ANALYSIS OF DROUGHT CONDITIONS IN NEW HAMPSHIRE

J. Matthew Davis
Department of Earth Sciences
University of New Hampshire

Mary Stampone
Department of Geography
University of New Hampshire

Prepared for:
New Hampshire Department of Environmental Services

December 2014

Table of Contents

Acknowledgements 1
INTRODUCTION 2
Study Objectives 3
Overview of Drought 4
DROUGHT MONITORING 8
Palmer Drought Indices 10
Standardized Precipitation Index 11
Stream flow 12
DATA 12
Climate Data 12
Streamflow Data 17
Soil Moisture Data 18
Groundwater Data 20
Snow Data 21
ANALYSIS 22
Climate Data 22
Streamflow 24
"Drought Scores" 27
Indices 28
Palmer Drought Indices 28
Standardized Precipitation Index 29
RESULTS 30
Drought Occurrences 30
Spatial Variability 31
Seasonality 33
Recurrence Intervals 34
Frequency of Occurrence 35
Optimized Drought Blend 37
DMA Composite Plots 38
Coastal Drainage 38

Southern Interior 39
South Western 39
White Mountains 40
North Country 40
Ground Water 46
Reservoirs (Lake Winnipesaukee) 48
Snow 51
Soil Moisture 55
APPLICATION ISSUES 56
U.S. Drought Monitor 57
nhdrought.org 57
2010 Drought Event Example 60
RECOMMENDATIONS 65
Drought Management Areas 65
Drought Classes 65
Drought Triggers and Associated Data Sources 66
Precipitation 66
Streamflow 68
Palmer Drought Indices 69
Groundwater Levels 70
Snow 73
Soil Moisture 73
Summary of Recommended Drought Triggers 74
WORKS CITED 76
APPENDIX A: Snow Depth Data for New Hampshire, 1884-2010 79
APPENDIX B: NCDC Fortran Programs 83
Code to Compute Palmer indices 83
Code to Compute Standardized Precipitation Index. 100
Appendix C: Parameter Estimates for Drought Blends 122
Seacoast Drainage 122
Southern Interior 123
South Western 124

White Mountains 125
North Country 126
Appendix D: Index Values at Drought Onset 127
Coastal Drainage 128
Southern Interior 132
South Western 136
White Mountains 140
North Country 143
Appendix E: SPIs for DMAs and Climate Divisions 146
Southern Climate Division 146
Northern Climate Division 147

Acknowledgements

Funding for this project was provided by the New Hampshire Department of Environmental Services through Cooperative Agreement #092811-88 with the University of New Hampshire. A significant portion of the data collection and analysis was conducted by Hannah Elkinton. The UNH Research Computing Center (Robert Anderson and Tad Hatch) provided assistance with the programming of the nhdrought.org website.

INTRODUCTION

Water scarcity is not often at the forefront of public concern in New Hampshire. Our climate is temperate, and the State typically receives abundant precipitation evenly distributed throughout the year. However, like any other region, New Hampshire is still prone to periodic anomalous decreases in rain- and snowfall leading to abnormally dry conditions – or drought. Notably, the State has experienced serious deficits during the early 1910s, the 1940s and famously, during the mid-1960s, during which time the State suffered a particularly severe drought (NH DES, 2008). In response to these concerns, the State of New Hampshire developed a Drought Management Plan (NHDES, 1990) that attempts to define the physical conditions used to rate the severity of a drought and triggering the specific management actions needed to

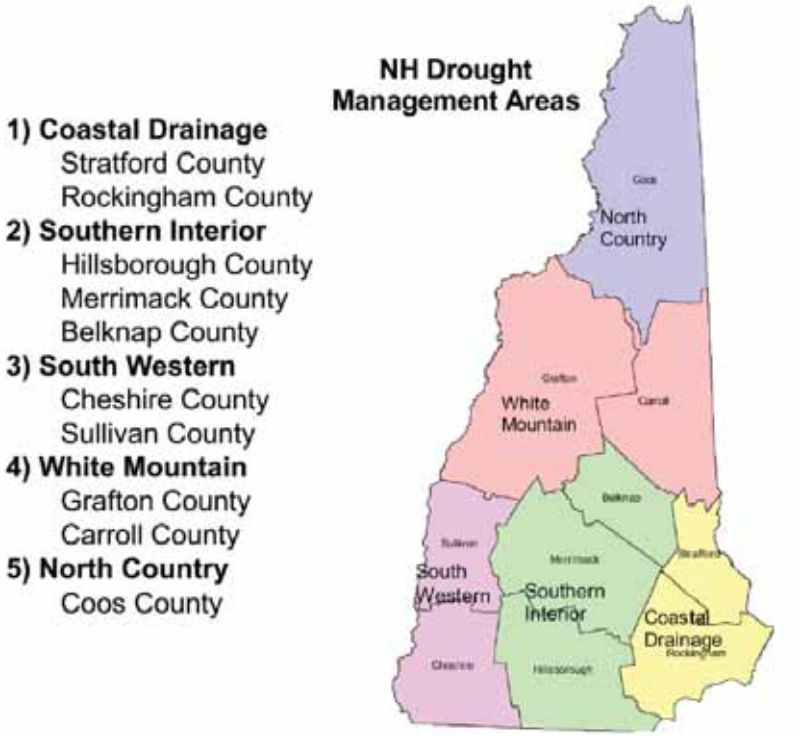


Figure 1. NH Drought Management Plan management areas and member counties. Taken from the New Hampshire Water Resources Primer (2008).

mitigate drought-related water stress. The 1990 Drought Management Plan (DMP) divides New Hampshire into five management areas: the North Country, White Mountain, South Western, Southern Interior and Coastal Drainage areas (Figure 1; NH DES, 2008). Drought Management Areas (DMA) boundaries are drawn along county lines; this configuration avoids the division of individual towns across management boundaries, which would unnecessarily complicate management response. The current DMP relies heavily on the Palmer Drought Severity Index (PDSI), which is typically calculated for both of New Hampshire's climate regions (north and south). Other indicators presently incorporated into the DMP include precipitation, stream flow, and groundwater levels. Departures in precipitation identified for various levels of drought have been chosen somewhat arbitrarily, and decreases in stream flow and groundwater in response to drought have been quantified for some levels of drought, but not all. As a result, the DMP's utility as a management tool is less than satisfactory.

Study Objectives

The following analysis of State historical drought conditions provides a basis for classifying and defining different drought levels and their associated meteorological and hydrological conditions. Drought conditions are assessed in terms of the meteorological (i.e. precipitation and temperature) and hydrological (i.e. stream flow and groundwater levels) variables that influence moisture availability in New Hampshire. Stream flow data, where low flows are interpreted as stream base flow in the absence of precipitation or other surface inputs (i.e. snow melt) and are derived from water stored upstream in the basin, provide an indirect measure of change in storage (Brutsaert, 2009). Additional correlation analyses considering relevant geo-spatial factors (topography, landcover, winter snow cover, etc.) that influence the hydrologic response to meteorological drought are also provided.

The correlation between stream low flows and drought indices calculated from historical climate data are analyzed to determine the most appropriate set of factors and indices for monitoring drought conditions in New Hampshire. By investigating these relationships, this study provides a more rigorous framework upon which State Drought Management responses can be formed.

This study was undertaken as part of a cooperative agreement between UNH and with NH-DES to revise the New Hampshire Drought Management Plan. NH-DES had primary responsibility for revising the DMP and UNH had primary responsibility for providing analysis and recommendations for drought triggers. This report summarizes the analysis and recommendations, specifically:

- Analysis of historical drought conditions and their associated hydrologic and meteorological metrics.
- Evaluate appropriateness and necessity of existing drought management areas.
- Evaluate the extent to which regional-scale drought level and impact reporting correlate with observed conditions in New Hampshire
- Identify alternative indices or additional data (e.g. soil moisture) that should supplement currently used indices in real-time drought monitoring.
- Apply information from historical drought conditions to inform appropriate drought levels and associated hydrometeorological triggers.
- Develop recommendations on the data collection necessary to detect, declare, and monitor drought conditions in the different hydrologic and climatologic regions of the state.

Overview of Drought

Droughts are regional meteorological events characterized by unusually or severely dry conditions, and may last several months to years. Drought, as an abnormal lack of moisture, is defined relative to long term climatic averages (30 years or longer) for any given region and the conditions that define a drought for one climate zone cannot be applied universally to others.

Likewise, drought conditions should not be confused with aridity, which describes a permanent feature of climate, rather than a temporary deviation from normal climate behavior. Operational definitions for drought vary by region and sector reflecting both the expected moisture availability for a given climate and demands on the water supply. For practical purposes, the definition of drought has therefore been expanded to include hydrologic and socioeconomic factors into four categories: meteorological, agricultural, hydrologic, and socioeconomic (Wilhite and Glantz, 1985).

Usually, moderate to extreme deficits in water availability are directly attributable to significant reductions in precipitation, although increased temperatures, wind, and solar radiation can also contribute to excessive drying (Dingman, 2008). These decreased precipitation conditions, known as meteorological drought, initially lead to drying at the surface, and a decrease in soil moisture (American Meteorological Society, 1997). As soil moisture diminishes to the point where water requirements of plants are no longer being met, the condition is considered to have transitioned to an agricultural drought (American Meteorological Society, 1997). If the precipitation deficit persists, surface and groundwater reservoirs will also begin to diminish, resulting in a hydrological drought. Often the impacts associated with hydrological droughts lag behind those of a meteorological drought, and may persist long after a meteorological drought has ended (Heim, 2002). A fourth classification of drought, called socio-economic drought, relates the supply and demand of economic goods to various aspects of the three previously defined droughts (American Meteorological Society, 1997). Considering the regional climate regime, water availability, and demands on the water supply, meteorological and hydrological drought are the most common drought conditions that occur statewide.

In New Hampshire, meteorological dry periods (reduced precipitation) and hydrologic dry periods (below normal stream flow) are typically concurrent, with the development of hydrologic dry periods largely dependent on the development of meteorological dry periods (Nash, 1993). More recently, Hodgkins et al. (2005) found a strong, significant correlation between summer precipitation and the magnitude of the lowest annual summer/early-fall stream flows in 23 watersheds across New England. Cases of non-concurrence generally occurred during the winter, and reflected the accumulation of precipitation as snowpack, where it was stored rather than entering stream flow (Nash 1993). However, these studies neglect the complex effects of temperature.

The primary interest in temperature is to better quantify the amount of water actually available in the system to potentially become stream flow. As noted above, increased temperatures often exacerbate drought by increasing evapotranspiration, effectually reducing the total water availability. Hodgkins et al. (2005) treats temperature as an entity separate from precipitation in the analysis of New England watersheds, and found a significant, though weak, negative correlation between temperature and the magnitude of the lowest summer/early-fall low flows. It is possible that the effects of temperature may also be significant during the cold season—where abnormally warm winter temperatures could impact the establishment or maintenance of snowpack (Burakowski, 2008; Hayhoe, 2007). As noted by Hodgkins et al. (2005), although snow melt does not contribute appreciably to summertime stream flows in New England, it does contribute to the recharge of groundwater, which then discharges to streams during the warmer season.

During a meteorological drought, water stored in aquifers and surface reservoirs becomes increasingly important to offset the deficit, especially in areas of high agricultural production.

However, New Hampshire's aquifers are constrained in both areal extent and potential yield by the State's underlying geology (USGS, 1996). Unconsolidated sand and gravel make up only 14% of our subsurface deposits, and are typically less than 100 feet thick (NH DES, 2008). In addition to our restricted groundwater storage, the State's surface water impoundments are generally targeted towards recreation and flood control, but also provide a mechanism for managing water supply, though with limited surface storage (NH DES, 2008). Thus, with New Hampshire's limited long-term water storage, even short-term precipitation deficits can have serious consequences for the State's water use.

By establishing correlations in New Hampshire for stream flow and available water (defined as the difference between precipitation and evapotranspiration), patterns in antecedent precipitation and temperature regimes associated with various magnitudes and durations of hydrological drought may be identified. This would potentially allow for more accurate projections of hydrological drought severity and duration. However, local responses around the State to drought conditions may depend on more than the characteristics of meteorological anomalies.

Although water stress is primarily tied to meteorological anomalies, the response of local hydrological systems to these anomalies may also be influenced by spatial characteristics inherent to a particular region. Larger studies of the northeastern United States indicate that, while the spatial characteristics of this region influence its response to various drought conditions as compared to the rest of the continental U.S., variation within this region is limited, and especially so over the even smaller sub-regions of New Hampshire (Dickerson and Dethier, 1970; Soule, 1990; and Leathers et al, 2000). Nash (1993) found few differences between the New Hampshire drought management regions in terms of the characteristics of dry periods,

although there was a slight bias for shorter but more severe dry periods to the south in the State and longer but less severe dry periods to the north in the State. Nonetheless, the variation of geo-spatial characteristics in New Hampshire may prove significant when topography, underlying geology, vegetation, and/or presence of snow pack are evaluated. All of these characteristics may impact regional ability to catch and retain precipitation in aquifers, surface reservoirs, and soils. Distribution of snowpack in particular may be important for characterizing the relative amount of springtime groundwater recharge over a particular management area, which influences the magnitude of summertime low flows (Hodgkins et al., 2005). These impacts, should they be identified through statistical analysis, would influence management decisions for each particular area, and may identify management areas that can be combined and managed under the same protocols.

DROUGHT MONITORING

Because drought has a wide influence on hydrology and associated spheres in agriculture, manufacturing, recreation, and drinking water supply, there is a strong desire to monitor, manage, and ultimately predict the occurrence and severity of drought. The Drought Monitor (DM), established in 1999, is the national platform for drought assessment and forecasting in the United States (Svoboda, 2002). The DM represents a partnership between the National Drought Mitigation Center (NDMC), the National Oceanic and Atmospheric Administration's Climate Prediction Center (NOAA/CPC), and the U.S. Department of Agriculture's World Agriculture Outlook Board (USDA/WAOB). The product is delivered weekly as a color-coded map with supplementary regional narratives. It designates five categories of drought, ranging from abnormally dry to exceptional drought, each associated with a percentile chance indicating the

likelihood of a particular magnitude of drought occurring in a particular year (Svoboda et al., 2002).

Although a variety of indicators are reviewed to create the DM maps, the primary indicators used to calculate the base index are the Palmer Drought Severity Index (PDSI), the 1-month Standardized Precipitation Index (SPI), and the Climate Prediction Center Soil Moisture (CPC/SM) model percentiles. These indicators are weighted, and used to calculate a "raw" Objective Blend of Drought Indicators (OBDI), which are computed for each climate division (Svoboda et al., 2002). Other indicators used to inform the accompanying narrative and to adjust the raw map based on regional input include: daily streamflow percentiles, percent of normal precipitation, Satellite Vegetation Health Index, Crop Moisture Index (CMI), the Keetch-Byram Drought Index, and the US Forest Service Fire Danger Map, among others. The rapid updating, ready availability, and solicitation of regional observations and expertise are among the benefits of this index.

However, a notable limitation of the DM stems from the raw OBDI index. Because the indices used to calculate this composite value respond to drought conditions over varying times scales, it is possible for drought conditions to be "averaged-out" when long- and short-term anomalies are in opposition. Another challenge in delivering weekly updates to the Drought Monitor is that the two major indices on which it relies are computed on a monthly basis. To address this disparity in time scales, Heim (2005) developed a methodology to compute updated Palmer and SPI indices by augmenting month-to-date precipitation and temperature records with climatological normal for remainder of the month.

Palmer Drought Indices

In the United States, drought conditions have been traditionally monitored using the Palmer Drought Severity Index (PDSI). Developed in the mid-sixties, the PDSI is a mathematical model estimating dryness based on precipitation and temperature inputs (Palmer, 1965; Alley, 1984; Heim, 2002). The index ratings can range from 'extremely wet' to 'extremely dry', and maps of drought conditions across the US are published weekly through the Climate Prediction Center[1].

The PDSI incorporates historical records of precipitation and temperature, and performs an accounting of moisture supply and demand based on the Thornthwaite method for determining potential evapotranspiration in a water balance model (Alley, 1984; Heim, 2002). It also utilizes Palmer's "climatologically appropriate for existing conditions" (CAFEC) quantities to normalize computations across varying climate regions (Alley, 1984; Heim, 2002). Thus, the index provides a dimensionless value that measures both anomalously dry and wet periods, and can be compared across space and time.

However, there have been several pertinent criticisms of the PDSI regarding the foundational assumptions of the model. There are concerns regarding how the water balance model handles potential evapotranspiration, soil moisture, runoff, and the distribution of precipitation and evapotranspiration over time (i.e. within a given week or month) (Alley, 1984; Heim, 2002). Additionally, the model fails to take into account the lag associated with the generation of excess water and the advent of runoff, as well as the seasonal or annual changes in vegetation cover and root development, and how these impact the water capacity of the modeled

[1] Available at http://www.cpc.ncep.noaa.gov/products/monitoring_and_data/

soil layers (Alley, 1984). Of particular relevance to New Hampshire, the PDSI does not take into account the effects of snowmelt and runoff (Alley, 1984), which have been shown to cause a break-down in the correlation between PDSI calculated and observed soil moisture content in regions where spring snow melt has a strong influence on soil moisture (Dai et al., 2004). Because of these limitations and others, the PDSI may not be the best means by which to designate drought in New Hampshire and should be supplemented with additional drought measures or replaced with an index that is better suited for this climate.

Standardized Precipitation Index

The Standardized Precipitation Index (SPI), like the PDSI, is a dimensionless index where negative and positive values correspond to dry and wet conditions, respectively. Historical precipitation data are used to compute the probability distributions of observed precipitation totals for a variety time scales, ranging from 1 - 48 months; probabilities are then normalized using the inverse normal (Gaussian) function (McKee et al. 1993, 1995; Heim 2002). The utility of the SPI is in its versatility for use over multiple time scales--allowing users to monitor the impacts of different types of drought as a function of duration (e.g. soil moisture conditions would respond to droughts on a relatively short time scale, where impacts to streamflow and groundwater would respond to more long-term anomalies). As a function of precipitation, SPI allows for evaluating both moisture deficits and surplus and, as a standardized index, is comparable across different climate zones (Guttman, 1998).

The World Meteorological Organization recommends the use of SPI for monitoring meteorological drought but it is limited for monitoring other types of drought (Trenberth et al. 2014). Users of the SPI should also note that length of precipitation record can impact SPI values. Historical records of varying length may have differing distributions, resulting in

different SPI values. Additionally, precipitation tends to be non-normally distributed so the method used to determine the probability distribution for total monthly precipitation will also impact the calculated SPI value (Mishra and Singh, 2010).

Stream flow

Stream flow records, and low flow records in particular, are useful indicators of drought both because of the abundance of available stream flow data, and the relationship of low flows to groundwater storage. Previous work has shown a high degree of correlation between meteorological droughts (i.e. precipitation deficits) and low flow stream data over 12- and 24-monthperiods (Huff and Changnon, 1964). Low flows are minimum flows averaged over consecutive-day periods, with seven days being a common length of time over which to average flows (Dingman, 2008). In the absence of precipitation inputs (or other surface water inputs, such as snow melt), low flows are interpreted as base flow in a stream—the stream flow derived from groundwater seeping into the stream channel (Dingman, 2008; Brutsaert, 2009). Thus, these low flows derived from water stored upstream can provide an indirect measure of changes in storage in response to long-term precipitation deficits (Brutsaert, 2009).

DATA

Historical data for the evaluation of past drought conditions in New Hampshire were obtained from a variety of sources and cover a range of hydrologic indicators. These indicators include climate data (precipitation, temperature), streamflow, soil moisture, ground water, reservoir levels, and seasonal snow cover.

Climate Data

Daily precipitation and temperature data were obtained for 20 stations within the United States Historical Climatology Network (US HCN), the Global Historic Climatology Network

(GHCN), and Quality Controlled Local Climatological Data (QCLCD) datasets. All stations were selected based on completeness of record and length (ideally, covering the sixty-year period from 1950-2010), with the aim to provide even, representative coverage across the state. In addition, stations were selected so that each drought management area has at least one meteorological station. Several stations in Vermont, Maine and Massachusetts were included in the analysis to minimize 'edge-effects' along the State boundary during spatial interpolation. Table 1 provides a complete list of station names, locations, and data sources.

In order to adequately represent atmospheric conditions within each drought management area for the 60-year period of analysis, several stations with incomplete records for part of the 1950-2010 period of record were included in the analysis. These stations are flagged for missing data according to the completeness of the station record for daily data over the 60-year period of analysis (Table 2). Flag attribution here is based on the completeness criteria for calculating station climate normal values as: complete (C), standard (S), representative (R), and provisional (P). Interpolated daily station data flagged as standard, representative, or provisional use filled values for missing daily data derived from nearby stations. Biases introduced by filled values are minimal and the filled station records are representative for each station over the period of record.

Station records are considered complete (C) if daily data for all months over the period of record are sufficiently complete (90 – 100%) for station data analysis. Complete station records may include less than 10% derived values for missing daily observations for use in interpolation at daily time scales. These station records are flagged as representative (R) for incomplete daily data or standard (S) if daily observations are missing for up to three consecutive years. Records flagged as standard may include monthly averages or totals derived from filled values for the

months with greater than 10% missing daily observations. Station records that are complete or representative over the station record but do not cover the entire period of record used in the analysis are flagged as provisional (P).

Table 1. Meteorological stations selected for analysis; includes the location, station identification number, start and end dates of data availability within the period of study, completeness flag, and the database from which the data was sourced.

Station	State	ID	Elev [m]	Data Availability (Period of Study)		Flag	Source
				Start	*End*		
Bethlehem 2	NH	270706	360	1950- 01	2010- 12	C/R	US HCN
Concord Mun. Airport	NH	271683	106	1950- 01	2010- 12	C	GHCN
Conway	NH	271732	146	1959- 01	1973- 09	P	GHCN
Durham	NH	272174	23	1950- 01	2010- 07	C/S	US HCN
First Connecticut Lake	NH	272999	503	1950- 01	2001- 12	P	US HCN
Greenland	NH	273626	26	1973- 08	2010- 12	P	GHCN
Hanover	NH	273850	178	1950- 01	2010- 12	C/S	US HCN
North Conway	NH	275995	166	1974- 03	2010- 12	P	QCLCD
Plymouth (1/2)	NH	276944/5	153/ 201	1950- 01	2007- 06	C/S	GHCN
Portsmouth	NH	276980	18	1956- 04	1970- 12	P	QCLCD
Keene	NH	274399	156	1950- 01	2010- 12	C/R	US HCN
Amherst	MA	190120	44	1950- 01	2010- 12	C/R	US HCN
Lawrence	MA	194105	15	1950- 01	2010- 12	C/R	US HCN
Farmington	ME	172765	128	1950- 01	2010- 12	C/R	US HCN
Lewiston	ME	174566	55	1950- 01	2002- 10	P	US HCN
Portland Jetport	ME	176905	14	1950- 01	2010- 12	C/R	QCLCD
Cavendish	VT	431243	256	1950- 01	2010- 12	C/R	US HCN
Chelsea	VT	431360	244	1950- 01	2000- 01	P	US HCN
Saint Johnsbury	VT	437054	213	1950- 01	2010- 12	C/R	US HCN

As noted in Table 1, several of the high-quality stations selected for analysis do not cover the complete study time period. These stations include Conway, North Conway, Portsmouth,

Greenland, and the two stations listed for Plymouth. Additionally, it may be assumed that even stations which are listed as covering the entire time period may have missing daily data. However, in order to use data from multiple stations to represent average conditions over a drought management area, , missing data needed to be minimized. The data filling process was two-fold: first, the six stations which do not cover the entire study period were paired as follows, and combined to create a single (paired) station: Greenland and Portsmouth, Conway and North Conway, and Plymouth-1 and Plymouth-2. The distance between these stations ranges from 3.9 km to 7.5 km and elevations differences are: 8 meters (Greenland and Portsmouth), 19 meters (Conway and North Conway), and 48 meters (Plymouth-1 and Plymouth-2). The second step was to fill each of the 17 remaining stations from their nearest geographical neighbor. Table 2 summarizes the location from which a particular station was filled, the percent of data missing prior to filling, and the percentage missing after filling was completed. Elevation corrections were not developed for either the filling of missing data or for the representativeness of individual stations to the drought management area as a whole.

Table 2. Meteorological data-filling summary; listed are the stations filled from, distance (km) between stations, and percentages of data missing at each station in each category (precipitation, maximum and minimum daily temperature), before and after filling. In cases of combined stations, the station used to measure distance has been starred.

Station	Filled From	Distance (km)	Elev Diff [m]	Percent Missing Pre- Fill			Percent Missing Post- Fill		
				Prcp	*Tmax*	*Tmin*	*Prcp*	*Tmax*	*Tmin*
Bethlehem 2	Saint Johnsbury	30.8	147	3.08	3.47	3.44	0.07	0.08	0.08
Conway*/ North Conway	Plymouth (1*/ 2)	53.1	30	16.01	15.97	15.97	0.99	1.95	1.78
Durham	Portsmouth	13.1	5	1.791	1.96	2.13	0.06	0.02	0.09
First Connecticut Lake	Saint Johnsbury	94.0	209	14.97	16.90	16.91	0.00	0.00	0.00
Greenland/ Portsmouth*	Durham	13.1	1	15.23	15.24	15.24	0.06	0.02	0.09
Hanover	Chelsea	34.2	66	1.71	2.08	1.69	0.27	0.39	0.40
Keene	Cavendish	55.2	100	2.54	2.55	2.54	0.01	0.00	0.00
Plymouth (1*/2)	Hanover	48.9	3	7.11	9.08	9.48	0.09	0.02	0.00
Amherst	Keene	63.5	112	0.91	0.80	0.71	0.00	0.01	0.00
Lawrence	Greenland/ Portsmouth*	51.3	9	3.30	1.43	1.76	0.10	0.00	0.00
Farmington	Lewiston	65.6	73	0.16	0.18	0.18	0.00	0.00	0.000
Lewiston	Portland Jetport	50.5	41	2.32	13.54	13.57	0.00	0.01	0.01
Portland Jetport	Lewiston	50.5	41	0.00	0.01	0.01	0.00	0.01	0.01
Cavendish	Hanover	43.4	78	0.19	0.30	0.22	0.00	0.00	0.000
Chelsea	Hanover	34.2	66	17.95	17.9	17.93	0.27	0.39	0.40
Saint Johnsbury	Bethlehem 2	30.8	147	1.26	1.40	1.40	0.06	0.07	0.07

Streamflow Data

Streamflow data were sourced from the United States Geological Survey (USGS) National Water Information System (NWIS) web interface. Stream basins selected for this study were preferentially chosen for length of record (covering the period 1950-2010), completeness of record, and minimal management or intervention (i.e. dams or other flow-controlling structures), with the goal being to identify two such basins per Drought Management Area.

The 1993 study conducted by Nash covered the same physical area and subdivisions (Drought Management Areas), and had much the same criteria for basin selection. Thus, Nash's stream candidates provided the foundation for the selection of candidates in this study. He identified 14 potential stream candidates from the greater Androscoggin, Connecticut, Merrimack, Saco and Piscataqua basins, listed in Table 3. Nash's criteria for selection also included an analysis of residence time for streams with reservoirs. Streams with reservoir residence times exceeding 30 days were eliminated from his study, except in three cases – the Merrimack, Ashuelot, and Mascoma rivers – which were retained for comparison purposes in his study (Nash 1993).

For this study, the Merrimack and Mascoma rivers were eliminated on the grounds of excessive regulation, with calculated residence times of 73.51 days and 56.80 days, respectively (Nash 1993). The Blackwater and Ossipee were eliminated for incompleteness of record—both gaging stations stopped collecting data approximately 40 years into the 60-year study period. Although the Souhegan river also has approximately 25 years of missing data (~1976-2001), the record still over-laps with several key drought periods, and was considered essential for the spatial analysis of drought, as it is the only stream basin contained entirely within the Southern Interior DMA. The Lamprey has also been retained for this study, because of its exceptionally complete record during the period of study and its size relative to the Coastal DMA. Thus, there

are 10 final stream candidates, all of which have been highlighted in Table 3, and are shown in Figure 2.

Table 3. Stream candidates as identified by Nash (1993), listed by Drought Management Area. Included are period of record, gauge location, and site number. Final candidates have been highlighted.

Drought Management Area	River	Gauge Location	Site Number	Record Length
1. Coastal Drainage	Oyster	Durham	01073000	1934-2010
	Lamprey	Newmarket	01073500	1934-2010
2. Southern Interior	Smith	Bristol	01078000	1918-2009
	Blackwater	Webster	01087000	1918-1989
	Merrimack	Franklin Junction	01081500	1903-2009
	Souhegan	Merrimack	01094000	1907-2009
3. South Western	Sugar	West Claremont	01152500	1928-2009
	Ashuelot	Hinsdale	01161000	1907-2009
4. White Mountain	Mascoma	Mascoma	01150500	1923-2004
	Pemigewasset	Plymouth	01076500	1903-2009
	Saco	Conway	01064500	1903-2010
	Ossipee	Effingham Falls	01065000	1942-1990
5. North Country	Diamond	Wentworth	01052500	1941-2010
	Upper Ammonoosuc	Groveton	01130000	1940-2004

Soil Moisture Data

Soil moisture data were obtained from two sources. For computation of drought indices, the soil moisture was sourced from the Climate Prediction Center (CPC) soil moisture model. This model is a one-layer bucket-type water balance model, where the driving inputs are precipitation and temperature (Fan 2004). Data are available at a monthly scale for the entire study period, with a resolution of 0.5 degrees. The half-degree block, whose center was closest to the calculated centroid of each DMA, was selected as representative of that area.

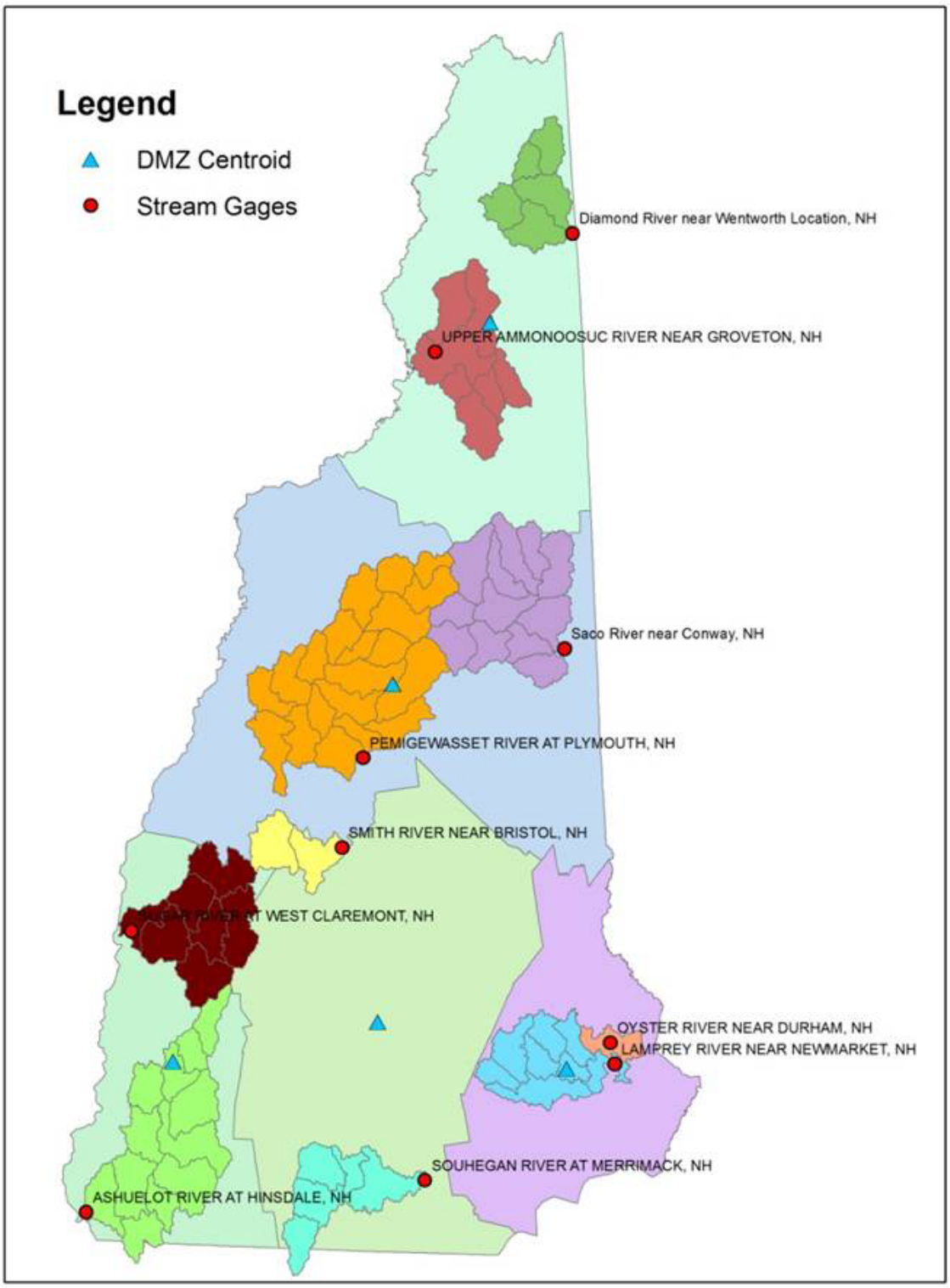


Figure 2. Map of drought management areas (DMA), stream gaging stations and associated drainage basins, and DMA centroids.

Soil moisture measurement data were also obtained from the two NRCS SCAN network stations located in New Hampshire (Mascoma River, Site #2043; and Hubbard Brook, Site #2069). Both are located in Grafton County (Drought Management Area 4). Because there is not sufficient historical data in multiple regions of the state and the historical data that do exist are limited in duration, it is not possible to incorporate soil moisture measurement data into the overall analysis of droughts throughout the five drought management areas. To provide some historical perspective on soil moisture conditions, the 25th percentiles for the average daily soil moisture at depths of 8, 20, and 40 cm are computed and provided as a benchmark.

Groundwater Data

As with streamflow data, groundwater data were sourced from the USGS NWIS web interface. Groundwater wells were also selected on the basis of length and completeness of record, where length of record was altered to include any wells with records dating back to the mid-1960s or earlier. Twelve wells were initially selected under these criteria, but four were eliminated as being impacted by nearby surface storage, or missing data during dry periods. Unfortunately, the number and distribution of wells dating back to the 1960's or further do not allow for there to be two representative wells per DMA (or in most cases, even one). Table 4 summarizes the period of record for which data are available for each well, and wells depths (only one well is listed as reaching into bedrock).

Table 4. Summary of selected groundwater wells.

Well ID	Town	DMA	Length of Record		Formation	Depth (ft)
			Start	*End*		
NH-LCW 1	Lancaster	5	1966	2011	Stratified Deposit	30
NH-ETW 1	Errol	5	1966	2011	Outwash	30
NT-HTW 5	Hooksett	2	1965	2011	Bedrock	103
NH-CVW 4	Concord	2	1966	2011	Lacustrine	41
NH-CVW 2	Concord	2	1963	2011	Stratified Deposit	60
NH-WCW 1	Warner	2	1965	2011	Outwash	43
NH-NLW 1	New London	2	1947	2011	Till	21

Snow Data

Snow depths are commonly used to assess drought conditions, particularly in the western states. For this study, we used a subset of the snow data compiled and analyzed by Burakowski and others [e.g. Burakowski et al., 2008] described in detail in Appendix A. For each Drought Management Area, the station with the most complete record for the period of study (Table 5) was characterized and evaluated as a potential metric for drought conditions in the DMA.

Table 5. Summary of selected snow data stations

Station ID	Name	DMA	Location			% Complete Oct 1 – May1 1950-2010
			Lat	*Long*	*Elev [m]*	
273626	Greenland	1	43.017	-70.833	25.9	60.0%
273182	Franklin Falls	2	43.467	-71.665	131.1	69.3%
275150	Marlow	3	43.118	-72.200	359.7	86.6%
278614	Tamworth4	4	43.858	-71.260	158.5	74.4%
271647	Colebrook	5	44.869	-71.540	341.4	74.2%

ANALYSIS

Climate Data

In order to re-calculate the various drought indices described above at the DMA level, both precipitation and temperature data had to be interpolated to the centroid of each DMA[2]. To achieve this, daily data values for each meteorological station were first summed to a monthly value. In the case of temperature, an average of the daily maximum and daily minimum values was calculated to obtain monthly maximum and minimum temperature values.

Once monthly datasets had been calculated, they were used to quantify spatial correlation and trending through variogram analysis. Variograms were calculated using WinGslib (Deutsch and Journel, 1998), using a lag separation distance of 60,000 feet, with a lag tolerance of 30,000 ft. Temperatures were found to trend strongly north-south. Monthly datasets for maximum and minimum temperature for each station were subsequently de-trended by subtracting the average value for the particular climate variable, for the particular station. Variogram ranges and sill values were then obtained from variogram estimates of the de-trended data. The ordinary kriging weight of each meteorological station was calculated for each of the five DMA centroids using the variogram ranges, sills, and geographic coordinates of the stations and centroids. These kriging weights were then used to calculate interpolated monthly precipitation, and maximum and minimum temperature values for each of the DMAs by multiplying each value at each station by its respective weight and summing the seventeen weighted values to obtain a single best estimate for the DMA.

[2] The geographic coordinates of the DMA centroids were computed using ArcGIS.

Kriging weights of the17 weather stations are shown in Table 6, with weights of the stations having the largest values underlined. In each Drought Management Area, three stations dominate and account for 90-99% of the weights. Negative weights often arise in the ordinary kriging equations as a result of data declustering and data shielding (Deutsch, 1996). When stations are clustered or multiple stations fall along the same line, the stations further from the estimation point may have slightly negative weights. Deutsch (1996) developed a method for removing negative weights though suggested that it only be applied in specific cases in which weights were being used to construct probability maps or dealing with non-negative physical

Table 6. Kriging weights for interpolation of meteorological data onto DMA centroids.

Station Name	DMA1	DMA2	DMA3	DMA4	DMA5
Amherst	-0.01	-0.01	-0.03	--	--
Bethlehem	--	-0.01	-0.01	0.21	0.37
Cavendish	--	0.02	0.21	-0.02	--
Chelsea	--	-0.02	-0.03	0.03	0.01
Concord	0.21	0.80	0.15	-0.01	-0.01
Conway/ North Conway	--	--	-0.01	0.21	0.13
Durham	0.59	-0.01	-0.01	0.01	--
Farmington	--	--	--	--	0.10
First Connecticut Lake	--	--	--	-0.01	0.46
Hanover	--	0.04	0.07	0.02	-0.01
Keene	--	0.11	0.63	-0.01	--
Lawrence	0.14	0.03	0.01	--	--
Lewiston	--	--	--	-0.01	0.04
Plymouth (1)/(2)	--	0.06	0.04	0.60	-0.04
Portland	-0.02	--	--	--	-0.02
Portsmouth/ Greenland	0.10	-0.01	-0.01	--	-0.01
St. Johnsbury	--	--	--	--	-0.01
Total	1.00	1.00	1.00	1.00	1.00

quantities that exhibit extreme variability (e.g. concentrations). Because neither of those criteria applies to temperature and precipitation, the weights were used as originally computed with the ordinary kriging equations. When data from a particular station were missing, the remainder of the weights were rescaled to sum to 1. For the calculation of the Palmer Index, which requires a single, average temperature value for each time step, the kriged maximum and minimum temperatures were averaged to get a single monthly value.

