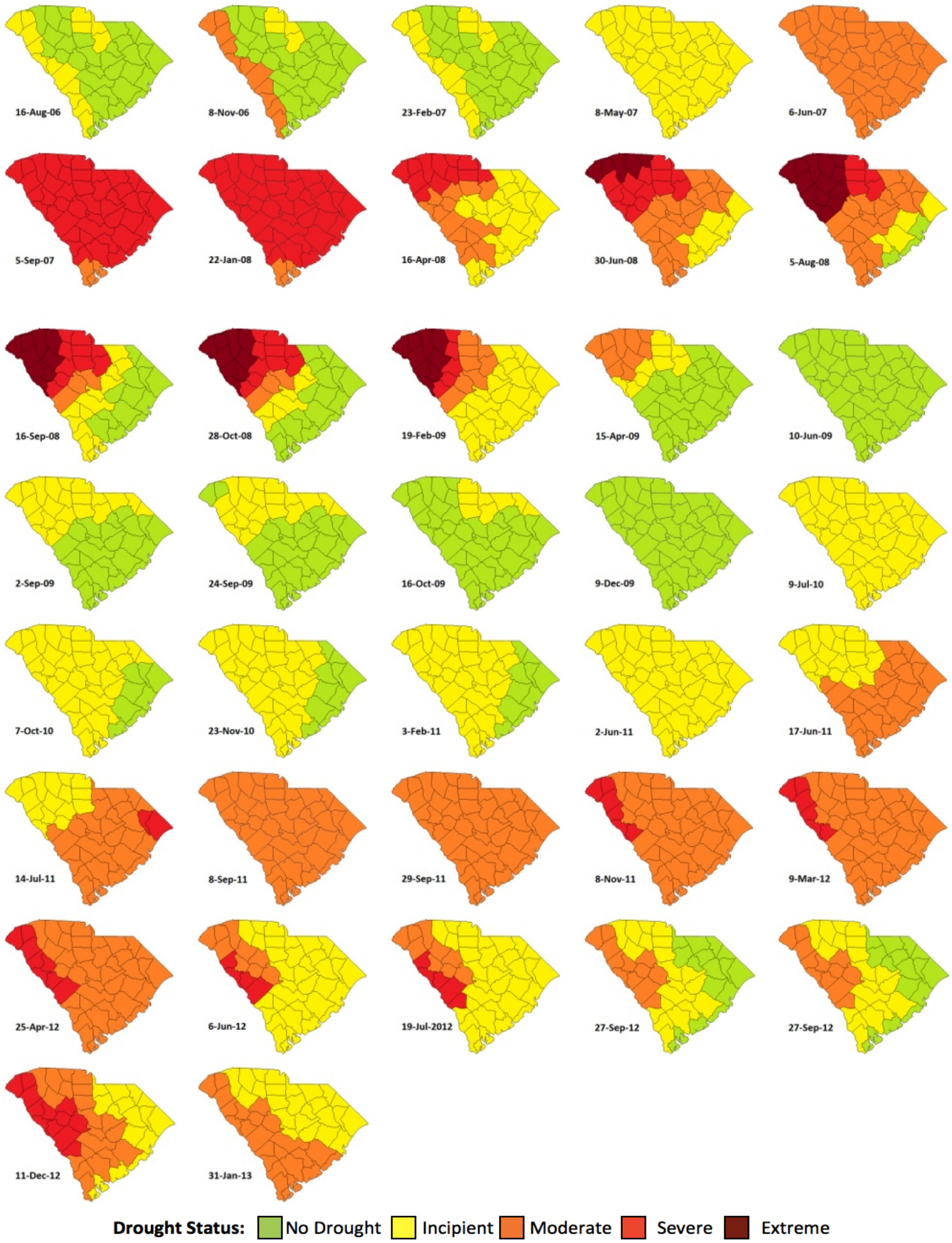


Figure 3.2: Drought status declarations as measured by the DRC.

3.1.1 1998-2002 South Carolina Drought

The 1998-2002 drought lasted longer and had a significant effect on the state's water resources, crops and forest fires. During this four-year drought, statewide conditions fluctuated from no drought to extreme. Individual counties experienced drought and recovered several times, especially during earlier stages of drought development. According to the DRC status declarations (Figure 3.2), the state was relieved by short periods of no drought in September 1998, January and May1999. Severe and extreme drought conditions lasted throughout summer 2002 for parts of the state and in August 2002 the DRC declared extreme alert status for the entire state. That year, the DRC declared the highest level of drought for all counties for the first and only time in the history of the drought management program.

Beginning in late August 2002, South Carolina received much greater than normal rainfall. Some locations fulfilled five-month normal rainfall in a period of just two and half months. In September 2002, the South Carolina Geological Survey reported that sinkholes occurring in Dorchester County were likely caused by a combination of extended drought and then heavy rains (SCDNR News Release #02 – 43, September 6, 2002). 20 out of 46 counties quickly recovered through three drought statuses ("extreme" to "incipient" or from "severe" to "no drought") and 14 jumped two stages ("severe" to "incipient"). Several times in the past, counties jumped two stages, severe to incipient, for example, or moderate to no drought, but never to the extent that it occurred in November 2002. No doubt, this event was the largest in non-consecutive path in drought stages DRC status updates.

3.1.2 2007-2008 South Carolina Drought

The 2007-2008 drought had a shorter duration and lower intensity than the previous drought. This drought started to develop during summer months of 2006. The entire West (Savannah) DMA and four counties in North-Central part of the state were among the earliest affected by the lower than normal rainfall and excessive heat.

In August 2006 about one third of the state entered incipient drought. The declaration for these counties lasted approximately one year and in May 2007, the rest of the state was upgraded to incipient drought. In June 2007, all forty-six counties were upgraded to moderate drought. Reports of dry conditions, especially in agriculture and forestry, influenced that decision.

From September 2007 to March 2008, Jasper and Beaufort counties remained in moderate drought, while the rest of the state was in severe drought. This devastating stage lasted longer than six months. The DRC meeting in January 2008 declared to keep the existing drought declaration despite improvements in rainfall. The precipitation had been above normal for 30 days prior to the meeting. However, this was not enough to return streamflows, groundwater, and reservoirs to a better status. The official State Climatology Office press release reports: "The Committee was also concerned because forecasters expect a return to below normal rainfall for February through April 2008." (SCDNR Special News Release, January 22, 2008).

Nearly the entire state experienced severe drought conditions for a prolonged period of time during 2007-2008. The State Climate Office issued several special news releases to implement water conservation measures. The Governor and SCDNR encouraged all South Carolinians and water providers to voluntarily conserve water. The

Office also provided useful tips on how to increase water efficiency and reduce water use.

In April 2008 the conditions improved for the majority of the counties. These counties were downgraded to incipient and moderate drought stage. However, the northwestern counties continued to experience severe drought. Darryl Jones, with the SC Forestry Commission, commented on the impacts and stated dry conditions over the previous year resulted in 2,800 fires and 17,000 acres burned, which exceeded their 10-year average for wildfires (SCDNR News Release, April 16, 2008).

Within several months, deteriorating conditions caused the DCR to declare extreme drought status for upstate counties. In June 2008 the DRC was concerned with the lack of normal winter and spring rainfall, resulting in insufficient recharge of groundwater to sustain streamflows (SCDNR News Release, June 30, 2008). Drought affected many lakes. For example, the Santee lakes lost over one foot depth of water in comparison with the lake level at the same time the previous year. The Savannah lakes continued to decline and were more than 10 feet below the target level (SCDNR News Release, June 30, 2008).

In August 2008, DRC moved more counties into the extreme drought category. The Committee placed 14 counties in extreme drought conditions in Santee and Savannah DMAs. Other areas of the state showed the largest spread in drought status severity. In August - October 2008, for the first time in the history of drought management program, South Carolina counties had the full range of drought stages from the incipient to extreme. In June 2009, the 2007-2008 drought officially ended when the DRC lifted drought status and declared an end of drought for the entire state.

CHAPTER 4

METHODOLOGY

This chapter explains the major elements of the methodology in five sections. The first section introduces the study area. The second section describes the collection of raw data from three online sources: the DRC archive on the SCDNR website, the Dynamic Drought Index Tool (DDIT) and the USDM archive. Section three discusses data calibration to a consistent unit of analysis (monthly values) and coding techniques, according to the regulations values. The fourth section explains how the coded data is analyzed between DRC alert phases and state drought indices. Limitations of the method are discussed in the final section.

4.1 Study Area

The following section introduces the study area and describes physiographic features of South Carolina counties selected for this research. Charleston, Edgefield, Florence, Oconee and Richland counties are distributed throughout the state and represent all DMAs. This research compares how the DRC and drought indices measure droughts for the last two drought events in different parts of the state.

This research project uses a sample of 5 out of 46 South Carolina counties to get a better understanding of variations between drought indices and DRC alert phases in different parts of the state. Charleston, Edgefield, Florence, Oconee and Richland counties represent four DMAs and distinctive landform regions (Table 4.1 and Figure 4.2). In addition, Edgefield County was chosen as one of the most drought prone

areas where drought often begins sooner and lasts longer in comparison to the other parts of the state.

Table 4.1: Selected counties in South Carolina.

County	DMAs	Landform Region
1. Charleston	ACE (Southern)	Coastal Zone
2. Edgefield	Savannah (West)	Piedmont
3. Florence	Pee Dee (Northeast)	Coastal Plain
4. Oconee	Savannah (West)	Blue Ridge and Piedmont
5. Richland	Santee (Central)	Sandhills and Inner Coastal Plain

According to Kovacik and Winberry (1987) the state contains six landform regions: Coastal Zone, Outer and Inner Coastal Plain, Sandhills, Piedmont and Blue Ridge (Figure 4.1). Drought indices also have different drought values for various sections of the state because of the influence of climatic variations and soil properties in the different areas of the state. Each of the selected counties has distinctive climatic, geological and hydrological properties.

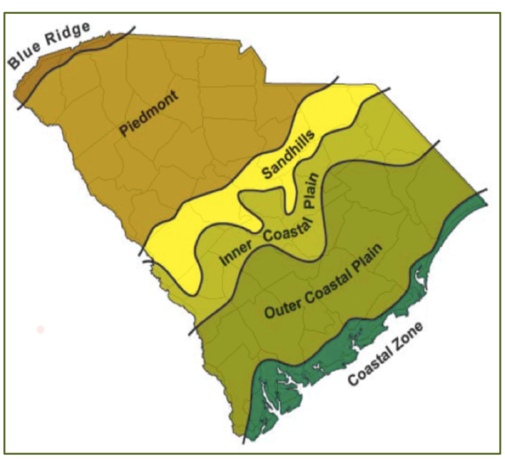


Figure 4.1: South Carolina landform regions (Source: Kovacik and Winberry 1987).

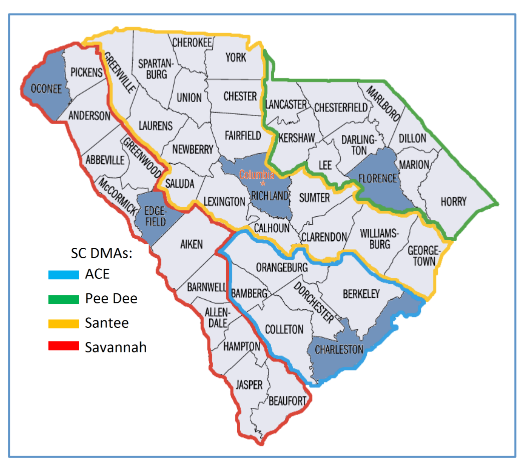


Figure 4.2: South Carolina's DMAs and counties selected for this research.

Charleston County is located in the southeast part of the state and stretches along the Atlantic Ocean. This Coastal Zone County is a part of the Southern or ACE DMA. ACE named for Ashepoo, Combahee, and Edisto Rivers. The landscape is dominated by swamps, marshes and sandy beaches near the coast. The topography then changes to rolling hills and forested land towards the Outer Coastal Plain. The proximity to the ocean provides a cooling effect decreasing temperatures and increasing humidity, making climate there more temperate in relation to other parts of the state.

Edgefield and **Oconee counties** are located in the West (Savannah) DMA, with Edgefield in Piedmont region and Oconee in both the Piedmont and Blue Ridge region. Savannah area named after Savannah River that runs along South Carolina and Georgia border. The area is generally hilly, with some areas in Oconee County having peaks reaching above 1,000 feet. The region generally has thin, stony clay soils, and contains few areas suitable for farming. The type of soils in these counties might have an impact on how drought indices measure drought. The Edgefield County was added to the list of the counties for the research because this county is believed to be the most drought-prone.

Florence County is situated within the Coastal Plain of South Carolina in the Northeastern (Pee Dee, named for the Pee Dee River) DMA, approximately 65 miles inland of the Atlantic Ocean. Tributaries of the Pee Dee River drain the area. The Coastal Plain is a relatively flat and fertile area of land. This county is largely used for farming.

The South Carolina state capital, Columbia, is in **Richland County**, in the center of the state. Richland County is located in the Central (Santee) DMA of the Sandhills region with a minor portion of the northwestern part of the county in the Piedmont. The

region, commonly referred as Midlands, is mostly a sandy region of South Carolina. The Sandhills region is located in the middle of the state, this boundary is regionally recognized and often called the Fall Line. Fall Line (Fall Zone) is the geomorphologic break between crystalline basement rock of Piedmont region and softer sedimentary rock of Coastal Plain region.

It is important to mention that not all drought indices reflect soil moisture component. The CMI, the Z-Index, the PDSI and the USDM (because it includes PDSI) are the ones that do include an estimate of soil moisture in their calculations.

4.1 Data Collection

The research investigates and analyses similarities and differences in measuring drought onset, duration, severity and recovery between the DRC drought status declarations and the following drought indices: the PDSI, the PHDI, the Z-Index, the SPIs (1-, 3-, 6-, 9- and 12-months), the CMI and the KBDI for the period of nine years. During the study period the state experienced two prolonged drought events. The time frame of the study is January 2000 to December 2008 on a monthly scale for a sample of five South Carolina counties. Charleston, Edgefield, Florence, Oconee and Richland counties represent diverse physiographic regions and state DMAs.

The analysis integrated three databases and utilized visual analysis and descriptive statistics to evaluate similarities and differences between the DRC and drought indices. The SCDNR website provided archived DRC drought status declarations. The DDIT for Basins in North and South Carolina (Carbone et al. 2008) provided outputs for drought indices for five selected counties. The USDM archive contributed drought weekly data on a county level.

Table 4.2: Database data coverage and study data set.

Database	Time Coverage	Frequency	Data Points for the Study Period
DRC Status	Jul. 1998 – Jul. 2012	Every 4-6 week when drought	31
DDIT	Jan. 1950 – Sep. 2009	Daily, weekly and monthly: depends on the index.	Daily KBDI – 3288 Weekly CMI – 468 Monthly other – 108
USDM GIS data	May 1999 – Sep. 2012	Weekly	468

http://www.dnr.sc.gov/climate/sco/Drought/drought_press_release.php
https://www.dnr.sc.gov/drought/index.php?pid=0
http://droughtmonitor.unl.edu/dmshps_archive.htm

The data archives cover different periods (Table 4.2). The DRC drought declarations are available starting 1998 until present. The USDM archive full-year data sets start in January 2000. The DDIT starts in 1950 and ends in 2009, which leaves 2008 as the last year when full-year drought indices data is available from this source. The selected study period is nine years or 108 consecutive months from January 2000 to December 2008.

4.1.1 Drought Response Committee Archive

The archived DRC drought status declarations and additional documents, such as news releases, notes and announcements are available online on the SCDNR State Climate Office website in the Drought section. The SCDNR website features the DRC archived updates, special meeting announcements and special status reports that provide justification of drought alert phases with climatic, hydrological, fire hazard data and other information.

The archive starts in September 1997 and the most current drought status declaration was made in April 2013 (Table 4.3). The archive consists of 120 entries

including 67 drought status reports, 44 special meeting announcements and 3 special status reports. Six entries (four in 1997 and two in 2001) are irretrievable.

The data set of the DRC alert phases is not confined to a strict temporal periodicity, however, as a general rule, the DRC meets every 4 to 6 weeks when at least a part of the state is in drought conditions. The DRC meets more often when drought conditions intensify. The DRC had created from 0 to 9 yearly status updates. The average number of drought status declarations is 4-5 per year, with relatively more meeting and more updates during drought years. The largest number of updates is delivered in 1999. The lowest number of meetings was one update in 2003 and no-drought year with no updates in 2005.

The available drought status reports were converted into maps of drought alert phases for each county and then into monthly outputs. During the study period the DRC made twenty-eight drought status declarations. When drought status update is made, it lasts until the next drought status declaration.

Table 4.3: News releases dates of the DRC drought status declarations.

Apr 24, 2013	*Mar 29, 2013	Jan 31, 2013	*Jan 22, 2013
Dec 11, 2012	*Nov 29, 2012	Sep 27, 2012	*Sep 20, 2012
Jul 19, 2012	*Jul 3, 2012	Jun 6, 2012	*May 25, 2012
Apr 25, 2012	*Apr 13, 2012	Mar 9, 2012	*Feb 17, 2012
Nov 8, 2011	*Oct 25, 2011	Sep 29, 2011	*Sep 19, 2011
Sep 8, 2011	*Aug 30, 2011	Jul 14, 2011	*Jul 8, 2011
Jun 17, 2011	*Jun 14, 2011	Jun 2, 2011	Feb 3, 2011
*Jan 13, 2011	Nov 23, 2010	*Nov 5, 2010	Oct 7, 2010
Jul 9, 2010	Dec 9, 2009	Oct 16, 2009	Sep 24, 2009
Sep 2, 2009	Jun 10, 2009	Apr 15, 2009	*Apr 6, 2009
*Mar 13, 2009	Feb 19, 2009	*Jan 15, 2009	Oct 28, 2008
* Oct 7, 2008	Sep 16, 2008	* Aug 29, 2008	Aug 15, 2008
Aug 5, 2008	# Jul 21,2008	* Jul 17, 2008	Jun 30, 2008
* Jun 13, 2008	Apr 16, 2008	* Mar 24,2008	Jan 22,2008
* Dec 21,2007	# Nov 01,2007	# Oct 24,2007	Sep 05,2007
* Aug 20,2007	Jun 06,2007	* May 25,2007	May 08,2007

* May 07, 2007	Feb 23, 2007	* Feb 22, 2007	Nov 8, 2006
* Oct 27, 2006	Sep 20, 2006	* Sep 12, 2006	Aug 16, 2006
* Aug 14, 2006	Apr 27, 2006	Nov 16, 2005	Jul 15, 2004
Jun 28, 2004	Jun 8, 2004	Apr 24, 2003	Nov 21,2002
Sep 24,2002	Sep 6,2002	Aug 26, 2002	Jul 24, 2002
Jul 12, 2002	Jun 19, 2002	Jan 14, 2002	Nov 20, 2001
Oct 19, 2001	Aug 1, 2001	May 31, 2001	Feb 8, 2001
Oct 26, 2000	Jul 26, 2000	Jun 7, 2000	May 24, 2000
May 16, 2000	Oct 21, 1999	Sep 30, 1999	* Sep 28, 1999
Sep 23, 1999	Sep 9, 1999	Aug 25, 1999	Aug 11, 1999
Jun 8, 1999	May 4, 1999	Apr 20, 1999	Jan 28, 1999
Dec 3, 1998	Nov 10, 1998	Sep 10, 1998	Aug 19, 1998
Aug 13, 1998	Jul 29, 1998	Jul 14, 1998	Jul 1, 1998
Sep 26, 1997	**Sep 26, 1997**	**Sep 18, 1997**	**Sep 12, 1997**

* Denotes a special meeting announcement.
# Denotes a special status report.
Source: SC DNR State Climate Office's Drought section web page:
http://www.dnr.sc.gov/climate/sco/Drought/drought_press_release.php

4.1.2 Dynamic Drought Index for Basins Archive

The DDIT is a web-based tool that allows to access drought indicators on different spatial resolutions in North Carolina and South Carolina. One of the main advantages of this database is the flexibility of the interface and interaction features. The system uses a 4 km grid resolution and the results can be spatially aggregated for states, counties, climate divisions, 2-8 digit hydrologic units, and watersheds of interests. Users can extract raw index values, percentiles or to create a blended index. The DDIT has options to deliver data as maps, graphs or tables for a period from 1950 to mid-2009. The DDIT database provided county scale data for monthly PDSI, PHDI, Z-Index, 1-, 3-, 6-, 9- and 12- month SPIs, weekly CMI and daily KBDI.

4.1.3 U.S. Drought Monitor Archive

The USDM map updates have been available for 13 years and it is a good tool to estimate recent droughts. Weekly maps provide frequently updated drought conditions. The USDM puts local conditions into region-specific or national perspective with three

modules of output: US territory, regions and states. The USDM archives are accessible under five categories: maps, tables, animations, 1999 archive and GIS data. The website provides an access to the second half of 1999 and the fully archived years are 2000 through present. This research utilizes GIS data from downloaded Excel spreadsheets that contain the weekly percent area statistics for South Carolina counties.

4.2 Calibrations and Coding

The data from the DRC archive was converted into drought status maps for each drought status declaration for all South Carolina counties. The data for Charleston, Edgefield, Florence, Oconee and Richland counties was extracted and converted into monthly drought statuses for the duration of the study and compiled into figures.

The DDIT and the USDM archives provided drought indices data on county scale. The raw data was collected for monthly, weekly and daily outputs. Monthly PDSI, PHDI, Z-Index, SPI1, SP3, SP6, SPI9, SPI12 had 108 data points. Weekly calculated CMI and USDM had 468 points and the KBDI had 3288 daily values. The raw drought indices data was converted into four drought categories according to criteria stated in the regulations (Table 2.1).

The research evaluates drought indices that are calculated on different time scales. In order to compare monthly, weekly and daily outputs, the weekly and daily values were converted into monthly averages. Weekly data for the USDM and the CMI were converted into drought stages and then into monthly drought alert phases if three or more consecutive weeks experienced drought conditions. In the case of USDM, monthly status was recorded if more than 75% of the county area entered any drought level for three or more consecutive weeks. The daily KBDI values were converted into appropriate drought

status if the average monthly values reached or exceeded trigger levels established in the Act and supporting regulations.

4.3 Figures and Data Analysis

The evaluation of the results is based on visual analysis and descriptive statistics of figures in the results chapter. Figures organize data of monthly drought statuses for Charleston, Edgefield, Florence, Oconee and Richland counties. Figures are color-coded according to drought statuses: no drought in green, incipient in yellow, moderate in orange, severe in red and extreme in burgundy. Each colored square represents a measure of drought severity for particular index for selected months in study period.

List of indices is on the y-axis and monthly drought measures are on the x-axis. On the x-axis the drought results are organized on a monthly scale in sets of years 2000-2002, 2003-2005 and 2006-2008. The indices are grouped in three sets and lay on the y-axis. The DRC, the USDM and the Palmer drought indices (the PDSI, the PHDI and the Z-Index) are the first group. Five SPI indices grouped in an ascending order (the SPI1, the SPI3, the SP6, the SPI9 and the SPI12) followed by two short-term indices the CMI and the KBDI.