Streamflow

In order to identify a drought event in the record, and consequently classify its severity, daily 28-day flow volumes were calculated for each catchment. A 28-day interval was selected to better capture persistence in low flows in the record. Once the 28-day flows were calculated, an average 28-day flow for each day of the year was calculated based on the 60 years of data used in this study. With these averages, a daily percent of average 28-day flow was calculated for each catchment. Those days in which the average 28-day flow was calculated to be less than 65% of the daily normal were considered drought days. Daily percents of average for each basin were then run through a script that identified the start date of an event (the first day that the percent of average streamflow fell below 65%), counted the number of consecutive days in which the percent of average streamflow remained below 65%, and then recorded the end date for the event once streamflow recovered to above 65% of average. Discrete events were then binned based on severity (number of consecutive days) as described above, to get a count of the number of events at each level of severity, for each basin.

For the purposes of this study, each drought event was categorized into five classes: events lasting less than 1 month, 1-3 months, 3-6 months, 6-9 months, or 9-12 months. These five

classes are designated as D0 through D4 and defined according to the duration for which the 28-day streamflow is less than 65% of normal.

It is recognized that the Classes D0 and D1 defined here may represent wetter conditions than those intended by the corresponding categories of the US Drought Monitor. However, when comparing 28-day flows used here with the 7-day flows used by the US Drought Monitor, the 28-day streamflow is more representative of sustained dry periods. For example, Figures 3 and 4 illustrate a short event in 1995 in which the 28-day streamflow dropped below 65% of normal (a D0 Class using the 28-day flow metric) while, during the same event, the 7-day flow dropped well below the 25th percentile, which would have contributed to (but not solely determined) the declaration of a D1 Category in the Drought Monitor Classification. Similarly, the longer term event during 1995 was sustained in the 28-day cumulative flow metric (D2 event using the 28-day flow metric) and was intermittent with the 7-day flow metric (ranging from Normal to D3). Further comparison of the classification used here and that of the US Drought Monitor is presented in the Results section.

The use of the 28-day cumulative flow as the primary metric for assessing dry periods is, to a certain extent, a compromise between the approach of Nash (who used monthly flows) and the US Drought Monitor (that focuses on weekly flows). The 28-day flows metric is superior to monthly flows in that it helps to track events that span across months but do not include entire months. The U.S. Drought Monitor uses the percentiles of weekly flows as one factor when differentiating between drought levels. While an analysis could use the 7-day flow as the foundation, the fundamental limitation (as illustrated in Figure 4) is that 7-day flows are much more variable and result in a greater number of shorter-duration drought events. When relying on commonly used drought indices that are based on monthly meteorological conditions, we

expect the high frequency of 7-day events will obscure any relationships that may exist between hydrologic drought and monthly meteorological conditions.

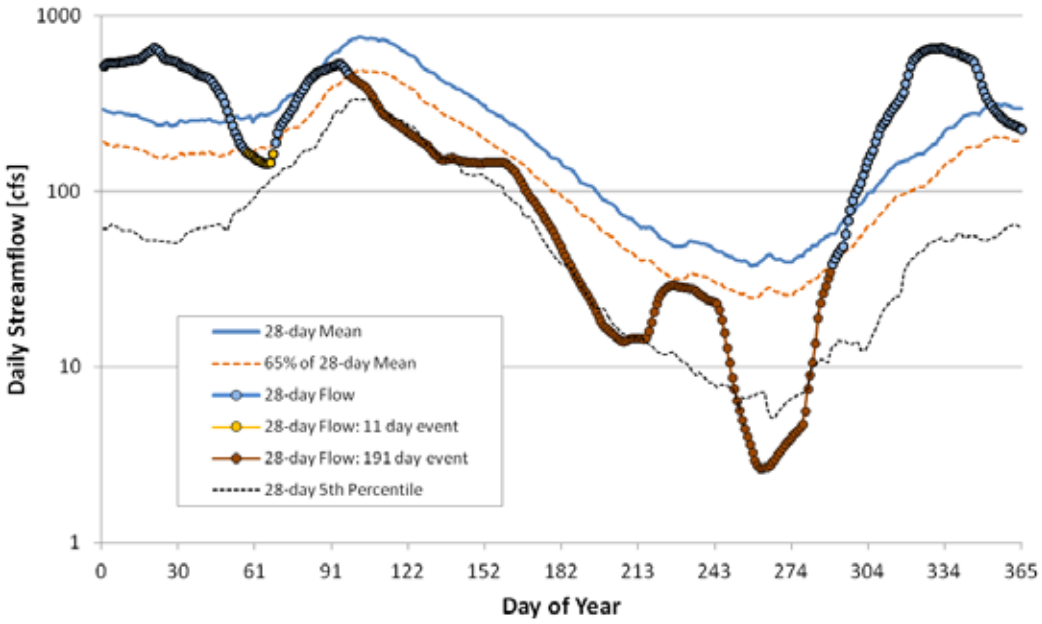


Figure 3. Example of drought events defined in the Lamprey River during the 1995 calendar year. Drought events are defined as a period when the mean 28-day streamflow is less than 65% of the 28-day mean for that day.

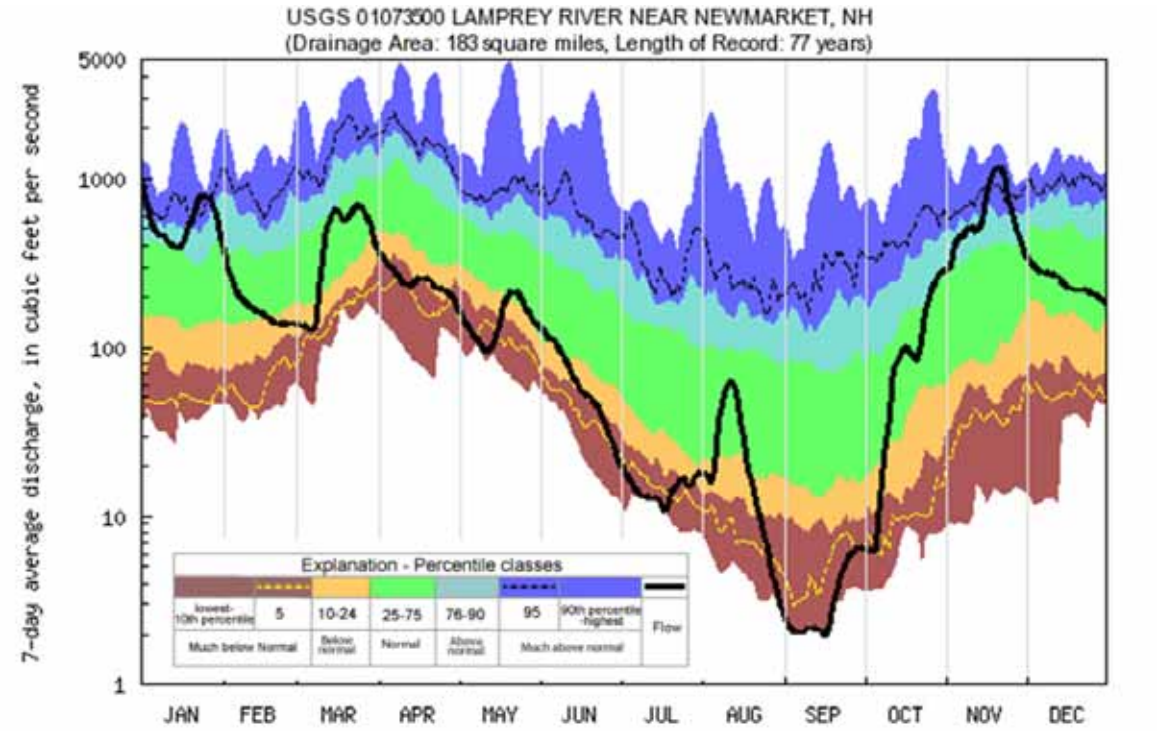


Figure 4. 7-day Hydrograph for same streamflow record presented in Figure 3. While the US Drought Monitor uses percentiles of 7-day flows to designate events, this results in many more events of relatively short duration.

The 28-day metric used to determine drought events and classify them according to duration, does not indicate the magnitude of the departure. In order to capture the severity of drought events, the 28-day flows were ranked so that periods when the flow was below the 5th percentile could be identified, graphed, and included in the drought analysis.

"Drought Scores"

To add a quantitative component of magnitude to the drought occurrence record, each month in the 60-year record was given a rating based on two criteria: drought event duration and streamflow percentiles. Each criterion was scored individually, and the final score for any given month is the sum of the two individual criteriion scores. For the streamflow percentiles, the individual score was assigned based on the number of days in which the calculated streamflow percentile was less than or equal to five and ranged from 0 to 4, where 0 indicates no days met this criteria, a 1 indicates 1 to 7 days met this criteria, a 2 indicates 8 to 14 days met this criteria,

a 3 indicates 15 to 21 days met this criteria, and a 4 indicates more than 21 days in the given month had a calculated streamflow percentile of five or less. For the magnitude criterion, the individual score was based on the maximum magnitude event determined to have occurred during the given month (where magnitude is determined by the length of a unique drought event). Scores for the magnitude criterion ranged from 0 to 5, where 0 indicates no drought event was recorded during the month, and a score of 5 indicates a maximum magnitude drought event was recorded (magnitude categories 1 to 5 correspond with drought lengths of less than 1 month, 1-3 months, 3-6 month, 6-9 months, and 9-12 months). Thus, the total score for any given month ranges from 0 to 9, where 0 indicates no/minimal drought conditions, and a 9 would indicate severe drought conditions.

Indices

In addition to quantifying the occurrence and magnitude of drought events in the five Drought Management Areas, commonly used drought indices were also computed using monthly meteorological and soil moisture data. The objective was to identify which of the commonly used drought indices are most applicable to actual conditions in New Hampshire. The indices of particular interest are the Palmer index and its derivatives as well as the Standardized Precipitation Index (SPI).

Palmer Drought Indices

Monthly meteorological data interpolated to the centroid of each Drought Management Area and used as input for computing the suite of Palmer indices [Palmer Drought Severity Index (PDSI), Palmer Hydrologic Drought Index (PHDI), the Palmer Z-index (Palmer-Z), and the Operational Palmer (WPLM)] for the period of study. The FORTRAN code was obtained from the National Climate Data Center and is provided for reference in Appendix B, The

computed indices were then evaluated for their relative effectiveness in capturing drought events, as defined primarily by streamflow.

Standardized Precipitation Index

In addition to the Palmer indices, the interpolated monthly precipitation data were used to compute the Standardized Precipitation Indices (SPI) for 1-month (SPI01), 3-month (SPI03), 6-month (SPI06), 12-month (SPI12), 24-month (SPI24), and 60-month (SPI60) periods. The FORTRAN code was also obtained from the NCDC and is provided in Appendix B for reference. As with the Palmer indices, the computed SPI indices were evaluated for their relative effectiveness in capturing drought events, as defined primarily by streamflow events.

RESULTS

The primary objectives of the data analysis are to (1) evaluate the necessity of the five drought management areas, (2) evaluate the relationship between the drought classes defined here using the 28-day streamflow with the drought categories of the U.S. Drought Monitor, and (3) investigate which of the drought indices, or blend of indices, provide the most useful representation of actual historical drought events. Collectively, these results will help to inform appropriate drought management strategies.

Drought Occurrences

Historic drought conditions for each drought management area (DMA) are delineated into five classes based on the duration metric for the 28-day streamflow as defined above. In addition to the 28-day flows, the lowest 5th percentiles of the 28-day flow record are also used as an indicator of drought magnitude.

Drought events are visualized using a combination of a time sequence of color-coded blocks that illustrate the time period of the drought event and a truncated line graph of the 28-day percentiles that includes the lowest 5th percentile (Figure 5). Each drought event is colored according to its drought class and, for visualization purposes, the percentile graph is filled brown between the daily value and the 5th percentile.

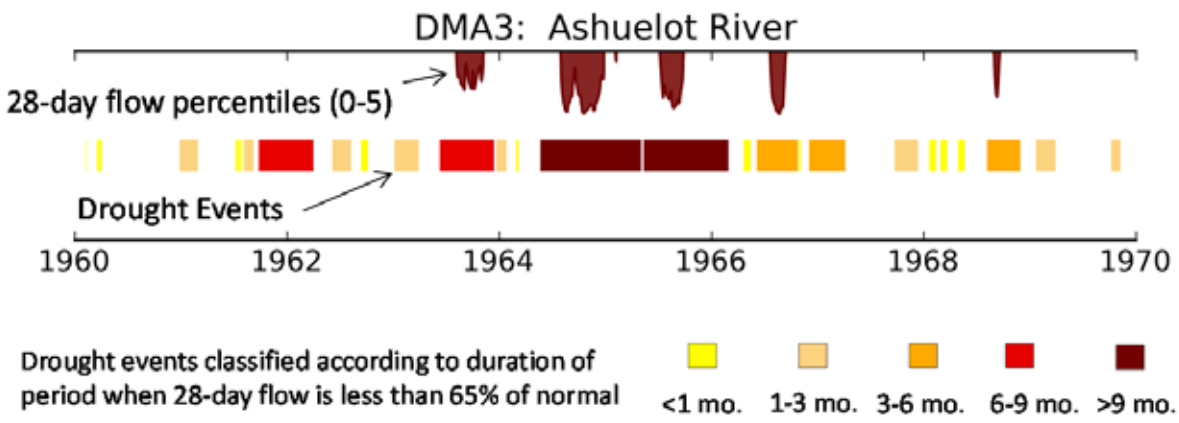


Figure 5. Annotated illustration of drought event visualization format used in this report.

Spatial Variability

Drought events for the period 1950-2010 for the five drought management areas are shown in Figure 6. Visual inspection of the records suggests that there are both north-to-south and west-to-east variations that warrant the continued use of the five drought management areas. The northern areas (North Country and White Mountains) did not experience significant departures in streamflow during the 1960s. In the southern areas, there also appears a west-to-east gradation in the 1960s drought with the South Western area being impacted the greatest and less impacts in the Coastal Drainage. The drought events in 2001-2002 and 2010, on the other hand, appear to have exhibited greater streamflow impacts in the Coastal Drainage with less impact in the South Western area.

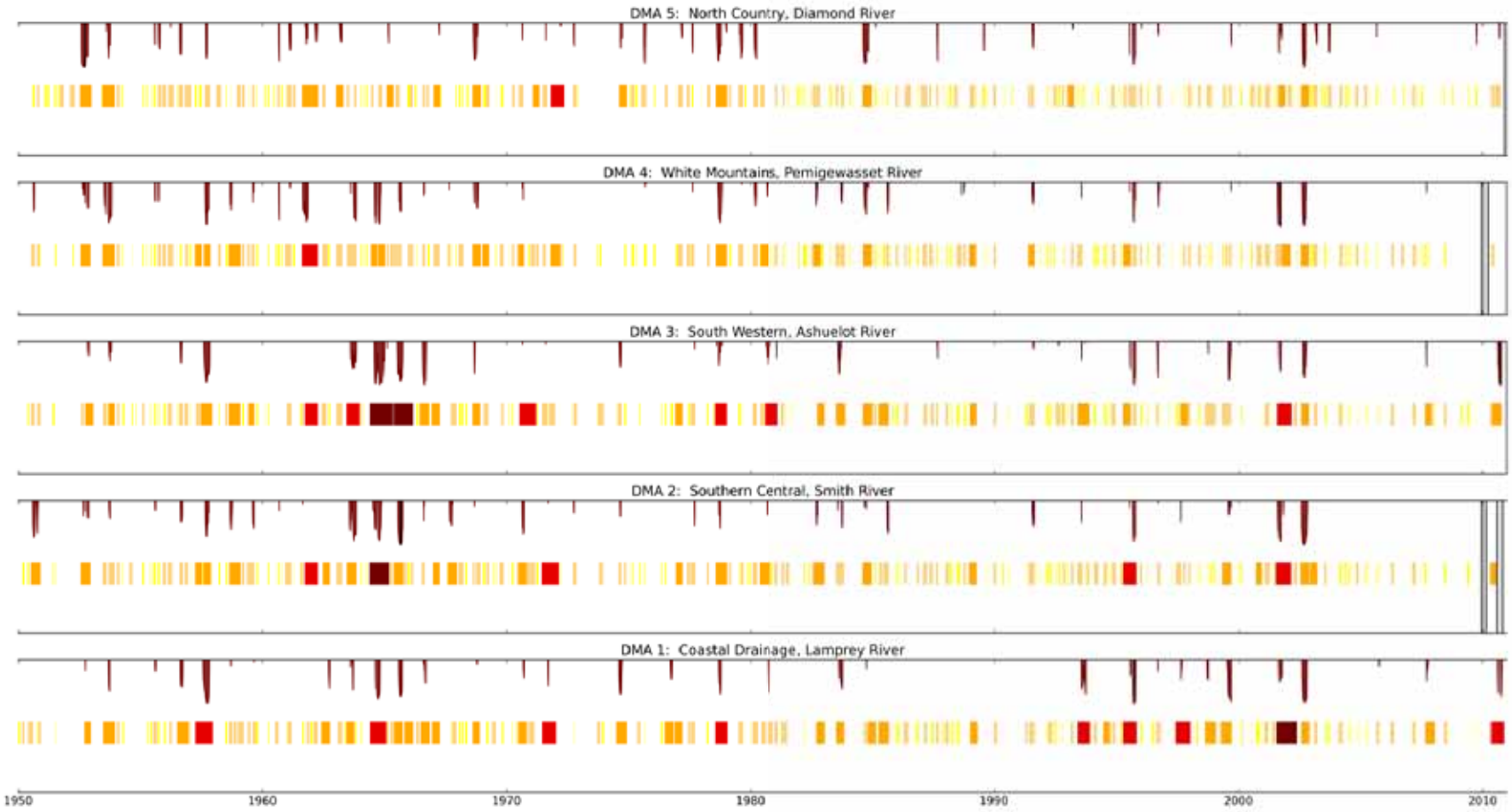


Figure 6. Summary of observed drought events showing 28-day streamflow less than the 5th percentile (brown filled lines along top axes) and drought events in which 28-day stream flow was below 65% of the mean for that day. Drought events are color coded based on duration: up to 1 month (yellow), 1-3 months (tan), 3-6 months (orange), 6-9 months (red), and greater than 9 months (brown); gray denotes missing data.

Seasonality

As illustrated in Figure 7, none of the Drought Management Areas show strong seasonal trends for either the onset or cessation of drought events. In all areas, there is a slightly greater

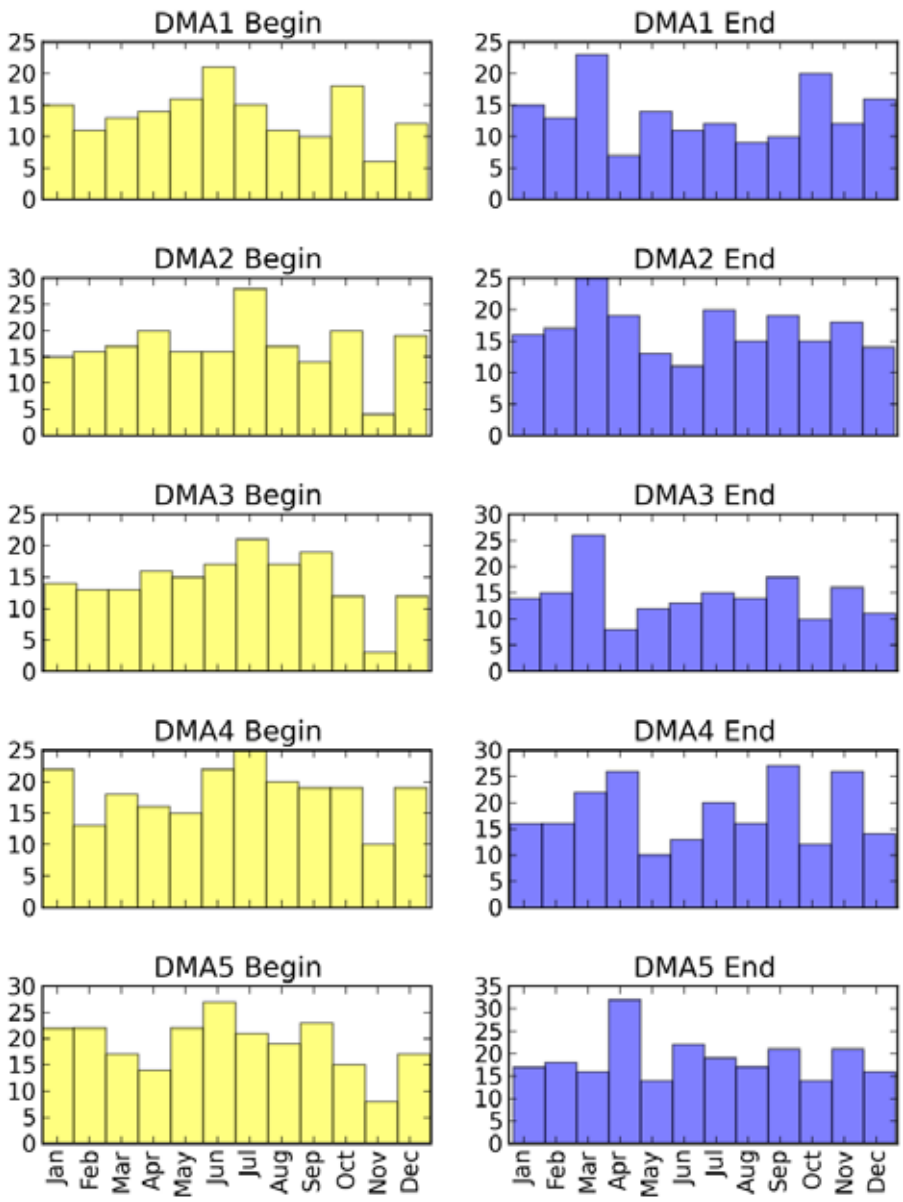


Figure 7. Months in which drought events begin (left graphs) and end (graphs on right), for the five Drought Management Areas.

tendency for drought onsets to occur in the months of June and July. The cessation of drought occurs more frequently in the month of March in the southern areas and the month of April in the northern areas, likely coinciding with the spring freshet.

Recurrence Intervals

Several studies use event renewal time (also referred to as interarrival time) to quantify the recurrence intervals for droughts of differing magnitudes (Shiau and Shen, 2001; Loaiciga, 2005). The event renewal time (R) is defined here as the period of time (in decimal months) between the onset of successive drought events of the same class. The mean of the event renewal times (E[R]) for each drought class can be interpreted as an empirical estimation of the recurrence interval for that drought class (e.g., Loaiciga, 2005).

Table 7. Expected Renewal Times (months) for five drought classes in the five Drought Management Areas. N is the number of events. N.Q. denotes Not Quantified.

	DMA1		DMA2		DMA3		DMA4		DMA5	
	N	E[R]	N	E[R]	N	E[R]	N	E[R]	N	E[R]
D0	68	10.9	103	7.1	89	8.2	125	5.8	128	5.8
D1	60	12.0	73	10.0	54	13.3	72	10.3	83	8.9
D2	24	29.2	24	34.6	21	35.1	21	30.4	16	40.5
D3	9	82.0	4	162.0	7	81.0	1	N.Q.	1	N.Q.
D4	1	N.Q.	1	N.Q.	1	N.Q.	0	N.Q.	0	N.Q.

Estimated recurrence intervals for each drought class in each Drought Management Area are summarized in Table 7. In general terms, events in the D0, D1, and D2 classes can be viewed statewide as having return periods of 6-9 months, 12 months, 3 years, respectively. For events of magnitude D3 and D4, the northern and southern areas appear to have different return intervals. For events of class D3, the southern areas (DMA1, DMA2, and DMA3) exhibit an approximate return interval of 10 years whereas the single occurrences in northern areas (DMA4

and DMA5) indicate a return interval of approximately 50 years. Similarly, for D4 events, the single occurrence in the southern zones suggests an approximate return interval of 50 years while no such events were observed in the 60 year record for the northern areas.

Frequency of Occurrence

The final characterization of the observed drought events in the five Drought Management Areas is their frequency of occurrence. Figure 8 shows the cumulative time spent in a drought class. Following the convention of the US Drought Monitor, lower classes are treated as persisting through the occurrence of higher classes. For example, the time spent in a 4 month drought is also included in the cumulative time for drought classes of 1-3 months and < 1 month.

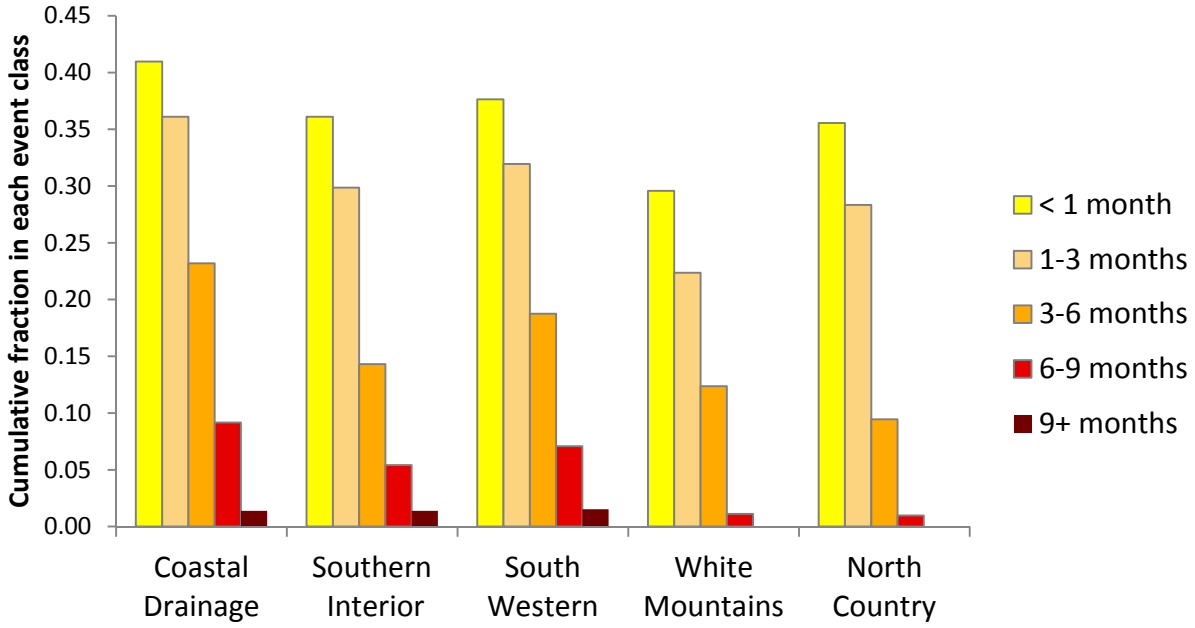


Figure 8. Fraction of time spent in each drought class. Fractions are cumulative in the sense that time in the higher classes (e.g. 3-6 months) is included in the lower classes (<1 mo and 1-3 months).

Table 8. Comparison of Drought Monitor Category Percentiles Occurrences of Drought Classes defined in this study.

Category	Drought Condition	Percentile chance (US Drought Monitor)	Percent time in class (New Hampshire)
D0	Abnormally dry	20 to 30	35
D1	Drought – moderate	10 to 20	30
D2	Drought – severe	5 to 10	15
D3	Drought – extreme	2 to 5	5
D4	Drought – exceptional	<2	1

Table 8 shows the New Hampshire drought Classes defined based on 28-day streamflow mapped onto the Drought Categories of the U.S. Drought Monitor. The percent time in Categories D0-D2 are greater than the corresponding percentile chance in the Drought Monitor, and percent time in D3 and D4 are within the ranges of Drought Monitor percent chance. However, observation of the current US Drought Monitor during early 2014 suggests that the D0 designation is often applied when the 28-day flow is not below the 65% of normal threshold. In addition, as discussed below, there may be a practical benefit to identifying the onset of dry conditions when the 28-day streamflow drops below 65% of normal (D0) and then tracking it as progresses into a mild drought condition.

One significant departure between the definition of drought classes based on the 28-day streamflow and the US Drought Monitor categories is the relative absence of the Extreme and Exceptional drought designations in the northern areas (recurrence intervals of approximately 25 and 50 years). An alternative approach would be to define different drought metrics so that statistics within each zone are honored. However, because we are using just one metric (28-day flow) to define drought events, it is possible that more severe droughts have occurred but were

not detected in the streamflow data. Additional work is necessary to better characterize drought events, particularly in the northern areas.

Optimized Drought Blend

It is becoming increasingly recognized that individual indices may not provide the best indicator of actual drought conditions. Combinations of indices, as weighted sums, may offer an opportunity to provide better correspondence with actual drought conditions and thereby lead to insights into the dominant factors that affect drought as well as a means for objectively computing drought conditions. Svoboda et al. (2002) propose the use of both long-term and short-term blends but recognize that the two may offset one another in some cases. As a means of exploring possible drought blends in New Hampshire, we used a non-linear multivariate parameter estimation method to evaluate the relative contributions of 11 different commonly used indices in explaining the drought events in the five Drought Management Areas.

The parameter estimation code PEST (Dougherty, 2010) was used to compare observed drought conditions to a model comprised of a weighted sum of indices. The model is expressed as the weighted sum of the 11 indices, the targets are the quantified Drought Scores, and the parameters are the weights associated with individual indices. Results of the optimization are summarized in Appendix C and shown graphically in the composite plots presented in the next section. In general, only the 3-month SPI was consistently associated with a positive and non-zero weight. With respect to the Palmer Indices, the PDSI appears to be the most relevant in the White Mountains and North Country, while the Operational Palmer is most relevant in the southern areas.

DMA Composite Plots

Figures 9-13 summarize results of drought occurrence, optimized drought blend, the 3-month and 6-month SPIs, and the Palmer Drought Severity Indices. These composites help to illustrate a number of important aspects about the occurrence of drought conditions in the State and the extent to which they correlate with some of the key indices. This section will provide a brief narrative for each zone and suggest possible relationships.

Coastal Drainage

The Coastal Drainage has experienced several distinct drought events over the past 60 years. The droughts in the late 1950s coincide well with deficits in precipitation that are captured by the SPI03 and SPI06 indices. While the sequence of droughts in the 1960s was prominent in the Coastal Drainage, they appear to have been less severe than the corresponding events in the Southern Interior and South Western Areas. The 1960s droughts appears to coincide the most with the SPI06 index, showing a prolonged period in which the medium range precipitation was well below normal. Based on the SPI03, it appears that there were some months that approached normal, providing some relief to stream flow conditions. The 1990 decade also exhibited a number of distinct drought events. These events are intriguing as they do not readily appear in the SPI03, SPI06, or PDSI indices. As discussed further below, these events may be associated with below normal snow in the Coastal region even though winter precipitation was above normal. The drought of 2001-2002 was most strongly felt in the Coastal Drainage and coincided with deficits both in precipitation and snow depth. From 2003-2010, the Coastal Drainage experienced above average precipitation but was impacted by a prominent drought event in the summer of 2010. The absence of this event in the SPI and Palmer indices highlights a limitation of using station data to compute indices and is discussed in more detail in the section on Application Issues.

Southern Interior

The drought events in the Southern Interior Area are similar to those observed in the Coastal Drainage Area, but differ in duration and magnitude. The drought in the late 1950s was not as severe in the Southern Interior Area but the drought events of the 1960s were more severe, compared to the Coastal Drainage. The 1960s droughts in the Southern Interior area are interesting in that the stream flow appears to recover more quickly than suggested by the 6-month SPI and the PDSI. While true for several events in several areas, this contrast is most apparent for the 1960s droughts in the Southern Interior area.

Compared with the Coastal Drainage, there were fewer droughts in the 1990s. Unfortunately, it is during this period that the Franklin Falls snow station is missing data, though the White Mountain area exhibited relatively normal snow depths during this period. The drought events in 2001-2002 were less severe than those in the Coastal Drainage, and like the Coastal Drainage, the recovery appeared to be slower than suggested by the 3-month and 6-month SPIs, as well as the PDSI. The 2010 drought was also less severe in the Southern Interior area though the indices are more indicative of the events (this is discussed in more detail below).

South Western

The east-to-west gradations of the severity of droughts in the 1950s and 1960s continues as the South Western area appears to have had the least impact from the 1950s events and the worst impact from the events in the 1960s (Figure 11). Like the Southern Interior area, the duration of drought events in the 1990s and the event in 2010 are consistent with the variability in precipitation indicated by the 3-month and 6-month SPIs, but lags in recovery.

White Mountains

Moving north to the White Mountains area (Figure 12), we begin to see fewer occurrences of the more extreme drought conditions. On the one hand, this suggests that the definition of drought should be recalibrated so that the frequency of drought occurrences is better aligned with statistical attributes and recurrence intervals that define drought. However, as noted above, it is possible that a different definition of drought, that included soil moisture for example, might show a higher frequency of the more extreme droughts in the White Mountains. Maintaining a consistent definition of drought statewide illustrates the relative differences in how the surface and groundwater systems respond to variations in precipitation. Of particular note is that the droughts of the 1990s and 2010, which are relatively prominent in the southern areas, are greatly diminished in the White Mountains.

North Country

The south to north trend of drought occurrences continues as we move north to look at the North Country area (Figure 13). Like the White Mountains, the precipitation and drought patterns are characterized by relatively high frequency variations that inhibit the establishment of sustained drought conditions. Unlike the other areas, the PDSI appears to better capture the drought events in the North Country.

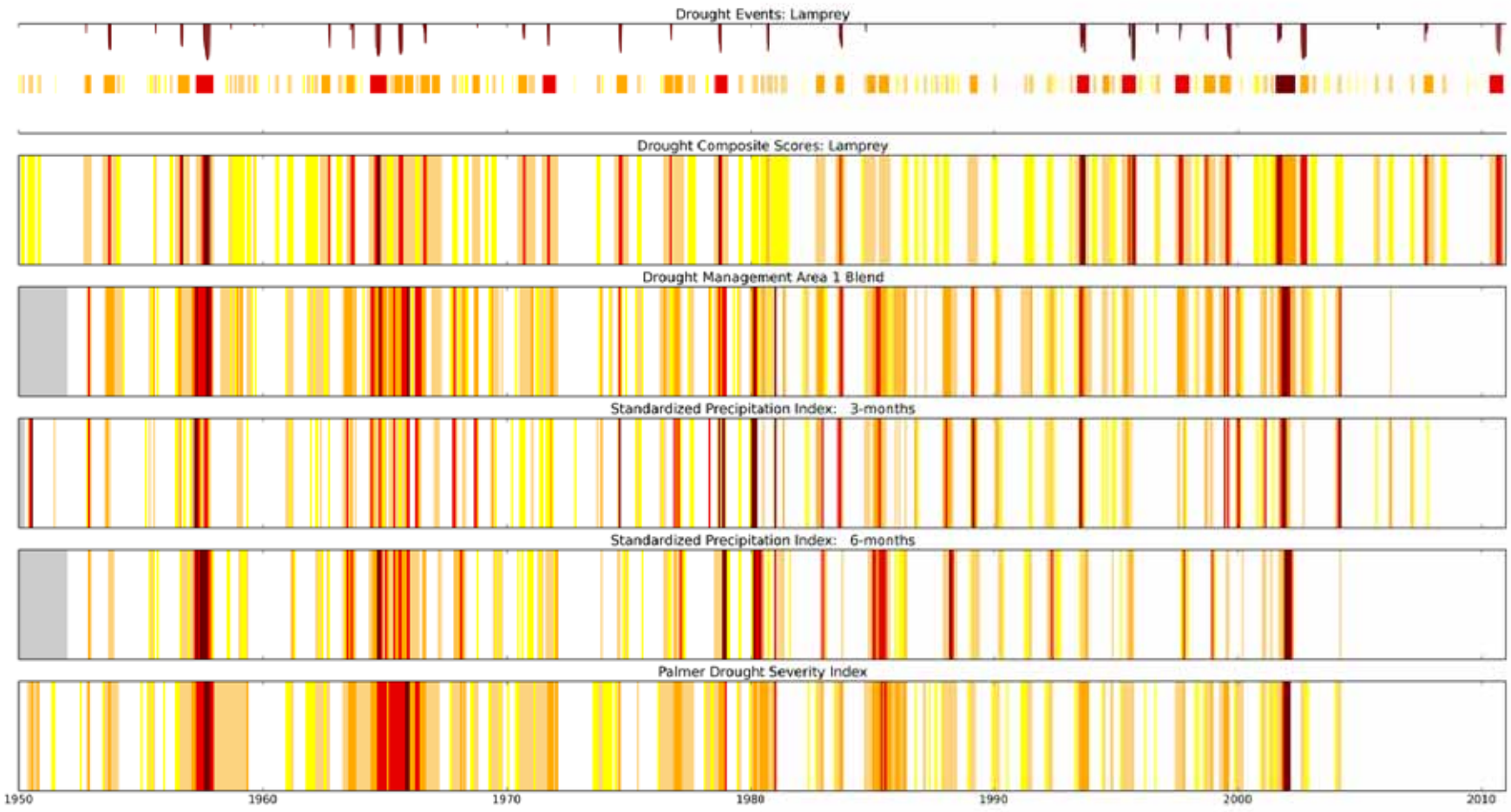


Figure 9. Summary of observed drought events in DMA1. Top panel shows the 28-day streamflow less than the 5th percentile (brown filled lines along top axis) and drought events in which 28-day stream flow was below 65% of the mean for that day. Drought events are color coded based on duration: up to 1 month (yellow), 1-3 months, 3-6 months, 6-9 months, and greater than 9 months (dark brown). Drought Composite Scores for the Lamprey River in which drought duration is combined with low flow data into a numerical score (see text). Area 1 Blend is the best fit blended index using weights from inverse modeling. Color scales for the Standardized Precipitation Indices are: yellow: -0.5 to -0.75; tan: -0.75—1.25; orange:-1.25 to -1.5; red: -1.5 to -20.; brown:less than -2.0. Color scale for the Palmer Drought Severity Index are : yellow:-0.5 to -1.0); tan: -1.0 to -2.0; orange:-2.0 to -3.0: red:-3.0 to -4.0; brown:less than -4.0 . Gray denotes missing data.

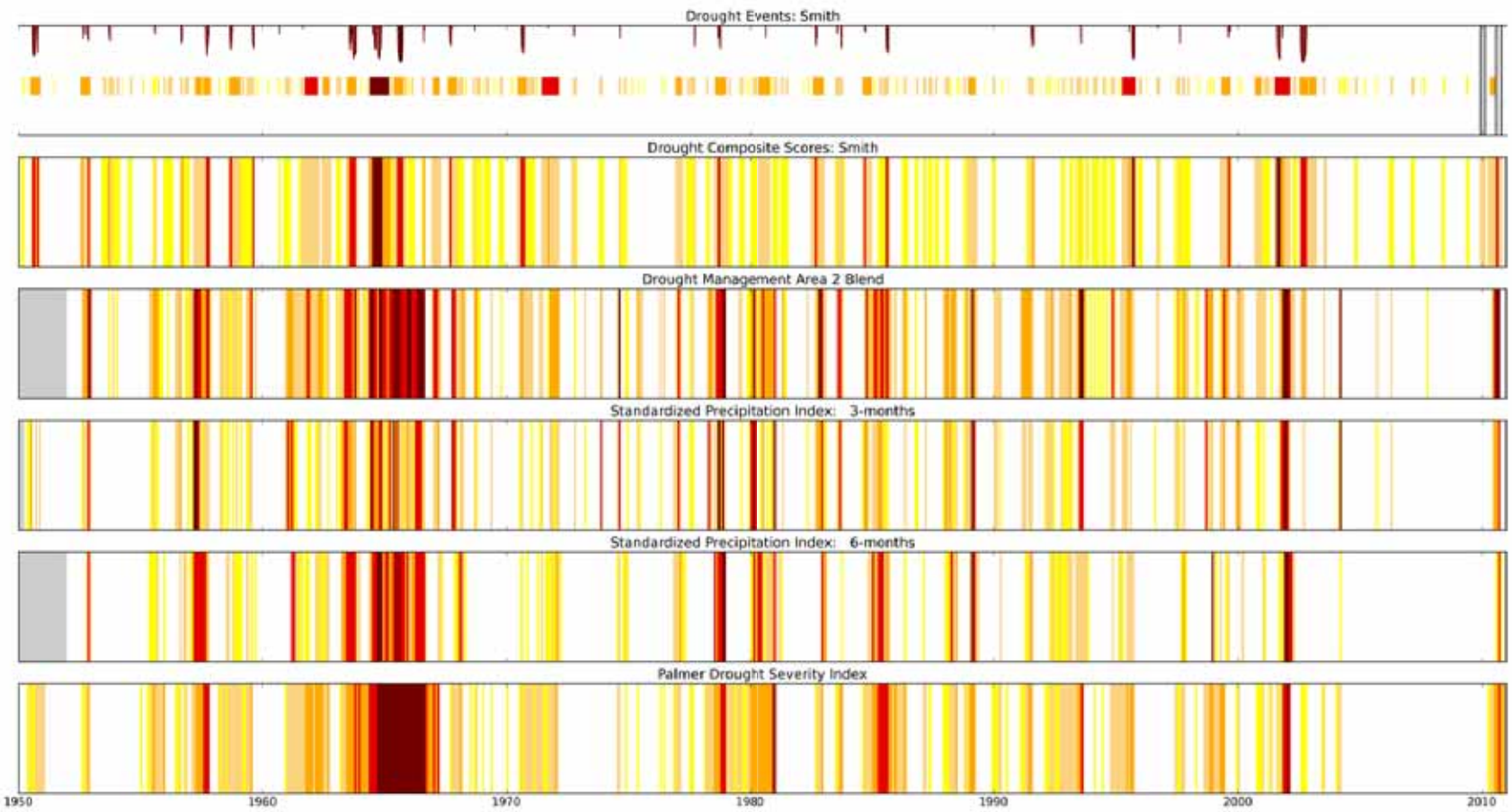


Figure 10. Summary of observed drought events in DMA2. Top panel shows 28-day streamflow less than the 5th percentile (brown filled lines along top axis) and drought events in which 28-day stream flow was below 65% of the mean for that day. Drought events are color coded based on duration: up to 1 month (yellow), 1-3 months, 3-6 months, 6-9 months, and greater than 9 months (dark brown). Drought Composite Scores for the Smith River in which drought duration is combined with low flow data into a numerical score (see text). Area 2 Blend is the best fit blended index using weights from inverse modeling. Color scales for the Standardized Precipitation Indices are: yellow: -0.5 to -0.75; tan: -0.75—1.25; orange:-1.25 to -1.5; red: -1.5 to -2.0; brown: less than -2.0. Color scale for the Palmer Drought Severity Index are : yellow:-0.5 to -1.0); tan: -1.0 to -2.0; orange:-2.0 to -3.0: red:-3.0 to -4.0; brown: less than -4.0 . Gray denotes missing data.

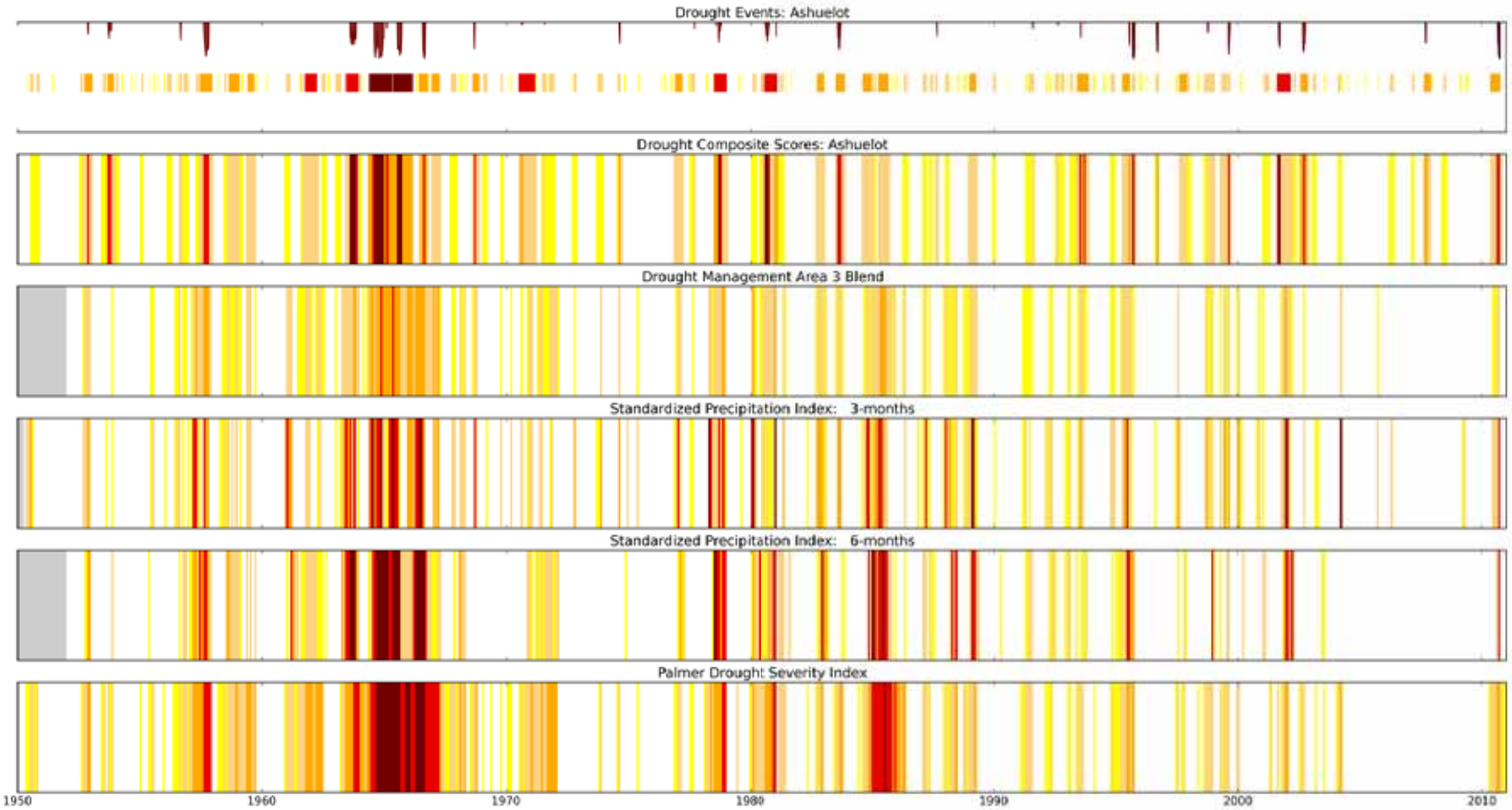


Figure 11. Summary of observed drought events in DMA3. Top panel shows 28-day streamflow less than the 5th percentile (brown filled lines along top axis) and drought events in which 28-day stream flow was below 65% of the mean for that day. Drought events are color coded based on duration: up to 1 month (yellow), 1-3 months, 3-6 months, 6-9 months, and greater than 9 months (dark brown). Drought Composite Scores for the Ashuelot River in which drought duration is combined with low flow data into a numerical score (see text). Area 3 Blend is the best fit blended index using weights from inverse modeling. Color scales for the Standardized Precipitation Indices are: yellow: -0.5 to -0.75; tan: -0.75—1.25; orange:-1.25 to -1.5; red: -1.5 to -2.0; brown: less than -2.0. Color scale for the Palmer Drought Severity Index are : yellow:-0.5 to -1.0); tan: -1.0 to -2.0; orange:-2.0 to -3.0: red:-3.0 to -4.0; brown: less than -4.0 . Gray denotes missing data.

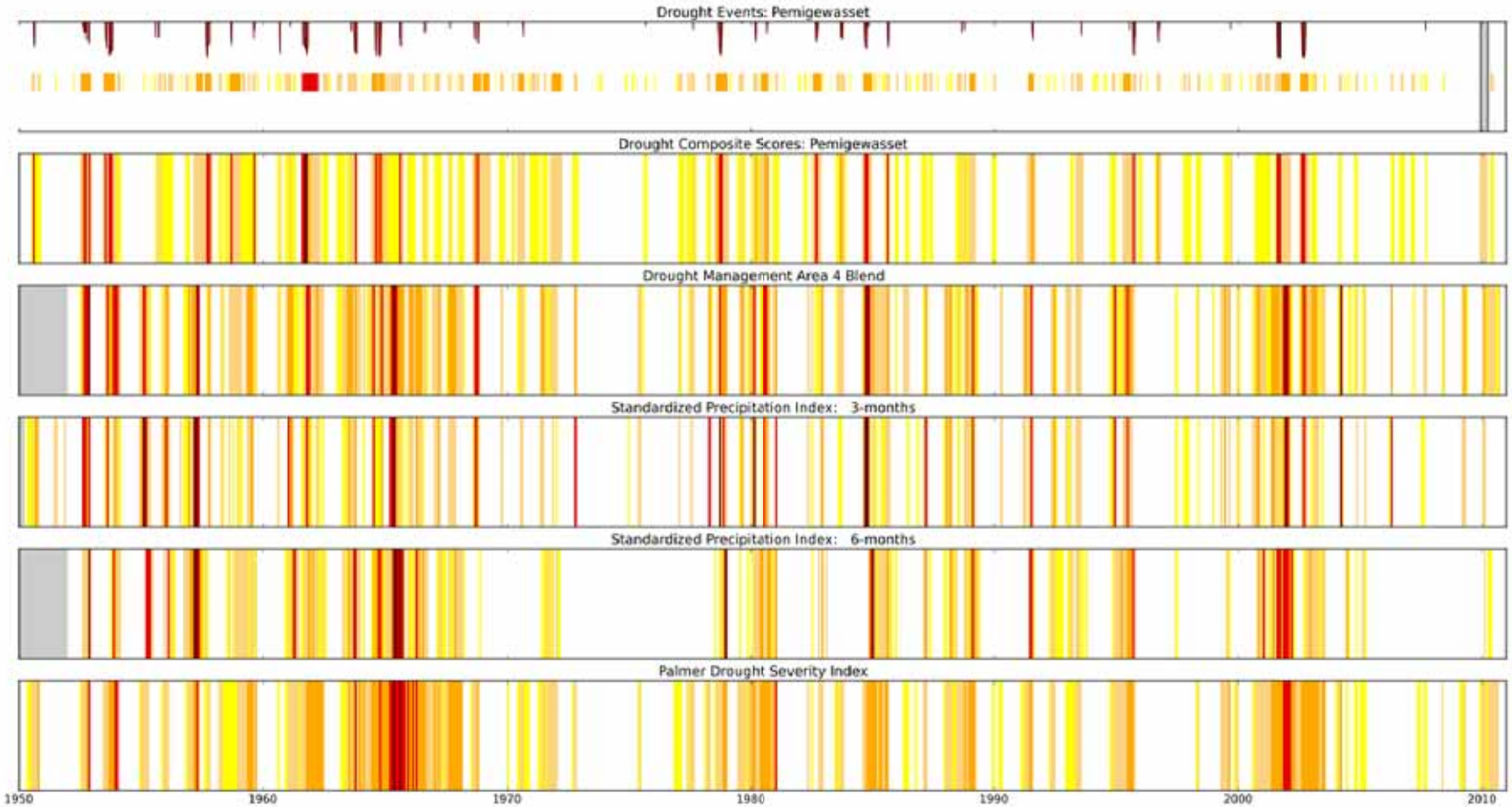


Figure 12. Summary of observed drought events in DMA4. Top panel shows 28-day s treamflow less than the 5th percentile (brown filled lines along top axis) and drought events in which 28-day stream flow was below 65% of the mean for that day. Drought events are color coded based on duration: up to 1 month (yellow), 1-3 months, 3-6 months, 6-9 months, and greater than 9 months (dark brown). Drought Composite Scores for the Pemigewasset River in which drought duration is combined with low flow data into a numerical score (see text). Area 4 Blend is the best fit blended index using weights from inverse modeling. Color scales for the Standardized Precipitation Indices are: yellow: -0.5 to -0.75; tan: -0.75—1.25; orange:-1.25 to -1.5; red: -1.5 to -2.0; brown: less than -2.0. Color scale for the Palmer Drought Severity Index are : yellow:-0.5 to -1.0); tan: -1.0 to -2.0; orange:-2.0 to -3.0: red:-3.0 to -4.0; brown: less than -4.0 . Gray denotes missing data.

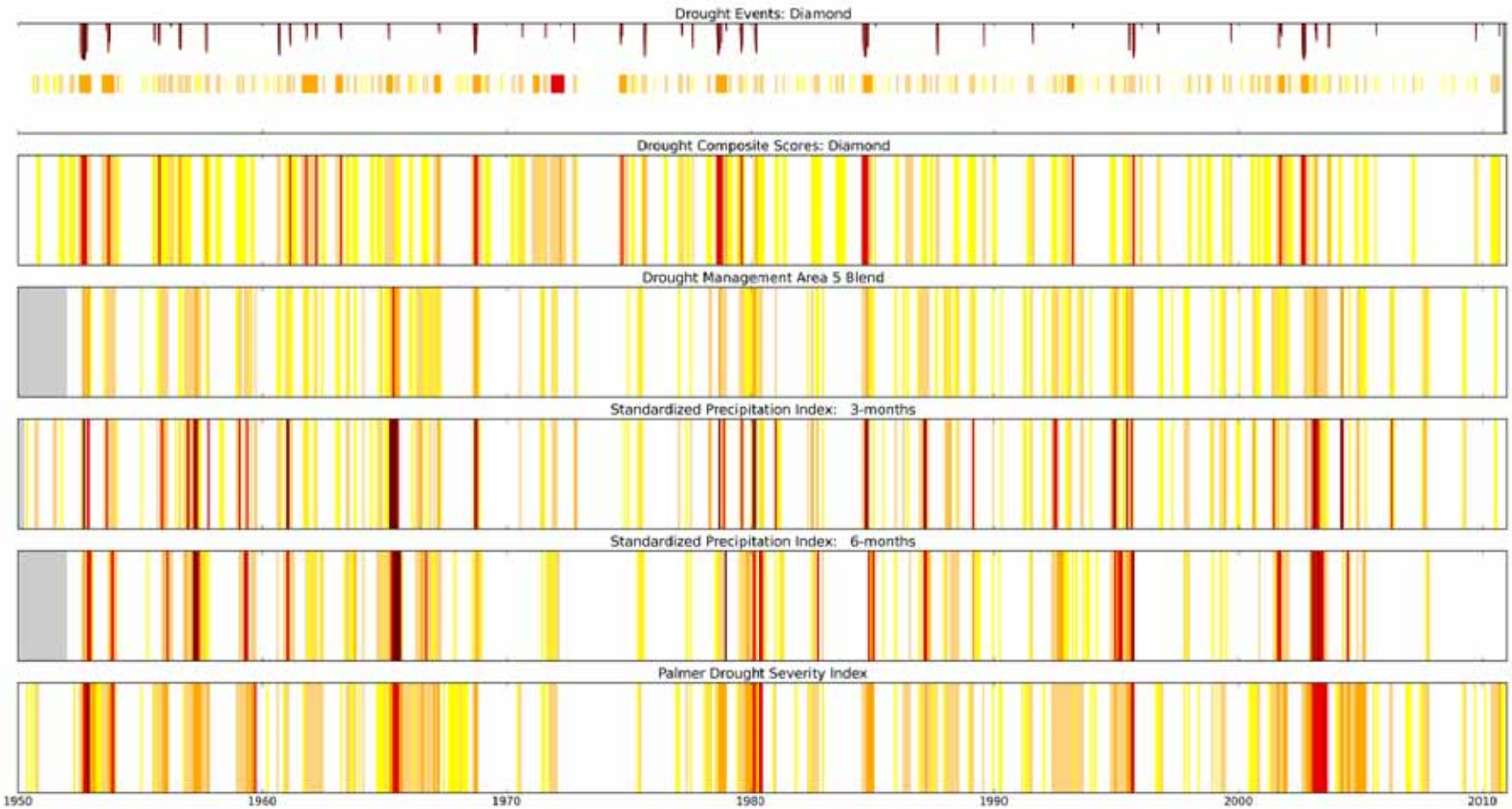


Figure 13. Summary of observed drought events in DMA5. Top panel shows 28-day streamflow less than the 5th percentile (brown filled lines along top axis) and drought events in which 28-day stream flow was below 65% of the mean for that day. Drought events are color coded based on duration: up to 1 month (yellow), 1-3 months, 3-6 months, 6-9 months, and greater than 9 months (dark brown). Drought Composite Scores for the Diamond River in which drought duration is combined with low flow data into a numerical score (see text). Area 5 Blend is the best fit blended index using weights from inverse modeling. Color scales for the Standardized Precipitation Indices are: yellow: -0.5 to -0.75; tan: -0.75—1.25; orange:-1.25 to -1.5; red: -1.5 to -2.0; brown: less than -2.0. Color scale for the Palmer Drought Severity Index are : yellow:-0.5 to -1.0); tan: -1.0 to -2.0; orange:-2.0 to -3.0: red:-3.0 to -4.0; brown: less than -4.0 . Gray denotes missing data.

Ground Water

Monthly groundwater levels from the wells shown in Table 4 were evaluated to identify correlations with observed drought events (as defined by 28-day streamflow being less than 65% of normal). There is a general trend for groundwater levels to be just below their monthly normal (Figure 14) at the onset of a drought event and then decline throughout the event reaching their minimum value at (or near) the end of the drought event.

While this finding provides insight into the behavior of groundwater levels during a drought event, the tendency of the departures to lag behind the event makes it difficult to use them as triggers indicating onset of a drought. Groundwater levels are probably more useful as indicators of drought recovery and ongoing susceptibility. For example, during the period starting in Spring 1980 through late Summer 1981, the Smith River experienced a number of short (D0 and D1) drought events and one longer (D2) event lasting for 170 days. The groundwater levels (wells WCW-1, NLW-1, CVW-1, and HTW-2) dropped below their monthly mean at the onset of the first event and remained significantly below normal through the summer of 1981. So, while the streamflow events were interrupted occasionally, the depleted groundwater condition continued to make the area susceptible to recurring, though short duration, surface water events.

The wells shown in Figure 14 were screened in a variety of materials, WCW-1 and EWT-1 are screened in glacial outwash while NLW-1, CVW-4, HTW-5, and completed in glacial till, lacustrine, and bedrock materials, respectively. The well completed in glacial till (NLW-1) shows a high frequency and the largest magnitude of variability with respect to monthly means (+/- 10 ft). The well completed in bedrock exhibits a shift in behavior during the late 1970s, where the variability decreases, but the frequency remains relatively high. Well ETW-1 exhibits a

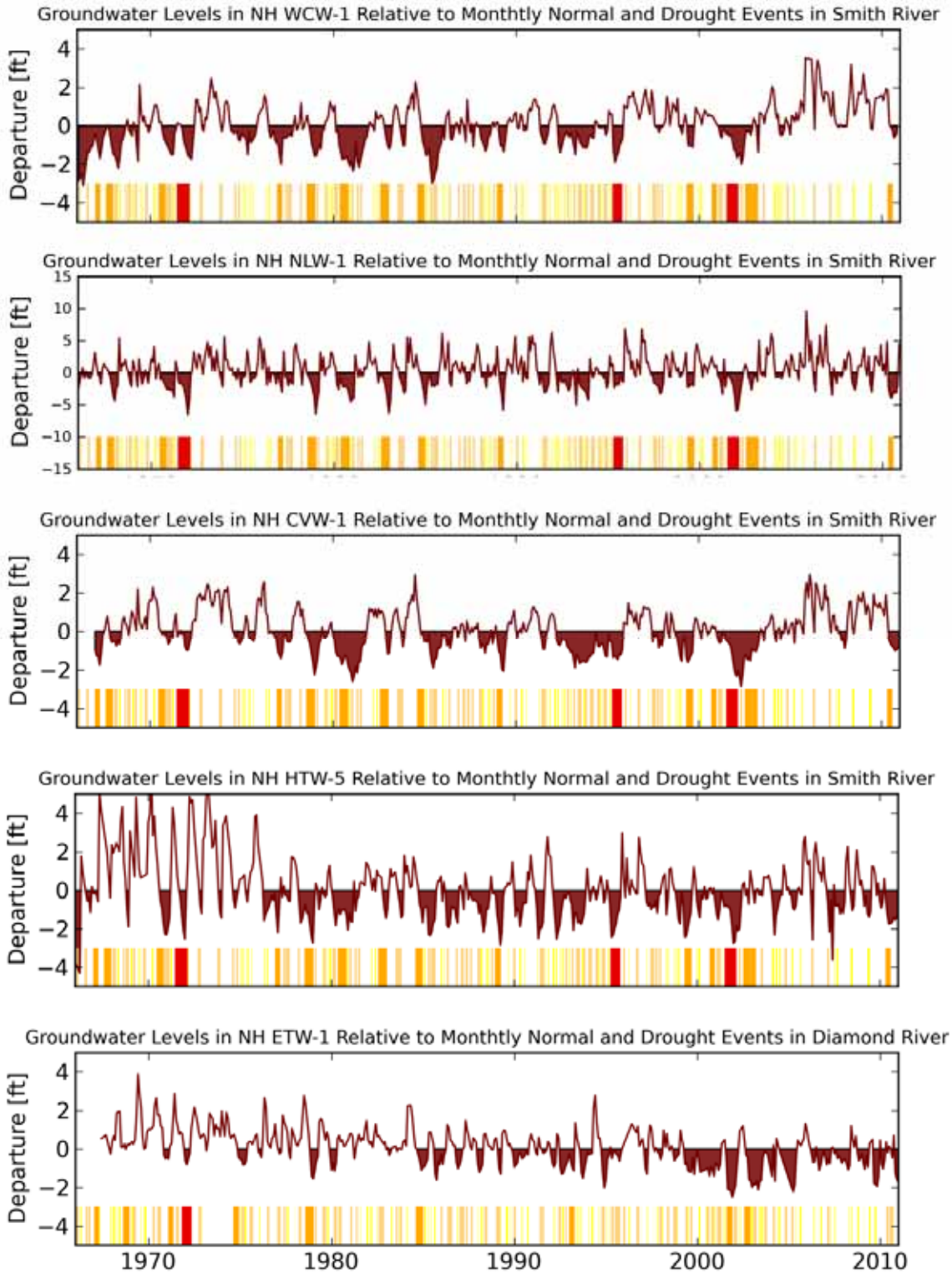


Figure 14. Groundwater levels relative to monthly mean values. See Table 4 for well designations.

distinct downward trend in water levels, perhaps due to local conditions. There is no indication in the streamflow or drought indices that suggest a change in hydrologic conditions. It is possible that the decline in the number of snow covered days (e.g Burakowski et al, 2008) is associated with less spring recharge and an overall reduction in groundwater levels. The well is located in close proximity to Akers Pond in Errol, NH and the trend may be related a change in the management of the pond level. No significant trends were detected in NH-LCW-1 (Lancaster, NH) but LCW-1 is located at the confluence of two streams and is likely affected by streamflow more than regional recharge patterns.

Reservoirs (Lake Winnipesaukee)

Lake Winnipesaukee represents the largest surface water reservoir in the state, and as such, was reviewed in the overall context of drought analysis in the state. Daily stage and outflow data for the lake was obtained from the NHDES Dam Bureau for 1982 through 2010 (no data prior to 1982 were available). Using the daily stage data, daily outflow data were adjusted to account for overall changes in lake volume, yielding a 'stage-adjusted' daily outflow volume. Daily stage-adjusted outflow volumes were then used to calculate 28-day outflow volumes, similar to that which had been calculated previously for streamflows, and an average 28-day outflow volume was calculated for each calendar day based on available data.

Rather than calculating a percent of normal, which presented a challenge when stage adjusted outflows were in some cases negative (indicating an overall increase in lake volume), two alternative metrics were considered: a departure from daily average, and daily percentiles. For the departures from daily averages, the most positive 5% of calculated departures (where departures are computed as the average 28-day outflow less the calculated daily 28-day outflow) were selected as indicative of drought, and discrete events where these conditions were met were

identified in the available data. For the daily percentiles, the lowest 5% of the daily 28-day outflows were selected as indicative of drought conditions, and discrete events where these conditions were met were identified in the available data as drought events.

The two metrics were then compared to DMA-specific indices to evaluate their ability to capture drought conditions. Because Lake Winnipesaukee straddles the Southern Interior and White Mountains DMAs, the reservoir data were compared to indices for both areas. Although events identified using the departures from daily averages metric were useful for identifying seasonal anomalies, the daily percentiles were ultimately identified as better representing more extreme drought conditions (Figure 15). Additionally, the daily percentiles for Lake Winnipesaukee appear better aligned with indices calculated for the White Mountains (DMA4) than the Southern Interior (DMA2).

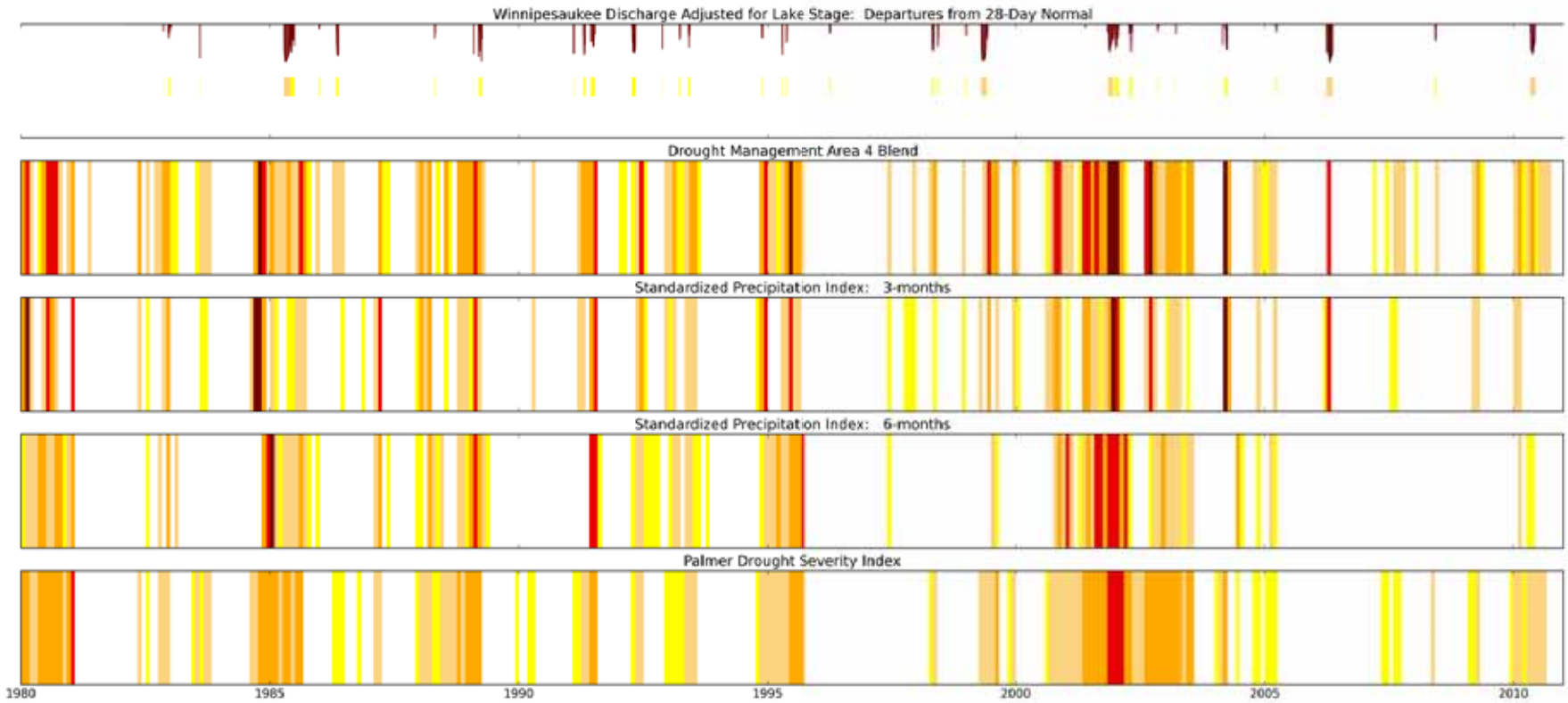


Figure 15. Summary of observed water deficit events in Lake Winnipesailee for period from 1980 to 2011. Top panel shows 28-day adjusted outflows less than the 5th percentile (brown filled lines along top axis) and drought events in which 28-day adjusted outflow was below 65% of the mean for that day. Drought events are color coded based on duration: up to 1 month (yellow), 1-3 months (tan), 3-6 months (orange), 6-9 months (red), and greater than 9 months (brown). Area 4 Blend is the best fit blended index using weights from inverse modeling. Color scales for the Standardized Precipitation Indices are: yellow: -0.5 to -0.75; tan: -0.75—1.25; orange:-1.25 to -1.5; red: -1.5 to -2.0; brown: less than -2.0. Color scale for the Palmer Drought Severity Index are : yellow:-0.5 to -1.0); tan: -1.0 to -2.0; orange:-2.0 to -3.0: red:-3.0 to -4.0; brown: less than -4.0 . Gray denotes missing data.

Snow

Snow cover data from each Drought Management Area were analyzed for the period 1950-2010. Stations with the most complete record for each Drought Management Area were selected (Table 5). For each station analyzed, the daily statistics were computed and provide a basis for evaluation of actual snowpack relative to historical daily values.

An attempt was made to test the hypothesis that timing of snow melt is correlated to low streamflow events. However, defining appropriate metrics for melting that could be applied consistently to each station was not possible. The primary challenges were 1) dealing with missing data and whether it should be interpreted as snow being absent, and 2) the ambiguity resulting from spring snow events that occurred after most, if not all, of the seasonal snowpack had melted.

For each water year, an annual Snow Surplus/Deficit (SSD) was computed that represents the fractional departure of the mean annual snow depth (Z_{WY}) from the mean of all years (Z-bar).

$$SSD = \frac{Z_{WY} - \overline{Z}}{\overline{Z}}$$

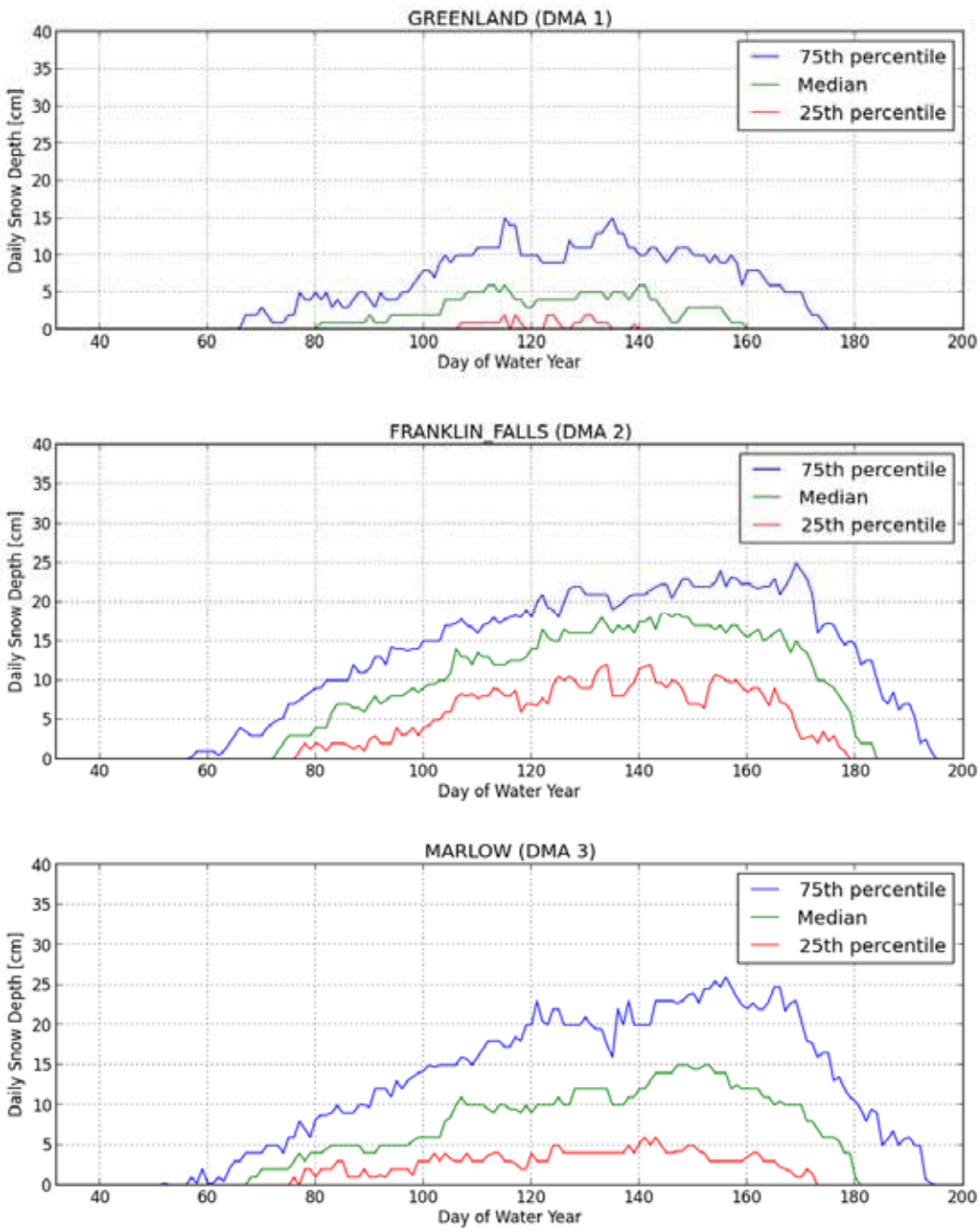


Figure 16a. Daily snow depth statistics for DMA1-3 (DMA 4 and 5 shown on following page).

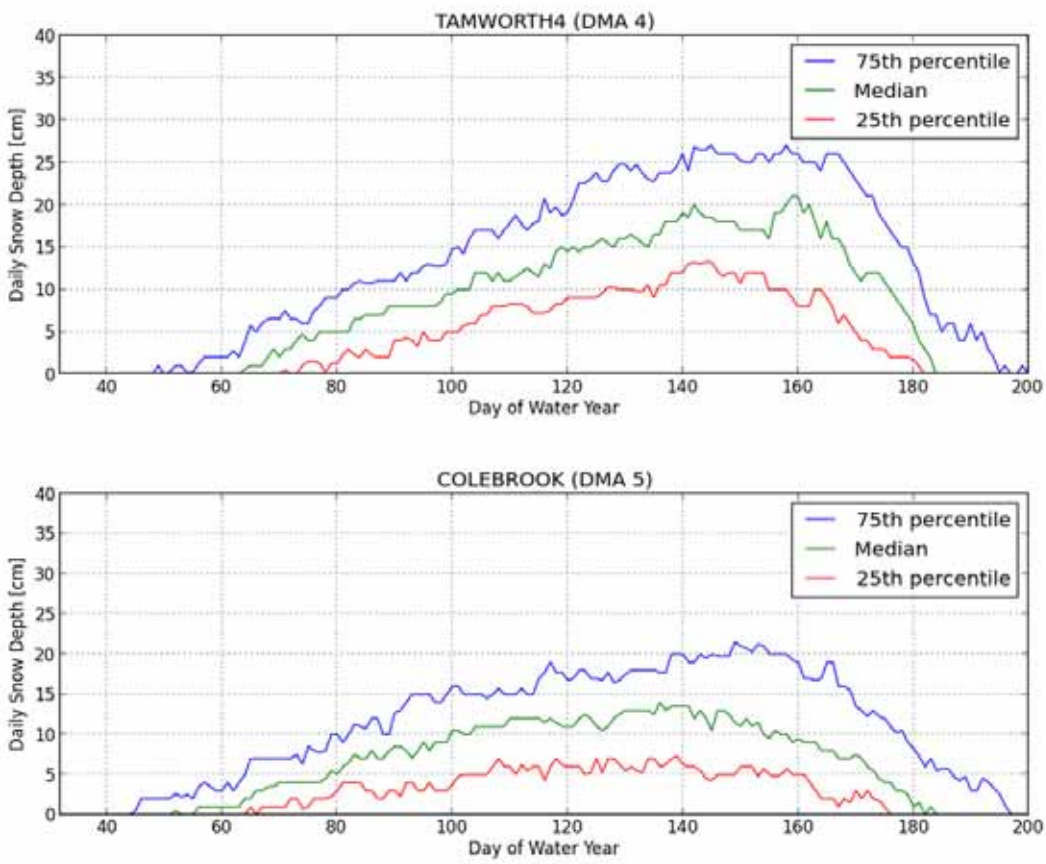


Figure 16b. Daily snow depth statistics for DMA 4 and DMA5 (continued from previous page).

As illustrated in Figure 17, the annual Snow Surplus Deficit often coincides with the three-month (Dec, Jan, Feb) standardized precipitation index, so many observed correlations between drought conditions and snow deficit may be due, in large part, to an overall precipitation deficit. One potentially important exception is in the Coastal Drainage (DMA1) from 1996-2000 in which snow pack was below normal while the 3-month SPI was above normal. Each of these summers experienced a drought event ranging from 30 days to 216 days[3].