The DRC met and issued a drought declaration twenty eight times (indicated by the "*" symbol in the year field).

Red border outlines vary from county to county and indicate two drought periods, as measured by the DRC within the study timeframe: 2000-2002 and 2007-2008.

The confirmatory analysis tests the hypotheses about the data. The hypothesis will be rejected if any of the individual indices have the capacity to measure droughts of

1998-2002 and 2007-2008 with the same onset, duration, severity and recovery as declared by the DRC.

4.4. Limitations

The nine-year data set is sufficient to make inference of drought conditions because during the selected period South Carolina experienced two droughts, 1998-2002 and 2007-2008, which were different in the area affected, duration and other characteristics. The earlier drought lasted almost two times longer, than the second one. The first drought in these periods had higher severity and affected larger territory and the other one was more intense for Savannah River basin. The research period starts when the first drought was ongoing and ends before the second drought's official end for the entire state, which provides fewer points to evaluate drought conditions.

There are several statistical tools that suit purpose of measuring degree of association between two qualities. The project utilized rank correlation coefficients such as Kendall's tau and Spearman's R. These statistical tools were used to analyze and compare the results of drought index outputs for the Florence County.

The data set has five categories (no drought, incipient, moderate, severe and extreme) and each category was assigned a number 0-4 reflecting the severity of drought month with 0 as no drought to 4 as extreme drought. The rank correlation coefficient statistical tools showed insignificant differences between the DRC drought declarations and values of drought indices. The results were not statistically significant and showed low-sensitivity of statistical tools for the research project because of the nature of the data set.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter analyses monthly values of drought indices and the DRC drought status declarations data that was compiled into figures. The chapter starts with brief county descriptions of results from Figures 5.1-5.5. The following four sections present key findings and discuss possible explanations of the results in each of four categories of measures – onset, duration, severity and recovery.

5.1 County description

The following Figures 5.1-5.5 are month by month values of the DRC and drought indices for a period of nine years for five South Carolina counties: Charleston, Edgefield, Florence, Oconee and Richland. The data from these figures demonstrates drought indices to have unique outputs for measuring drought and no pairing of indices shows identical results across the four metrics in measuring drought for any months in any county studied. As was suggested, no drought index shows matching results with the DRC in measuring drought, however some common trends have been observed and will be discussed later in this chapter.

The dataset allows an evaluation of the DRC and drought indices ability to measure **drought onset** in six instances (once for Charleston, Edgefield, Oconee and Richland counties and two times for Florence County). According to the DRC, Charleston, Edgefield, Florence, Oconee and Richland counties already experienced drought conditions in January 2000 when the dataset starts. Florence County, the only

county among the studied one which entered the first drought in May 2000, covered by data which allows analysis of drought onset for this county during two droughts. Oconee and Edgefield counties entered the second drought event in August 2006, while other three counties entered the second drought event in May 2007.

The results put the DRC **drought duration** in context of drought indices' measures, for both droughts and results vary within counties. The DRC measured the 2000-2002 drought lasted 39 months in Edgefield, Oconee and Richland, 35 months in Florence and 34 months in Charleston. The 2007-2008 drought mostly affected the Savannah River Basin and had less impact on other parts of the state. The second drought is more than two times shorter in Charleston (15 months) and Florence (16 months) counties. This drought is the longest in Oconee and Richland counties and lasted for 29 months there. Between these two major drought events most indices identified an inception of drought in 2004. In June 2004 the DRC declared an incipient drought for all South Carolina counties. However, the dry period did not last long, the declaration was lifted the following month.

The DRC and drought indices measure **drought severity** in Charleston County to be less than in other counties. The county with the most severe drought in months 2000-2002 is Edgefield County, and 2007-2008 is Oconee County.

The first drought period ends in November 2002 in Charleston County and in March 2003 other counties. The second drought period ends in October 2008 for Charleston County and in September 2008 for Florence County. In December 2008, when the study data set stops, Edgefield, Oconee and Richland still experienced drought conditions, which made seven cases to measure **drought recovery**.

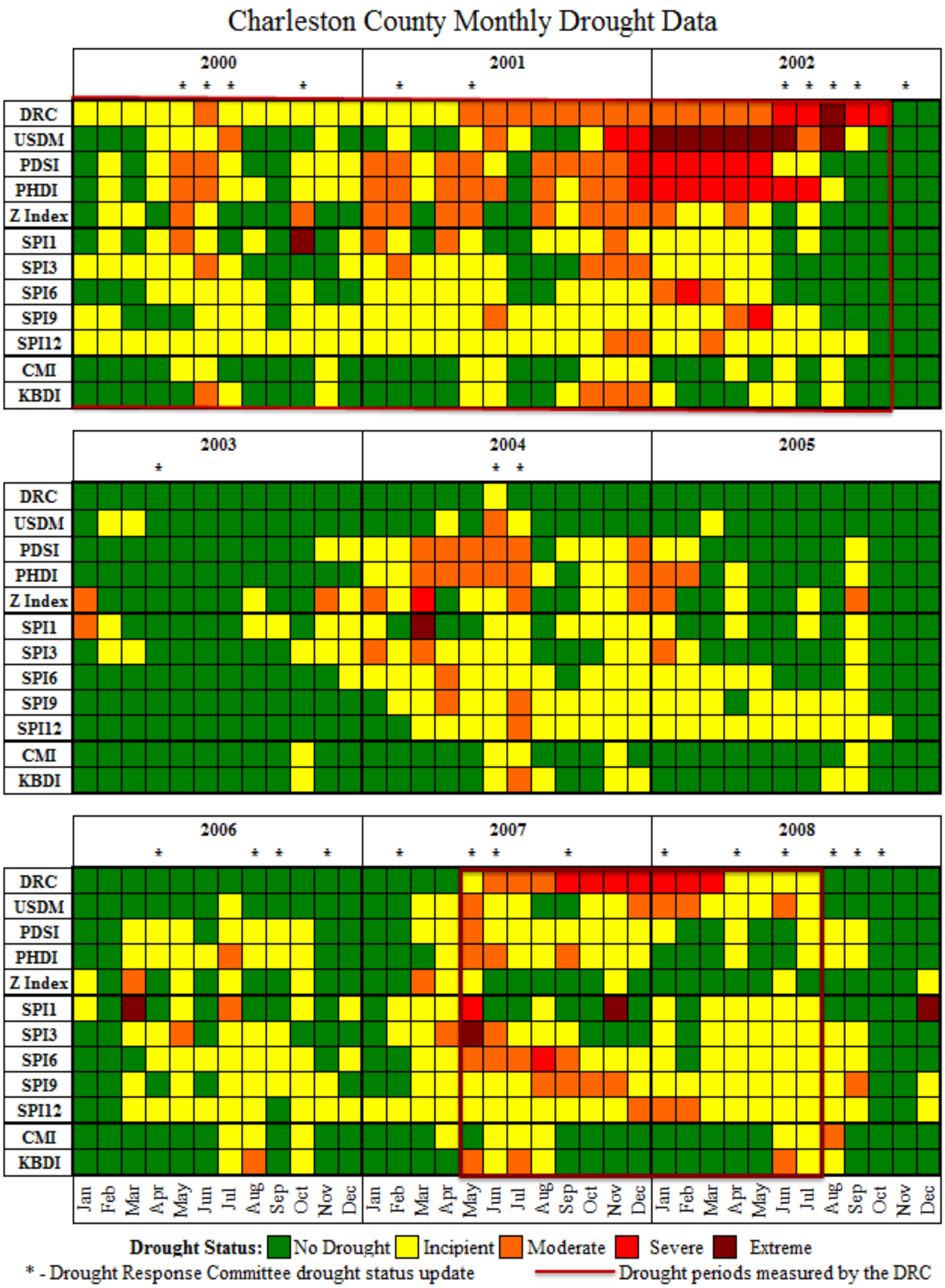


Figure 5.1: Charleston County drought indices results.

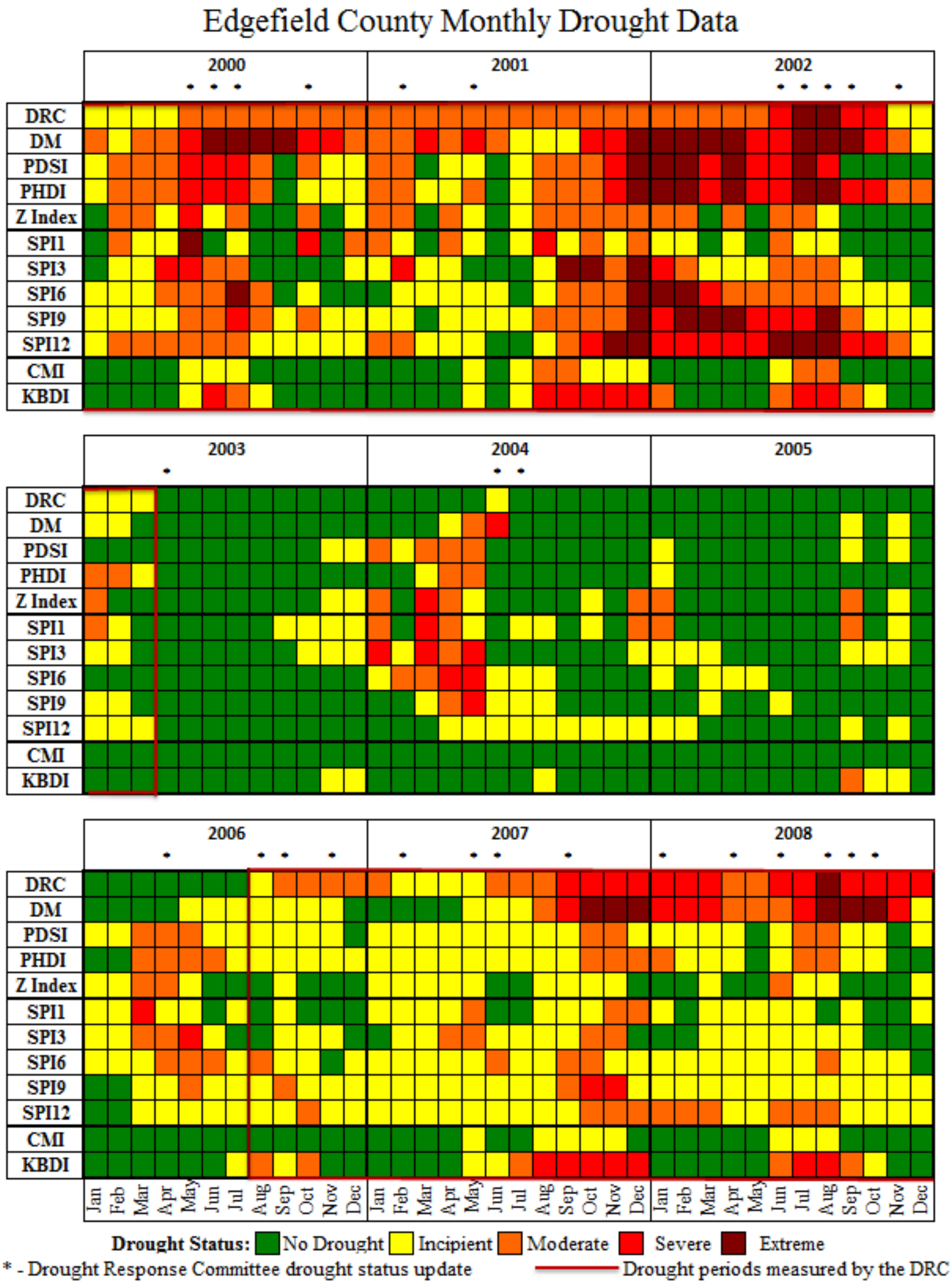


Figure 5.2: Edgefield County drought indices results.