[3] ['1996/8/22', '1996/10/20', 59 days]; ['2000/9/13', '2000/10/13', 30 days]; ['2000/10/17', '2000/11/16', 30 days]; ['1998/8/13', '1999/1/25', 165 days]; ['1999/4/6', '1999/9/16', 163 days]; ['1997/6/7', '1998/1/9', 216 days]

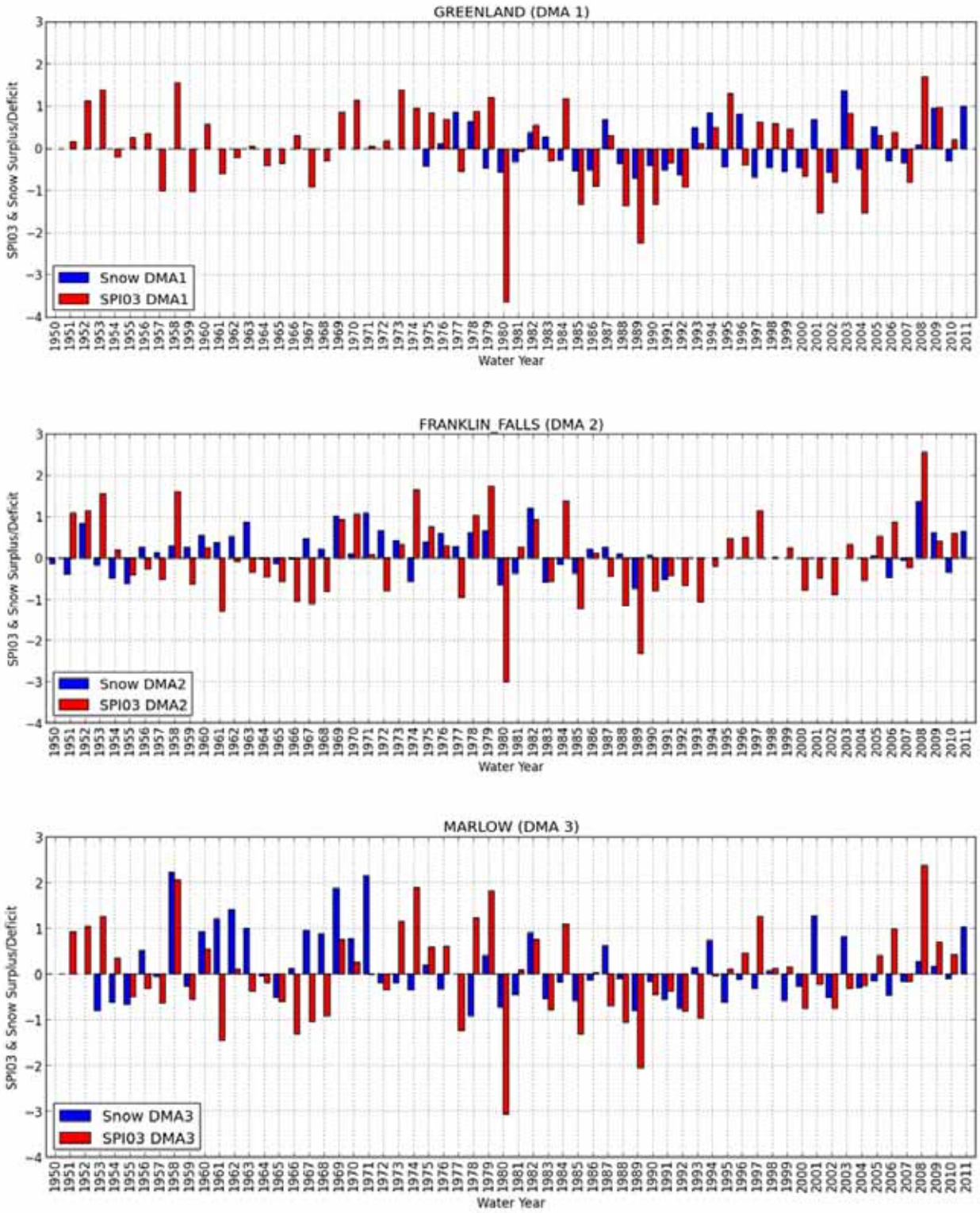


Figure 17a. Comparison of annual snow deficit and 3-month SPI for the month of March (DJF) over the period of study in Drought Management Areas 1-3. Continued on following page.

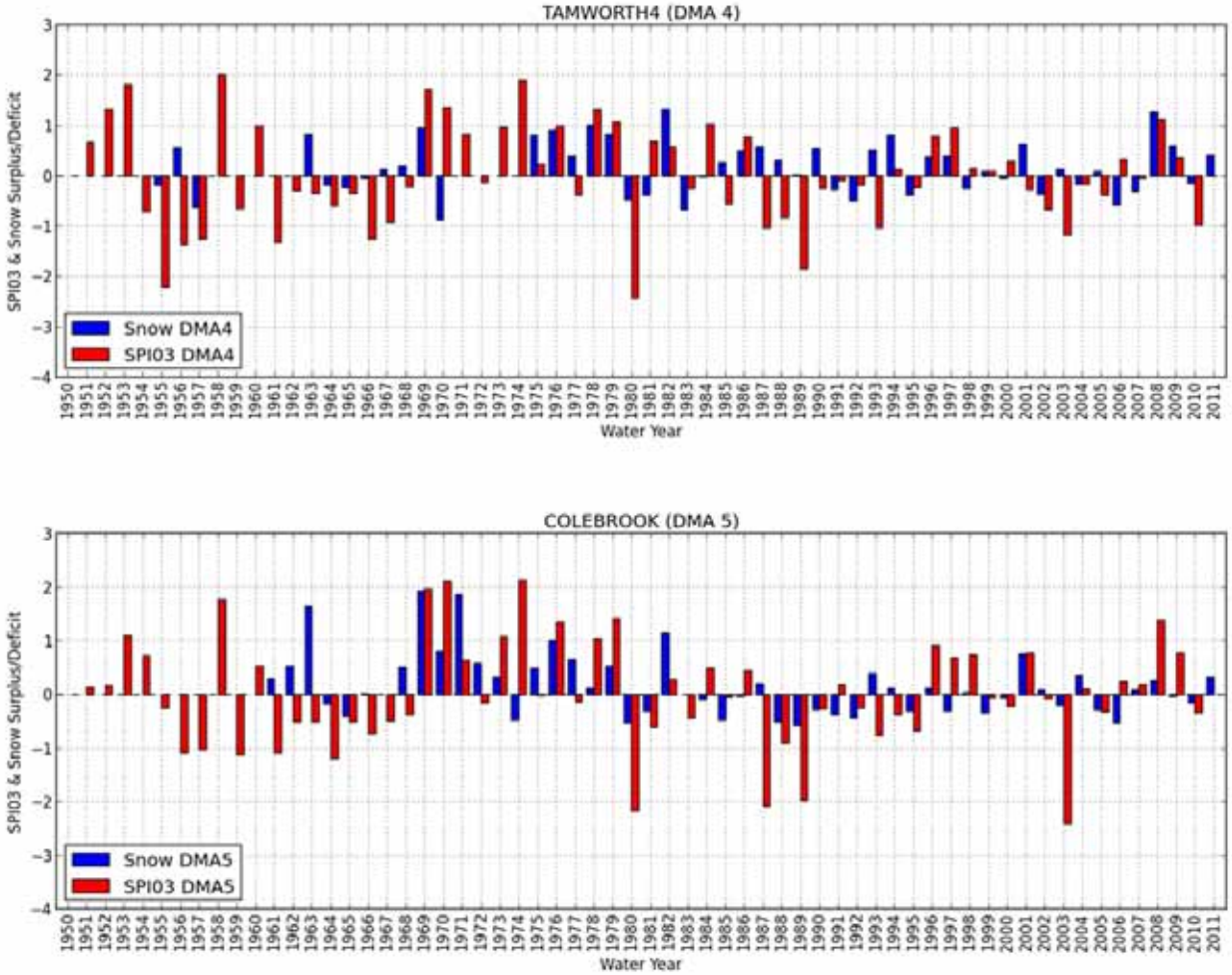


Figure 17b. Comparison of annual snow deficit and that 3-month SPI for the month of March (DJF) for period of study in Drought Management Areas 4 and 5. Continued from previous page.

Soil Moisture

There are two SCAN monitoring stations in New Hampshire that actively collect and report soil moisture data. Because both stations are in the same county (and both in DMA4), the longer record at the Hubbard Brook station was selected for analysis. Percentiles for the daily values from 2003-2013 (Figure 18) were computed to serve as a baseline for assessing future drought conditions.

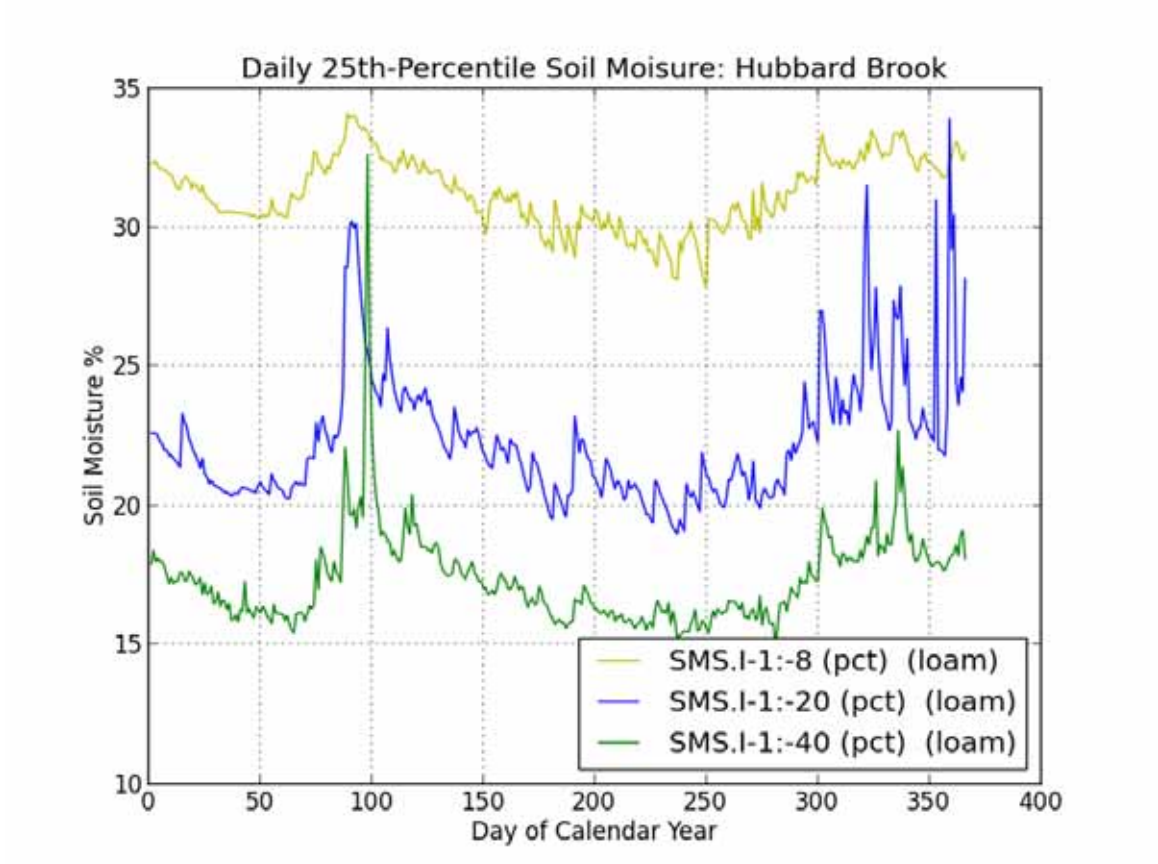


Figure 18. Daily statistics for soil moisture at the Hubbard Brook SCAN station. Depth of sensors are 8, 20, and 40 centimeters and represented by yellow, blue, and green lines, respectively.

APPLICATION ISSUES

The primary objective of the analysis presented above is to arrive at recommendations of what meteorological and hydrological data are most representative of actual drought conditions. The remainder of this report will begin to focus on applying the knowledge gained through the data analysis to assess which data products are likely to be most useful and how that data can be most efficiently incorporated into the drought management process.

There are three interrelated issues that will be addressed. First, is the process for providing input to the U.S. Drought Monitor; second, is the brief overview of a data collection process that has the potential to improve the efficiency of how the Drought Management Team

accesses the information necessary to make informed recommendations to the U.S. Drought Monitor authors; third, is an assessment of which specific precipitation and NCDC data products appear to be most applicable for assessing drought conditions in New Hampshire.

U.S. Drought Monitor

The emergence of the US Drought Monitor over the past decade as the national standard for declaring and documenting drought conditions appears to be one vehicle through which the NH Drought Management Team (NH DMT) can convey its recommendations for drought conditions. The US Drought Monitor is authored by a core team of professionals who rotate lead authorship responsibility. Each week, the lead author electronically distributes a draft product and seeks input from local authorities for suggested edits. The process often has a short timeline for feedback so it is essential that the NH DMT has the capacity to provide feedback in a timely manner.

nhdrought.org

One objective of the current project was to develop recommendations on the data collection necessary to detect, declare, and monitor drought conditions in the different hydrologic and climatologic regions of the state. Currently, the Drought Management Team relies upon a compilation of meteorological and hydrological data prepared by the Dam Bureau and/or the State Climatologist. This process involves downloading data and images from many different data sources (USGS, NCDC, NH DES, etc) and compiling into a document to disseminate to members of the Drought Management Team. The process is time intensive and may not be the most practical approach when the DMT needs to respond quickly to draft maps from the U.S. Drought Monitor authors.

Following the approach used in North Carolina, we developed a prototype website that automatically collects, collates, and displays pertinent data organized according to each drought management area (http://www.nhdrought.org) and documentation is available from the author in a separate report. The front-end organizational structure is summarized in Figure 19. The prototype website is hosted by Webfaction and operates via the Wordpress content management system. Data mining programs are written in Python and documentation is available on the website[4] or from the author upon request.

In addition to the website acting as a repository for data products provided by other agencies, additional data products specific to the conditions in New Hampshire could be developed. As noted above, the Standardized Precipitation Indices are very useful in assessing the climatological conditions associated with drought events. However, these vary considerably between drought management areas (Figures 9-13) and are not well represented by those computed by the NCDC for the two climate divisions (Appendix E). For the SPIs to be most beneficial, they will need to be calculated (and updated) on a regular basis, for each drought management area. Automating this process would not be a difficult task, should the State feel that it is warranted.

[4] http://nhdrought.org/dm-python-scripts/

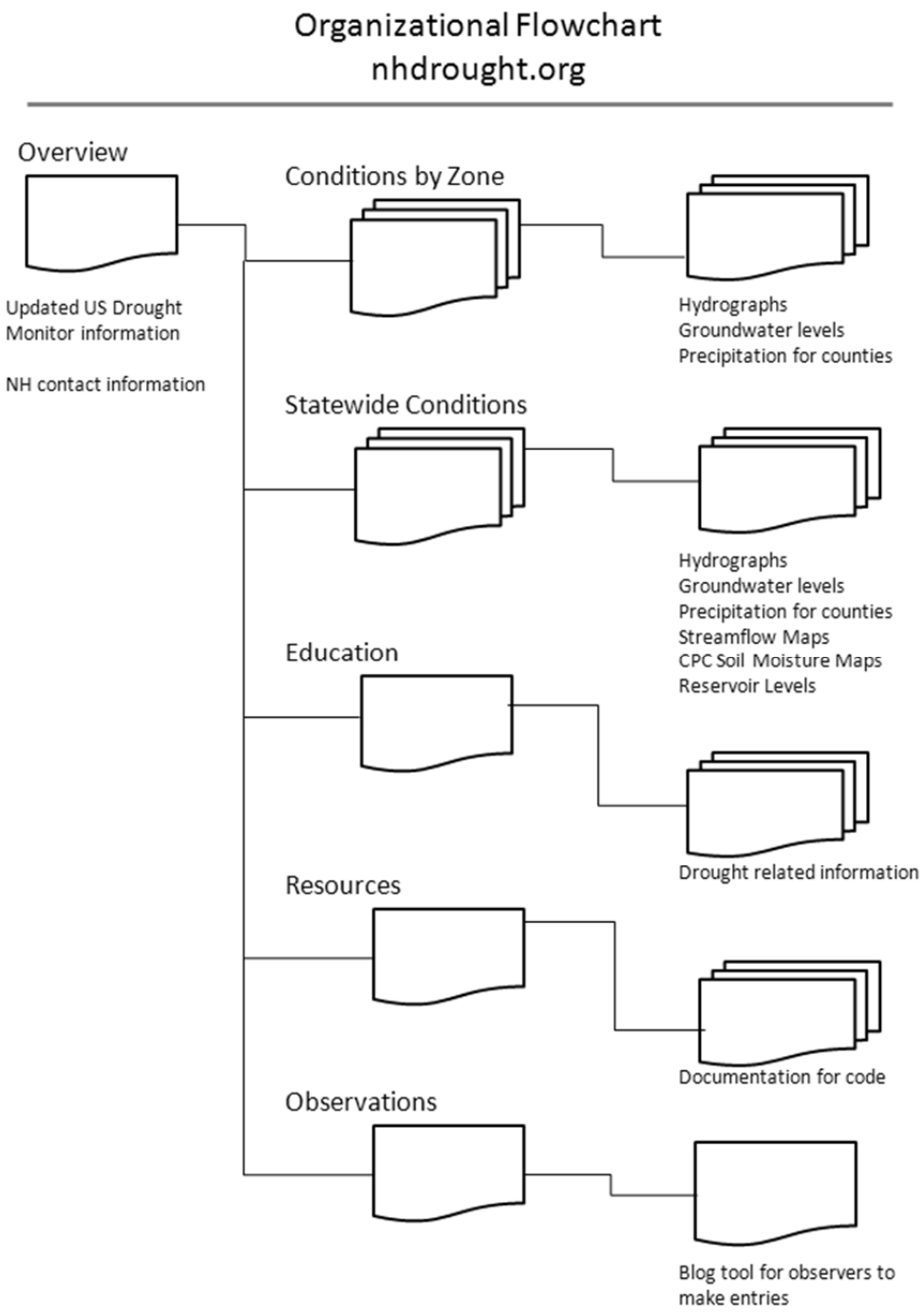


Figure 19. Schematic illustration of organizational structure for nhdrought.org website.

2010 Drought Event Example

During the last year of the 1951-2010 climate period considered in this analysis, the southern part of New Hampshire experienced an extended period of hydrological drought (Figure 20). This event is analyzed in some detail to illustrate how the indices available from NCDC may not accurately reflect actual conditions.

Table 9 shows the average precipitation recorded for New Hampshire's five management regions compared with normal precipitation for the period of March through September in 2010. Although March had unusually abundant precipitation (Stampone, 2010a), setting records for the month in several seacoast towns, the six succeeding months experienced deficits of varying magnitude across the State (Stampone, 2010b). Exacerbating matters, New Hampshire also experienced a concurrent nine-month period of above normal temperatures throughout the state.

Table 9. Average actual precipitation measurements for NH's five Drought Management Regions compared with normal precipitation for the period of March through September, 2010. Modified from DES (2010). Data originally sourced from NERFC.

		March	April	May	June	July	August	September
Coastal Drainage	Actual (Inches)	10.60	2.19	2.04	2.86	2.52	4.15	1.83
	Normal (Inches)	3.94	4.26	3.79	3.73	3.67	3.62	3.77
	% Normal	*269.0*	*51.4*	*53.8*	*76.7*	*68.7*	*114.6*	*48.5*
Southern Interior	Actual (Inches)	7.89	2.15	1.77	3.29	2.81	3.31	2.53
	Normal (Inches)	3.60	3.74	3.82	3.73	3.88	3.80	3.58
	% Normal	*219.17*	*57.49*	*46.34*	*88.20*	*72.42*	*87.11*	*70.67*
South Western	Actual (Inches)	5.76	1.93	2.21	3.93	2.78	2.83	4.60
	Normal (Inches)	3.47	3.58	3.94	3.78	4.02	3.99	3.30
	% Normal	*165.99*	*53.91*	*56.09*	*103.97*	*69.15*	*70.93*	*139.39*
White Mountain	Actual (Inches)	5.40	3.28	1.92	4.76	3.48	3.92	4.97
	Normal (Inches)	3.81	3.89	4.10	4.20	4.30	4.32	3.97
	% Normal	*141.73*	*84.32*	*46.83*	*113.33*	*80.93*	*90.74*	*125.19*
North Country	Actual (Inches)	4.48	3.92	2.34	6.31	3.47	5.44	6.09
	Normal (Inches)	3.57	3.61	4.14	4.61	4.53	4.70	4.20
	% Normal	*125.49*	*108.59*	*56.52*	*136.88*	*76.60*	*115.74*	*145.00*

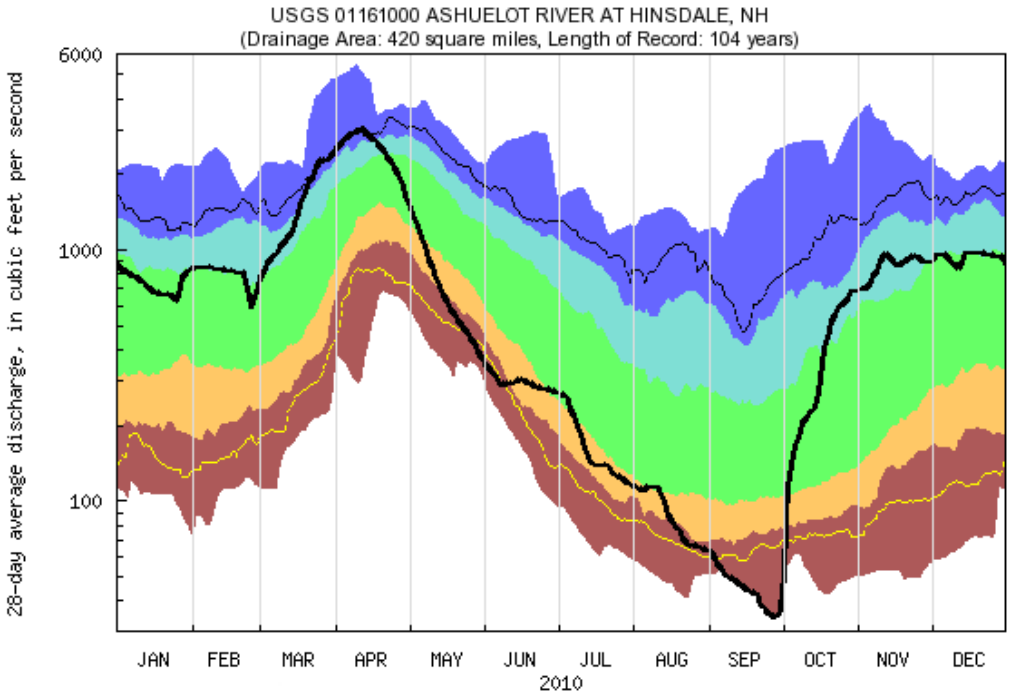


Figure 20. 28-day flow hydrograph for Ashuelot River in calendar year 2010 illustrating extended period of low flow conditions associated with D3 event.

To illustrate the limitations of the PDSI, Figure 21 shows the PDSI map for the last week of August, 2010. While the preceding months had experienced significant precipitation deficits coupled with above normal temperatures, especially in southern and coastal New Hampshire, the PDSI represents both of New Hampshire's climate regions as experiencing 'normal' condition. By comparison, the Drought Monitor product presents much of New Hampshire as being 'abnormally dry'. The inability of the National Climate Data Center's PDSI data product to recognize a dry period can likely be attributed to the unusually large amount of precipitation the State received during March of that year, which would have been factored into its recursive calculations. Nonetheless, this demonstrates the limited usefulness of the National Climate Data Center's PDSI data product in assessing drought conditions in New Hampshire.

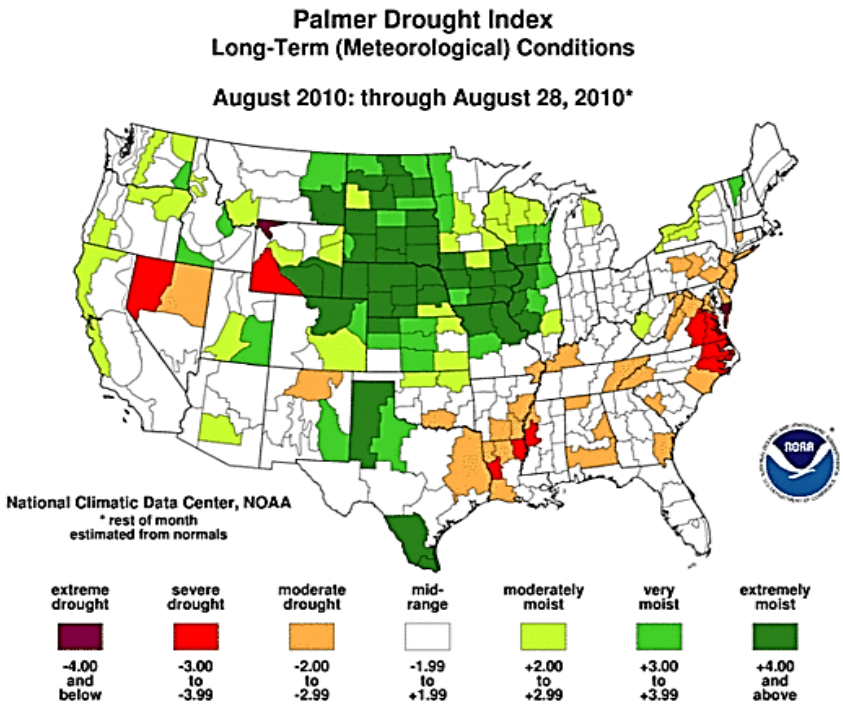


Figure 21. Palmer Drought Severity Index map for the week ending on August 28, 2010. Note that the both the north and south climate regions of New Hampshire are scored as having normal meteorological conditions, despite the southern portion of the state having experienced 4-5 months of below normal precipitation coupled with above normal temperatures. Figure provided by the National Climate Data Center, NOAA (2010).

The U.S. Drought Monitor did a slightly better job of representing the actual conditions in the state but still represented the conditions wetter than actual. D0 through part of the state and only D1 in the south western area (Figure 22) did not line up with observed conditions of D2 conditions in the Southern Interior and South Western management areas and D3 in the Coast Drainage area (Figures 9-11). In addition, the West to East gradation in the DM product appears to be largely reversed from what was observed in streamflow data with the DM depicting the Coastal Drainage as ranging only from normal to Abnormally Dry throughout the period.

The source of the discrepancy between the drought indices and the actual conditions appears to be the reliance of the drought indices on individual station data. For both the Palmer Drought Severity Indices computed in this study (that use precipitation data interpolated onto area centroids) as well as those obtained from the NCDC, the relatively normal conditions in Greenland/Portsmouth station, result in near normal drought indices.

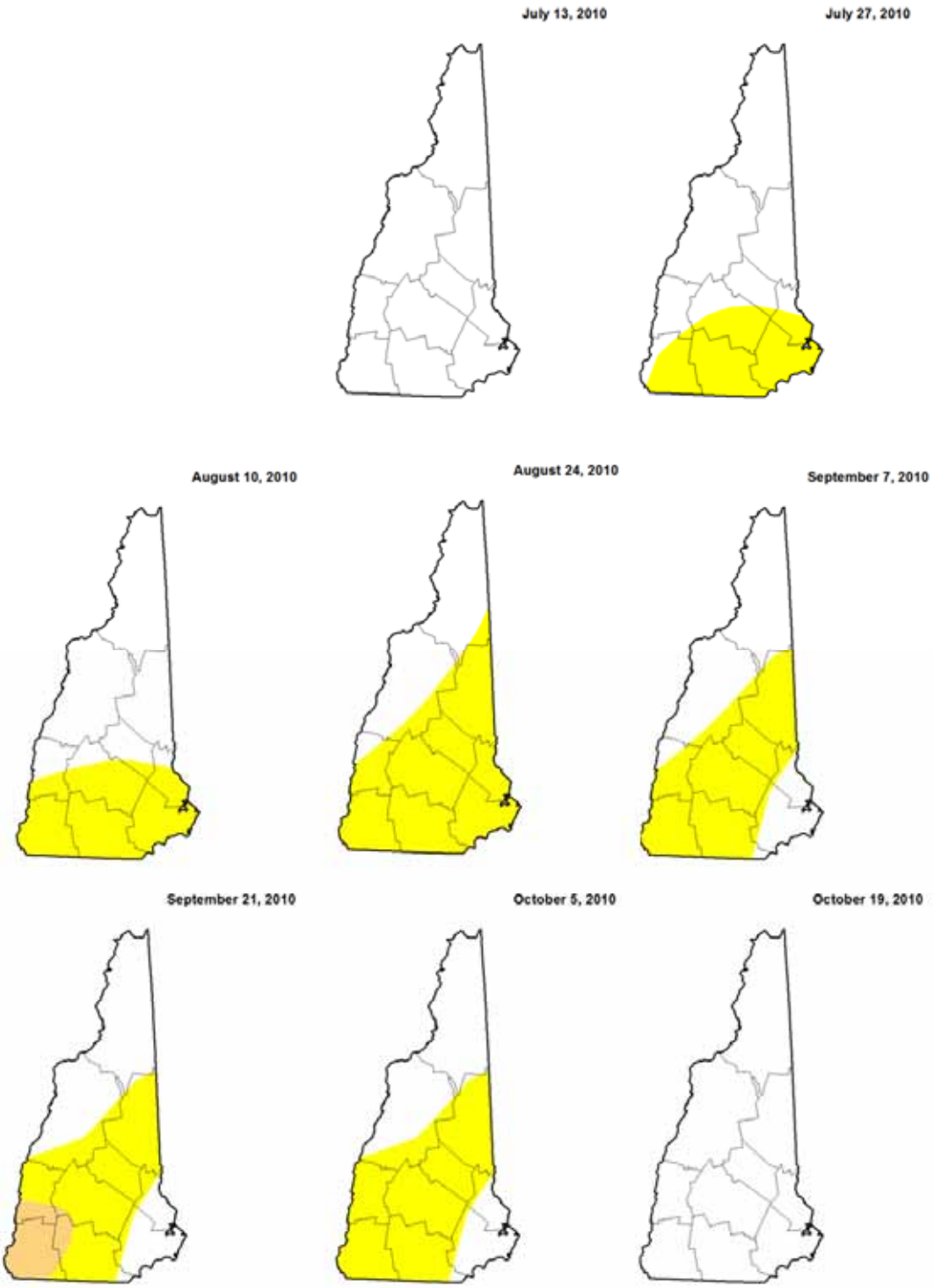


Figure 22. Bi-weekly US Drought Monitor Maps of New Hampshire for Summer 2010.

This raises the question of whether such strong dependence (and bias) can be avoided when assessing drought conditions at relatively small spatial scales. Fortunately, the precipitation data, at the county level, available from the Northeast River Forecasting Center does appear to be better aligned with actual observed conditions.

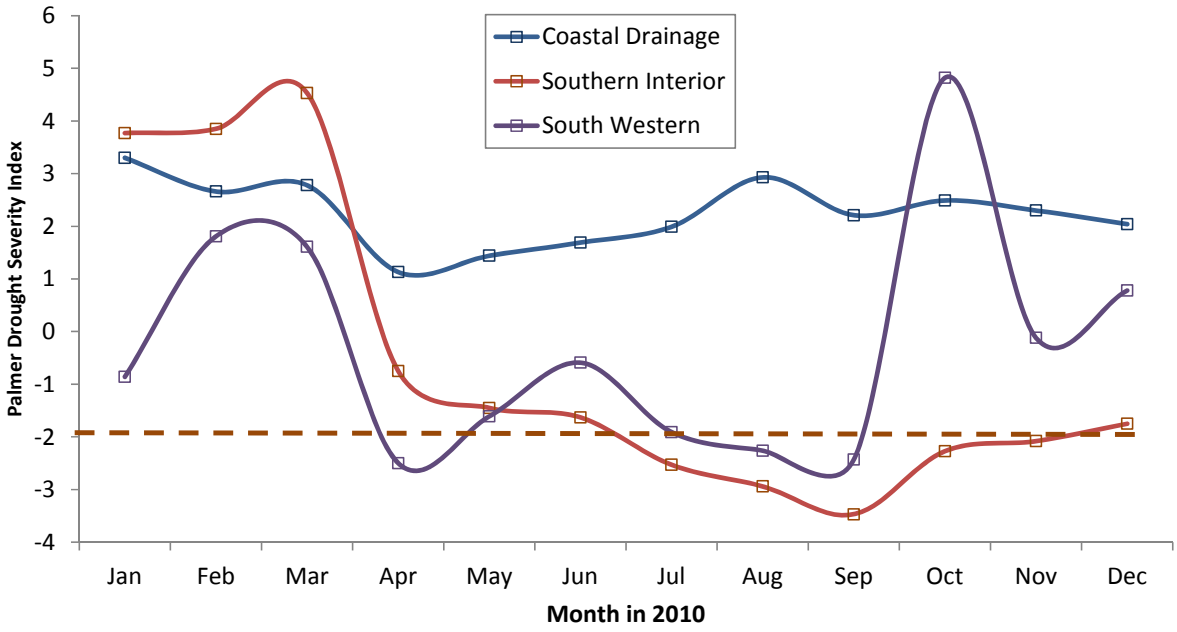


Figure 23. Computed PDSI for southern drought management areas using interpolated precipitation data from this study. Note PDSI in the Coastal Drainage suggests normal to moderately moist conditions at a time when streamflows were experiencing D3 conditions.

Based on the 2010 case study, we can make the following recommendations:

- The Palmer Drought Indices available from the NCDC are not well aligned with observed conditions and should not be relied upon for drought management practices in New Hampshire.
- The US Drought Monitor product appears to also use station data and, as a result, has the potential to lead to bias when there is a strong spatial variability in precipitations, as was the case in 2010.

- Precipitation data from Northeast River Forecasting Center[5] appear to capture strong spatial gradients. Because it is available monthly on a county level, it should be used as the primary precipitation product for assessing drought conditions in New Hampshire.

RECOMMENDATIONS

Drought Management Areas

Our analysis suggests that there remains justification in maintaining the five distinct drought management areas. Using a daily streamflow threshold of 65% of the daily mean in each of the areas results in slightly different characteristics for each zone. The North Country Area has a prevalence of short (7-30 day) events and none exceeding nine months while the zone in the Southern part of the state tend to experience fewer short events and more long ones. In addition to the differences in the event duration, the timing of drought events are quite variable between DMAs. For example, as illustrated in Figures 9-13, the 1960s drought that was quite severe in the southern part of the state was only moderately felt in the North Country and White Mountain areas. It is recommended to continue with the five Drought Management Areas as currently defined.

Drought Classes

The current analysis is based largely on defining an abnormally dry event beginning when the 28-day average streamflow is less than 65% of normal. As noted, this definition results in a higher percentage of time under dry conditions than might occur with the 7-day

[5] http://www.erh.noaa.gov/nerfc/watersupply/ess_MON_YEAR (MON = three letter month abbreviation, YEAR is four-digit year.

streamflow percentile definition. As data collection and interaction with the US Drought Monitor authors evolve in the future, the relative merits of a smoother metric (i.e. 28-day flow) that may have a lower threshold for triggering a D0 or D1 event should be compared against the alternative metric of using the 7-day streamflow percentiles, as suggested by Svoboda et al. (2002).

Drought Triggers and Associated Data Sources

There are a number of data sources that can help to inform the New Hampshire Drought Management Team of the current conditions and these observations and recommendations should be provided to the U.S. Drought Monitor so it can more accurately reflect the conditions in the State. The thresholds for specific indices used as drought triggers are based on an assessment of historical conditions and compilation of the index value as a drought progresses through stages D1 through D4 (see Appendix D). The recommended data sources consider both those that are readily available as well as those that would require additional work to compute based on local meteorological observations.

Precipitation

The Standardized Precipitation Indices (SPI) were found to be good indicators of different levels of drought conditions (Appendix D). Based on an analysis of the SPI indices at the onset of different drought classes, it is recommended to use the following schedule as a basis for providing input to the US Drought Monitor.

- D0: 1-Month SPI < 0.0
- D1: 3-Month SPI < 0.0
- D2: 3-Month SPI <-1.0
- D3: 6-Month SPI < -1.0
- D4: 12-Month SPI < -1.0

These SPI thresholds are lower than those typically used by the US Drought Monitor (Svoboda et al, 2002) and suggest that New Hamspshire is more sensitive to below normal precipitation. This sensitivity is consistent with the hydrogeologic conditions that provide very little groundwater storage of excess precipitation.

Because of the spatial variation in precipitation and the variable behavior of the associated SPI indices, it is recommended that precipitation data from the Northeast River Forecasting Center (NEFC) be used to update the SPI index for each Drought Management Area (DMA) on a weekly basis. Current county level data can be accessed in text form from:

http://www.erh.noaa.gov/nerfc/watersupply/BOSESPTAR

County level month-to-date precipitation should be averaged to obtain a month-to-date precipitation for the entire DMA. In the computation of the SPI, the precipitation value for the current (incomplete) month (P_{update}) should be computed as the weighted sum of the observed month-to-date precipitation (P_{MTD}) and the average monthly precipitation (P_{Norm}) with the weights computed from the day of update (D) relative to the total number of days in the month (D_M).

$$P_{update} = P_{MTD}\left(\frac{D}{D_M}\right) + P_{Norm}\left(1 - \frac{D}{D_M}\right)$$

In lieu of regular updating of the Standardize Precipitation Index (SPI) for each Drought Management Area, the State should work to develop an alternative method to approximate the SPI indices from the long-term totals and corresponding normals available from NERFC at the url shown above. Differences between the SPIs computed from local data and those provided by the NCDC (Appendix E) suggest that NCDC values are only weakly correlated to actual conditions for periods when the SPI < -1.0.

Streamflow

Streamflow is a key indicator of drought conditions. The 28-day average flow for at least one USGS gauging location in each Drought Management Area should be evaluated on a regular basis.

Table 10. Recommended stream gauge stations for assessing drought conditions.

Drought Management Area		River	Gauge Location	USGS Site Number
DMA1	Coastal Drainage	Lamprey	Newmarket	01073500
DMA2	Southern Interior	Souhegan	Merrimack	01094000
DMA3	South Western	Ashuelot	Hinsdale	01161000
DMA4	White Mountains	Pemigewasset	Plymouth	01076500
DMA5	North Country	Diamond	Wentworth	01052500

It is recommended that drought levels be determined based on the number of consecutive days that the 28-day average flow (Q_{28}) at the gauging stations described below is less than 65% of the 28-day normal.

- D0: Q_{28} < 65% Normal for more than 1 day
- D1: Q_{28} < 65% Normal for more than 30 consecutive days
- D2: Q_{28} < 65% Normal for more than 90 consecutive days
- D3: Q_{28} < 65% Normal for more than 180 consecutive days
- D4: Q_{28} < 65% Normal for more than 270 consecutive days

The recommended methodology for assessing the duration for which the 28-day streamflow is less than 65% of normal is to develop an automated method for downloading and storing daily streamflow from the gauge stations shown in Table 2 and comparing the 28-day flows to the daily means for the day.