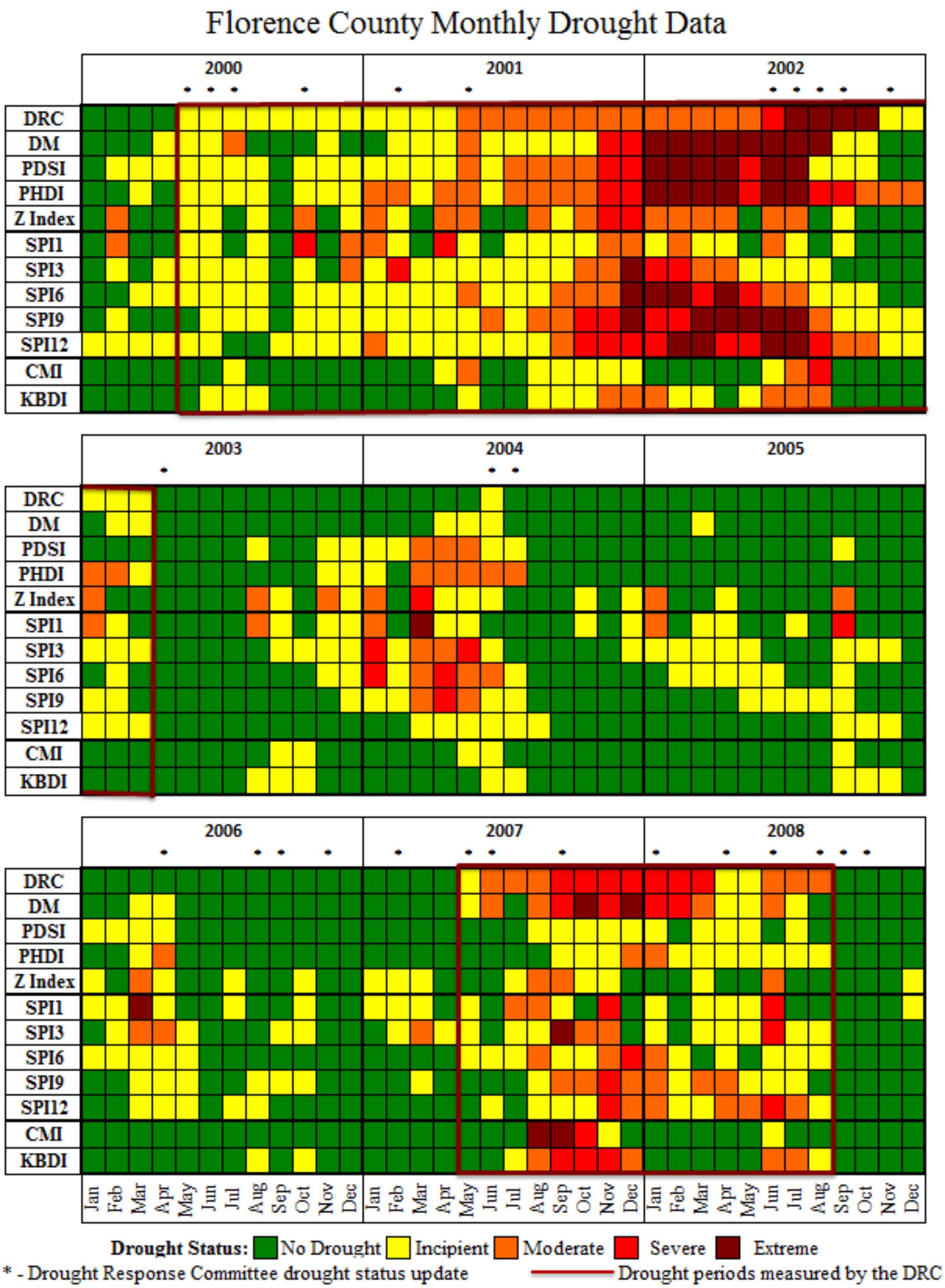


Figure 5.3: Florence County drought indices results.

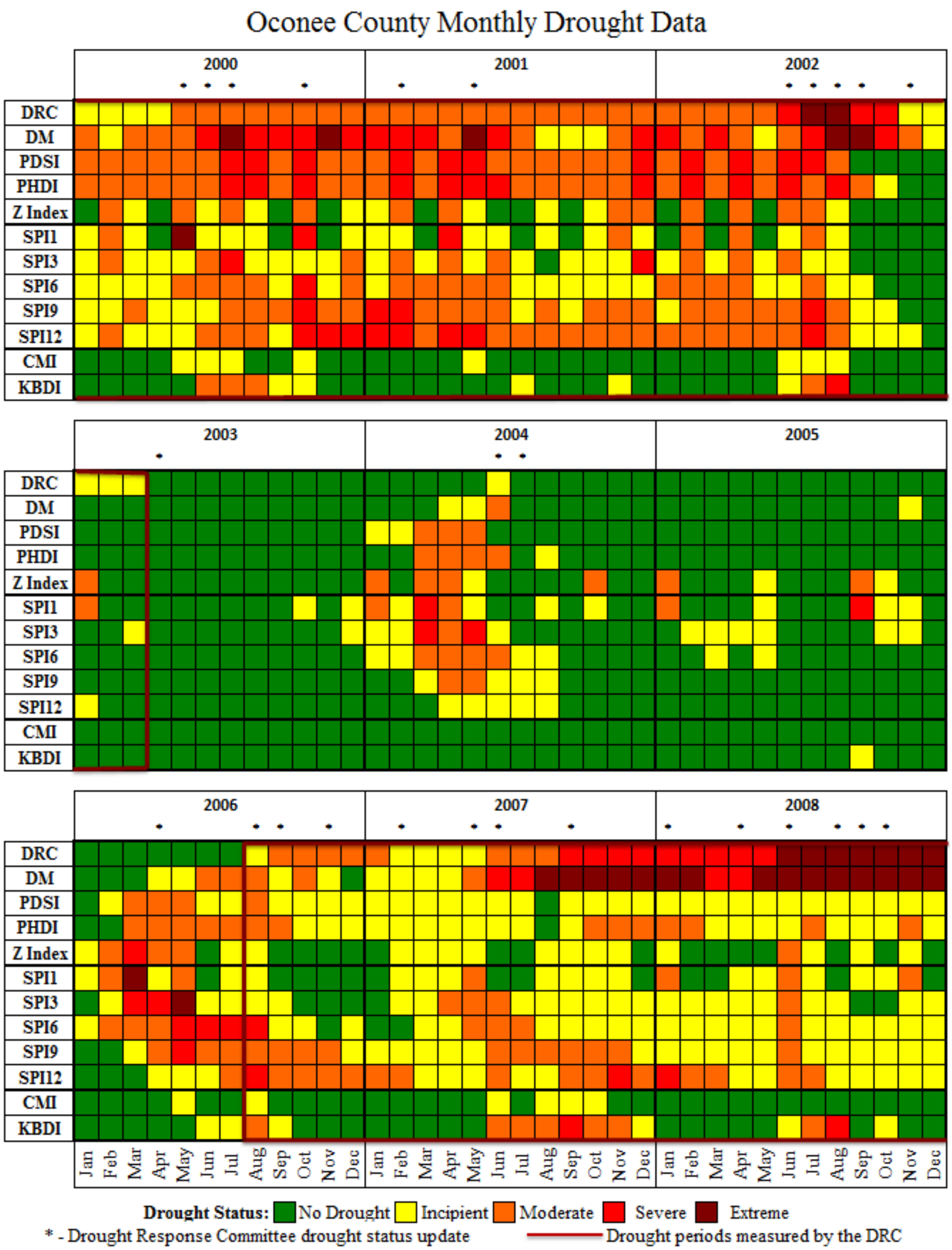


Figure 5.4: Oconee County drought indices results.

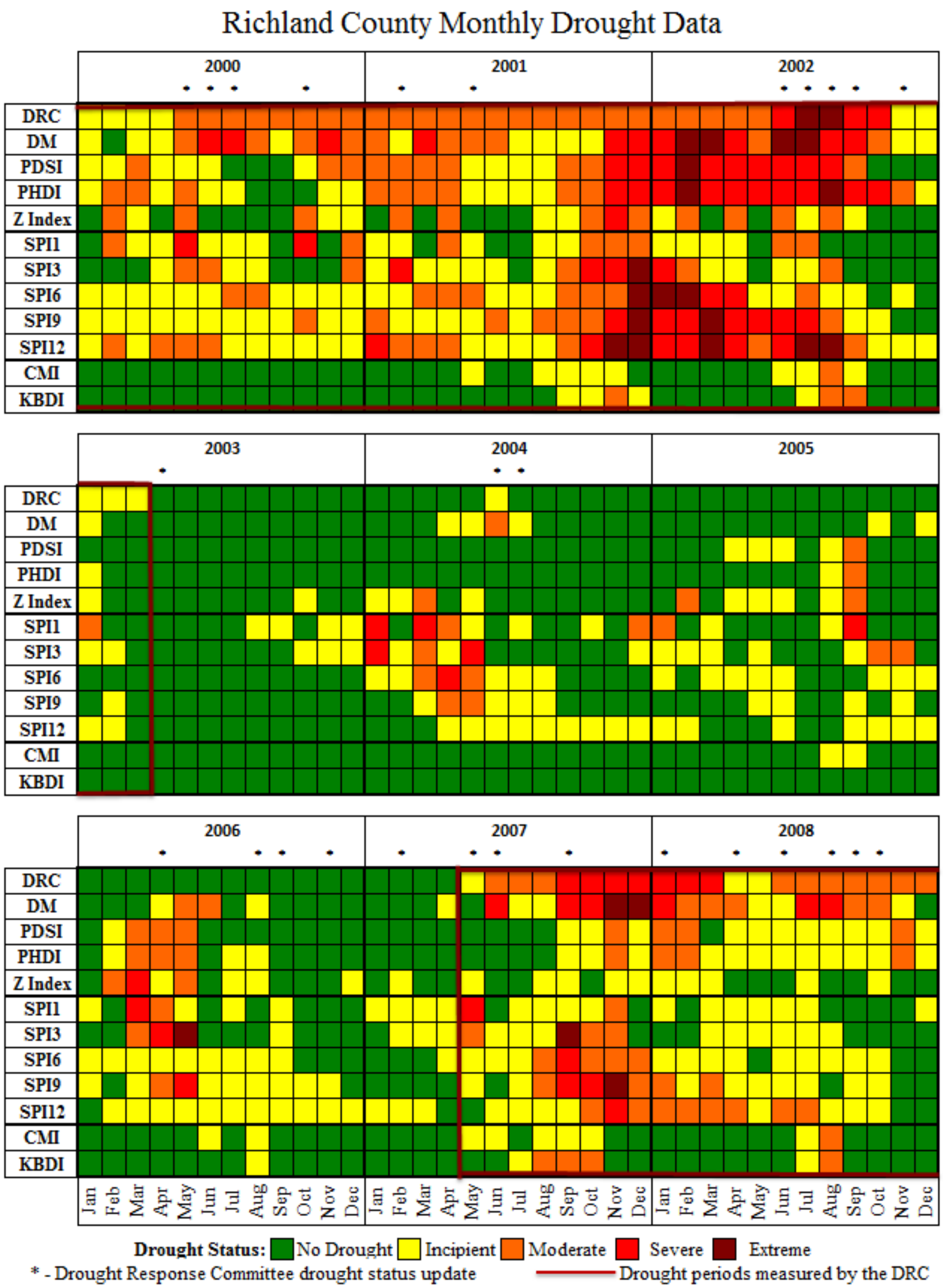


Figure 5.5: Richland County drought indices results.