In lieu of an automated script, the 28-day flows can be accessed from the USGS Streamflow Duration Hydrograph Builder available at the USGS Water Watch url http://waterwatch.usgs.gov/index.php?id=sitedur and compared to the daily percentiles. A map of current 28-day streamflows compared with long-term normals can also be accessed through

the USGS Water Watch site at:

http://waterwatch.usgs.gov/index.php?m=pa28d_dry&r=nh&w=map

Palmer Drought Indices

The Palmer Indices are commonly used by the US Drought Monitor to assess drought conditions regionally. The Palmer indices are potentially useful because they incorporate both precipitation and temperature into a simple model of water availability. The main weakness with the Palmer indices in assessing drought in northern New England is that they don't explicitly incorporate snow or snowmelt. In addition, based on the summer of 2010, it appears that the Palmer indices currently provided by the National Climate Data Center for the climate zones in New Hampshire do not capture the localized drought events. It also appears that the US Drought Monitor relies upon station data rather than NERFC data in their assessment of conditions.

If the Palmer Indices are to be used in NH, it is recommended that they be recomputed using precipitation data obtained from NERFC (as described above for Precipitation). Temperature data can be obtained from a number of sources, including:

- Daily minimum and maximum temperature data can be downloaded directly using the NCDC Climate Data Online (CDO) data product. The stations in Table 11 are recommended:
- An alternative method for obtaining average monthly temperature is to use reported values of heating and cooling degree days from available weather services. Weather Underground has an application programming interface (API) that enables the download of month-to-date heating and cooling degree days as well as monthly normals. Assuming a degree day based temperature of 65F, these values can be used to compute average daily temperature for each zone.

$$T_{update} = T_{MTD}\left(\frac{D}{D_M}\right) + T_{Norm}\left(1 - \frac{D}{D_M}\right)$$

where T_{MTD} and T_{Norm} are obtained from heating and cooling degree days (HDD and CDD, respectively) using:

$$T_{MTD} = 65 - HDD_{MTD} + CDD_{MTD}$$
$$T_{Norm} = 65 - HDD_{Norm} + CDD_{Norm}$$

The month-to-date degree days represent the sum of the departures of the average daily temperature from 65F. The Palmer input files should be updated with monthly precipitation and temperature and the indices recomputed for each zone on a regular basis. Of the Palmer indices, the Palmer Drought Severity index should be used:

- D0: P_{DSI} Not Applicable
- D1: $P_{DSI} < 0.0$
- D2: $P_{DSI} < -1.0$
- D3: $P_{DSI} < -2.0$
- D4: $P_{DSI} < -3.0$

If the Palmer indices are not to be computed using local observational data, the Palmer indices from the NCDC are not recommended for use in assessing drought conditions in New Hampshire.

Groundwater Levels

Of the groundwater levels currently being monitored that also have long-term records, most are in the Southern Interior Area (DMA2). The one long term record that is present in DMA5 and remains part of the active network appears to be influenced by water levels in a nearby lake. For DMA2, the Warner well appears to contain the most useful information with respect to drought conditions. Data for the Warner Well can be accessed from: http://groundwaterwatch.usgs.gov/AWLSites.asp?S=431540071452801

Table 12. Recommended groundwater monitoring well.

Drought Management Area		County	Well Name	USGS Site Number
DMA2	Southern Interior	Merrimack	Warner	01094000

The long-term groundwater records available for the current study are limited to wells in just two of the drought management areas (DMA 2 and DMA 5) and only the wells in the Southern Interior region (DMA2) were sufficiently free from surface water effects to consider in the analysis. We recommend that the State continue to collect data and establish long term records for more wells, representing each of the Drought Management Areas. It is further recommended that the State evaluate data from the existing monitoring wells, not considered here due to limited length of record, to see if they may have the potential to provide additional indicators of the onset and recovery of drought.

Table 13. Current meteorological stations accessible through the NOAA Climate Data Online (CDO) service.

	Station Name	GHCND ID	Elev [m]	Lat	Long
DMA 1	EPPING	USC00272800	48.8	43.030	-71.084
	GREENLAND	USC00273626	25.9	43.017	-70.833
	ROCHESTER	USC00277253	70.1	43.300	-70.983
	WEST HEMPSTEAD	USC00279278	91.4	42.911	-71.201
	ROCHESTER SKYHAVEN AIRPORT	USW00054791	98.5	43.278	-70.922
	DURHAM 2 N	USW00054794	36.3	43.172	-70.928
DMA 2	BRADFORD 2	USC00270913	252.1	43.258	-72.003
	EAST MILFORD	USC00272302	73.2	42.827	-71.626
	FRANCESTOWN	USC00273055	228.6	42.985	-71.796
	FRANKLIN FALLS DAM	USC00273182	131.1	43.467	-71.666
	GREENVILLE 1 NNE	USC00273658	274.3	42.783	-71.799
	LAKEPORT 2	USC00274480	152.4	43.549	-71.464
	MACDOWELL DAM	USC00275013	295.7	42.894	-71.984
	MASSABESIC LAKE	USC00275211	77.1	42.989	-71.393
	MEREDITH 3 NNE	USC00275350	253.0	43.700	-71.466
	MANCHESTER AIRPORT	USW00014710	68.6	42.933	-71.438
	CONCORD MUNICIPAL AIRPORT	USW00014745	105.5	43.195	-71.501
DMA 3	KEENE	USC00274399	155.8	42.939	-72.325
	NEWPORT	USC00275868	240.8	43.384	-72.175
	OTTER BROOK LAKE	USC00276550	207.3	42.945	-72.237
	SURRY MOUNTAIN LAKE	USC00278539	170.7	42.997	-72.313
	WALPOLE 3	USC00278858	283.5	43.074	-72.405
	JAFFREY MUN AIRPORT SILVER RANCH	USW00054770	317.0	42.805	-72.004
DMA 4	BATH 3	USC00270493	198.1	44.151	-71.968
	BENTON 5 SW	USC00270681	365.8	44.034	-71.949
	BETHLEHEM 2	USC00270706	359.7	44.306	-71.658
	NORTH CONWAY	USC00275995	165.8	44.030	-71.138
	TAMWORTH 4	USC00278614	158.5	43.858	-71.260
	WENTWORTH	USC00279091	189.0	43.952	-71.916
	LEBANON MUNICIPAL AIRPORT	USW00094765	182.3	43.626	-72.305
DMA 5	BERLIN	USC00270690	283.5	44.449	-71.184
	COLEBROOK	USC00271647	341.4	44.861	-71.540
	JEFFERSON	USC00274329	376.4	44.417	-71.501
	LANCASTER	USC00274556	262.1	44.491	-71.573
	NORTH STRATFORD	USC00276234	277.4	44.750	-71.630
	PINKHAM NOTCH	USC00276818	612.6	44.263	-71.255
	YORK POND	USC00279966	466.3	44.500	-71.333
	WHITEFIELD MT WASHINGTON AIRPORT	USW00054728	327.4	44.368	-71.545
	BERLIN MUNICIPAL AIRPORT	USW00094700	353.0	44.576	-71.179

Snow

Drought events related to deficits in snow depth appear to be largely explained by low winter precipitation. There are some instances, specifically in the Coastal Drainage in the late 1990s, when drought conditions followed winters that experienced above normal precipitation but below normal snow.

Soil Moisture

USDA – SCAN Measured Data

While soil moisture is a very important indicator of drought conditions, there are little available data in the State. There are two monitoring stations that currently exist as part of the USDA Soil Climate Analysis Network (SCAN). Unfortunately, both stations are located in the same county and the same Drought Management Area, limiting their usefulness for assessing drought conditions statewide. Daily statistics have been summarized for the Hubbard Brook soil moisture data (Figure 19) which provides a baseline for comparing drought conditions in the future.

Table 14. Soil moisture monitoring station

Drought Management Area		County	Name	USDA SCAN Number
DMA3	White Mountains	Grafton	Hubbard Brook	2069

Climate Prediction Center

The Climate Prediction Center in NOAA provides monthly updates to soil moisture conditions in the conterminous US. The model considers a 1.6 meter soil column with a porosity of 0.47 and the model output is in mm of soil moisture, with a maximum value of 760mm. Correlations between historical CPC soil moisture and observed drought

conditions appear to be very weak. It is recommended that the CPC Soil Moisture product be considered as advisory in assessing the long-term recovery of drought.

Future Data Collection

Additional soil moisture data may prove beneficial in understanding actual conditions in different parts of the state. Traditional monitoring by government agencies tends to be very costly but new monitoring systems that are commercially available in the agricultural industry provide a potential opportunity for a low-cost web-based soil moisture monitoring network. We recommend that DES pilot test devices that may enable an efficient and cost effective approach to enhance soil moisture data. It would be of particular interest to contrast soil moisture deficits along a south-to-north transect to see if the diminished variability of streamflow is also observed for soil moisture. Alternatively, multiple soil moisture sensors could be installed in a single watershed to develop a better understanding of how well individual point measurements represent regional conditions.

Summary of Recommended Drought Triggers

Table 15 (following page) summarizes the recommended drought triggers based on the analysis of historical drought events[6] and computation of SPI and Palmer indices computed from local meteorological data.

[6] Drought being when the 28-day streamflow is less than 65% of normal for some period of time

Table 15. Summary of recommended drought triggers for different drought levels. Recommendations for Standardized Precipitation and Palmer Indices are based on index values computed from meterological data for each drought management area. These differ significantly from those provided by the National Climate Data Center.

	WATCH **D0** Abnormally Dry	**ALERT** **D1** Moderate	**WARNING** **D2** Severe	**EMERGENCY** **D3** Extreme	**DISASTER** **D4** Exceptional
Conditions to be used by NH Drought Management Team as basis for recommendations to US Drought Monitor					
PRECIPITATION 1-month SPI 3-month SPI 6-month SPI 12-month SPI	< 0.0 Not Applicable Not Applicable Not Applicable	Not Applicable < 0.0 Not Applicable Not Applicable	Not Applicable < -1.0 Not Applicable Not Applicable	Not Applicable Not Applicable < -1.0 Not Applicable	Not Applicable Not Applicable Not Applicable < -1.0
STREAM FLOW 28-day streamflow 65% of normal	Up to 1 month	1-3 months	3-6 months	6-9 months	> 9 months
PALMER INDEX PDSI	Not Applicable	< 0.0	< -1.0	<-2.0	< -3.0
GROUNDWATER	Not Applicable	Monthly levels drop below mean	Monthly levels persist below monthly mean		Not Quantified

WORKS CITED

Alley, William M. "The Palmer Drought Severity Index: Limitations and Assumptions." Journal of Climate and Applied Meteorology 23 (1984): 1100-109. Print.

American Meteorological Society. "Meteorological Drought." Bulletin of the American Meteorological Society 78.5 (1997): 847-49. Print.

Brutsaert, Wilfried. "Annual Drought Flow and Groundwater Storage Trends in the Eastern Half of the United States during the past Two-third Century." Theoretical and Applied Climatology 100.1-2 (2009): 93-103. Print.

Burakowski, Elizabeth A., Cameron P. Wake, Bobby Braswell, and David P. Brown. "Trends in Wintertime Climate in the Northeastern United States: 1965-2005." Journal of Geophysical Research 113.D20114 (2008).

Dai, Aiguo, Kevin E. Trenberth, and Taotao Qian. "A Global Dataset of Palmer Drought Severity Index for 1870-2002: Relationship with Soil Moisture and Effects of Surface Warming." Journal of Hydrometeorology 5.6 (2004): 1117. Print.

Deutsch, C.V., 1996, Correcting for negative weights in ordinary kriging, Computers and Geosciences, 22(7), 765-773.

Deutsch, C.V. and A.G. Journel, 1998, GSLIB, Geostatistical Software Library and User's Guide, Oxford University Press, New York.

Dickerson, W. H., and B. E. Dethier. "Drought Frequency in the Northeastern United States." Northeastern Regional Research Publication 595 (1970): 5-20. Print.

Dingman, S. Lawrence. Physical Hydrology. Long Grove (IL): Waveland, 2008. Print.

Dougherty, J., 2010, PEST: Model-Independent Parameter Estimation User Manual, 5th Ed., Watermark Numerical Computing, 336p.

Fan, Yun. "Climate Prediction Center Global Monthly Soil Moisture Data Set at 0.5° Resolution for 1948 to Present." Journal of Geophysical Research 109.D10 (2004): n. pag. Print.

Guttman, N.B., 1998: Comparing the Palmer Drought Index and the Standardized Precipitation Index. *J. Amer. Water Resour. Assoc.*, **34**, 113-121.

Hayhoe, Katharine, Cameron P. Wake, Thomas G. Huntington, Lifeng Luo, Mark D. Schwartz, Justin Sheffield, Eric Wood, Bruce Anderson, James Bradbury, Art DeGaetano, Tara J. Troy, and David Wolfe. "Past and Future Changes in Climate and Hydrological Indicators in the US Northeast." Climate Dynamics 28 (2007): 381-407. Print.

Heim Jr, R. R. "A Review of Twentieth Century Drought Indices Used in the United States." Bulletin of the American Meteorological Society 83.8 (2002): 1149-165. Print.

Heim Jr., R.R., “Computing the monthly Palmer Drought Index on a weekly basis: A case study comparing two estimation techniques”, Geophysical Research Letters 32 (2005): L06401, 4 pp. Print.

Hodgkins, Glenn A., Robert W. Dudley, and Thomas G. Huntington. "Summer Low Flows In New England During The 20Th Century." Journal of the American Water Resources Association 41.2 (2005): 403-11. Print.

Huff, F. A., and S. A. Changnon, Jr. "Relation between Precipitation Drought and Low Streamflow." Illinois State Water Survey (1964): 167-80. Print.

Leathers, D.J., A.J. Grundstein, and A.W. Ellis. "Growing Season Moisture Deficits across the Northeastern United States." Climate Research 14 (2000): 43-55. Print.

Loaiciga, H.A, 2005, Drought, tree rings, and reservoir design, Journal of the American Water Resources Association, August, 949-958.

McKee, T.B., N.J. Doesken, and J. Kleist, 1993. The relationship of drought frequency and duration to time scales. 8th Conference on Applied Climatology, 17-22 January, Anaheim, CA, 179-184.

McKee, T.B., N.J. Doesken, and J. Kleist, 1995. Drought monitoring with multiple time scales. 9th Conference on Applied Climatology, Dallas, TX, 233-236.

Mishra, A.K. and V.P. Singh, A review of drought concepts, Journal of Hydrology, v. 391, 1-2, 202-216. 2010.

Nash, William C. "Spatial and Temporal Characteristics of Hydrologic and Meteorologic Dry Periods in New Hampshire." Thesis. University of New Hampshire, 1993. Print.

National Climate Data Center. "Weekly Palmer Drought Indices: August 28, 2010." National Oceanic and Atmospheric Administration. Web. 2011. <http://www.ncdc.noaa.gov/temp-and-precip/drought/weekly-palmers.php?year=2010&month=08&day=28>.

NH DES, New Hampshire Drought Management Plan, NH-DES-WRB-90-1, 1990.

NH DES, "Chapter 12: Floods and Droughts." NH Water Resources Primer. Ed. Sarah Pillsbury, Paul Currier, and Paul Susca. 2008. 12-1-2-18. Print. NH DES, R-WD-08-23

Palmer, Wayne C. "Meteorological Drought." United States Weather Bureau R.S. 45 (1965): 1-58. Print.

Shiau, J.T., and H.W. Shen, 2001, Recurrence analysis of hydrologic droughts of differing severity, Journal of Water Resources Planning and Management, vol 127 no. 1, p. 30-40.

Soule, P. T. "Spatial Patterns of Multiple Drought Types in the Contiguous United States: a Seasonal Comparison." Climate Research 1 (1990): 13-21. Print.

Stampone, M, State Climate Office.Overview of Southeastern New Hampshire Precipitation: March 2010, Durham, NH: 2010a. Print.

Stampone, M., State Climate Office.September 2010 Weather and Climate Summary. By Mary D. Stampone. Durham, NH: 2010b. Print.

Svoboda, M., D. LeComthe, M. Hayes, R. Heim, K. Gleason, J. Angel, B. Rippey, R. Tinker, M. Palecki, D. Stooksbury, D. Miskus, and S. Stephens, 2002, The Drought Monitor, Bulletin of the American Meteorological Society, August, 2002, p. 1181-1190.

The State of New Hampshire. Department of Environmental Services. Aggregated Precipitation Data for N.H. Drought Management Areas. 2010. Print.

Trenberth et al (2014) Global warming and changes in drought. Nature Climate Change 4, 17-22. doi:10.1038/nclimate2067

U.S. Geological Survey. "U.S. Geological Survey Programs in New Hampshire." Fact Sheet FS-029-96 (1996). Print.

Wilhite, D.A.; and M.H. Glantz. 1985. Understanding the Drought Phenomenon: The Role of Definitions. *Water International* 10(3):111–120

APPENDIX A: Snow Depth Data for New Hampshire, 1884-2010

Elizabeth Burakowski
University of New Hampshire, Durham, NH
15-July-2011

Snow Depth Data in New Hampshire

The number of climate stations with long-term snow depth data limits the use of snow cover in drought and other climate research. In New Hampshire, over 189 climate stations have at least one month of snow depth data on record, yet only 66 stations have records that span at least 30 years between 1884 and 2010. Many of the 66 stations that record snow depth unfortunately have a substantial amount of October through April snow depth data flagged as missing, ranging from 0.4% at the most temporally complete long-term station and up to 95.6% at the least temporally complete station. Fourteen out of the 66 stations were missing less than 15% of their Oct-April daily values over their entire period of record.

Filling Missing Snow Depth

In addition to snow cover, the 66 stations also provide daily data on snowfall, precipitation, and minimum and maximum temperatures. The additional climate data can be used to fill missing data values under a number of circumstances following a series of logical arguments based on work by Hughes and Robinson (1993) and Burakowski et al. (2008), and are listed in greater detail in Table A1. For example, if the day previous to the missing day has a recorded snow depth of zero and the following day's snow depth is recorded as zero and there is no recorded snowfall on the day of the missing value, it can be assumed that the missing value was zero. Likewise, if the previous day's snow depth value is equal to the following day's snow depth value and the missing day's snow fall value is zero, it follows that the missing value is equal to the previous and following day's value. When a series of days in a row are all flagged as missing and the day before and day after the missing series have equal snow depth values, the missing snow depth values can be filled using the snow depth values that bracket the missing stretch, provided there is no recorded snowfall in between. Lastly, if the daily mean temperature is between -12C and 4C, a quadratic depth change equation can be used to model snowpack decreases due to temperature, described in more detail below.

The quadratic depth change equation is calculated to estimate the decrease in snow depth in response to daily mean temperature at 1C intervals. For every station, the previous day's snow depth is compared to the current day's snow depth for days on which there is no recorded snowfall; if a decrease in snow depth has occurred, the change in snow depth and daily mean temperature is recorded. Depth change values at each 1C temperature interval are then adjusted for the number of times snow cover is observed but no change in snow depth was recorded. A regression analysis results in a quadratic equation that relates changes in snow depth to mean daily air temperature (Figure A1). The quadratic equation is used to fill missing snow depth values provided the previous day's snow depth, the missing day's mean air temperature, and the missing day's snowfall values are not flagged as missing.

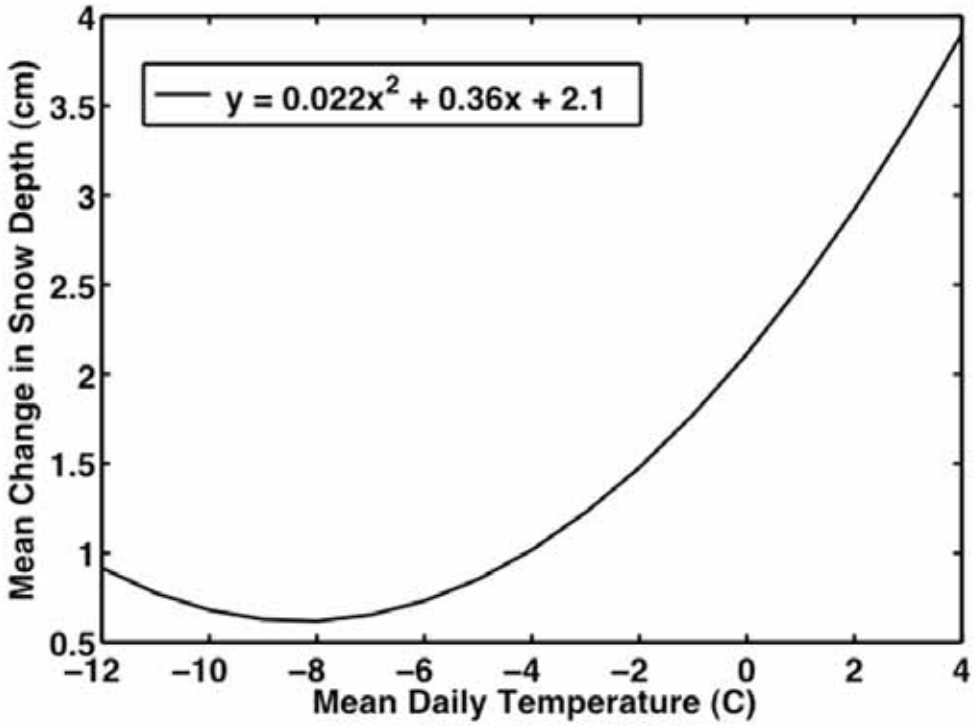


Figure A1. Association between mean change in snow depth (cm) and mean daily temperature (^{o}C), averaged for 66 stations in New Hampshire.

On average, each station fills 1.7% of missing values using logical arguments and/or the quadratic depth change equation. Stations such as Wolfeboro (Figure A2) that have temporally complete snowfall and temperature records benefit the most from data filling, with 16% of missing values filled. The vast majority (78.9%) of data filling came from use of the quadratic

depth change equation (Table A1). After filling, sixteen stations have less than 15% of daily snow depth values missing compared with fourteen stations prior to filling.

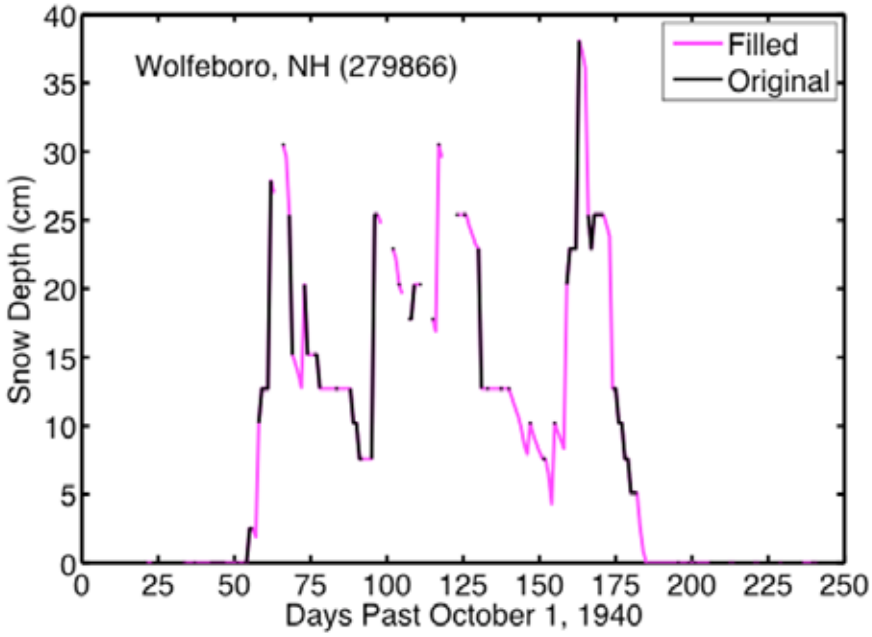


Figure A2. Example of daily snow depth (cm) between 1-Oct-1940 and 30-April-1941 in Wolfeboro, NH. Original values in black; filled values in pink.

Table A1. Description of data filling flags

Flag	Description	% of total flags
0	Data not filled	--
1	Fill with previous day's snow depth if previous day's snow depth is equal to following day's snow depth	6.8%
2	Fill two consecutive missing days with previous day's snow depth if last recorded snow depth is equal to next available recorded snow depth and there is no recorded snowfall on any of the two missing days	5.5%
3	Fill three consecutive missing days with previous day's snow depth if last recorded snow depth is equal to next available recorded snow depth and there is no recorded snowfall on any of the three missing days	4.2%
4	Fill four consecutive missing days with previous day's snow depth if last recorded snow depth is equal to next available recorded snow depth and there is no recorded snowfall on any of the four missing days	4.6%
6	Fill missing snow depth with previous day's snow depth, plus any recorded snowfall and minus any melting/compaction calculated from the quadratic depth change equation for days when daily mean temperature falls between -12C and 4C.	78.9%

References:

Burakowski, EA, CP Wake, B Braswell, and DP Brown. 2008. Trends in wintertime climate in the northeastern United States: 1965-2005. *Journal of Geophysical Research 113*: D20114, doi: 10.1029/2008JD009870.

Hughes, MG and DR Robinson. 1993. Creating temporally complete snow cover records using a new method for modeling snow depth changes. *Glaciological Data, 25:* 150-163.

APPENDIX B: NCDC Fortran Programs

Code to Compute Palmer indices

Obtained from: ftp://ftp.ncdc.noaa.gov/pub/data/software/palmer/

While code uses monthly precipitation, it can be used to with current partial monthly precipitation by extrapolating the month-to-date precipitation to the end of the month.

```
!  PALMERNH.f90
!
!  FUNCTIONS:
!     PALMERNH      - Entry point of console application.
!

!****************************************************************************
!
!  PROGRAM: PALMERNH
!
!  PURPOSE:  Entry point for the console application.
!
!****************************************************************************

      program PALMERNH

!     implicit none

! Variables

!
      parameter (nbcaly=1950,necaly=2010,nbegyr=1950,nendyr=2010,  &
       nendmo= 12,tmsng=99.99,pmsng=-9.99,amsng=-99.99,  &
       inunit=10,ioutp=1,ioutt=1,ioutsp=1,ioutpe=1,ioutpl=1,  &
       ioutpr=1,ioutr=1,iouttl=1,ioutet=1,ioutro=1,ioutsss=1,  &
       ioutssu=1,ioutwp=1,ioutpd=1,ioutz=1,ioutph=1,ioutcp=1,  &
       ioutbyr=1950,iouteyr=2010)
!
!     This program computes the Palmer Drought Severity Index
!     (PDSI), the Palmer Hydrologic Drought Index (PHDI), the
!     real-time operational Palmer Drought Index (WPLM), and the Z
!     Index.  It is a modified version of the program in use at
!     the National Climatic Data Center; the old version was written
!     for mainframe computers with tape drives.  Code taken from the
!     old version is in upper case; new  code is in lower case.  This
!     version is Fortran F77 compatible and is designed for disk rather
!     than tape input/output/storage.  As written, it accepts climatic
!     division temperature and precipitation data obtainable from the
!     NCDC web site under the ftp address:

!        ftp://ftp.ncdc.noaa.gov/pub/data/cirs

!     It is a flexible program in that parameter settings control the
```

```
!     input, output, years of analysis, etc.  These parameter settings
!     are set within the program and are not input from a read statement.
!     Changing the settings therefore requires editing the parameter
!     statement in the program and then recompiling.  Note that the required
!     input are temperature and precipitation data that are serially
!     complete from the beginning to the end of the analysis period
!     of record.  The temperature and precipitation data must be in
!     the same sort order.  There is a simple option for filling in
!     missing data with constant monthly values; the user can modify
!     this routine as needed for serially completing the data record.
!     Another required input is the soils constant file which contains
!     under soil layer water capacity, Thornthwaite coefficients for
!     computing evapotranspiration, and the negative tangent of the
!     latitude of the location.
!
!     A description of the parameter settings follows:
!
!     nbcalyr, necalyr       beginning, ending years of the period for
!                            which the calibration, or "climatologically
!                            appropriate" average values are computed
!     nbegyr, nendyr         beginning, ending years for the analysis
!                            nbcalyr and necalyr must be contained within
!                            nbegyr and nendyr
!     nendmo                 last month in nendyr for which data are
!                            available
!     tmsng, pmsng           missing value code for temp, prec input files
!     amsng                  missing value code for all output
!     inunit                 basic input unit device number from which all
!                            input and output devices are determined
!     output codes           0 = no, 1 = yes; all output is year/month array
!                            in the format identification, year, 12 monthly
!                            values
!     output file (device)
!       ioutp (iout20)       precip used for analysis (should = prec input)
!       ioutt (iout21)       temp used for analysis (should = temp input
!       ioutsp (iout22)      soil water content
!       ioutpe (iout23)      potential evapotranspiration
!       ioutpl (iout24)      potential loss
!       ioutpr (iout25)      potential recharge
!       ioutr (iout26)       recharge
!       iouttl (iout27)      total loss
!       ioutet (iout28)      evapotranspiration
!       ioutro (iout29)      runoff
!       ioutsss (iout30)     surface layer water content
!       ioutssu (iout31)     under layer water content
!
!       ioutwp (iout11)      operational  Palmer (WPLM)
!       ioutpd (iout12)      PDSI
!       ioutz (iout13)       Z Index
!       ioutph (iout14)      PHDI
!       ioutcp (iout15)      evap+recharge+runoff-loss
!
!     ioutbyr,iouteyr        beginning, ending year for output
!
!     NOTE that the climatologically appropriate values, coefficents,
!     etc. are output automatically to device iout10.  If you do not want
!     this output, comment out the appropriate write statement to device
```

```
!     iout10.
!
!     The input device assignments are:
!        inunit     temperature input data
!        in1        precipitation input data
!        in2        constant temp data for filling in missing data
!        in3        constant prec data for filling in missing data
!        in4        soil constants
!
!     NOTE that the id of the soils constants file must match the id
!     of the temp and precip id input.  If there is not a match, the
!     program will stop with an error message that says "no constants".
!     This program is written for the climate division input data;
!     if you want to run the program on site data, include the
!     appropriate state-division code in the identification of the site.
!     The present code calls the state-division code id for temp input,
!     jd for precip input, jjd for soils constant input, and kd for
!     keeping track of the identification.  For site data, an approach is
!     to keep the current state-division codes, but append a site
!     identification such as station number with variable names istn for
!     temp input and jstn for precip input.  The input read statements and
!     format as well as the output write statements and format will have
!     to be changed accordingly.  The file of soil constants for climatic
!     divisions used in this program are available from NCDC.  The user can
!     provide his own constants if desired with appropriate modifications
!     to the read/format statements.
!
!     The device numbers XX (ioutXX, inXX) are coded inunit+XX
!
!
!                    National Climatic Data Center
!                    Asheville, NC
!                    December 1997
!
!
      dimension tt(12),pp(12),temp(nendyr-nbegyr+1,12),prec(nendyr-  &
       nbegyr+1,12),tmsg(12),pmsg(12),indexj(40),indexm(40),  &
       pdat(nendyr-nbegyr+1,12),spdat(nendyr-nbegyr+1,12),   &
       pedat(nendyr-nbegyr+1,12),pldat(nendyr-nbegyr+1,12),  &
       prdat(nendyr-nbegyr+1,12),rdat(nendyr-nbegyr+1,12),   &
       tldat(nendyr-nbegyr+1,12),etdat(nendyr-nbegyr+1,12),  &
       rodat(nendyr-nbegyr+1,12),tdat(nendyr-nbegyr+1,12),   &
       sssdat(nendyr-nbegyr+1,12),ssudat(nendyr-nbegyr+1,12),&
       tsum(12),psum(12),spsum(12),pesum(12),plsum(12),      &
       prsum(12),rsum(12),tlsum(12),etsum(12),rosum(12),     &
       pdsi(nendyr-nbegyr+1,12),phdi(nendyr-nbegyr+1,12),    &
       wplm(nendyr-nbegyr+1,12),                             &
       phi(12),days(12),alp(12),bet(12),                     &
       gam(12),del(12),trat(12),sabsd(12),akhat(12),ak(12),  &
       cp(nendyr-nbegyr+1,12),z(nendyr-nbegyr+1,12),         &
       ppr(nendyr-nbegyr+1,12),px1(nendyr-nbegyr+1,12),      &
       px2(nendyr-nbegyr+1,12),px3(nendyr-nbegyr+1,12),      &
       sx(96),sx1(40),sx2(40),sx3(40),x(nendyr-nbegyr+1,12)
      DATA DAYS /31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.,31./
      DATA PHI  /-.3865982,-.2316132,-.0378180, .1715539, .3458803,  &
                 .4308320, .3916645, .2452467, .0535511,-.15583436, &
                -.3340551,-.4310691 /
```

```
!
!     set input/output device assignments

!       input the name of the parameter file
!       write(*,*)'Input the name of the parameter file'
!       read(*,'(a)')parfile
!       open (unit=12,file=parfile,status='old')
!       read(12,*)


      in1=inunit+1
      in2=inunit+2
      in3=inunit+3
      in4=inunit+4
      iout10=inunit+10
      iout11=inunit+11
      iout12=inunit+12
      iout13=inunit+13
      iout14=inunit+14
      iout15=inunit+15
      iout20=inunit+20
      iout21=inunit+21
      iout22=inunit+22
      iout23=inunit+23
      iout24=inunit+24
      iout25=inunit+25
      iout26=inunit+26
      iout27=inunit+27
      iout28=inunit+28
      iout29=inunit+29
      iout30=inunit+30
      iout31=inunit+31

        open(unit=75,file='data.dat',status='unknown')
        open(unit=76,file='indices.dat',status='unknown')
      kd=0
      kstn=0
      iend=0
 1    do j=1,nendyr-nbegyr+1
        do m=1,12
          temp(j,m)=tmsng
          prec(j,m)=pmsng
        enddo
      enddo
!
!     read input temp and precip data
!
 2    read(inunit,1000,end=4)id,iyr,(tt(m),m=1,12) !temperature file: fort.10
      read(in1,1000,end=5)jd,jyr,(pp(m),m=1,12)    !precip file:  fort.11
 1000 format (i4,1x,i4,12f7.2)
      if(iyr.ne.jyr.and.id.ne.jd) STOP "TEMP, PRECIP OUT OF SYNC"
      if(kd.eq.0) kd=id
      if(id.ne.kd) then
        if(kyr.lt.nendyr) STOP "DATA DO NOT GO TO END YR"
        backspace (inunit)
        backspace (in1)
        goto 3
```

```
      elseif (iyr.lt.nbegyr) then
        goto 2
      elseif (iyr.gt.nendyr) then
        goto 2
      else
        iend=0
        kyr=iyr
        do m=1,12
          temp(iyr-nbegyr+1,m)=tt(m)
          prec(iyr-nbegyr+1,m)=pp(m)
        enddo
        goto 2
      endif
      goto 3
 4    if(iyr.ne.jyr.and.id.ne.jd) STOP "TEMP, PRECIP OUT OF SYNC"
      if(iyr.lt.nendyr) STOP "TEMP DATA FOR LAST ID DO NOT GO TO END YR"
 5    if(iyr.ne.jyr.and.id.ne.jd) STOP "TEMP, PRECIP OUT OF SYNC"
      if(iyr.lt.nendyr) STOP "PREC DATA FOR LAST ID DO NOT GO TO END YR"
      iend=1
 3    continue
!
!    check for missing data and fill in
!
      do j=1,nendyr-nbegyr+1
        do m=1,12
          if ((j.eq.nendyr-nbegyr+1).and.(m.gt.nendmo)) goto 11
          if(temp(j,m).ne.tmsng) then
                    write (*,*) j,m,temp(j,m)
                    goto 10
               endif
              write(*,*) "missing temp data"
 12       read(in2,1001,end=14)iid,(tmsg(mm),mm=1,12)
 1001 format(i4,12f7.2)
          if(iid.ne.id) goto 12
          temp(j,m)=tmsg(m)
 14       STOP "NO VALUE TO FILL IN MSG DATA"
 10       if(prec(j,m).ne.pmsng) goto 11
 13       write(*,*) "missing precip data"
              read(in3,1001,end=14)iid,(pmsg(mm),mm=1,12)
          if(iid.ne.id) goto 13
          prec(j,m)=pmsg(m)
 11     enddo
      enddo
!
!     read in soils constants    Soils file = fort.14
!
      rewind (in4)
 15   read(in4,1002,end=16)jjd,wcbot,b,h,tla
 1002 format(i5,4f8.4)
      if (jjd.ne.kd) then
        goto 15
      else
        goto 17
      endif
 16   STOP "NO CONSTANTS"
!
 17   WCTOP = 1.0
```

```
      SS  = WCTOP
      SU = WCBOT
      WCTOT = WCBOT + WCTOP
      DO 20 M = 1,12
        TSUM  (M) = 0
        PSUM  (M) = 0
        SPSUM (M) = 0
        PESUM (M) = 0
        PLSUM (M) = 0
        PRSUM (M) = 0
        RSUM  (M) = 0
        TLSUM (M) = 0
        ETSUM (M) = 0
        ROSUM (M) = 0
        do j=1,nendyr-nbegyr+1
          pdsi(j,m)=amsng
          phdi(j,m)=amsng
          z(j,m)=amsng
          wplm(j,m)=amsng
          cp(j,m)=amsng
          pdat(j,m)=amsng
          spdat(j,m)=amsng
          pedat(j,m)=amsng
          pldat(j,m)=amsng
          prdat(j,m)=amsng
          rdat(j,m)=amsng
          tldat(j,m)=amsng
          etdat(j,m)=amsng
          rodat(j,m)=amsng
          tdat(j,m)=amsng
          sssdat(j,m)=amsng
          ssudat(j,m)=amsng
        enddo
 20     continue
!
!       loop on years (j) and months (m)
!
        do 70  j=1,nendyr-nbegyr+1
          iy=j+nbegyr-1
!
!       IS IT A LEAP YEAR?
!
          LYEAR = (IY/4*4)/IY

        do 60 m=1,12
          if ((j.eq.nendyr-nbegyr+1).and.(m.gt.nendmo)) goto 60
          t=temp(j,m)
          p=prec(j,m)
!    ------------------------------------------------------------------
!     HERE START THE WATER BALANCE CALCULATIONS
!    ------------------------------------------------------------------
      SP = SS + SU
      PR = WCBOT + WCTOP - SP
!    ------------------------------------------------------------------
!     1 - CALCULATE PE (POTENTIAL EVAPOTRANSPIRATION)
!                 soil constants are:
!                              TLA =
```

```
!                               b=
!                               h=
!   ------------------------------------------------------------------
      IF (T.LE.32.) THEN
          PE   = 0.0
      ELSE
          DUM  = PHI(M)*TLA
          DK   = ATAN(SQRT(1. - DUM*DUM)/DUM)
          IF (DK.LT.0.) DK = 3.141593 + DK
          DK   = (DK + .0157)/1.57
          IF (T.GE.80.) THEN
              PE = (SIN(T/57.3 - .166) - .76)*DK
          ELSE
              DUM=log(t-32)
              PE = (EXP(-3.863233 + B*1.715598 -B*log(h) + B*DUM))*DK
          ENDIF
      ENDIF
!   ------------------------------------------------------------------
!     CONVERT DAILY TO MONTHLY
!   ------------------------------------------------------------------
      IF (M.EQ.2.AND.LYEAR.EQ.1) THEN
          PE = PE * 29.
      ELSE
          PE = PE * DAYS(M)
      ENDIF
!   ------------------------------------------------------------------
!     2 - PL  POTENTIAL LOSS
!   ------------------------------------------------------------------
      IF (SS.GE.PE) THEN
          PL  = PE
      ELSE
          PL   = ((PE - SS) * SU) / (WCBOT + WCTOP) + SS
          PL   = AMIN1(PL,SP)
      ENDIF

!   ------------------------------------------------------------------
!     3 - CALCULATE RECHARGE, RUNOFF, RESIDUAL MOISTURE, LOSS TO BOTH
!         SURFACE AND UNDER LAYERS, DEPENDING ON STARTING MOISTURE
!         CONTENT AND VALUES OF PRECIPITATION AND EVAPORATION.
!   ------------------------------------------------------------------
      IF (P.GE.PE) THEN
!     ----------------- PRECIP EXCEEDS POTENTIAL EVAPORATION
          ET = PE
          TL = 0.0
          IF ((P - PE).GT.(WCTOP - SS)) THEN
!         ------------------------------ EXCESS PRECIP RECHARGES
!                                        UNDER LAYER AS WELL AS UPPER
              RS = WCTOP - SS
              SSS = WCTOP
              IF ((P - PE -RS).LT.(WCBOT - SU)) THEN
!             ---------------------------------- BOTH LAYERS CAN TAKE
!                                                THE ENTIRE EXCESS
                  RU = P - PE - RS
                  RO = 0.0
              ELSE
!             ---------------------------------- SOME RUNOFF OCCURS
                  RU = WCBOT - SU
```

```
                RO = P - PE - RS - RU
            ENDIF
            SSU = SU + RU
            R   = RS + RU
        ELSE
!           ------------------------------ ONLY TOP LAYER RECHARGED
            R   = P - PE
            SSS = SS + P - PE
            SSU = SU
            RO  = 0.0
        ENDIF
    ELSE
!   ----------------- EVAPORATION EXCEEDS PRECIPITATION
        R  = 0.0
        IF (SS.GE.(PE - P)) THEN
!           ------------------------ EVAP FROM SURFACE LAYER ONLY
            SL  = PE - P
            SSS = SS - SL
            UL  = 0.0
            SSU = SU
        ELSE
!           ------------------------ EVAP FROM BOTH LAYERS
            SL  = SS
            SSS = 0.0
            UL  = (PE - P - SL) * SU / (WCTOT + 1.0)
            UL  = AMIN1(UL,SU)
            SSU = SU - UL
        ENDIF
        TL  = SL + UL
        RO  = 0.0
        ET  = P  + SL + UL
    ENDIF
!   ---------------------------------------------------------------
!   FOR CALIBRATION YEARS, SUM VALUES NEEDED TO CALCULATE THE
!   NORMAL CLIMATE COEFFICIENTS (ALPHA, BETA, ETC.)
!   ---------------------------------------------------------------
    IF(IY.GE.NBCALY.AND.IY.LE.NECALY) THEN
        TSUM (M) = TSUM (M) + T
        PSUM (M) = PSUM (M) + P
        SPSUM(M) = SPSUM(M) + SP
        PESUM(M) = PESUM(M) + PE
        PLSUM(M) = PLSUM(M) + PL
        PRSUM(M) = PRSUM(M) + PR
        RSUM (M) = RSUM (M) + R
        TLSUM(M) = TLSUM(M) + TL
        ETSUM(M) = ETSUM(M) + ET
        ROSUM(M) = ROSUM(M) + RO
    ENDIF
    pdat(j,m)=p
    spdat(j,m)=sp
    pedat(j,m)=pe
    pldat(j,m)=pl
    prdat(j,m)=pr
    rdat(j,m)=r
    tldat(j,m)=tl
    etdat(j,m)=et
    rodat(j,m)=ro
```

```
      tdat(j,m)=t
      sssdat(j,m)=sss
      ssudat(j,m)=ssu
        write(75,6200)m,iy,p,t,sp,pe,pl,pr,r,tl,et,ro,sss,ssu
6200  format(i2,',',i4,',',1x14(f7.2,','))
      SS       = SSS
      SU       = SSU

   60 CONTINUE
!    -------------------------- END OF MONTH LOOP
!
!     output the intermediate variables
!
      if(iy.ge.ioutbyr.and.iy.le.iouteyr)then
       if(ioutt.eq.1)write(iout20,4321)kd,iy,(tdat(j,m),m=1,12)
       if(ioutp.eq.1)write(iout21,4321)kd,iy,(pdat(j,m),m=1,12)
       if(ioutsp.eq.1)write(iout22,4321)kd,iy,(spdat(j,m),m=1,12)
       if(ioutpe.eq.1)write(iout23,4321)kd,iy,(pedat(j,m),m=1,12)
       if(ioutpl.eq.1)write(iout24,4321)kd,iy,(pldat(j,m),m=1,12)
       if(ioutpr.eq.1)write(iout25,4321)kd,iy,(prdat(j,m),m=1,12)
       if(ioutr.eq.1)write(iout26,4321)kd,iy,(rdat(j,m),m=1,12)
       if(iouttl.eq.1)write(iout27,4321)kd,iy,(tldat(j,m),m=1,12)
       if(ioutet.eq.1)write(iout28,4321)kd,iy,(etdat(j,m),m=1,12)
       if(ioutro.eq.1)write(iout29,4321)kd,iy,(rodat(j,m),m=1,12)
       if(ioutsss.eq.1)write(iout30,4321)kd,iy,(sssdat(j,m),m=1,12)
       if(ioutssu.eq.1)write(iout31,4321)kd,iy,(ssudat(j,m),m=1,12)
      endif
   70 CONTINUE
!     ------------------------- END OF YEAR LOOP
!   ---------------------------------------------------------------------
!     LOOP 90 IS BY MONTH: CAFEC COEFFICIENTS CALCULATIONS AND
!     'T' RATIO FOR EACH MONTH
!   ---------------------------------------------------------------------
      DO 90 M = 1, 12
!
!     ALPHA CALCULATION
!     -----------------
      IF(PESUM(M).NE.0.) THEN
          ALP(M) = ETSUM(M) / PESUM(M)
      ELSE
          IF (ETSUM(M).EQ.0.) THEN
              ALP(M) = 1.0
          ELSE
              ALP(M) = 0.0
          ENDIF
      ENDIF
!
!     BETA CALCULATION
!     ----------------
      IF (PRSUM(M).NE.0.) THEN
          BET(M) = RSUM(M)/PRSUM(M)
      ELSE
          IF (RSUM(M).EQ.0.) THEN
              BET(M) = 1.0
          ELSE
              BET(M) = 0.0
          ENDIF
```

```
      ENDIF
!
!     GAMMA CALCULATION
!     -----------------
      IF (SPSUM(M).NE.0.) THEN
          GAM(M) = ROSUM(M) / SPSUM(M)
      ELSE
          IF (ROSUM(M).EQ.0.) THEN
              GAM(M) = 1.
          ELSE
              GAM(M) = 0.0
          ENDIF
      ENDIF
!
!     DELTA CALCULATION
!     -----------------
      IF (PLSUM(M).NE.0.) THEN
          DEL(M) = TLSUM(M) / PLSUM(M)
      ELSE
          DEL(M) = 0.0
      ENDIF

!   ------------------------------------------------------------------
!     CALCULATION OF Z-INDEX WEIGHTING FACTORS (VARIABLE AK)
!     TRAT(M) IS THE 'T' RATIO OF AVERAGE MOISTURE DEMAND TO AVERAGE
!             MOISTURE SUPPLY IN MONTH M.
!   ------------------------------------------------------------------
          TRAT(M) = (PESUM(M)+RSUM(M)+ROSUM(M)) / (PSUM(M)+TLSUM(M))
!   ------------------------------------------------------------------
!     'SUM' VARIABLES NOW BECOME AVERAGES OVER THE CALIBRATION PERIOD
!   ------------------------------------------------------------------
      numyr=necaly-nbcaly+1
      TSUM (M) = TSUM(M)  / NUMYR
      PSUM (M) = PSUM (M) / NUMYR
      SPSUM(M) = SPSUM(M) / NUMYR
      PESUM(M) = PESUM(M) / NUMYR
      PLSUM(M) = PLSUM(M) / NUMYR
      PRSUM(M) = PRSUM(M) / NUMYR
      RSUM (M) = RSUM (M) / NUMYR
      TLSUM(M) = TLSUM(M) / NUMYR
      ETSUM(M) = ETSUM(M) / NUMYR
      ROSUM(M) = ROSUM(M) / NUMYR

   90 CONTINUE
!     ----------------------END OF MONTHLY COEFFICIENT LOOP


      DO 100 M = 1, 12
      SABSD(M)  = 0.0
  100 continue

!   ------------------------------------------------------------------
!     REREAD MONTHLY PARAMETERS FOR CALCULATION OF
!     THE 'K' MONTHLY WEIGHTING FACTORS USED IN Z-INDEX CALCULATION
!   ------------------------------------------------------------------
      do 102 j=nbcaly-nbegyr+1,necaly-nbegyr+1
       do 101 m=1,12
```

```
      PHAT     = ALP(M)*PEdat(j,m) + BET(M)*PRdat(j,m) +  &
            GAM(M)*SPdat(j,m) - DEL(M)*PLdat(j,m)
      D        = Pdat(j,m) - PHAT
      SABSD(M)= SABSD(M) + ABS(D)
 101  continue
 102  continue
      SWTD = 0.0
      DO 130 MO = 1,12
      DBAR = SABSD(MO) / NUMYR
      AKHAT(MO) = 1.5 * log10((trat(mo)+2.8)/dbar) + .5
      SWTD = SWTD + DBAR*AKHAT(MO)
 130  CONTINUE
      DO 140 MO = 1,12
      AK(MO) = 17.67 * AKHAT(MO) / SWTD

!    ------------------------------------------------------------------
!     PRINT OUT COEFFICIENTS AND OTHER STUFF for calibration years
!    ------------------------------------------------------------------
      write(iout10,6060) kd,MO, ALP(MO), BET(MO), GAM(MO), DEL(MO), &
                  AK(MO),PSUM (MO), SPSUM(MO), PRSUM(MO), PESUM(MO),  &
                  PLSUM(MO), ETSUM(MO), RSUM (MO), TLSUM(MO),  &
                  ROSUM(MO)
 140  continue
 6060 format(i4.4,i3,4f9.4,f9.3,9f9.2)
 150  CONTINUE

      V   = 0.0
      PRO = 0.0
      X1  = 0.0
      X2  = 0.0
      X3  = 0.0
      K8  = 1
      k8max = 1
!    ------------------------------------------------------------------
!     LOOP FROM 160 TO 230 REREADS data FOR CALCULATION OF
!     THE Z-INDEX (MOISTURE ANOMALY) AND PDSI (VARIABLE X).
!     THE FINAL OUTPUTS ARE THE VARIABLES PX3, X, AND Z  WRITTEN
!     TO FILE 11.
!    ------------------------------------------------------------------
      do 231 j=1,nendyr-nbegyr+1
      iy=j+nbegyr-1
        do 230 m=1,12
         indexj(k8)=j
         indexm(k8)=m
         if ((j.eq.nendyr-nbegyr+1).and.(m.gt.nendmo)) then
           goto 230
         endif
 160  ZE  = 0.0
      UD  = 0.0
      UW  = 0.0
      CET = ALP(M) * PEdat(j,m)
      CR  = BET(M) * PRdat(j,m)
      CRO = GAM(M) * SPdat(j,m)
      CL  = DEL(M) * PLdat(j,m)
      CP(j,m)  = CET + CR + CRO - CL
      CD  = Pdat(j,m)- CP(j,m)
      Z(j,m)   = AK(M) * CD
```

```
      IF (PRO.EQ.100. .OR. PRO.EQ.0.) THEN
!     ------------------------------------ NO ABATEMENT UNDERWAY
!                                          WET OR DROUGHT WILL END IF
!                                             -.5 =< X3 =< .5
          IF (X3.GE.-.5 .AND. X3.LE..5) THEN
!         --------------------------------- END OF DROUGHT OR WET
              PV  = 0.0
              PPR(j,m) = 0.0
              PX3(j,m) = 0.0
!             ------------ BUT CHECK FOR NEW WET OR DROUGHT START FIRST
              GO TO 200
          ELSE IF (X3.GT..5) THEN
!         ----------------------- WE ARE IN A WET SPELL
               IF (Z(j,m).GE..15) THEN
!              ------------------ THE WET SPELL INTENSIFIES
                  GO TO 210
              ELSE
!             ------------------ THE WET STARTS TO ABATE (AND MAY END)
                  GO TO 170
              ENDIF
          ELSE IF (X3.LT.-.5) THEN
!         ------------------------- WE ARE IN A DROUGHT
               IF (Z(j,m).LE.-.15) THEN
!              -------------------- THE DROUGHT INTENSIFIES
                  GO TO 210
              ELSE
!             ------------------ THE DROUGHT STARTS TO ABATE (AND MAY END)
                  GO TO 180
              ENDIF
          ENDIF
      ELSE
!     ------------------------------------------ABATEMENT IS UNDERWAY
          IF (X3.GT.0.) GO TO 170
!         ----------------------- WE ARE IN A WET SPELL
          IF (X3.LE.0.) GO TO 180
!         ----------------------- WE ARE IN A DROUGHT
      ENDIF
!   ------------------------------------------------------------------
!      WET SPELL ABATEMENT IS POSSIBLE
!   ------------------------------------------------------------------
  170 UD = Z(j,m) - .15
      PV = UD + AMIN1(V,0.)
      IF (PV.GE.0) GO TO 210
!     --------------------- DURING A WET SPELL, PV => 0 IMPLIES
!                           PROB(END) HAS RETURNED TO 0
      ZE = -2.691 * X3 + 1.5
      GO TO 190
!   ------------------------------------------------------------------
!      DROUGHT ABATEMENT IS POSSIBLE
!   ------------------------------------------------------------------
  180 UW = Z(j,m) + .15
      PV = UW + AMAX1(V,0.)
      IF (PV.LE.0) GO TO 210
!     --------------------- DURING A DROUGHT, PV =< 0 IMPLIES
!                           PROB(END) HAS RETURNED TO 0
      ZE = -2.691 * X3 - 1.5
!   ------------------------------------------------------------------
```

```
!     PROB(END) = 100 * (V/Q)  WHERE:
!                 V = SUM OF MOISTURE EXCESS OR DEFICIT (UD OR UW)
!                 DURING CURRENT ABATEMENT PERIOD
!             Q = TOTAL MOISTURE ANOMALY REQUIRED TO END THE
!                 CURRENT DROUGHT OR WET SPELL
!   ------------------------------------------------------------------
  190 IF (PRO.EQ.100.) THEN
!     -------------------- DROUGHT OR WET CONTINUES, CALCULATE
!                          PROB(END) - VARIABLE ZE
          Q = ZE
      ELSE
          Q = ZE + V
      ENDIF
      PPR(j,m) = (PV / Q) * 100.
      IF (PPR(j,m).GE.100.) THEN
          PPR(j,m) = 100.
          PX3(j,m) = 0.
      ELSE
          PX3(j,m) = .897 * X3 + Z(j,m)/3.
      ENDIF
!   ------------------------------------------------------------------
!     CONTINUE X1 AND X2 CALCULATIONS.
!     IF EITHER INDICATES THE START OF A NEW WET OR DROUGHT,
!     AND IF THE LAST WET OR DROUGHT HAS ENDED, USE X1 OR X2
!     AS THE NEW X3.
!   ------------------------------------------------------------------
  200 PX1(j,m) = .897 * X1 + Z(j,m)/3.
      PX1(j,m) = AMAX1(PX1(j,m),0.)
      IF (PX1(j,m).GE.1.) THEN
          IF (PX3(j,m).EQ.0.) THEN
!         ------------------- IF NO EXISTING WET SPELL OR DROUGHT
!                             X1 BECOMES THE NEW X3
              X(j,m)   = PX1(j,m)
              PX3(j,m) = PX1(j,m)
              PX1(j,m) = 0.
              iass=1
              CALL ASSIGN (iass,k8,ppr,px1,px2,px3,x,pdsi,phdi,wplm, &
               j,m,nendyr,nbegyr,sx1,sx2,sx3,sx,indexj,indexm)
              GO TO 220
          ENDIF
      ENDIF
      PX2(j,m) = .897 * X2 + Z(j,m)/3.
      PX2(j,m) = AMIN1(PX2(j,m),0.)
      IF (PX2(j,m).LE.-1.) THEN
          IF (PX3(j,m).EQ.0.) THEN
!         ------------------- IF NO EXISTING WET SPELL OR DROUGHT
!                             X2 BECOMES THE NEW X3
              X(j,m)   = PX2(j,m)
              PX3(j,m) = PX2(j,m)
              PX2(j,m) = 0.
              iass=2
              CALL ASSIGN (iass,k8,ppr,px1,px2,px3,x,pdsi,phdi,wplm,  &
               j,m,nendyr,nbegyr,sx1,sx2,sx3,sx,indexj,indexm)
              GO TO 220
          ENDIF
      ENDIF
      IF (PX3(j,m).EQ.0.) THEN
```

```
!    -------------------- NO ESTABLISHED DROUGHT (WET SPELL), BUT X3=0
!                         SO EITHER (NONZERO) X1 OR X2 MUST BE USED AS X3
         IF (PX1(j,m).EQ.0.) THEN
             X(j,m) = PX2(j,m)
             iass=2
             CALL ASSIGN (iass,k8,ppr,px1,px2,px3,x,pdsi,phdi,wplm,  &
              j,m,nendyr,nbegyr,sx1,sx2,sx3,sx,indexj,indexm)
             GO TO 220
         ENDIF
         IF (PX2(j,m).EQ.0) THEN
             X(j,m) = PX1(j,m)
             iass=1
             CALL ASSIGN (iass,k8,ppr,px1,px2,px3,x,pdsi,phdi,wplm,  &
              j,m,nendyr,nbegyr,sx1,sx2,sx3,sx,indexj,indexm)
             GO TO 220
         ENDIF
     ENDIF
!   ---------------------------------------------------------------------
!    AT THIS POINT THERE IS NO DETERMINED VALUE TO ASSIGN TO X,
!    ALL VALUES OF X1, X2, AND X3 ARE SAVED IN FILE 8. AT A LATER
!    TIME X3 WILL REACH A VALUE WHERE IT IS THE VALUE OF X (PDSI).
!    AT THAT TIME, THE ASSIGN SUBROUTINE BACKTRACKS THROUGH FILE
!    8 CHOOSING THE APPROPRIATE X1 OR X2 TO BE THAT MONTH'S X.
!   ---------------------------------------------------------------------
     IF (K8.GT.40) STOP 'X STORE ARRAYS FULL'
     SX1(K8) = PX1(j,m)
     SX2(K8) = PX2(j,m)
     SX3(K8) = PX3(j,m)
     X(j,m)  = PX3(j,m)
     K8      = K8 + 1
     k8max=k8
     GO TO 220
!   ---------------------------------------------------------------------
!    PROB(END) RETURNS TO 0.  A POSSIBLE ABATEMENT HAS FIZZLED OUT,
!    SO WE ACCEPT ALL STORED VALUES OF X3
!   ---------------------------------------------------------------------
 210 PV  = 0.0
     PX1(j,m) = 0.0
     PX2(j,m) = 0.0
     PPR(j,m) = 0.0
     PX3(j,m) = .897 * X3 + Z(j,m)/3.
     X(j,m)   = PX3(j,m)
     IF (K8.EQ.1) THEN
       PDSI(j,m) = X(j,m)
       PHDI(j,m) = PX3(j,m)
       IF ( PX3(j,m).EQ. 0.0 ) PHDI(j,m)=X(j,m)
       CALL CASE (PPR(j,m),PX1(j,m),PX2(j,m),PX3(j,m),WPLM(j,m))
     ELSE
       iass=3
       CALL ASSIGN (iass,k8,ppr,px1,px2,px3,x,pdsi,phdi,wplm, &
        j,m,nendyr,nbegyr,sx1,sx2,sx3,sx,indexj,indexm)
     ENDIF
!   ---------------------------------------------------------------------
!    SAVE THIS MONTH'S CALCULATED VARIABLES (V,PRO,X1,X2,X3) FOR
!    USE WITH NEXT MONTHS DATA
!   ---------------------------------------------------------------------
 220 V   = PV
```

```
      PRO = PPR(j,m)
      X1  = PX1(j,m)
      X2  = PX2(j,m)
      X3  = PX3(j,m)
  230   continue
4321    format (I4.4,I5,12F7.2)
!   ---------------------- READ THE NEXT MONTH'S DATA
  231 continue
      j=nendyr-nbegyr+1
      m=12
!   ---------------------------------------------------------------------
!     FINISH UP BY CLEARING OUT FILE 8 AND WRITING IT TO FILE 11
!   ---------------------------------------------------------------------
 240  do k8=1,k8max-1
      PDSI(indexj(k8),indexm(k8)) = X(indexj(k8),indexm(k8))
      PHDI(indexj(k8),indexm(k8)) = PX3(indexj(k8),indexm(k8))
      IF (PX3(indexj(k8),indexm(k8)).EQ. 0.0 ) &
        PHDI(indexj(K8),indexm(k8))=X(indexj(k8),indexm(k8))
      CALL CASE(PPR(j,m),PX1(j,m),PX2(j,m),PX3(j,m),  &
        WPLM(indexj(k8),indexm(k8)))
      enddo
!
!     output the indices
!

        do 920 j=1,nendyr-nbegyr+1
            do 920 m=1,12
                   iy=j+nbegyr-1

write(76,6201)m,iy,WPLM(j,m),pdsi(j,m),z(j,m),phdi(j,m),cp(j,m)
920     continue
6201  format(i2,',',i5,',',5(f7.2,','))

      do j=1,nendyr-nbegyr+1
      iy=j+nbegyr-1
      if(iy.ge.ioutbyr.and.iy.le.iouteyr.and.ioutwp.eq.1) &
       write (iout11,4321) kd,IY,(WPLM(j,m),m=1,12)
      if(iy.ge.ioutbyr.and.iy.le.iouteyr.and.ioutpd.eq.1) &
       write (iout12,4321) kd,IY,(pdsi(j,m),m=1,12)
      if(iy.ge.ioutbyr.and.iy.le.iouteyr.and.ioutz.eq.1)  &
       write (iout13,4321) kd,IY,(z(j,m),m=1,12)
      if(iy.ge.ioutbyr.and.iy.le.iouteyr.and.ioutph.eq.1) &
       write (iout14,4321) kd,IY,(phdi(j,m),m=1,12)
      if(iy.ge.ioutbyr.and.iy.le.iouteyr.and.ioutcp.eq.1) &
       write (iout15,4321) kd,IY,(cp(j,m),m=1,12)
      enddo
  999 CONTINUE
      kd=id
      if(iend.eq.1) goto 998
      goto 1
  998 END



      SUBROUTINE ASSIGN (iass,k8,ppr,px1,px2,px3,x,pdsi,phdi,wplm,  &
               j,m,nendyr,nbegyr,sx1,sx2,sx3,sx,indexj,indexm)
```

```
      DIMENSION SX1(40), SX2(40), SX3(40), SX(96),  &
       pdsi(nendyr-nbegyr+1,12),phdi(nendyr-nbegyr+1,12), &
       wplm(nendyr-nbegyr+1,12),ppr(nendyr-nbegyr+1,12),  &
       px1(nendyr-nbegyr+1,12),px2(nendyr-nbegyr+1,12),   &
       px3(nendyr-nbegyr+1,12),x(nendyr-nbegyr+1,12),     &
       indexj(40),indexm(40)
!
!   ------------------------------------------------------------------
!     FIRST FINISH OFF FILE 8 WITH LATEST VALUES OF PX3, Z,X
!     X=PX1 FOR I=1, PX2 FOR I=2, PX3,  FOR I=3
!   ------------------------------------------------------------------
      SX(K8) = X(j,m)
      ISAVE  = iass
      IF (K8.EQ.1) THEN
          PDSI(j,m) = X(j,m)
          PHDI(j,m) = PX3(j,m)
          IF ( PX3(j,m) .EQ. 0.0 ) PHDI(j,m)=X(j,m)
          CALL CASE (PPR(j,m),PX1(j,m),PX2(j,m),PX3(j,m),WPLM(j,m))
          RETURN
      ELSE
      ENDIF
      IF (Iass.EQ.3) THEN
!     ---------------- USE ALL X3 VALUES
          DO 10 Mm = 1, K8-1
   10     SX(Mm) = SX3(Mm)
          GO TO 70
      ELSE
!     -------------- BACKTRACK THRU ARRAYS, STORING ASSIGNED X1 (OR X2)
!                    IN SX UNTIL IT IS ZERO, THEN SWITCHING TO THE OTHER
!                    UNTIL IT IS ZERO, ETC.
          DO 60 Mm = K8-1, 1, -1
          GO TO (20,40) ISAVE
   20     IF (SX1(Mm).EQ.0) GO TO 50
   30     ISAVE = 1
          SX(Mm) = SX1(Mm)
          GO TO 60
   40     IF (SX2(Mm).EQ.0) GO TO 30
   50     ISAVE = 2
          SX(Mm) = SX2(Mm)
   60     CONTINUE
      ENDIF

!   ------------------------------------------------------------------
!     PROPER ASSIGNMENTS TO ARRAY SX HAVE BEEN MADE,
!     OUTPUT THE MESS
!   ------------------------------------------------------------------
   70 DO 80 N = 1,K8
      PDSI(indexj(n),indexm(n)) = SX(N)
      PHDI(indexj(n),indexm(n)) = PX3(indexj(n),indexm(n))
      IF(PX3(indexj(n),indexm(n)).EQ. 0.0)PHDI(indexj(n),indexm(n))=SX(N)
      CALL CASE (PPR(indexj(n),indexm(n)),PX1(indexj(n),indexm(n)), &
      PX2(indexj(n),indexm(n)),PX3(indexj(n),indexm(n)), &
      WPLM(indexj(n),indexm(n)))
   80 CONTINUE
      K8 = 1
      k8max=k8
```

```
      RETURN
   90 CONTINUE
      STOP 'UNEXPECTED EOF ON FILE 8 IN SUBROUTINE ASSIGN'
      END




      SUBROUTINE CASE (PROB,X1,X2,X3,PALM)
!
!     THIS SUBROUTINE SELECTS THE PRELIMINARY (OR NEAR-REAL TIME)
!     PALMER DROUGHT SEVERITY INDEX (PDSI) FROM THE GIVEN X VALUES
!     DEFINED BELOW AND THE PROBABILITY (PROB) OF ENDING EITHER A
!     DROUGHT OR WET SPELL.
!
!     X1   - INDEX FOR INCIPIENT WET SPELLS (ALWAYS POSITIVE)
!     X2   - INDEX FOR INCIPIENT DRY SPELLS (ALSAYS NEGATIVE)
!     X3   - SEVERITY INDEX FOR AN ESTABLISHED WET SPELL (POSITIVE)
!            OR DROUGHT (NEGATIVE)
!     PALM - THE SELECTED PDSI (EITHER PRELIMINARY OR FINAL)
!
!
      IF (X3.NE.0.) GO TO 10
!     IF X3=0 THE INDEX IS NEAR NORMAL AND EITHER A DRY OR WET SPELL
!     EXISTS.  CHOOSE THE LARGEST ABSOLUTE VALUE OF X1 OR X2.
      PALM = X1
      IF ( ABS(X2) .GT. ABS(X1) ) PALM=X2
      GO TO 100
!
   10 CONTINUE
      IF ( PROB.GT.0. .AND. PROB.LT.100. ) GO TO 20
!     A WEATHER SPELL IS ESTABLISHED AND PALM=X3 AND IS FINAL
      PALM = X3
      GO TO 100
!
   20 CONTINUE
      PRO = PROB/100.
      IF (X3 .GT. 0.) GO TO 30
!     TAKE THE WEIGHTED SUM OF X3 AND X1
      PALM = (1.-PRO)*X3 + PRO*X1
      GO TO 100
!
   30 CONTINUE
!     TAKE THE WEIGHTED SUM OF X3 AND X2
      PALM = (1.-PRO)*X3 + PRO*X2
  100 RETURN
      END


!     end program
```

Code to Compute Standardized Precipitation Index.