5.2 Drought Onset

The comparison of the DRC drought declarations to other indices in measuring drought onset is synthesized in Table 5.1 and Table 5.2. Both tables have identical contents but color-coded differently to help to increase the understanding of specifics in measuring drought onset. Table 5.1 shows matches and highlights positive and negative numbers of months to show the lead and lag of drought indices in contrast to the DRC in declaring drought. The second table demonstrates the change in months between the DRC and drought indices in detecting drought onset. My initial hypothesis was, the DRC drought alert phases lag behind drought indices entering drought. The following discussion documents a more complex pattern that varies by index and county.

Table 5.1: Number of month difference in the DRC declarations in relation to drought indices to measure drought onset for two droughts color coded to highlight lag, match and advance cases.

SC County	Drought Onset	USDM	PDSI	PHDI	Z-Index	SPI1	SPI3	SPI6	SPI9	SPI12	CMI	KBDI
Florence	May-00	1	3	0	0	0	1	2	-1	4	-2	-1
Charleston	May-07	2	2	1	2	3	3	2	2	7	-1	0
Edgefield	Aug-06	3	7	5	-1	-1	-1	7	5	5	-9	1
Florence	May-07	0	-3	-4	-2	0	3	0	-3	-1	-3	-2
Oconee	Aug-06	4	6	5	1	1	6	7	5	4	0	2
Richland	May-07	0	-4	-4	0	4	3	1	0	-1	0	2

19.7%	DRC and index match	54.5%	Index before DRC	25.8%	DRC before index

Table 5.1 shows the DRC in relation to indices to measure drought onset for SC counties. In this table the green color is assigned to indices that declared drought at the same time as the DRC. Blue color indicates drought detection by the DRC before drought index. When drought indices precede the DRC status it is colored in red. For example, the

Florence County DRC drought status declarations lag behind five drought indices for drought that started May 2000 (Figure 5.3 and Table 5.1).

This table shows than the DRC lags behind other indices to detect drought in more than 50% of cases. The match between the DRC and drought indices happens little less than 20% times. The 2007-2008 drought was ongoing for a large part of the state, especially West and Central DMAs when the DRC updated the drought declaration for those parts of the state. The majority of drought indices put Edgefield and Oconee Counties in drought many months before the DRC did. Both counties are in Savannah DMA that got the hardest hit by the drought 2007-2008. Northeast and Southern parts of the state were not affected as much by that drought. Oconee County drought indices declares drought 4-5 months before the DRC.

Florence County has the largest number of indices lag the DRC in declaring the onset of 2007-2008 drought. The DRC exceeds seven drought indices to measure drought onset in May 2007. In this case the DRC matches the USDM, SPI1 and SPI6 and lags only SPI3 to measure drought onset.

In Charleston County, the incipient drought declaration in May 2007 lags behind drought indices with an exception of the short-term KBDI and the CMI. The DRC lags behind the most drought indices by 2-3 months.

The DRC drought status declaration for Edgefield County lags seven and exceeds three short-term indices. The incipient drought alert phase for Oconee County was declared in August 2006. This declaration matches the CMI output and lags behind all other indices. Richland County has the most diverse results. The declaration matches three indices, lags three indices, and exceeds five.

Table 5.2: Number of months between the DRC and drought indices in measuring drought onset color-coded to highlight the number of months differences between the DRC and the indices.

SC County	Drought Onset	USDM	PDSI	PHDI	Z-Index	SPI1	SPI3	SPI6	SPI9	SPI12	CMI	KBDI
Florence	May-00	1	3	0	0	0	1	2	-1	4	-2	-1
Charleston	May-07	2	2	1	2	3	3	2	2	7	0	0
Edgefield	Aug-06	3	7	5	-1	-1	-1	7	5	5	-9	1
Florence	May-07	0	-3	-4	-2	0	3	0	-3	-1	-3	-2
Oconee	Aug-06	4	6	5	1	1	6	7	5	4	0	2
Richland	May-07	0	-4	-4	0	4	3	1	0	-1	0	2

19.7%	Match	21.2%	1 month	16.7%	2 months	13.6%	3 months	28.8%	≥ 4 months

Table 5.2 illustrates the change in month counts between the DRC and drought indices to measure drought onset. This table is color coded to demonstrate the range of discrepancies in months between the DRC and the values of drought indices. In this instance, the direction of the change is omitted and only numerical value is taken into consideration when coding. The perfect matches are light green and darker green is a one-month difference between the DRC and a drought index. The three blue colors show 2, 3 and more than 4-month differences.

The match and the one-month difference between the DRC declarations and drought index occurred for 40.9% of the DRC decisions. The DRC matches or declares drought status within one month of the DRC, shorter SPIs, CMI and KBDI. The most frequent is the 4-months or more difference between the DRC drought declarations and indices.

Indices for Edgefield and Oconee counties show that these counties were in drought up to seven month ahead of the DRC declarations. The Committee met in April 2006 when the majority of indices showed drought for several months already for those

counties and not for the Coastal counties. The DRC declared the no drought status for the entire state at this time. That is why the Edgefield and Oconee counties have the longest periods between the indices drought statuses and actions of the DRC.

In declaring drought onset, in most cases, the DRC followed drought indices within 3-4 months. The results vary within DMAs. The DRC has more matching drought declarations for Florence and Richland counties in Pee Dee and Santee DMAs in contrast to declarations of drought onset for Oconee and Charleston County.

As both tables show, the DRC lags behind drought indices in determining drought onset in some cases and exceeds in other cases. The DRC declares drought two times more often after drought indicators were in drought and matched the onset according to drought indicators about 20% of the time. The USDM, the Z-Index and the SPI-1 measure drought onset about the same time as the DRC. Those indicators are more sensitive to changing drought conditions and can detect drought earlier in contrast to more long-term drought indices, such as the PDSI, the PHDI, 6-, 9- and 12- months SPIs.

Drought onset, as measured by the DRC was more consistent with the CMI and the KBDI than other indices, perhaps because of the increased attention to the feedback from agriculture and forestry. The CMI is an indicator of agricultural drought which works only in the growing season and is ineffective for a long-term drought-monitoring year around. However, the CMI had a perfect match with the DRC on three accounts, while showed 9-month lag in measuring drought onset in Edgefield County. The KBDI measures drought within the closest to the DRC month difference in comparison to all other indices.

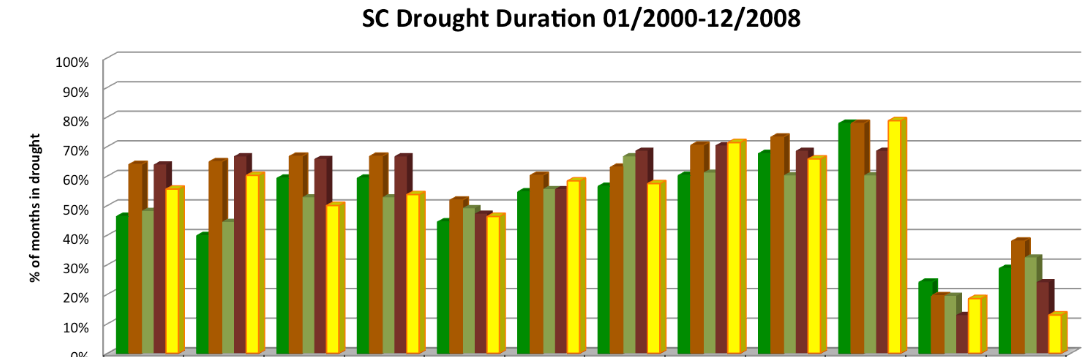
5.3 Drought Duration

This section evaluates drought duration without taking into account drought severity. Incipient, moderate, severe and extreme drought months are weighted equally. The severity analysis in the following Section 5.4 examines the duration of each severity stage for counties and drought indices. The initial hypothesis was that the DRC drought alert phases and drought indices identify different durations when measuring drought. The following analysis generally confirms that expectation. Even though the overall drought duration measured by the DRC is different from other indices, as a general rule, measured duration stays within a +/- 10% range from the DRC. The exceptions are the SPI12, the CMI and the KBDI. The SPI12 measures the longest drought duration for most counties. The CMI and the KBDI measure lower drought duration than other indices consistently for all counties.

Drought duration measures in percent of total months in drought from Figures 5.1-5.5 are presented in Figure 5.6**.** The Figure 5.6 shows Charleston, Edgefield, Florence, Oconee and Richland counties duration of combined drought stages for the DRC and drought indices in a context of measuring drought duration and taking into account all drought months, and not drought severity.

The study period consists of 108 months and the results of finding an average drought duration show that Edgefield County experienced the largest number of drought months as measured by majority of drought indices. The DRC, the PHDI and the SPI6 measured similar drought duration for Oconee County as for Edgefield County. Charleston County is in drought the least, followed by Florence and Richland counties.

They are measured to have same drought duration of about 50% of time for the study period.



	DRC	DM	PDSI	PHDI	Z-Index	SPI1	SPI3	SPI6	SPI9	SPI12	CMI	KBDI
Charleston	46%	40%	59%	59%	44%	55%	56%	60%	68%	78%	24%	29%
Edgefield	64%	65%	67%	67%	52%	60%	63%	70%	73%	78%	19%	38%
Florence	48%	44%	53%	53%	49%	56%	67%	61%	60%	60%	19%	32%
Oconee	64%	67%	66%	67%	47%	56%	69%	70%	69%	69%	13%	24%
Richland	56%	60%	50%	54%	46%	58%	57%	71%	66%	79%	19%	13%

Figure 5.6: South Carolina counties in any drought stage as measured by drought indices on a monthly scale for period 01/2000-12/2008 (n=108).

The total DRC drought declarations in month counts have the most similar values with the USDM. As far as total duration of drought the USDM, the PDSI, the PHDI and the SPI3 have very close results in measuring overall drought duration.

The SPI12 measured drought conditions to last longer than any other index. The SPI12 is a slow changing drought index and it puts counties in drought 60%-79% of the study period. This index is based on a 12-month period and changes less frequently which keeps area in drought longer. The SPI9 and SPI6 follow the SPI12 and measure drought on average 67% of the time. Averagely the DRC, the USDM and the SPI1 measure drought 55%-57%. The PDSI, the PHDI and the SPI3 range 58%-63%.

The least drought duration is measured by the short-term CMI. The results fell in rage of 13%-24% of months in all drought stages, which is up to six times less often than

measures of the SPI12. The KBDI measured the second less frequent drought duration. The KBDI on average puts the state into drought conditions 27% of total months in the study period with Edgefield County 38% of months and Richland County 13% of months. These results are expected for the CMI because this index is useful for the growing season only. The CMI and the KBDI put the state into drought conditions less often than any other index, however these two indicators have a high influence on the DRC drought declarations decisions as indicated by results. The CMI and the KBDI are important for the state drought declarations because they are good indicators of real-time effects on the ground and provide feedback of crop conditions and fire potential.

The following section talks about drought severity as measured for two drought periods and overall drought period. It is important to mention that, when drought duration is measured within drought periods, the DRC measures drought duration the longest in comparison to all other indices.

5.4 Drought Severity

The DRC declarations use four stages of drought intensity: incipient, moderate, severe and extreme. This study began with the hypothesis that the DRC drought alert phases would indicate different levels of drought severity than drought indices. The analysis showed that each county had a unique distribution of drought duration and severity as measured by drought indices and the DRC. It also revealed that the USDM measured the highest severity than any other drought index (Figure 5.7 – 5.8).

The DRC tends to change drought severity gradually. As a common rule, the DRC does not change severity more than one category when upgrades drought severity. However, when the DRC downgrades drought status, sometimes it jumps more than two-

three categories. For example, the first drought period the DRC downgraded drought severity from severe to no drought in Charleston County and from extreme to incipient in Florence County (Figure 5.7). The tendency of the DRC to jump more than one stage in measuring drought severity happens more often in the beginning of the dataset and not as often for the second drought event.