Obtained from: ftp://ftp.ncdc.noaa.gov/pub/data/software/palmer/

As with the Palmer code, this code uses monthly precipitation data, and it can be used to compute SPI by extrapolating month-to-date precipitation to the entire month. At the end of the month, the two will be equal.

```
      PROGRAM SPICOMPUTE

      parameter (nlen=7,maxyrs=200,amssng=-99.99,inunit=10,
     1   ibegyr=1850,iout=10,bmssng=-9.99,incode=2,ihist=1,icur=1,
     2   icuryr=2000,icurmo= 9)


c     This is the driver (main) program used to compute the
c     Standardized Precipitation Index (SPI).  It computes
c     the probability of precipitation based on all available
c     input data. The time scales are 1,2,3,6,9,12,24-month
c     SPI values.  These can be changed by changing the
c     "data nrun" statement.  The parameter statement gives the
c     user the option of outputting sequential files for the period
c     of record or one file for all sites and time scales for a
c     specified year/month or both.
c
c    INPUT        nlen      number of time scales
c                 maxyrs    maximum number of years of record
c                 bmssng    input value for missing data
c                 amssng    output value for missing data
c                 incode    1 for integer input data; 2 for decimal
c                 inunit    device number for input data
c                 ibegyr    first year of data
c                 ihist     1 to output arrays of sequential data (id, yr,
c                           12 monthly values); 0 to suppress these arrays
c                 icur      1 to output only data for the specified
c                           year icuryr and month icurmo (id, yr, mo,
c                           nlen values) in the order corresponding to
c                           the data statement nrun; 0 to suppress
c                 icuryr    year of output (see icur above)
c                 icurmo    month of output (see icur above)
c                 iout      device number for output data:
c
c    OUTPUT                *1     parameters, n-counts, etc for SPI(nlen)
c                          *2     SPI(nlen)
c                          *3     precip probabilities
c                          *4     accumulated precip values
c                          iout+5 SPI for all time scales for given yr/mo
c                          iout+6 precipitation probabilities for all
c                                 time scales for given yr/mo
c                          iout+7 accumulated precip values for all
c                                 time scales for given yr/mo
c
c                          the * indicates iout times nlen
```

```
c
c
c     OTHER ROUTINES CALLED
c        subroutine read
c        subroutine spipe3
c
c     CAVIAT
c        SPI values in central part of the precip distribution can
c        be considered to be accurate and reasonable if the number
c        of independent non-zero accumulated precipitation amounts
c        is greater than about 40; values in the tails of the
c        distribution can be considered accurate and reasonable
c        if the number of non-zero accumulated amounts is greater
c        than about 60.
c
c     NOTE
c        Look at READ subroutine to put input data in proper format.
c
c     written by Ned Guttman in January 1998; some of the software
c     and logic based on software provided by John Kleist, Colorado
c     State Univ.
c
c
      dimension pp(maxyrs*12),probne(maxyrs*12),
     1   pcpacc(maxyrs*12),pzero(12),spi(maxyrs*12),num(12),
     2   numpos(12),nrun(nlen),spiout(12),prob(12),pacc(12),
     3   curspi(nlen),curpro(nlen),curacc(nlen)
      double precision par1(12),par2(12),par3(12),xmom1(12),
     1   xmom2(12),xmom3(12),x(maxyrs),y(maxyrs*12),
     2   index(maxyrs*12),temparr(maxyrs+1)
      data nrun /1,2,3,6,9,12,24/
      do im=1,nlen
        curspi(im)=amssng
        curpro(im)=amssng
        curacc(im)=amssng
      enddo
      iread=0
      if(icur.eq.1) then
        write(iout+5,1014)(nrun(i),i=1,nlen)
        write(iout+6,1015)(nrun(i),i=1,nlen)
        write(iout+7,1016)(nrun(i),i=1,nlen)
      endif
1014  format('  ID   YR MO SPI-',17(i2,5x))
1015  format('  ID   YR MO PROB-',17(i2,6x))
1016  format('  ID   YR MO ACCUM-',17(i2,7x))
1     if (iread.eq.1) goto 50
c
c     read input data
c
      call read(incode,pp,inunit,amssng,bmssng,ibegyr,maxyrs,id,iread)
      do 10 i=1,nlen
c
c     compute SPI values, probabilities, accumulated precip
c
        call spipe3 (nrun(i),pp,par1,par2,par3,pzero,spi,probne,
     1     pcpacc,xmom1,xmom2,xmom3,amssng,num,numpos,maxyrs,
     2     index,y,x,temparr)
```

```
c
c       write out monthly arrays of ncounts, lmoments, parameters,etc.
c
          do k=1,12
          write((iout*i)+1,1000)id,nrun(i),k,xmom1(k),xmom2(k),xmom3(k),
     1       par1(k),par2(k),par3(k),num(k),numpos(k),pzero(k)
1000      format (i4.4,2i3,6f13.8,2i5,f5.3)
          enddo
c
c         identify first and last non-missing data so that output
c         arrays do not contain a bunch of missing data.
c
          ifirst=1
20          if (spi(ifirst).eq.amssng) then
              ifirst=ifirst+1
              goto 20
            endif
          ilast=maxyrs*12
30          if (spi(ilast).eq.amssng) then
              ilast=ilast-1
              goto 30
            endif
          do im=1,12
            spiout(im)=amssng
            prob(im)=amssng
            pacc(im)=amssng
          enddo
          do 40 j=ifirst,ilast
            iy=(j-1)/12+ibegyr
            im=mod (j-1,12)+1
            spiout(im)=spi(j)
            prob(im)=probne(j)
            pacc(im)=pcpacc(j)
            if(icur.eq.1) then
              if(iy.eq.icuryr.and.im.eq.icurmo)curspi(i)=spiout(im)
              if(iy.eq.icuryr.and.im.eq.icurmo)curpro(i)=prob(im)
              if(iy.eq.icuryr.and.im.eq.icurmo)curacc(i)=pacc(im)
            endif
            if (im.eq.12.or.j.eq.ilast) then
c
c        write out arrays if ihist=1
c
                if(ihist.eq.1) then
                  write ((iout*i)+2,1001)id,iy,(spiout(im),im=1,12)
                  write ((iout*i)+3,1003)id,iy,(prob(im),im=1,12)
                  write ((iout*i)+4,1002)id,iy,(pacc(im),im=1,12)
                endif
c
c         change the format statements for different output formats
c

1001     format (i4.4,i5,12f7.2)
1003     format (i4.4,i5,12f8.3)
1002     format (i4.4,i5,12f9.2)

                do im=1,12
                  spiout(im)=amssng
```

```
                prob(im)=amssng
                pacc(im)=amssng
              enddo
           endif
40       continue
10       continue
c
c        write out array of current month spi for all id's
c
         if(icur.eq.1) then
           write(iout+5,1004)id,icuryr,icurmo,(curspi(im),im=1,nlen)
           write(iout+6,1005)id,icuryr,icurmo,(curpro(im),im=1,nlen)
           write(iout+7,1006)id,icuryr,icurmo,(curacc(im),im=1,nlen)
         endif
              do im=1,nlen
                curspi(im)=amssng
                curpro(im)=amssng
                curacc(im)=amssng
              enddo
1004     format (i4.4,i5,i3,17f7.2)
1005     format (i4.4,i5,i3,17f8.3)
1006     format (i4.4,i5,i3,17f9.2)
         goto 1
50       end


       SUBROUTINE READ(incode,pp,inunit,amssng,bmssng,ibegyr,
     1    maxyrs,jd,iread)
c
c        INPUT:  inprec      input data array: id,iyr,monthly integer
c                            precip amounts in hundredths
c                precin      input data array: id,iyr,monthly decimal
c                            precip amounts in hundredths
c                inunit      device number for reading input data
c                amssng      missing data code for output
c                bmssng      missing data code for input
c                incode      1 for integer; 2 for digital input data
c                ibegyr      earliest possible beginning year of data
c                maxyrs      maximum possible years of data
c
c        OUTPUT: pp          one dimensional array of precip data
c                jd          location identification number
c                iread       iread=1 indicates end of data file
c
c
       dimension pp(maxyrs*12),inprec(12),precin(12)
       if(incode.ne.1.and.incode.ne.2) STOP "INCODE ERROR"
       iread=0
c
c      set precip array to missing
c
1      do 10, i=1,maxyrs*12
         pp(i)=amssng
10     continue
       jd=0
20     continue
```

```
c
c     set input format to correspond to your input data source.
c     program assumes integer format (value is divided by 100
c     later in the program to get values to hundredths)
c

      if(incode.eq.1) then
        inmssng=bmssng
        read(inunit,1000,end=40)id,iyr,(inprec(j),j=1,12)
1000  format (i4,1x,i4,12i7)

c
c     check for new station id
c
        if (id.ne.jd.and.jd.ne.0) goto 30
        iy=iyr-ibegyr
        do im=1,12
            if(inprec(im).eq.inmssng) goto 23
c
c     convert integer precip to decimal precip (hundredths)
c
            pp(iy*12+im)=float(inprec(im))/100.0
 23       enddo
      else
        read(inunit,1001,end=40)id,iyr,(precin(j),j=1,12)
1001  format (i4,1x,i4,12f7.2)
        if (id.ne.jd.and.jd.ne.0) goto 30
        iy=iyr-ibegyr
        do im=1,12
            if(precin(im).eq.bmssng) goto 24
            pp(iy*12+im)=precin(im)
 24       enddo
      endif
      jd=id
      goto 20
30    continue
      backspace (inunit)
      return
40    iread=1
      return
      end


        SUBROUTINE SPIPE3(nrun,pp,par1,par2,par3,pzero,spi,probne,
     1  pcpacc,xmom1,xmom2,xmom3,amssng,num,numpos,maxyrs,index,y,
     2  x,temparr)
c
c       INPUT:  pp                 one dimensional array of input data
c                                  where input is monthly precip data
c                                  beginning with a January value
c               nrun               length of moving totals
c               amssng             value for missing data
c               maxyrs             maximum possible number of years of
c                                  data
c
c       OUTPUT: par1,par2,par3     parameters (mean, s.d., skewness) of
c                                  Pearson Type III distribution used to
```

```
c                                   fit the input data > 0
c               xmom1,xmom2,xmom3 l-moments of the input data > 0
c               pzero             relative  frequency of input data = 0
c               spi               standardized precip index
c               probne            probability of observed data <= x
c               pcpacc            data accumulated over length nrun
c               num               number of non-missing observations
c               numpos            number of non-zero observations
c
c       This program used the program of John Kleist, Colorado State
c       Univ., that computed spi values from a 2 parameter ML gamma
c       probability distribution, as a basis for the moving totals, etc.
c       code.  I added the PE3 l-moment computations.  The subroutines
c       and functions in upper case came from Jon Hosking, IBM.
c               Ned Guttman
c               Nov. 1997
c

        dimension pp(maxyrs*12),probne(maxyrs*12),pcpacc(maxyrs*12),
     1    pzero(12),spi(maxyrs*12),num(12),numpos(12)
        double precision par1(12),par2(12),par3(12),index(maxyrs*12),
     1    xmom1(12),xmom2(12),xmom3(12),xmom(3),para(3),
     2    y(maxyrs*12),x(maxyrs),temparr(maxyrs+1),
     3    cdfpe3,derf,dlgamma,gamind,quastn
c
c
c       save par1,par2,par3 to 8 decimal places if you want to use
c       them later for any additional calculations...not keeping
c       enough decimal places leads to errors in probabilities!
c
c
c       the first nrun-1 index values will be missing
c
        do 10 j=1,nrun-1
          index(j)=amssng
          probne(j)=amssng
          pcpacc(j)=amssng
 10     continue
c
c       sum nrun precip values; store them in appropriate index location
C
c       if any value is missing, set the sum to missing
c
        do 30 j=nrun,maxyrs*12
          index(j)=0.0
          do 20 i=0,nrun-1
            if(pp(j-i).ne.amssng)then
              index(j)=index(j)+pp(j-i)
              pcpacc(j)=index(j)
            else
              index(j)=amssng
              probne(j)=amssng
              pcpacc(j)=amssng
              goto 30
            endif
 20       continue
 30     continue
```

```
c
c       to maintain seasonality, do everything by month
c
        do 50 i=0,11
           n=0
           nz=0
           np=0
           if (nrun.le.12) then
             do 40 j=nrun+i,maxyrs*12,12
               if(index(j).ne.amssng) then
c
c          this routine calculates lmoments and parameters of the PE3
c          distribution for all input data.  if you want to compute the
c          parameters for a specific period of record, then the limits
c          of j must be set appropriately for temparr. it is recommended
c          that for both monitoring and historical perspective that
c          all data be used for computing the probabilities, and that
c          the historical time series be the "latest" and most complete
c          output.
c
c          n-count for all non-missing data, including zeroes
c
                 n=n+1
                 if(index(j).gt.0) then
c
c          n-count for all non-missing, non-zero data; temparr is for
c          non-zero, non-missing precipitation
c
                   np=np+1
                   temparr(np)=index(j)
                 else
c
c          n-count for all non-missing, zero data
c
                   nz=nz+1
                 endif
               endif
 40          continue
        elseif (nrun.gt.12) then
          j=nrun+i
c
c         step the sequence of data by the length of nrun to get
c         independent samples
c
          if (nrun.gt.12.and.nrun.le.24) nstep=24
          if (nrun.gt.24.and.nrun.le.36) nstep=36
          if (nrun.gt.36.and.nrun.le.48) nstep=48
          if (nrun.gt.48.and.nrun.le.60) nstep=60
          if (nrun.gt.60.and.nrun.le.72) nstep=72
 41       if (j.gt.maxyrs*12) GOTO 42
c
c          this routine calculates lmoments and parameters of the PE3
c          distribution for all input data.  if you want to compute the
c          parameters for a specific period of record, then the limits
c          of j must be set appropriately for temparr
c
```

```
            if(index(j).ne.amssng) then
              n=n+1
              if(index(j).gt.0) then
                np=np+1
                temparr(np)=index(j)
              else
                nz=nz+1
              endif
              j=j+nstep
              goto 41
            else
c
c          look for next non-missing nrun>12 value
c
              j=j+12
              goto 41
            endif
          endif
 42     im=mod(nrun+i-1,12)+1
        pzero(im)=float(nz)/float(n)
        num(im)=n
        numpos(im)=np
c
c       order the data
c
        call sort(temparr,x,np,maxyrs)
c
c       fit l-moments for non-zero precip; if 2nd moment=0, routine
c       fails and all 3 moments set to zero (condition indicates all
c       data values are equal).  also, if not enough non-zero data
c       (less than 3), routine fails and all moments set to zero.
c
        call samlmr(x,np,xmom,3,-0.00D0,ODO,ifail)
        xmom1(im)=xmom(1)
        xmom2(im)=xmom(2)
        xmom3(im)=xmom(3)
c
c       compute parameters of Pearson type III (3-parameter gamma); the
c       three parameters are the mean, s.d., skewness of the NON-ZERO data.
c       The mean for all the data is (1-pzero)*par1 or (1-pzero)*xmom1
c       since par1=xmom1
c
        call pelpe3(xmom,para,ifail)
c
c       if ifail not = 0, then all 3 parameters are set to zero
c       if routine fails, output is sent to unit 6 by pelpe3 routine
c
        par1(im)=para(1)
        par2(im)=para(2)
        par3(im)=para(3)
 50     continue
c
c       compute the probability (cdfpe3), take into account the
c       mixed distribution if pzero not equal to zero, truncate
c       the probability from .001 to .999, transform the probability to
c       spi (quastn). ifail=1 indicates invalid parameter 2 (negative).
c       if routines fail, output is sent to unit 6 by called routines.
```

```
c
        do 60 j=nrun,maxyrs*12
          im=mod(j-1,12)+1
          para(1)=par1(im)
          para(2)=par2(im)
          para(3)=par3(im)
c
c         set missing values to amssng
c
 61       if(index(j).eq.amssng) then
             probne(j)=amssng
             spi(j)=amssng
             goto 60
          endif
          if(index(j).ne.amssng) then
             index(j)=cdfpe3(index(j),para,ifail,amssng)
c
c         if cdf routine fails, set probne and spi = amssng
c
             if(ifail.ne.0) then
               index(j)=amssng
               goto 61
             endif
             y(j)=pzero(im)+(1-pzero(im))*index(j)
c
c            force the probabilities and therefore the spi to be bounded
c            by +/- 3.09
c
             if(y(j).gt..999)y(j)=.999
             if(y(j).lt..001)y(J)=.001
             probne(j)=y(j)
             index(j)=quastn(y(j))
             spi(j)=index(j)
          endif
 60     continue
        return
        end
c
c
      DOUBLE PRECISION FUNCTION CDFPE3(X,PARA,ifail,amssng)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  DISTRIBUTION FUNCTION OF THE PEARSON TYPE 3 DISTRIBUTION
C
```

```
C  OTHER ROUTINES USED: DERF,DLGAMA,GAMIND
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION PARA(3)
      DATA ZERO/0D0/,HALF/0.5D0/,ONE/1D0/,TWO/2D0/,FOUR/4D0/
      DATA RTHALF/0.70710 67811 86547 524D0/
C
C         SMALL IS USED TO TEST WHETHER SKEWNESS IS EFFECTIVELY ZERO
C
      DATA SMALL/1D-6/
C
      ifail=0
      CDFPE3=ZERO
      IF(PARA(2).LE.ZERO)GOTO 1000
      GAMMA=PARA(3)
      IF(DABS(GAMMA).LE.SMALL)GOTO 10
      ALPHA=FOUR/(GAMMA*GAMMA)
      Z=TWO*(X-PARA(1))/(PARA(2)*GAMMA)+ALPHA
      IF(Z.GT.ZERO)CDFPE3=GAMIND(Z,ALPHA,DLGAMA(ALPHA))
      IF(GAMMA.LT.ZERO)CDFPE3=ONE-CDFPE3
      RETURN
C
C         ZERO SKEWNESS
C
   10 Z=(X-PARA(1))/PARA(2)
      CDFPE3=HALF+HALF*DERF(Z*RTHALF)
      RETURN
C
1000  WRITE(6,7000)
      ifail=1
      cdfpe3=amssng
      RETURN
C
 7000 FORMAT(' *** ERROR *** ROUTINE CDFPE3 : PARAMETERS INVALID')
      END
c
c
      SUBROUTINE PELPE3(XMOM,PARA,ifail)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  PARAMETER ESTIMATION VIA L-MOMENTS FOR THE PEARSON TYPE 3 DISTRIBUTION
C
C  PARAMETERS OF ROUTINE:
C  XMOM   * INPUT* ARRAY OF LENGTH 3. CONTAINS THE L-MOMENTS LAMBDA-1,
```

```
C                   LAMBDA-2 AND TAU-3.
C  PARA    *OUTPUT* ARRAY OF LENGTH 3. ON EXIT, CONTAINS THE PARAMETERS
C                   IN THE ORDER MU, SIGMA, GAMMA (MEAN, S.D., SKEWNESS).
C
C  OTHER ROUTINES USED: DLGAMA
C
C  METHOD: RATIONAL APPROXIMATION IS USED TO EXPRESS ALPHA, THE SHAPE
C  PARAMETER OF THE GAMMA DISTRIBUTION, AS A FUNCTION OF TAU-3.
C  RELATIVE ACCURACY OF THE APPROXIMATION IS BETTER THAN 3E-5.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION XMOM(3),PARA(3)
      DATA ZERO/0D0/,THIRD/0.33333333D0/,HALF/0.5D0/,ONE/1D0/,TWO/2D0/
C
C         SMALL IS USED TO TEST WHETHER SKEWNESS IS EFFECTIVELY ZERO
C
      DATA SMALL/1D-6/
C
C         CONSTANTS USED IN MINIMAX APPROXIMATIONS
C
      DATA C1,C2,C3/ 0.2906D0,  0.1882D0,  0.0442D0/
      DATA D1,D2,D3/ 0.36067D0,-0.59567D0, 0.25361D0/
      DATA D4,D5,D6/-2.78861D0, 2.56096D0,-0.77045D0/
      DATA PI3,ROOTPI/9.4247780D0,1.7724539D0/
C
      ifail=0
      T3=DABS(XMOM(3))
      IF(XMOM(2).LE.ZERO.OR.T3.GE.ONE)GOTO 1000
      IF(T3.LE.SMALL)GOTO 100
      IF(T3.GE.THIRD)GOTO 10
      T=PI3*T3*T3
      ALPHA=(ONE+C1*T)/(T*(ONE+T*(C2+T*C3)))
      GOTO 20
   10 CONTINUE
      T=ONE-T3
      ALPHA=T*(D1+T*(D2+T*D3))/(ONE+T*(D4+T*(D5+T*D6)))
   20 CONTINUE
      RTALPH=DSQRT(ALPHA)
      BETA=ROOTPI*XMOM(2)*DEXP(DLGAMA(ALPHA)-DLGAMA(ALPHA+HALF))
      PARA(1)=XMOM(1)
      PARA(2)=BETA*RTALPH
      PARA(3)=TWO/RTALPH
      IF(XMOM(3).LT.ZERO)PARA(3)=-PARA(3)
      RETURN
C
C         ZERO SKEWNESS
C
  100 CONTINUE
      PARA(1)=XMOM(1)
      PARA(2)=XMOM(2)*ROOTPI
      PARA(3)=ZERO
      RETURN
C
c1000 WRITE(6,7000)
 1000 DO 1010 I=1,3
 1010 PARA(I)=ZERO
      ifail=1
```

```
      RETURN
C
 7000 FORMAT(' *** ERROR *** ROUTINE PELPE3 : L-MOMENTS INVALID')
      END
C
C
C
      SUBROUTINE SAMLMR(X,N,XMOM,NMOM,A,B,ifail)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  SAMPLE L-MOMENTS OF A DATA ARRAY
C
C  PARAMETERS OF ROUTINE:
C  X       * INPUT* ARRAY OF LENGTH N. CONTAINS THE DATA, IN ASCENDING
C                   ORDER.
C  N       * INPUT* NUMBER OF DATA VALUES
C  XMOM    *OUTPUT* ARRAY OF LENGTH NMOM. ON EXIT, CONTAINS THE SAMPLE
C                   L-MOMENTS L-1, L-2, T-3, T-4, ... .
C  NMOM    * INPUT* NUMBER OF L-MOMENTS TO BE FOUND. AT MOST MAX(N,20).
C  A       * INPUT* ) PARAMETERS OF PLOTTING
C  B       * INPUT* ) POSITION (SEE BELOW)
C
C  FOR UNBIASED ESTIMATES (OF THE LAMBDA'S) SET A=B=ZERO. OTHERWISE,
C  PLOTTING-POSITION ESTIMATORS ARE USED, BASED ON THE PLOTTING POSITION
C  (J+A)/(N+B)  FOR THE J'TH SMALLEST OF N OBSERVATIONS. FOR EXAMPLE,
C  A=-0.35D0 AND B=0.0D0 YIELDS THE ESTIMATORS RECOMMENDED BY
C  HOSKING ET AL. (1985, TECHNOMETRICS) FOR THE GEV DISTRIBUTION.
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION X(N),XMOM(NMOM),SUM(20)
      DATA ZERO/0D0/,ONE/1D0/
      ifail=0
      IF(NMOM.GT.20.OR.NMOM.GT.N)GOTO 1000
      DO 10 J=1,NMOM
   10 SUM(J)=ZERO
      IF(A.EQ.ZERO.AND.B.EQ.ZERO)GOTO 50
      IF(A.LE.-ONE.OR.A.GE.B)GOTO 1010
C
C         PLOTTING-POSITION ESTIMATES OF PWM'S
C
      DO 30 I=1,N
      PPOS=(I+A)/(N+B)
      TERM=X(I)
      SUM(1)=SUM(1)+TERM
```

```
      DO 20 J=2,NMOM
      TERM=TERM*PPOS
   20 SUM(J)=SUM(J)+TERM
   30 CONTINUE
      DO 40 J=1,NMOM
   40 SUM(J)=SUM(J)/N
      GOTO 100
C
C         UNBIASED ESTIMATES OF PWM'S
C
   50 DO 70 I=1,N
      Z=I
      TERM=X(I)
      SUM(1)=SUM(1)+TERM
      DO 60 J=2,NMOM
      Z=Z-ONE
      TERM=TERM*Z
   60 SUM(J)=SUM(J)+TERM
   70 CONTINUE
      Y=N
      Z=N
      SUM(1)=SUM(1)/Z
      DO 80 J=2,NMOM
      Y=Y-ONE
      Z=Z*Y
   80 SUM(J)=SUM(J)/Z
C
C         L-MOMENTS
C
  100 K=NMOM
      P0=ONE
      IF(NMOM-NMOM/2*2.EQ.1)P0=-ONE
      DO 120 KK=2,NMOM
      AK=K
      P0=-P0
      P=P0
      TEMP=P*SUM(1)
      DO 110 I=1,K-1
      AI=I
      P=-P*(AK+AI-ONE)*(AK-AI)/(AI*AI)
  110 TEMP=TEMP+P*SUM(I+1)
      SUM(K)=TEMP
  120 K=K-1
      XMOM(1)=SUM(1)
      IF(NMOM.EQ.1)RETURN
      XMOM(2)=SUM(2)
      IF(SUM(2).EQ.ZERO)GOTO 1020
      IF(NMOM.EQ.2)RETURN
      DO 130 K=3,NMOM
  130 XMOM(K)=SUM(K)/SUM(2)
      RETURN
C
 1000 ifail=1
      do i=1,3
        xmom(i)=0
      enddo
      WRITE(6,7000)
```

```
      RETURN
 1010 WRITE(6,7010)
      RETURN
 1020 ifail=1
      do i=1,3
        xmom(i)=0
      enddo
      WRITE(6,7020)
      RETURN
C
 7000 FORMAT(' *** ERROR *** ROUTINE SAMLMR : PARAMETER NMOM INVALID')
 7010 FORMAT(' *** ERROR *** ROUTINE SAMLMR :',
     *  ' PLOTTING-POSITION PARAMETERS INVALID')
 7020 FORMAT(' *** ERROR *** ROUTINE SAMLMR : ALL DATA VALUES EQUAL')
      END
C
C
C
      DOUBLE PRECISION FUNCTION DERF(X)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  ERROR FUNCTION
C
C  BASED ON ALGORITHM 5666, J.F.HART ET AL. (1968) 'COMPUTER
C  APPROXIMATIONS'
C
C  ACCURATE TO 15 DECIMAL PLACES
C
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      DATA ZERO/0D0/,ONE/1D0/,TWO/2D0/,THREE/3D0/,FOUR/4D0/,P65/0.65D0/
C
C         COEFFICIENTS OF RATIONAL-FUNCTION APPROXIMATION
C
      DATA P0,P1,P2,P3,P4,P5,P6/
     *  0.22020 68679 12376 1D3,    0.22121 35961 69931 1D3,
     *  0.11207 92914 97870 9D3,    0.33912 86607 83830 0D2,
     *  0.63739 62203 53165 0D1,    0.70038 30644 43688 1D0,
     *  0.35262 49659 98910 9D-1/
      DATA Q0,Q1,Q2,Q3,Q4,Q5,Q6,Q7/
     *  0.44041 37358 24752 2D3,   0.79382 65125 19948 4D3,
     *  0.63733 36333 78831 1D3,   0.29656 42487 79673 7D3,
     *  0.86780 73220 29460 8D2,   0.16064 17757 92069 5D2,
     *  0.17556 67163 18264 2D1,   0.88388 34764 83184 4D-1/
C
```

```
C         C1 IS SQRT(2), C2 IS SQRT(2/PI)
C         BIG IS THE POINT AT WHICH DERF=1 TO MACHINE PRECISION
C
      DATA C1/1.4142 13562 37309 5D0/
      DATA C2/7.9788 45608 02865 4D-1/
      DATA BIG/6.25D0/,CRIT/5D0/
C
      DERF=ZERO
      IF(X.EQ.ZERO)RETURN
      XX=DABS(X)
      IF(XX.GT.BIG)GOTO 20
      EXPNTL=DEXP(-X*X)
      ZZ=DABS(X*C1)
      IF(XX.GT.CRIT)GOTO 10
      DERF=EXPNTL*((((((P6*ZZ+P5)*ZZ+P4)*ZZ+P3)*ZZ+P2)*ZZ+P1)*ZZ+P0)/
     *  (((((((Q7*ZZ+Q6)*ZZ+Q5)*ZZ+Q4)*ZZ+Q3)*ZZ+Q2)*ZZ+Q1)*ZZ+Q0)
      IF(X.GT.ZERO)DERF=ONE-TWO*DERF
      IF(X.LT.ZERO)DERF=TWO*DERF-ONE
      RETURN
C
   10 DERF=EXPNTL*C2/(ZZ+ONE/(ZZ+TWO/(ZZ+THREE/(ZZ+FOUR/(ZZ+P65)))))
      IF(X.GT.ZERO)DERF=ONE-DERF
      IF(X.LT.ZERO)DERF=DERF-ONE
      RETURN
C
   20 DERF=ONE
      IF(X.LT.ZERO)DERF=-ONE
      RETURN
      END
C
C
C
      DOUBLE PRECISION FUNCTION DLGAMA(X)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  LOGARITHM OF GAMMA FUNCTION
C
C  BASED ON ALGORITHM ACM291, COMMUN. ASSOC. COMPUT. MACH. (1966)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DATA SMALL,CRIT,BIG,TOOBIG/1D-7,13D0,1D9,2D36/
C
C         C0 IS 0.5*LOG(2*PI)
C         C1...C7 ARE THE COEFFTS OF THE ASYMPTOTIC EXPANSION OF DLGAMA
```

```
C
      DATA C0,C1,C2,C3,C4,C5,C6,C7/
     *   0.91893 85332 04672 742D 0,  0.83333 33333 33333 333D-1,
     *  -0.27777 77777 77777 778D-2,  0.79365 07936 50793 651D-3,
     *  -0.59523 80952 38095 238D-3,  0.84175 08417 50841 751D-3,
     *  -0.19175 26917 52691 753D-2,  0.64102 56410 25641 026D-2/
C
C         S1 IS -(EULER'S CONSTANT), S2 IS PI**2/12
C
      DATA S1/-0.57721 56649 01532 861D 0/
      DATA S2/ 0.82246 70334 24113 218D 0/
C
      DATA ZERO/0D0/,HALF/0.5D0/,ONE/1D0/,TWO/2D0/
      DLGAMA=ZERO
      IF(X.LE.ZERO)GOTO 1000
      IF(X.GT.TOOBIG)GOTO 1000
C
C         USE SMALL-X APPROXIMATION IF X IS NEAR 0, 1 OR 2
C
      IF(DABS(X-TWO).GT.SMALL)GOTO 10
      DLGAMA=DLOG(X-ONE)
      XX=X-TWO
      GOTO 20
   10 IF(DABS(X-ONE).GT.SMALL)GOTO 30
      XX=X-ONE
   20 DLGAMA=DLGAMA+XX*(S1+XX*S2)
      RETURN
   30 IF(X.GT.SMALL)GOTO 40
      DLGAMA=-DLOG(X)+S1*X
      RETURN
C
C         REDUCE TO DLGAMA(X+N) WHERE X+N.GE.CRIT
C
   40 SUM1=ZERO
      Y=X
      IF(Y.GE.CRIT)GOTO 60
      Z=ONE
   50 Z=Z*Y
      Y=Y+ONE
      IF(Y.LT.CRIT)GOTO 50
      SUM1=SUM1-DLOG(Z)
C
C         USE ASYMPTOTIC EXPANSION IF Y.GE.CRIT
C
   60 SUM1=SUM1+(Y-HALF)*DLOG(Y)-Y+C0
      SUM2=ZERO
      IF(Y.GE.BIG)GOTO 70
      Z=ONE/(Y*Y)
      SUM2=((((((C7*Z+C6)*Z+C5)*Z+C4)*Z+C3)*Z+C2)*Z+C1)/Y
   70 DLGAMA=SUM1+SUM2
      RETURN
C
 1000 WRITE(6,7000)X
      RETURN
C
 7000 FORMAT(' *** ERROR *** ROUTINE DLGAMA :',
     *  ' ARGUMENT OUT OF RANGE :',D24.16)
```

```
      END
C
C
C
      DOUBLE PRECISION FUNCTION GAMIND(X,ALPHA,G)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  THE INCOMPLETE GAMMA INTEGRAL
C
C  BASED ON ALGORITHM AS239, APPL. STATIST. (1988) VOL.37 NO.3
C
C  PARAMETERS OF ROUTINE:
C  X      * INPUT* ARGUMENT OF FUNCTION (UPPER LIMIT OF INTEGRATION)
C  ALPHA  * INPUT* SHAPE PARAMETER
C  G      * INPUT* LOG(GAMMA(ALPHA)). MUST BE SUPPLIED BY THE PROGRAM,
C                  E.G. AS DLGAMA(ALPHA).
C
C  OTHER ROUTINES USED: DERF
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DATA ZERO/0D0/,HALF/0.5D0/,ONE/1D0/,TWO/2D0/,THREE/3D0/,X13/13D0/,
     *  X36/36D0/,X42/42D0/,X119/119D0/,X1620/1620D0/,X38880/38880D0/,
     *  RTHALF/0.70710 67811 86547 524D0/
C
C         EPS,MAXIT CONTROL THE TEST FOR CONVERGENCE OF THE SERIES AND
C           CONTINUED-FRACTION EXPANSIONS.
C         OFL IS A LARGE NUMBER, USED TO RESCALE THE CONTINUED FRACTION.
C         UFL IS SUCH THAT EXP(UFL) IS JUST .GT. ZERO.
C         AHILL CONTROLS THE SWITCH TO HILL'S APPROXIMATION.
C
      DATA EPS/1D-12/,MAXIT/100000/,OFL/1D30/,UFL/-180D0/,AHILL/1D4/
      GAMIND=ZERO
      IF(ALPHA.LE.ZERO)GOTO 1000
      IF(X.LT.ZERO)GOTO 1010
      IF(X.EQ.ZERO)RETURN
C
      IF(ALPHA.GT.AHILL)GOTO 100
      IF(X.GT.ONE.AND.X.GE.ALPHA)GOTO 50
C
C         SERIES EXPANSION
C
      SUM=ONE
      TERM=ONE
      A=ALPHA
```

```
      DO 10 IT=1,MAXIT
      A=A+ONE
      TERM=TERM*X/A
      SUM=SUM+TERM
      IF(TERM.LE.EPS)GOTO 20
   10 CONTINUE
      WRITE(6,7020)
   20 ARG=ALPHA*DLOG(X)-X-G+DLOG(SUM/ALPHA)
      GAMIND=ZERO
      IF(ARG.GE.UFL)GAMIND=DEXP(ARG)
      RETURN
C
C         CONTINUED-FRACTION EXPANSION
C
   50 CONTINUE
      A=ONE-ALPHA
      B=A+X+ONE
      TERM=ZERO
      PN1=ONE
      PN2=X
      PN3=X+ONE
      PN4=X*B
      RATIO=PN3/PN4
      DO 70 IT=1,MAXIT
      A=A+ONE
      B=B+TWO
      TERM=TERM+ONE
      AN=A*TERM
      PN5=B*PN3-AN*PN1
      PN6=B*PN4-AN*PN2
      IF(PN6.EQ.ZERO)GOTO 60
      RN=PN5/PN6
      DIFF=DABS(RATIO-RN)
      IF(DIFF.LE.EPS.AND.DIFF.LE.EPS*RN)GOTO 80
      RATIO=RN
   60 PN1=PN3
      PN2=PN4
      PN3=PN5
      PN4=PN6
      IF(DABS(PN5).LT.OFL)GOTO 70
      PN1=PN1/OFL
      PN2=PN2/OFL
      PN3=PN3/OFL
      PN4=PN4/OFL
   70 CONTINUE
      WRITE(6,7020)
   80 ARG=ALPHA*DLOG(X)-X-G+DLOG(RATIO)
      GAMIND=ONE
      IF(ARG.GE.UFL)GAMIND=ONE-DEXP(ARG)
      RETURN
C
C         ALPHA IS LARGE: USE HILL'S APPROXIMATION (N.L. JOHNSON AND
C         S. KOTZ, 1970, 'CONTINUOUS UNIVARIATE DISTRIBUTIONS 1', P.180)
C
C         THE 'DO 110' LOOP CALCULATES 2*(X-ALPHA-ALPHA*DLOG(X/ALPHA)),
C         USING POWER-SERIES EXPANSION TO AVOID ROUNDING ERROR
C
```

```
  100 CONTINUE
      R=ONE/DSQRT(ALPHA)
      Z=(X-ALPHA)*R
      TERM=Z*Z
      SUM=HALF*TERM
      DO 110 I=1,12
      TERM=-TERM*Z*R
      SUM=SUM+TERM/(I+TWO)
      IF(DABS(TERM).LT.EPS)GOTO 120
  110 CONTINUE
  120 WW=TWO*SUM
      W=DSQRT(WW)
      IF(X.LT.ALPHA)W=-W
      H1=ONE/THREE
      H2=-W/X36
      H3=(-WW+X13)/X1620
      H4=(X42*WW+X119)*W/X38880
      Z=(((H4*R+H3)*R+H2)*R+H1)*R+W
      GAMIND=HALF+HALF*DERF(Z*RTHALF)
      RETURN
C
 1000 WRITE(6,7000)ALPHA
      RETURN
 1010 WRITE(6,7010)X
      RETURN
C
 7000 FORMAT(' *** ERROR *** ROUTINE GAMIND :',
     *  ' SHAPE PARAMETER OUT OF RANGE :',D16.8)
 7010 FORMAT(' *** ERROR *** ROUTINE GAMIND :',
     *  ' ARGUMENT OF FUNCTION OUT OF RANGE :',D16.8)
 7020 FORMAT(' ** WARNING ** ROUTINE GAMIND :',
     *  ' ITERATION HAS NOT CONVERGED. RESULT MAY BE UNRELIABLE.')
      END
C
C
C
      DOUBLE PRECISION FUNCTION QUASTN(F)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  QUANTILE FUNCTION OF THE STANDARD NORMAL DISTRIBUTION
C
C  BASED ON ALGORITHM AS241, APPL. STATIST. (1988) VOL.37 NO.3
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
```

```
      DATA ZERO/0D0/,HALF/0.5D0/,ONE/1D0/
      DATA SPLIT1/0.425D0/,SPLIT2/5D0/,CONST1/0.180625D0/,CONST2/1.6D0/
C
C         COEFFICIENTS OF RATIONAL-FUNCTION APPROXIMATIONS
C
      DATA A0,A1,A2,A3,A4,A5,A6,A7,B1,B2,B3,B4,B5,B6,B7/
     *                                 0.33871 32872 79636 661D  1,
     *  0.13314 16678 91784 377D  3,  0.19715 90950 30655 144D  4,
     *  0.13731 69376 55094 611D  5,  0.45921 95393 15498 715D  5,
     *  0.67265 77092 70087 009D  5,  0.33430 57558 35881 281D  5,
     *  0.25090 80928 73012 267D  4,  0.42313 33070 16009 113D  2,
     *  0.68718 70074 92057 908D  3,  0.53941 96021 42475 111D  4,
     *  0.21213 79430 15865 959D  5,  0.39307 89580 00927 106D  5,
     *  0.28729 08573 57219 427D  5,  0.52264 95278 85285 456D  4/
      DATA C0,C1,C2,C3,C4,C5,C6,C7,D1,D2,D3,D4,D5,D6,D7/
     *                                 0.14234 37110 74968 358D  1,
     *  0.46303 37846 15654 530D  1,  0.57694 97221 46069 141D  1,
     *  0.36478 48324 76320 461D  1,  0.12704 58252 45236 838D  1,
     *  0.24178 07251 77450 612D  0,  0.22723 84498 92691 846D -1,
     *  0.77454 50142 78341 408D -3,  0.20531 91626 63775 882D  1,
     *  0.16763 84830 18380 385D  1,  0.68976 73349 85100 005D  0,
     *  0.14810 39764 27480 075D  0,  0.15198 66656 36164 572D -1,
     *  0.54759 38084 99534 495D -3,  0.10507 50071 64441 684D -8/
      DATA E0,E1,E2,E3,E4,E5,E6,E7,F1,F2,F3,F4,F5,F6,F7/
     *                                 0.66579 04643 50110 378D  1,
     *  0.54637 84911 16411 437D  1,  0.17848 26539 91729 133D  1,
     *  0.29656 05718 28504 891D  0,  0.26532 18952 65761 230D -1,
     *  0.12426 60947 38807 844D -2,  0.27115 55568 74348 758D -4,
     *  0.20103 34399 29228 813D -6,  0.59983 22065 55887 938D  0,
     *  0.13692 98809 22735 805D  0,  0.14875 36129 08506 149D -1,
     *  0.78686 91311 45613 259D -3,  0.18463 18317 51005 468D -4,
     *  0.14215 11758 31644 589D -6,  0.20442 63103 38993 979D-14/
C
      Q=F-HALF
      IF(DABS(Q).GT.SPLIT1)GOTO 10
      R=CONST1-Q*Q
      QUASTN=Q*(((((((A7*R+A6)*R+A5)*R+A4)*R+A3)*R+A2)*R+A1)*R+A0)
     *        /(((((((B7*R+B6)*R+B5)*R+B4)*R+B3)*R+B2)*R+B1)*R+ONE)
      RETURN
   10 R=F
      IF(Q.GE.ZERO)R=ONE-F
      IF(R.LE.ZERO)GOTO 1000
      R=DSQRT(-DLOG(R))
      IF(R.GT.SPLIT2)GOTO 20
      R=R-CONST2
      QUASTN=(((((((C7*R+C6)*R+C5)*R+C4)*R+C3)*R+C2)*R+C1)*R+C0)
     *      /(((((((D7*R+D6)*R+D5)*R+D4)*R+D3)*R+D2)*R+D1)*R+ONE)
      GOTO 30
   20 R=R-SPLIT2
      QUASTN=(((((((E7*R+E6)*R+E5)*R+E4)*R+E3)*R+E2)*R+E1)*R+E0)
     *      /(((((((F7*R+F6)*R+F5)*R+F4)*R+F3)*R+F2)*R+F1)*R+ONE)
   30 IF(Q.LT.ZERO)QUASTN=-QUASTN
      RETURN
C
 1000 WRITE(6,7000)F
      QUASTN=ZERO
      RETURN
```

```
C
 7000 FORMAT(' *** ERROR *** ROUTINE QUASTN :',
     *  ' ARGUMENT OF FUNCTION INVALID')
      END
C
C
C
      SUBROUTINE SORT(temparr,X,N,maxyrs)
C*********************************************************************
C*                                                                   *
C*  FORTRAN CODE WRITTEN FOR INCLUSION IN IBM RESEARCH REPORT RC20525, *
C*  'FORTRAN ROUTINES FOR USE WITH THE METHOD OF L-MOMENTS, VERSION 3' *
C*                                                                   *
C*  J. R. M. HOSKING                                                 *
C*  IBM RESEARCH DIVISION                                            *
C*  T. J. WATSON RESEARCH CENTER                                     *
C*  YORKTOWN HEIGHTS                                                 *
C*  NEW YORK 10598, U.S.A.                                           *
C*                                                                   *
C*  VERSION 3     AUGUST 1996                                        *
C*                                                                   *
C*********************************************************************
C
C  SORTS THE ARRAY X INTO ASCENDING ORDER
C
C  PARAMETERS OF ROUTINE:
C  X      *IN/OUT* ARRAY OF LENGTH N. CONTAINS THE NUMBERS TO BE SORTED.
C                  ON EXIT, CONTAINS THE SORTED NUMBERS.
C  N      * INPUT* NUMBER OF ELEMENTS TO BE SORTED
C
C  METHOD USED IS SHELL SORT WITH SEQUENCE OF INCREMENTS AS IN
C  D.F.KNUTH (1969) 'THE ART OF COMPUTER PROGRAMMING', VOL.3, P.95
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION X(N),temparr(maxyrs+1)
      IF(N.LE.1)RETURN
      do i=1,n
        x(i)=temparr(i)
      enddo
      J=4
      DO 10 I=1,100
      J=3*J+1
      IF(J.GE.N)GOTO 20
   10 CONTINUE
   20 CONTINUE
      M=(J/3)
      DO 60 MM=1,100
      M=M/3
      IF(M.EQ.0)RETURN
      DO 50 I=M+1,N
      TEST=X(I)
      J=I
      DO 30 JJ=1,100
      J=J-M
      IF(J.LE.0)GOTO 40
      IF(TEST.GE.X(J))GOTO 40
   30 X(J+M)=X(J)
```

```
40 CONTINUE
50 X(J+M)=TEST
60 CONTINUE
   END
```

Appendix C: Parameter Estimates for Drought Blends

Seacoast Drainage

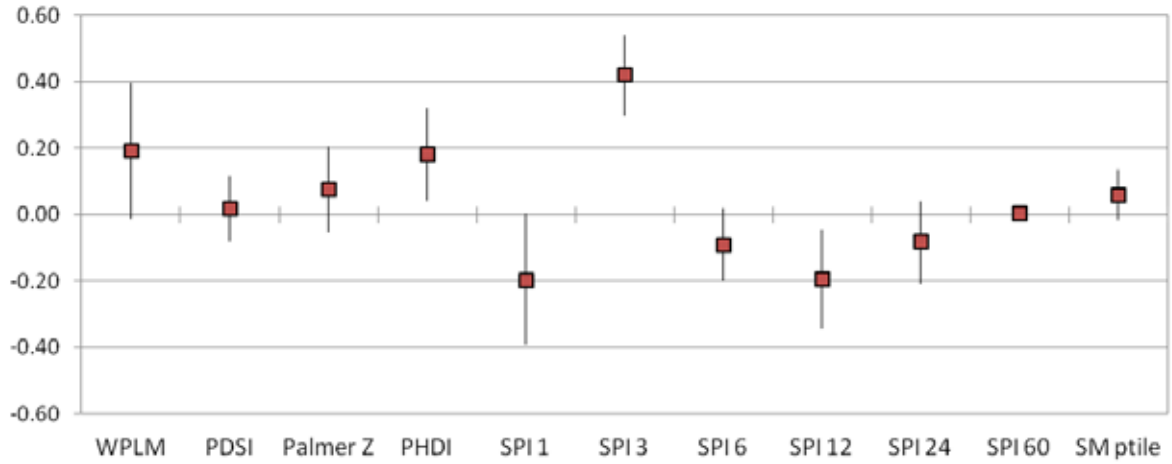
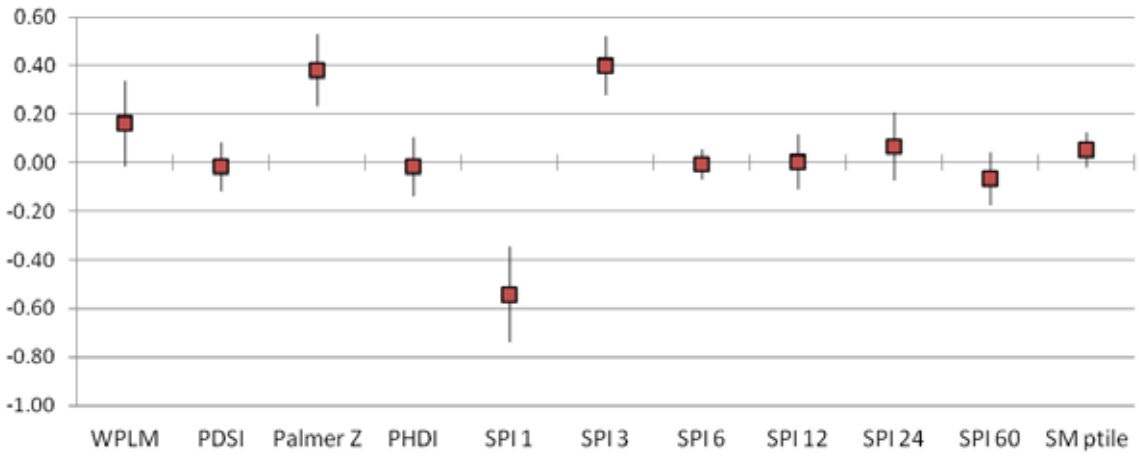


Figure C-1. Weights for DMA1

Table C1. Summary of weights for Drought Management Area 1.