5.4.1 Comparison of 1998-2002 and 2007-2008 drought periods

The following figures show drought severity as measured by the DRC and drought indices for each county with the use of data from Figures 5.1 – 5.5 (sections of drought periods measured by the DRC). Figures 5.7 and 5.8 present drought severity values for two drought periods for each county. The figures consist of two parts, the top represents a drought period as measured by the DRC and the drought indices within the same time frame. The bottom part organizes the data in more comprehensible way by aligning the drought severity information in four drought types within the period.

As it was mentioned earlier, drought periods varied within counties and drought events. The 2000-2002 drought lasted longer and had stronger severity for the counties (Figure 5.7 and Figure 5.8). Charleston and Florence counties have more months in incipient stage while Edgefield and Oconee Counties experienced more moderate drought months within this drought period. The DRC has more months in moderate drought stage than any other index. Drought duration for overall study period is similar to USDM, SPI1 and SPI3. The DRC measures drought duration to be longer than drought indices within drought periods identified by the DRC. When taking into account drought duration identified by the DRC drought periods, the DRC was similar to the SPI drought duration outputs.

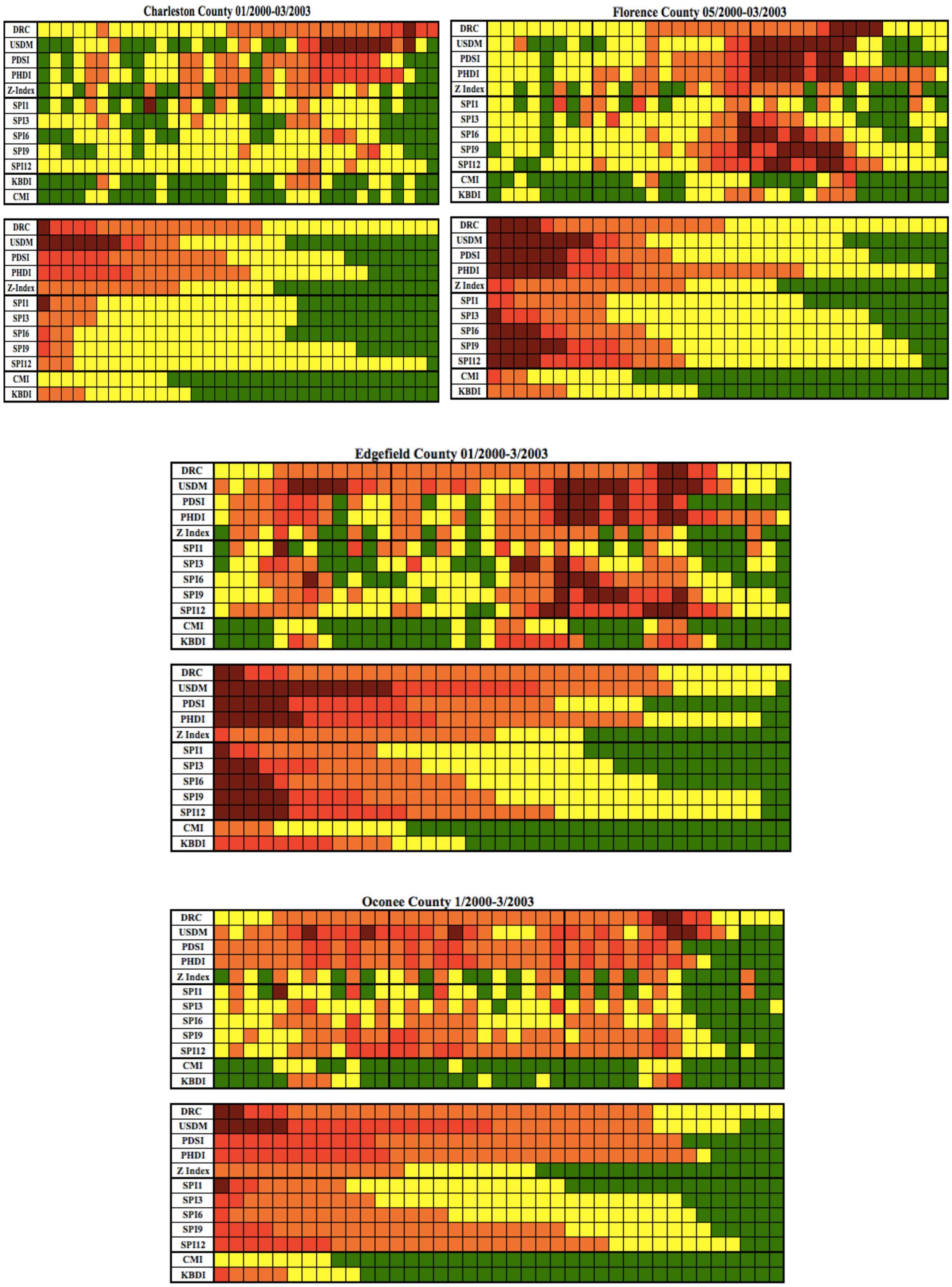


Figure 5.7: Monthly severity of the 2000-2002 drought measured by the DRC and drought indices for South Carolina counties (cont. next page).

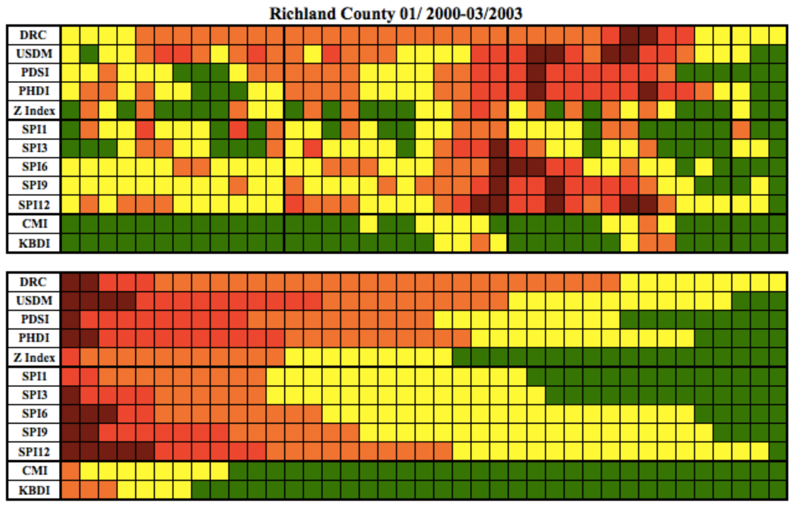


Figure 5.7: Monthly severity of the 2000-2002 drought measured by the DRC and drought indices for South Carolina counties.

The following 2007-2008 drought was two times shorter for most counties. This drought has more months in overall lower severity with the majority of months in incipient drought for all counties and less months in severe and extreme stage. In this case the DRC measured drought duration similar to SPI12 and SPI9 for Charleston, Oconee and Edgefield counties.

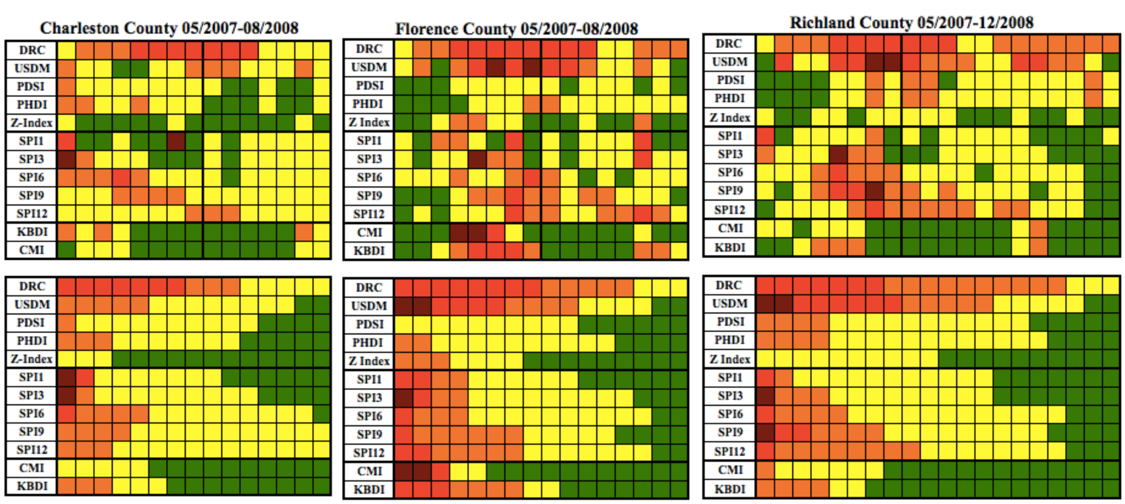


Figure 5.8: Monthly severity of the 2007-2008 drought measured by the DRC and drought indices for South Carolina Counties (cont. next page).

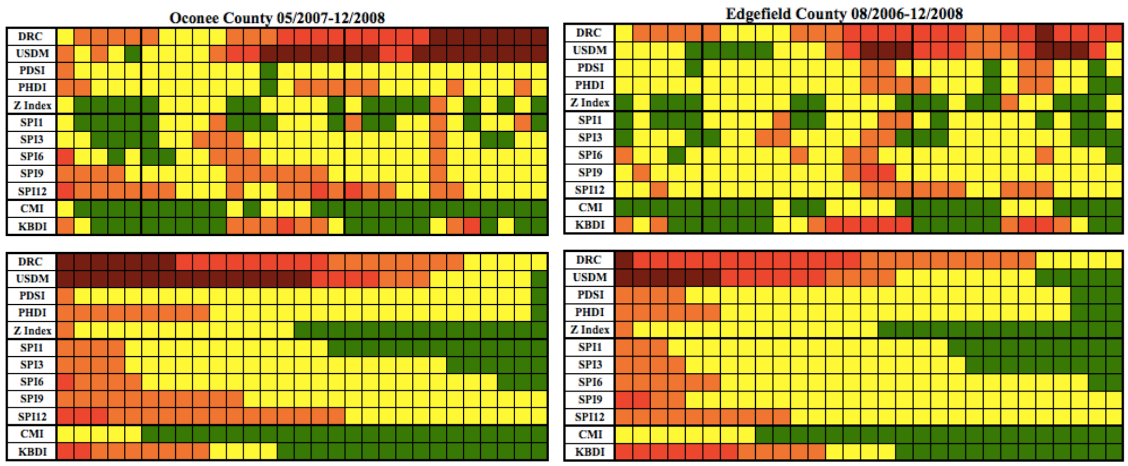


Figure 5.8: Monthly severity of the 2007-2008 drought measured by the DRC and drought indices for South Carolina Counties.

5.4.2 Overall drought severity of the study period

The previous section discusses drought severity within two drought periods. This section examines drought severity within the nine-year study period. Table 5.3 presents a range of each county's severity level durations for a period of 108 months according to the drought indices. As a general rule, the range of months in incipient stage is the largest, followed by moderate, severe and extreme. In the case of Oconee County, the extreme stage has a higher range than the severe stage. The largest percentage range is within incipient drought stage. For example, Charleston has 19%-71% of months in incipient drought as measured by the DRC and drought indices while percent ranges for other drought severities stay much smaller (moderate 1%-20% and extreme 0%-6% of months). The extreme drought stage has the smallest range of months in that stage of drought. Four out of five counties experienced 0% months in extreme drought for the Z-Index, the CMI and the KBDI. The inconsistencies between drought indices present extra difficulties for drought decision-makers to measure drought successfully.

Table 5.3: Range of drought duration in each drought severity for South Carolina counties as measured by different drought indices and given as percentage of months evaluated.

	Charleston	Edgefield	Florence	Oconee	Richland
Incipient	19%-71%	14%-49%	14%-48%	11%-49%	6%-51%
Moderate	1%-20%	4%-32%	6%-21%	0%-36%	2%-32%
Severe	0%-10%	0%-16%	2%-8%	0%-17%	0%-15%
Extreme	0%-6%	0%-17%	0%-9%	0%-19%	0%-6%

The following set of Figures 5.9-5.13 demonstrate drought severities as measured by the DRC and each drought index for each county for the entire study period. The columns are color coded according to drought stages outlined in the Act and supporting regulations and range from: yellow = incipient to burgundy = extreme. The figures show that the DRC is usually at a higher end of severe percentage. At the moderate percentage, a trend is present but not as prominent as the other one. Each index has a unique percent distribution of months in drought for four drought stages, probably influenced by climatological patterns of ongoing droughts and physiographic features of each county in different DMAs.

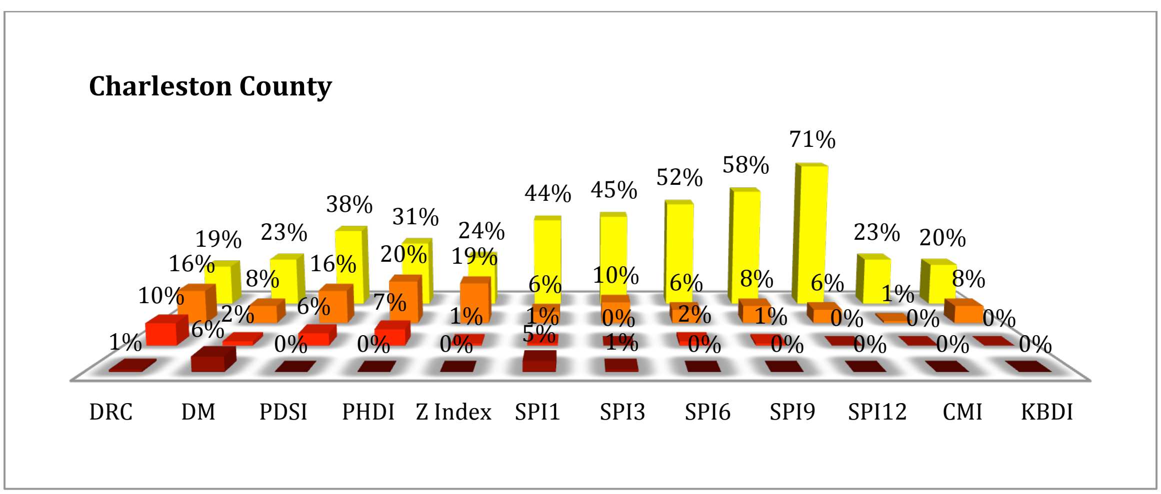


Figure 5.9: Charleston County drought severity as measured by the DRC and drought indices 01/2000-12/2008.

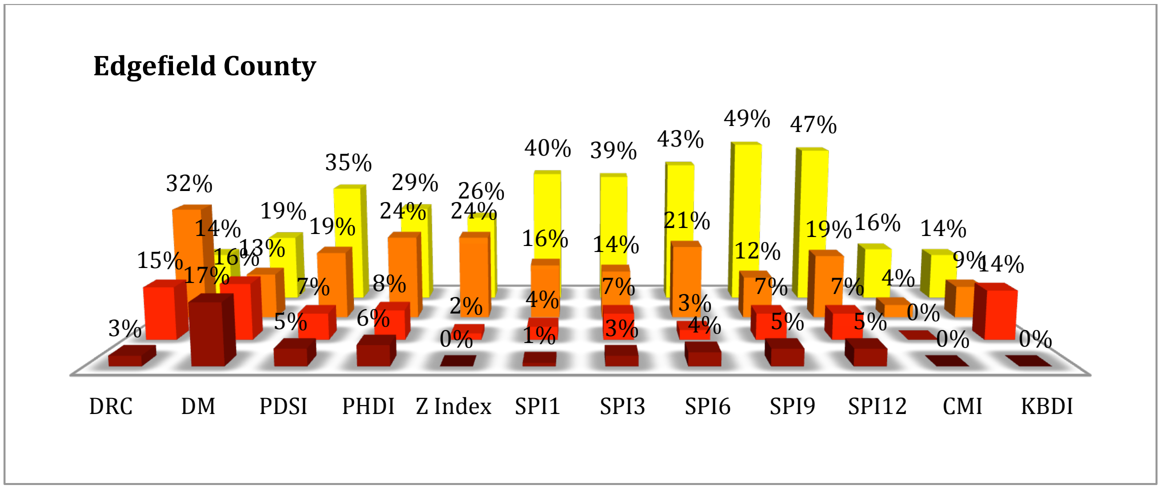


Figure 5.10: Edgefield County drought severity as measured by the DRC and drought indices 01/2000-12/2008.

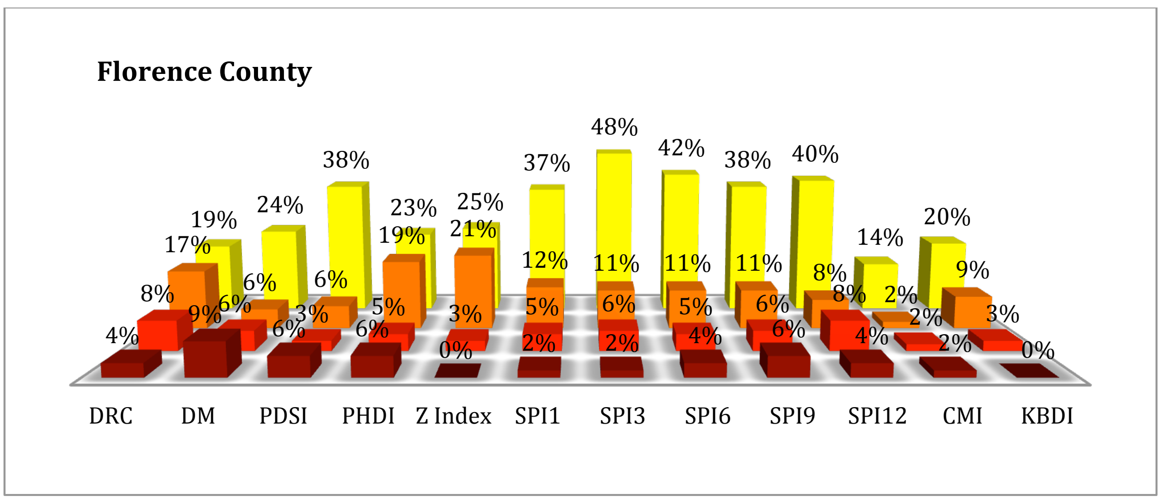


Figure 05.11: Florence County drought severity as measured by the DRC and drought indices 01/2000-12/2008.

The SPIs in measuring incipient drought follow gradual increase of months in drought (see Charleston County Figure 5.9). The similar distribution is measured for other counties except Oconee County. The distribution of drought severities for the SPI is distributed gradually for most counties also.

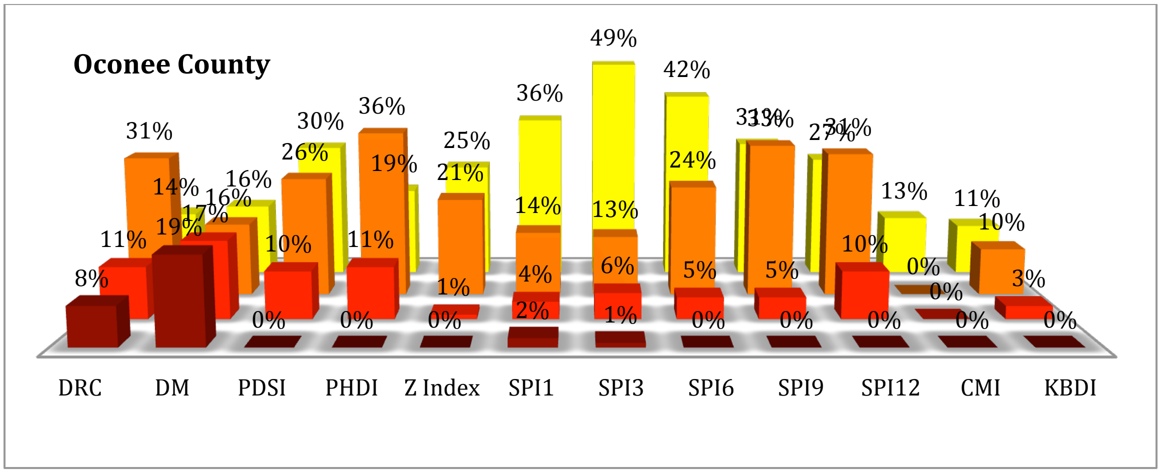


Figure 5.12: Oconee County drought severity as measured by the DRC and drought indices 01/2000-12/2008.

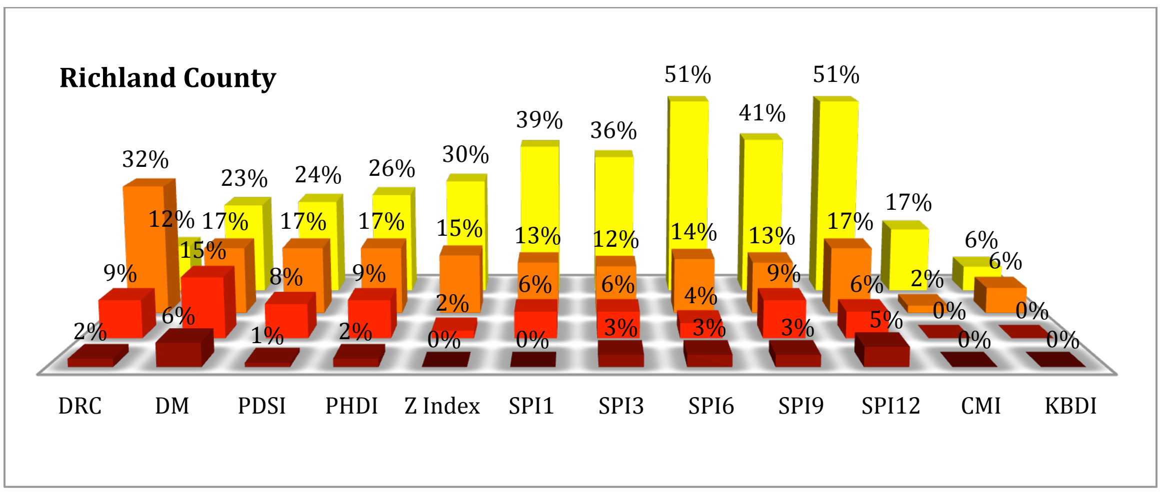


Figure 5.13: Richland County drought severity as measured by the DRC and drought indices 01/2000-12/2008.

The DRC drought declaration is the only measure that did not have counties fluctuating in and out of drought conditions. The SPI12 is the only index that is similar to the DRC persistency in keeping counties in drought with no drought relief breaks. In contrast to the DRC and the SPI12, all other indices indicate months of drought relief during each declared drought period. The DRC tends to ramp up severity gradually and in

order from incipient to extreme. In few cases the DRC changed drought severity declarations not in order. For example, Charleston County in April 2003 was downgraded to no drought after month in severe stage. However, the no drought declaration was supported by all other indices that month. The PDSI and PHDI have similar lengths and severities, with the PHDI keeping counties in drought longer with higher severity.

The SPIs are mostly consistent in drought duration and severity development from shorter and more sensitive SPI1 to the longest SPI12. The CMI and the KBDI show less drought months and lower severity as well. Typically, the CMI stays in incipient severity and reaches severe and extreme stage only for Florence County. The KBDI measured more drought months than the CMI, with each county in at least moderate drought months, but never reaches extreme drought stage.

Table 5.8: Differences in color codes between the USDM and the DRC.

Drought Stages	Index		Drought Stages
	DRC	USDM	
Incipient			D0 Abnormally Dry
Moderate			D1 Moderate
Severe			D2 Severe
Extreme			D3 Extreme
Exceptional			D4 Exceptional

The weekly USDM has more flexibility to respond to shorter drought events because it produces more frequent updates than most other indices and the DRC. In general, the USDM has stronger severity values than the DRC or any other drought index for both droughts. That can be explained by the fact that the USDM has more drought stages and different color-coding setup than the DRC. The USDM uses 5 drought categories and the DRC has four. Even though the USDM uses same colors as the DRC,

the USDM shifts codes severity at the moderate stage (see Table 5.4).

The first stage of drought, incipient by the DRC standards and D0 Abnormally Dry by the USDM, are both colored yellow. The second stage is moderate for both, but the DRC's color is orange and the USDM is another color that the DRC does not utilize, pale orange. That is where the color coding discrepancies and measuring of drought severity by the DRC and the USDM originate. The next stage, severe, is red for the DRC but orange for the USDM. The extreme drought is burgundy for the DRC and red for the USDM. The DRC does not use the D4 stage separately, it integrates this level with the previous one. The USDM reaches D1 moderate and D2 severe more often than DRC.

Due to these differences the USDM have stronger drought severity outputs than the DRC drought alert phases. Because of this shift in color codes, decision-makers that are familiar with the DRC color scheme consider the USDM outputs less severe than they actually occurred.

5.5 Drought Recovery

The recovery section uses the same techniques as the onset section (5.2) in evaluation of drought recovery to address the hypothesis: the DRC alert phases lag behind drought indices in drought recovery. The comparison of the timing and the monthly differences of the DRC drought status declarations the drought indices in measuring drought recovery are indicated in Tables 5.5-5.6. Overall, the analysis supports this hypothesis, however the results show that the DRC measures drought recovery faster (1-2 months) than measures drought onset (3-4 months).

Charleston County was the first to exit both drought periods. The DRC declared recovery from 1998-2002 drought for Charleston County in November 2002, and in April

2003 the Committee removed the drought declaration for all South Carolina counties. This month drought indices and the DRC unanimously declared no drought for the first time since the beginning of the study period in January 2000. The 2007-2008 drought ended for Charleston County in August 2008 and for Florence County in September 2008. Edgefield, Oconee and Richland were in drought conditions into December 2008. For Florence County, all drought indices measured no drought the same month as the DRC changed the status, and the no drought status lasted for the next three months for all drought indices.

In declaring drought recovery the DRC matches drought indices 15.6% and lags behind 74% (Table 5.5). For 1998-2002 drought the DRC did not precede any indices in measuring drought recovery. Two entries for recovery from 2007-2008 drought show that the Augusts 2008 DRC's status declaration to end drought in Charleston County was supported by only three indices. For the same drought period, the DRC declaration to end drought matched five drought indices for Florence County.

Table 5.9: The DRC declarations in relation to drought indices to measured drought recovery for two droughts.

SC County	Drought Recovery	USDM	PDSI	PHDI	Z-Index	SPI1	SPI3	SPI6	SPI9	SPI12	CMI	KBDI
Charleston	Nov-02	1	3	2	3	3	5	5	3	1	2	2
Edgefield	Apr-03	1	7	0	2	1	1	4	1	0	7	5
Florence	Apr-03	0	5	0	2	1	1	3	1	0	7	5
Oconee	Apr-03	3	7	5	2	2	0	6	5	2	7	7
Richland	Apr-03	2	6	2	2	2	1	3	1	1	6	6
Charleston	Aug-08	0	-2	-2	1	0	-2	-2	-2	-2	-1	-1
Florence	Sep-08	1	1	0	2	2	0	0	1	0	2	0

15.6%	DRC and index match	74%	Index before DRC	10.4%	DRC before index

The perfect matches of the months and 1-month differences in identifying drought recovery happened more than 33%. The SPI12 and the USDM had the closest periods

within counties in determining drought recovery. The Z-Index measured the end of drought mostly two months before the DRC declarations. The PDSI, the CMI and the KBDI indicated the end of 1998-2002 drought, especially for Edgefield, Florence, Oconee and Richland counties many months before the rest of the indices, suggesting that these indices are not measuring drought effectively in non-growing season.

Table 5.10: Differences in months between the DRC and drought indices in measuring drought recovery.

SC County	Drought Recovery	USDM	PDSI	PHDI	Z-Index	SPI1	SPI3	SPI6	SPI9	SPI12	CMI	KBDI
Charleston	Nov-02	1	3	2	3	3	5	5	3	1	2	2
Edgefield	Apr-03	1	7	0	2	1	1	4	1	0	7	5
Florence	Apr-03	0	5	0	2	1	1	3	1	0	7	5
Oconee	Apr-03	3	7	5	2	2	0	6	5	2	7	7
Richland	Apr-03	2	6	2	2	2	1	3	1	1	6	6
Charleston	Aug-08	0	-2	-2	1	0	-2	-2	-2	-2	-1	-1
Florence	Sep-08	1	1	0	2	2	0	0	1	0	2	0

15.6%	Match	23.4%	1 month	27.3%	2 months	9.1%	3 months	24.7%	≥ 4 months

The DRC agreed with drought indices more often in measuring drought recovery than evaluating an onset of drought conditions. The DRC lagged behind to detect drought recovery due to the frequency of the meetings, but lifted drought declarations when all indices show no drought in all but one case (Charleston, August 2008, Figure 5.1). As a general rule, the DRC lifted drought declarations within 1-2 months in comparison to drought indices values. In contrast, the DRC's measures of drought onset lagged behind drought indices for 3-4 months and longer.

The key findings of this research are summarized in the chapter 6. The conclusion outlines trends and major patterns of similarities and differences in measuring drought between the DRC and drought indices. The following chapter also describes limitations

of the study and suggests questions for future research. The concluding paragraphs suggest the significance of the study and put this research in a broader context of improving drought monitoring and early warning systems.

CHAPTER 6

CONCLUSION

This study examined four characteristics of drought. Drought onset, duration, severity and recovery were compared between the drought decision-makers decisions and values of drought indices for the same period. The study examined how state drought decisions relate to drought indices. The research covers a 9-year period during which the state experienced two major drought events. The data set length limits this research to values of 108 months. South Carolina has 46 counties that are organized into four drought management areas (DMAs). The research examined at least one county in each DMA. This study is a unique contribution to drought indices research as this type of analysis has not been done previously.

As it has been suggested, no single indicator measured droughts to the same extent as the DRC. The Figures 5.1-5.5 demonstrate that during the study period there was no single month when all of indices agreed in measuring drought severity. The Outer Coastal Plain County ACE (Southern) DMA's Charleston County experienced the least number of months in drought. The Piedmont region in the West (Savannah) DMA's Edgefield County had the largest number of drought months.

The research compared the DRC declarations and drought indices and the following patterns emerged. With respect to the four original hypotheses, the study illustrated the significance of differences in indices and counties. Overall the hypothesis came to be understood as quite general. The only hypothesis fully supported by the data

was that the DRC alert phases lag behind drought indices in drought recovery.

Going beyond the initial hypotheses, the research has four key findings:

1. The DRC changes less frequently than other indices. Figures 5.1-5.5 show the DRC outputs are presented as a continuous string of drought months between meetings in contrast to drought indices that alternate drought and no drought months within each drought episode. It can be explained by the fact that the DRC on average have 5-6 meeting per year, and drought indices have more frequent outputs.

1a) The DRC values are similar to the SPI12 in measuring drought duration and are conservative when measuring drought severity.

1b) The DRC tends to gradually change drought severity declarations.

1c) The DRC in most cases lagged in detecting drought by 2-3 months.

1d) The DRC was consistent with drought indices in measuring drought recovery and lagged 1-2 months (Table 5.5).

2. The DRC and the USDM have significant differences in ways to monitor and measure drought, both of them use a cumulative approach and consult different drought indicators when declaring drought updates. However, the USDM demonstrates the highest drought severity among other drought indices. The USDM uses five drought stages and the DRC uses four. The color-coding for both USDM and the DRC are similar, however, the USDM's severe stage is coded by orange color when the DRC's severe is red. Because color codes have different categorization (Table 5.4) the DRC seems to tend to interpret the USDM maps as less severe than they actually are.

3. The SPIs are a good measure of developing drought conditions, as it was suggested by the literature (Hayes et al. 2011 and Vicente-Serrano et al. 2012) In most cases the SPIs showed lower severity in measuring drought than the USDM, the PDSI and the PHDI.

4. The CMI and KBDI measured shorter drought durations than other drought indices. However, the DRC tends to consult these indices when it declares drought updates because they are linked directly to agricultural and fire risk impacts on the ground.

Overall these findings suggest the following. The DRC appears sensitive to drought management challenges, such as communicating water use restrictions, and is conservative in the way it changes status. The DRC tends to wait to declare no drought until all indicators are in "no drought" stage in order to protect ground water by keeping attention on water conservation for a longer period of time.

The DRC is more consistent with respect to drought indices in how it defines the end of drought rather than in how it declares drought onset. The SPIs proved to be similar to the DRC in measuring drought onset, but tend to measure lower drought severity than other indices. The ancillary indicators, such as CMI and the KBDI report fewer drought months than other indices but are good measures of drought impacts to agriculture and forestry.

As a suggestion for future directions in improving drought monitoring and the management program, drought decision-makers might find useful an integration of theoretical drought forecasts when estimating drought conditions. Drought Monitoring

and Hydrologic Forecasting with the VIC model[2] is an example of such a tool, and others are also available. The use of drought forecast models provides decision-makers with a future outlook of drought conditions that cannot be fulfilled by the exclusive use of drought indices.

More research is needed to fill gaps in understanding how drought decision-makers use drought indices to measure drought for other temporal and spatial scales. This research uses a sample of five South Carolina counties in different drought management areas. The DRC usually makes drought decisions based on DMAs. Future research can look into different spatial scale and compare drought indices output for overall DMAs or climate divisions and physiographic regions. It will be also useful to do case studies with patterns of drought emergence, for example fast vs. slow on set droughts. One of the limitations of the study is the length of data set archives, which restricted the number of cases of drought onset and recovery examined. It would be interesting to understand how drought measurement patterns change during a longer time frame.

Steinmann and Cavalcanti (2006) suggest that drought indices are one of several inputs to drought decision-making, and not a replacement for human expertise and other quantitative and qualitative information about drought conditions. Future investigations may also examine the process of declaring drought status as discussions take place in the DRC meetings.

Consistent and effective drought monitoring allows application of timely impact reduction techniques. Proactive drought management also allows time to deal with

[2] http://hydrology.princeton.edu/forecast/current.php

situations using a risk management strategy, rather than a crisis management strategy, which helps to reduce drought impacts.

The benefit of the South Carolina's Drought Management program case study is the fact that the program uses one of the largest number of drought indicators available on a state level. Future research can evaluate how decision-makers in other regions use drought indicators, and perhaps with different analysis tools. This research uses visual analysis of figures and there is a need to integrate statistical tools to measure a degree of interdependency between drought indices and decision-makers drought declarations.

The analysis of drought indices provides a better understanding of the complexity of drought measurement and evaluation for government officials, stakeholders in water resource management, and others concerned about drought management. It is also consistent with the WMO aim to help countries, regions and communities move toward approaches that embrace drought preparedness and mitigation, focusing on the need for more coordinated proactive polices to manage the risks of drought (WMO and UNCCD 2012). The South Carolina drought management program, including the work of the DRC, is a valuable example of an assessment of drought indicators for policy purposes and can be used in advisement for drought triggers in other regions of the country and the world.

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