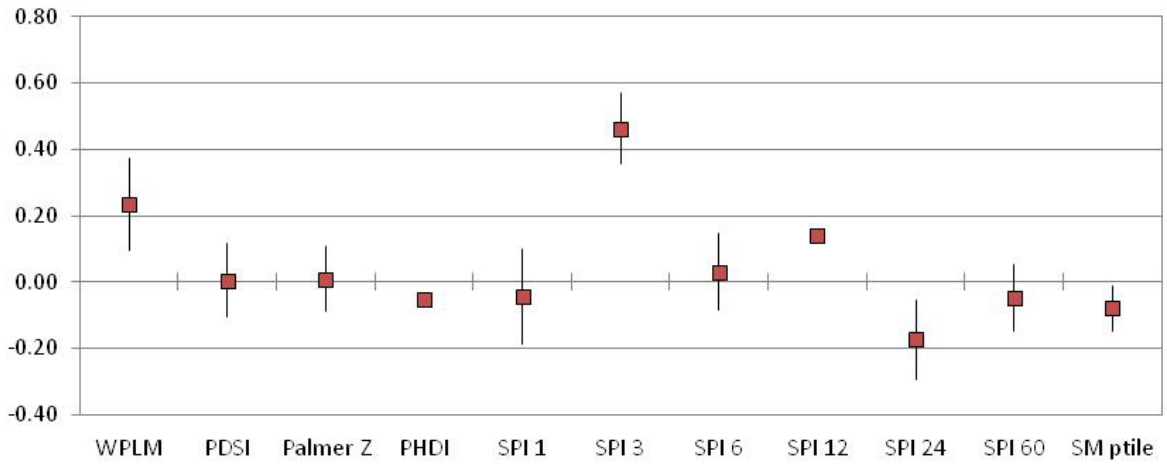
	Drought Management Area 1 (Coastal Drainage)		
Parameter	**Estimated Value**	**95% Percent Confidence Limits**	
		Lower Limit	*Upper Limit*
wplm	1.92E-01	-1.23E-02	3.96E-01
pdsi	1.92E-02	-7.89E-02	1.17E-01
palmer-z	7.73E-02	-5.13E-02	2.06E-01
phdi	1.83E-01	4.56E-02	3.20E-01
spi01	-1.95E-01	-3.92E-01	1.23E-03
spi03	4.21E-01	3.02E-01	5.41E-01
spi06	-8.89E-02	-1.98E-01	1.99E-02
spi12	-1.93E-01	-3.41E-01	-4.48E-02
spi24	-8.17E-02	-2.04E-01	4.07E-02
spi60	6.82E-03	6.76E-03	6.89E-03
smptile	5.97E-02	-1.59E-02	1.35E-01

Southern Interior



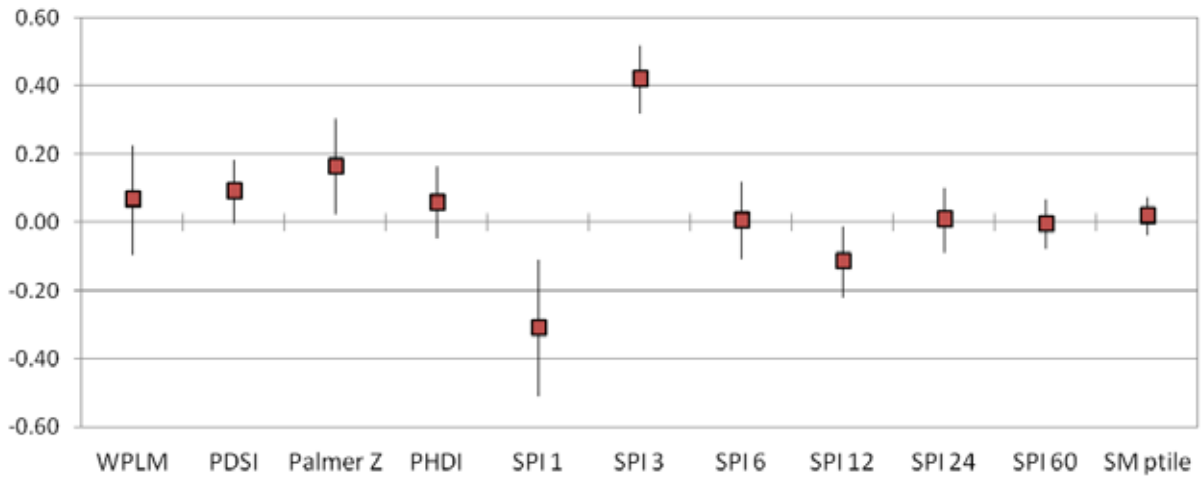
	Drought Management Area 2 (Southern Interior)		
Parameter	**Estimated Value**	**95% Percent Confidence Limits**	
		Lower Limit	*Upper Limit*
wplm	1.63E-01	-1.41E-02	3.40E-01
pdsi	-1.56E-02	-1.16E-01	8.44E-02
palmer-z	3.80E-01	2.32E-01	5.29E-01
phdi	-1.50E-02	-1.35E-01	1.05E-01
spi01	-5.43E-01	-7.40E-01	-3.46E-01
spi03	4.00E-01	2.79E-01	5.21E-01
spi06	-5.90E-03	-6.54E-02	5.36E-02
spi12	3.90E-03	-1.07E-01	1.15E-01
spi24	6.79E-02	-7.23E-02	2.08E-01
spi60	-6.39E-02	-1.70E-01	4.26E-02
smptile	5.19E-02	-1.94E-02	1.23E-01

South Western



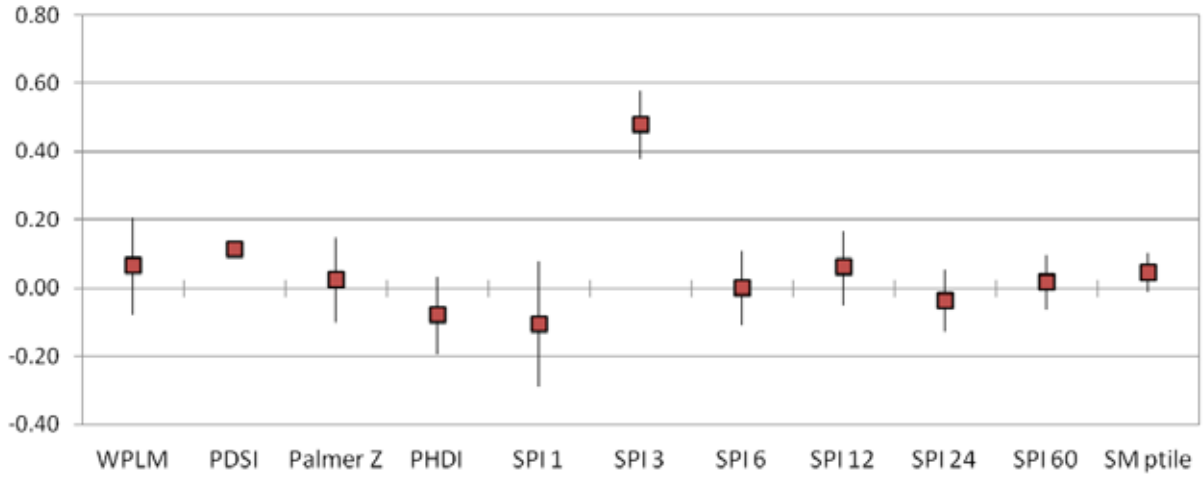
	Drought Management Area 3 (South Western)		
Parameter	**Estimated Value**	**95% Percent Confidence Limits**	
		Lower Limit	*Upper Limit*
wplm	2.35E-01	9.70E-02	3.73E-01
pdsi	5.44E-03	-1.08E-01	1.19E-01
palmer-z	9.62E-03	-9.04E-02	1.10E-01
phdi	-5.21E-02	-5.27E-02	-5.15E-02
spi01	-4.25E-02	-1.86E-01	1.01E-01
spi03	4.63E-01	3.57E-01	5.68E-01
spi06	2.99E-02	-8.58E-02	1.46E-01
spi12	1.41E-01	1.39E-01	1.42E-01
spi24	-1.73E-01	-2.92E-01	-5.50E-02
spi60	-4.73E-02	-1.48E-01	5.35E-02
smptile	-7.98E-02	-1.48E-01	-1.18E-02

White Mountains



	Drought Management Area 4 (While Mountains)		
Parameter	**Estimated Value**	**95% Percent Confidence Limits**	
		Lower Limit	*Upper Limit*
wplm	6.55E-02	-9.29E-02	2.24E-01
pdsi	8.99E-02	-2.36E-03	1.82E-01
palmer-z	1.64E-01	2.65E-02	3.02E-01
phdi	5.76E-02	-4.75E-02	1.63E-01
spi01	-3.11E-01	-5.08E-01	-1.13E-01
spi03	4.18E-01	3.20E-01	5.17E-01
spi06	4.18E-03	-1.08E-01	1.16E-01
spi12	-1.16E-01	-2.21E-01	-1.09E-02
spi24	7.33E-03	-8.72E-02	1.02E-01
spi60	-6.72E-03	-7.85E-02	6.51E-02
smptile	1.80E-02	-3.70E-02	7.30E-02

North Country



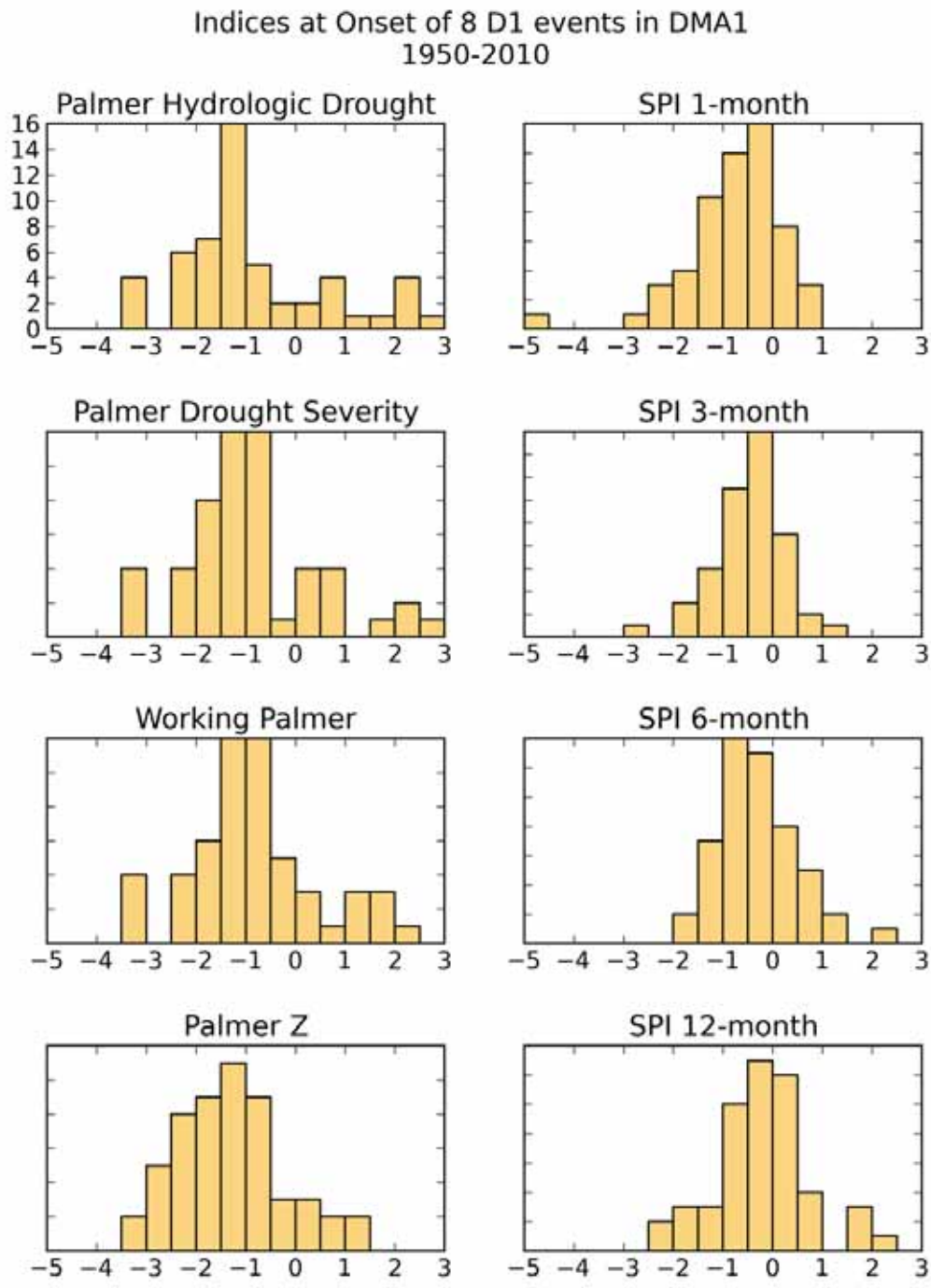
	Drought Management Area 5 (North Country)		
Parameter	**Estimated Value**	**95% Percent Confidence Limits**	
		Lower Limit	*Upper Limit*
wplm	6.50E-02	-7.57E-02	2.06E-01
pdsi	1.12E-01	1.11E-01	1.12E-01
palmer-z	2.27E-02	-9.95E-02	1.45E-01
phdi	-7.96E-02	-1.92E-01	3.27E-02
spi01	-1.05E-01	-2.87E-01	7.75E-02
spi03	4.79E-01	3.80E-01	5.78E-01
spi06	8.67E-04	-1.07E-01	1.09E-01
spi12	6.03E-02	-4.71E-02	1.68E-01
spi24	-3.76E-02	-1.28E-01	5.32E-02
spi60	1.57E-02	-6.23E-02	9.37E-02
smptile	4.45E-02	-1.19E-02	1.01E-01

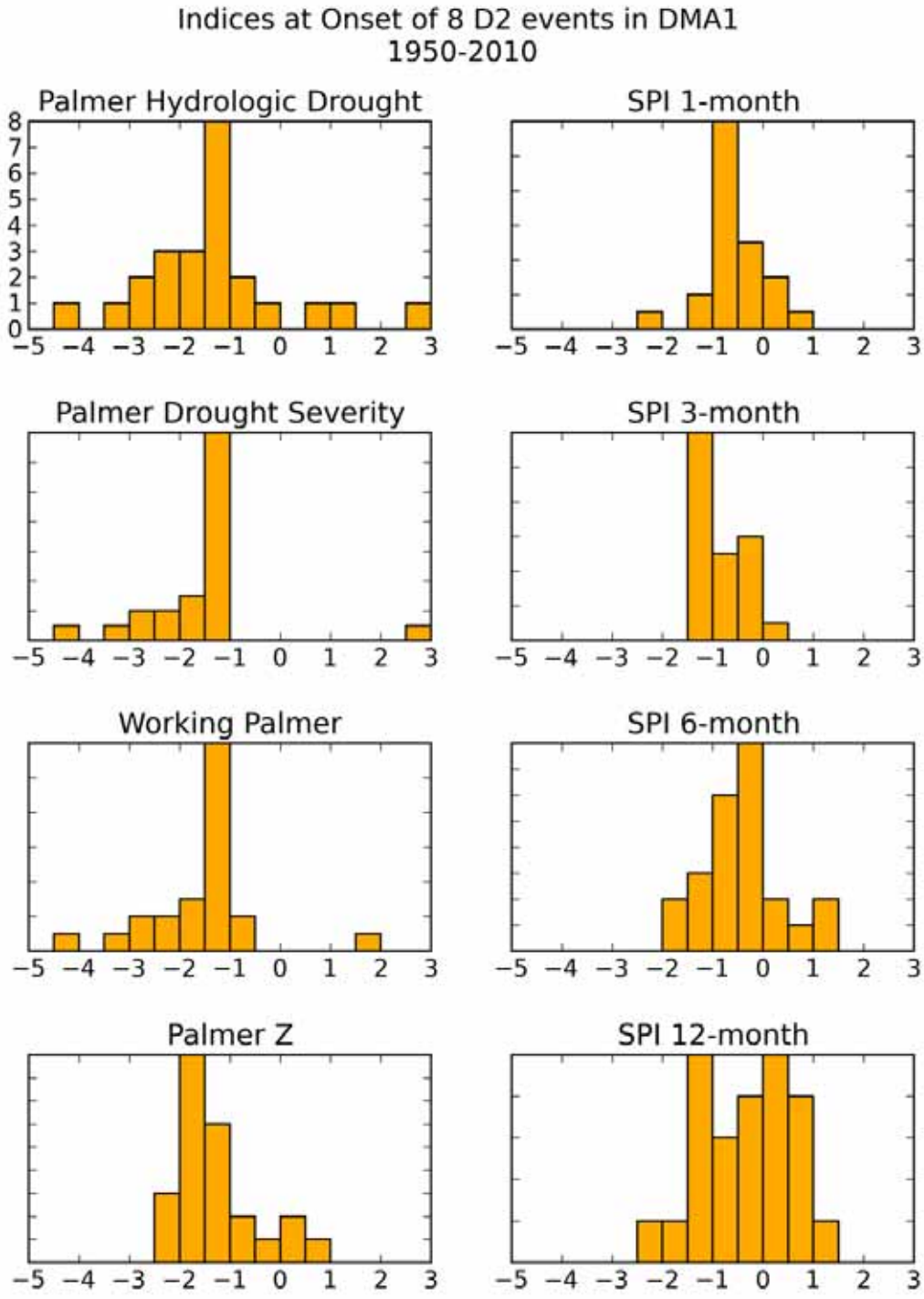
Appendix D: Index Values at Drought Onset

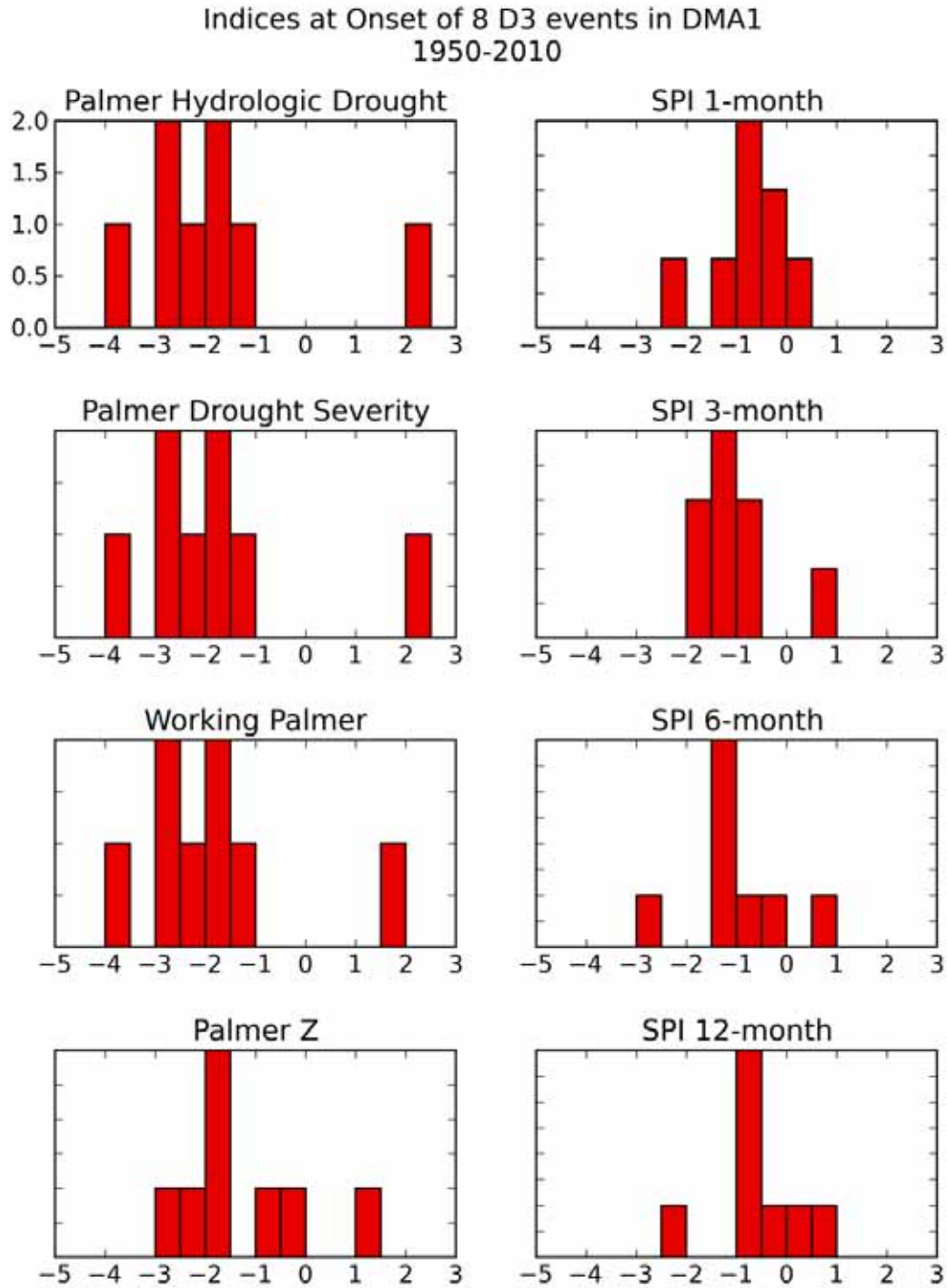
One of the main challenges in this project was to identify which indices best align with the onset of drought events and determine an appropriate representative value of the index for each drought level. To assist in the effort, the computed value of the drought indices most likely to be useful (as determined by the PEST analysis) were identified at the beginning of each drought event in each Drought Management Area. Monthly drought indices were interpolated onto a day at a set time after the specific drought event began. Because each drought event was classified based on its entire duration, it was necessary to project past the actual begin date to estimate a date at which the drought event would have progressed to the next Drought Management Category.

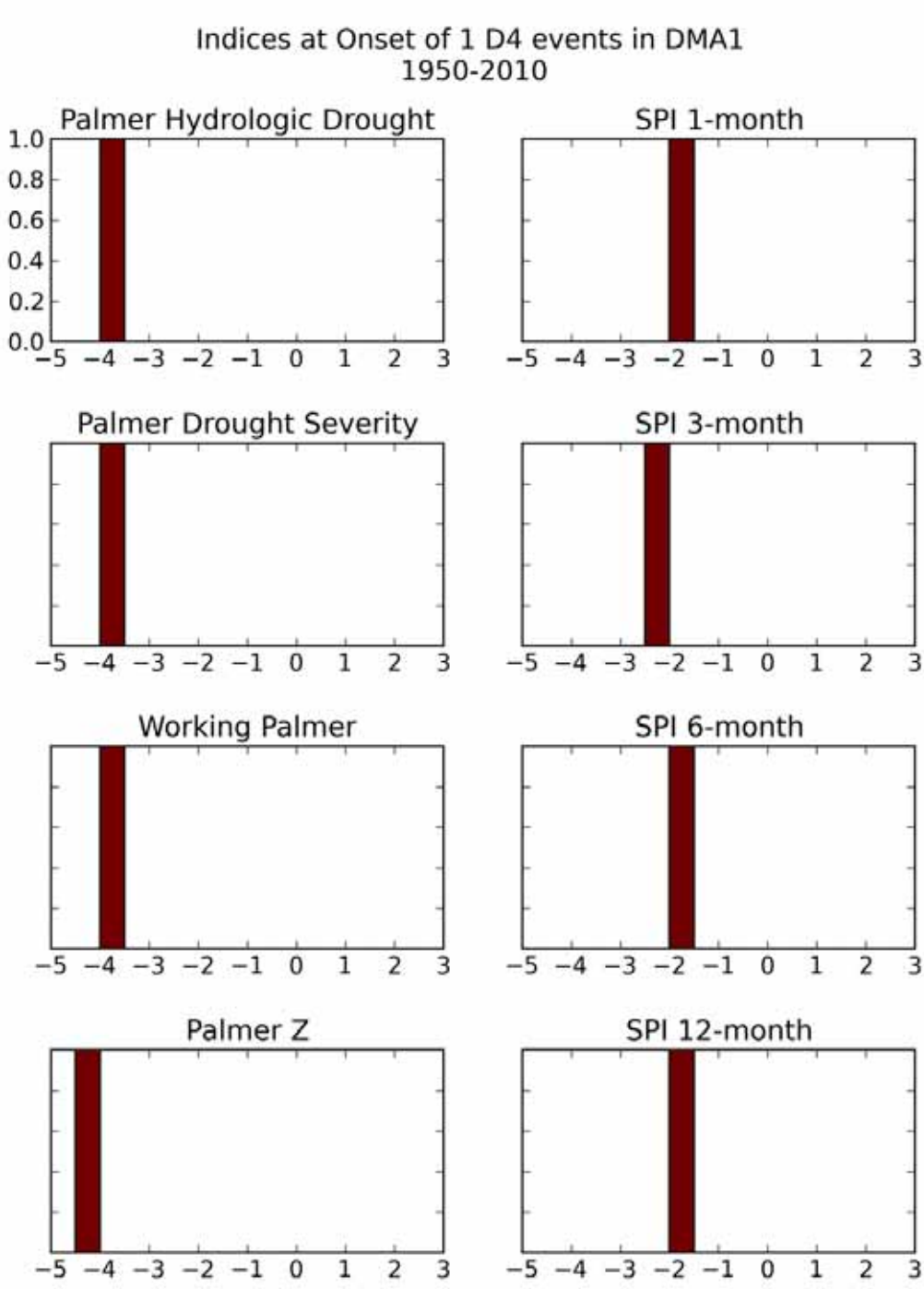
Drought Class	Class Duration	Assumed Onset relative to start of D0
D1	1-3 month	15 days
D2	3-6 months	45 days
D3	6-9 months	90 days
D4	9-12 months	180 days

Coastal Drainage

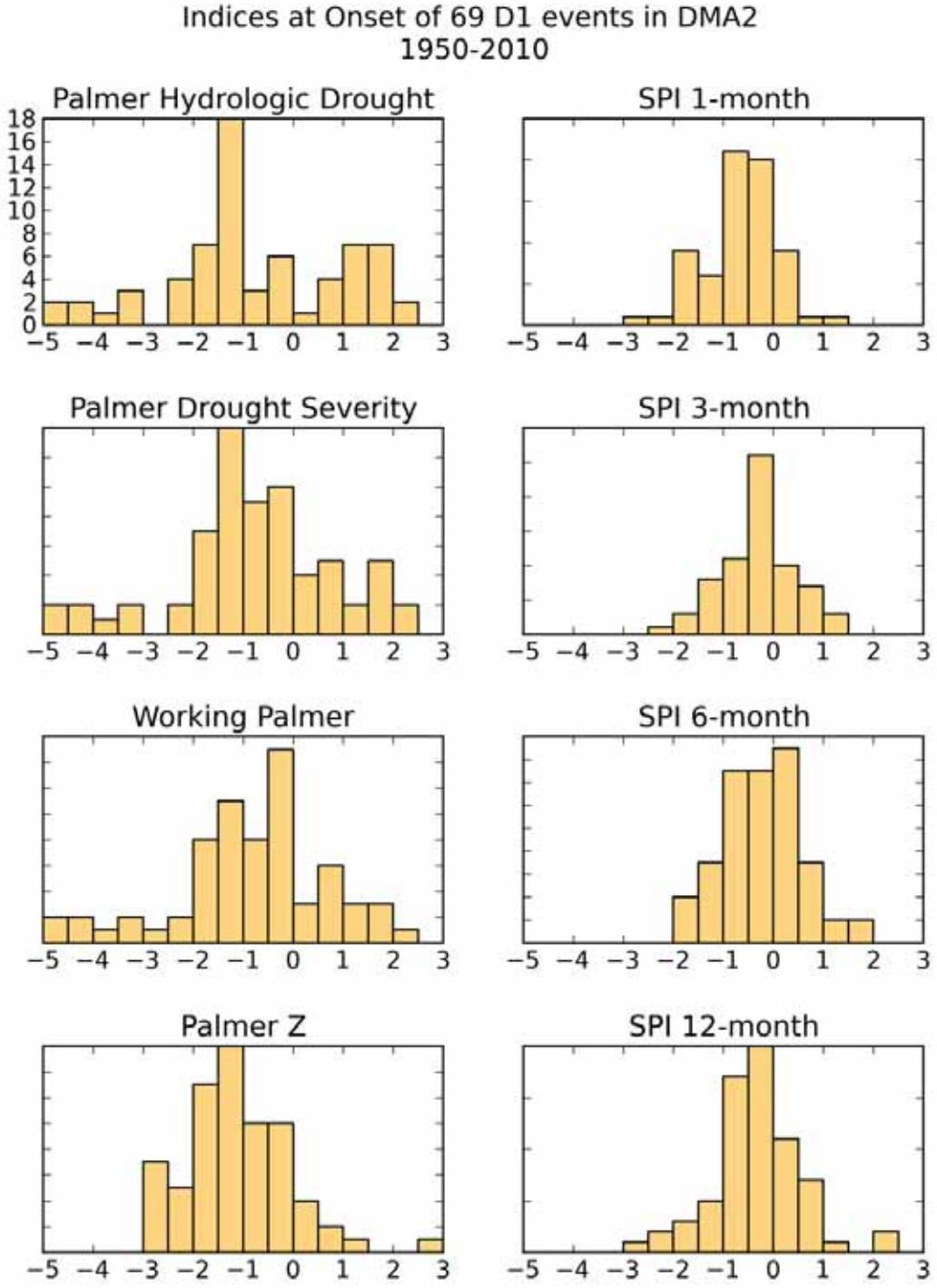


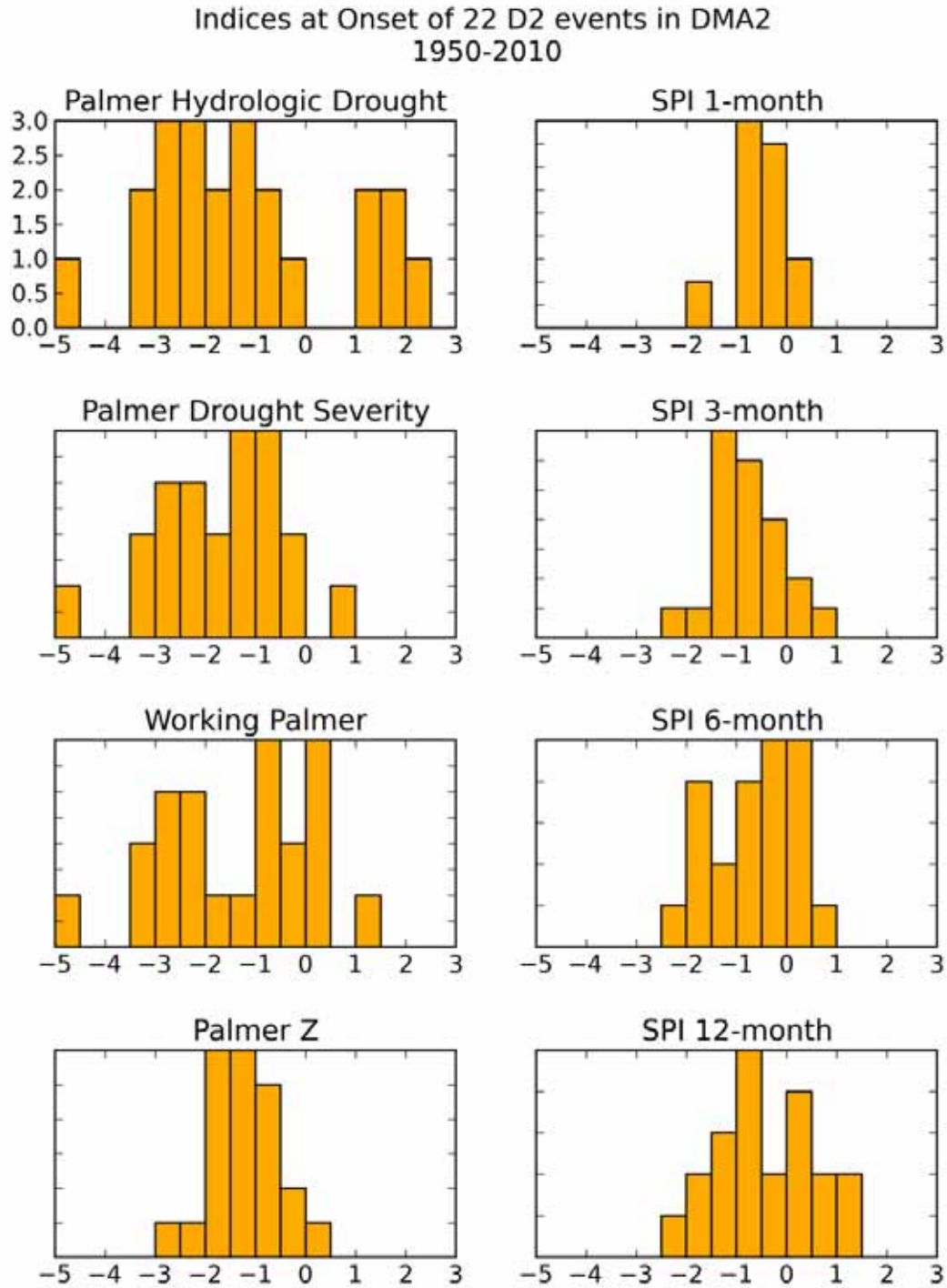

Indices at Onset of 8 D2 events in DMA1
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month

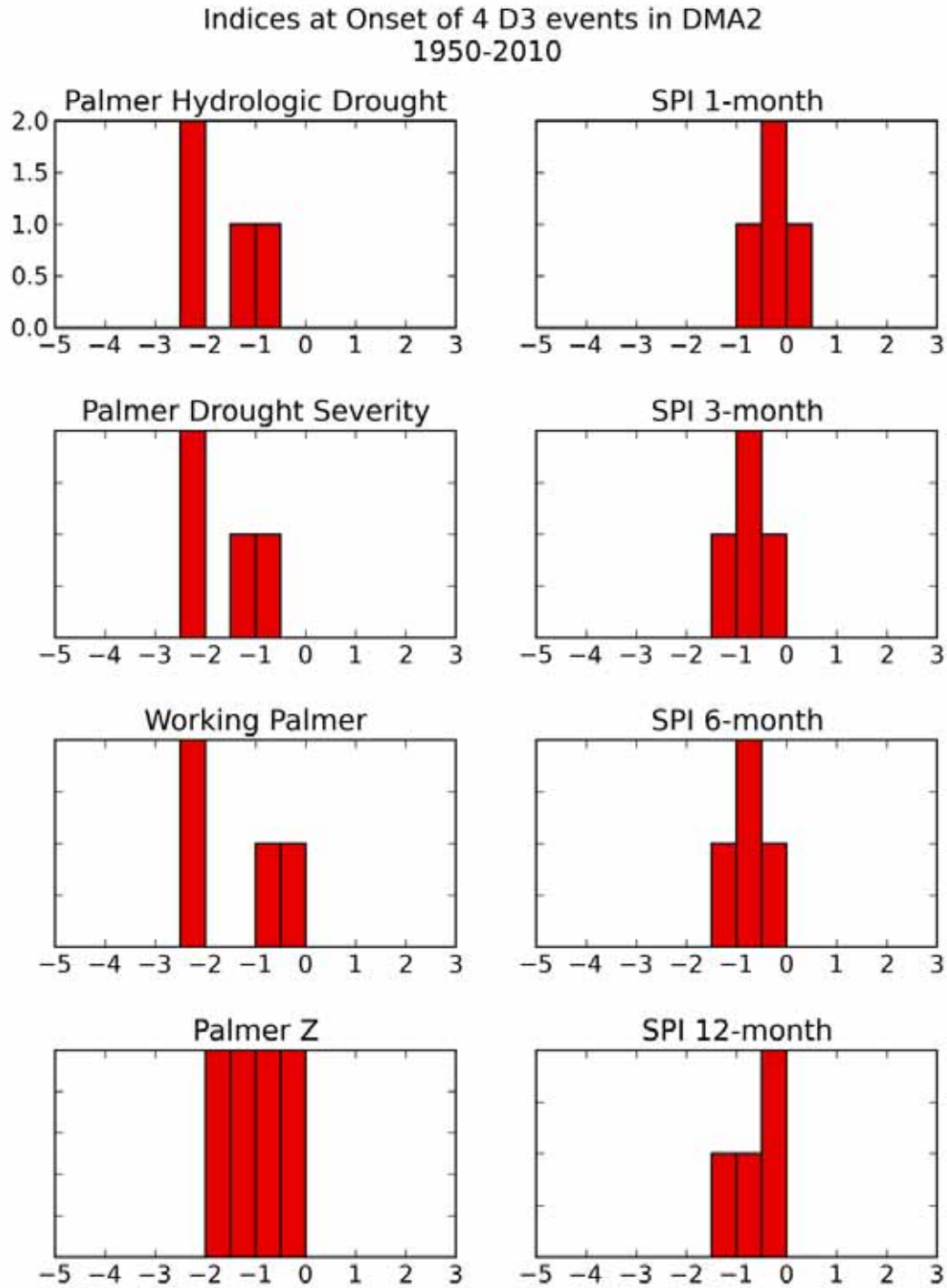

Indices at Onset of 8 D3 events in DMA1
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
2.0
1.5
1.0
0.5
0.0
−5 −4 −3 −2 −1 0 1 2 3

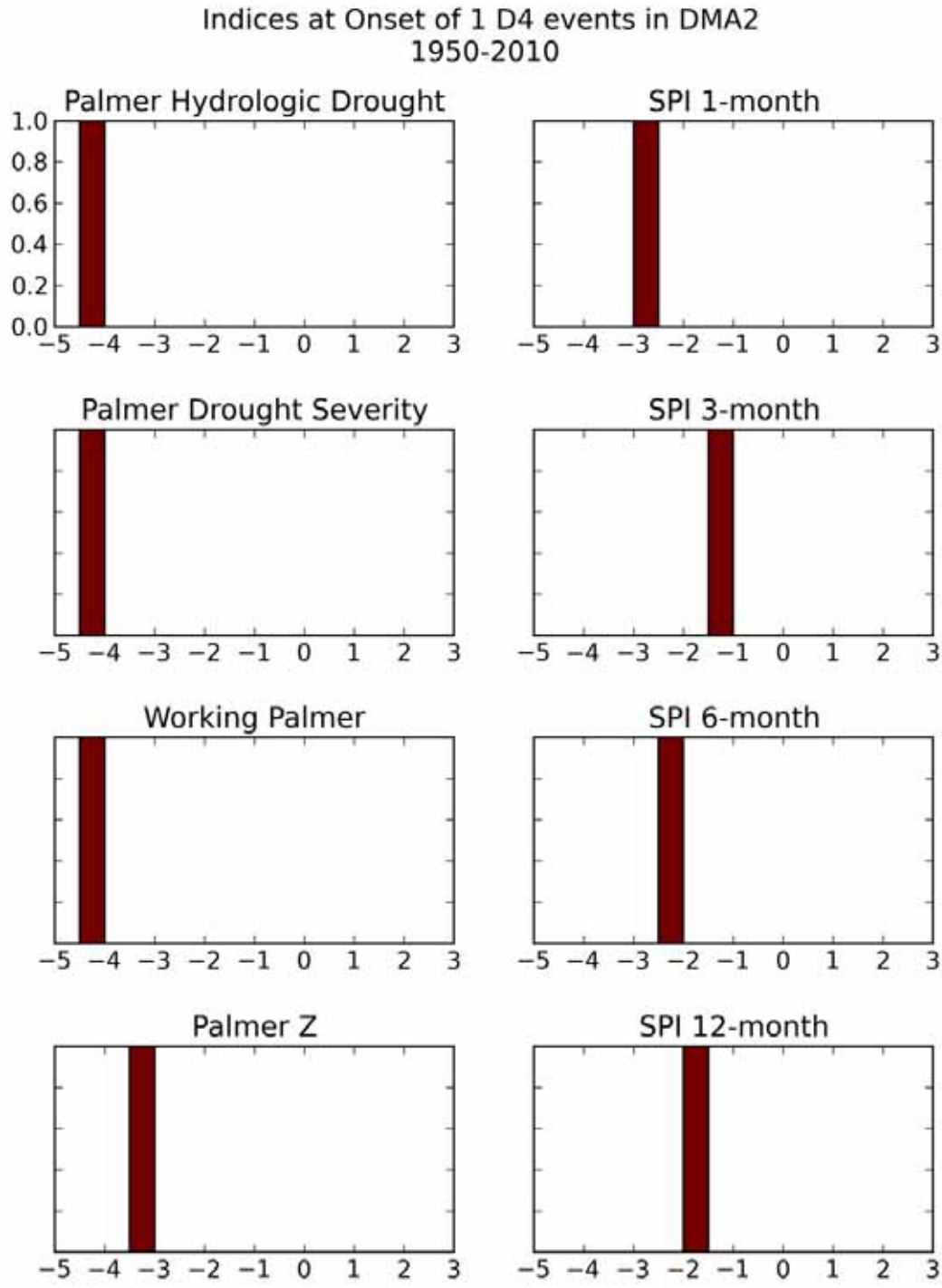

Indices at Onset of 1 D4 events in DMA1
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
1.0
0.8
0.6
0.4
0.2
0.0
−5 −4 −3 −2 −1 0 1 2 3

Southern Interior

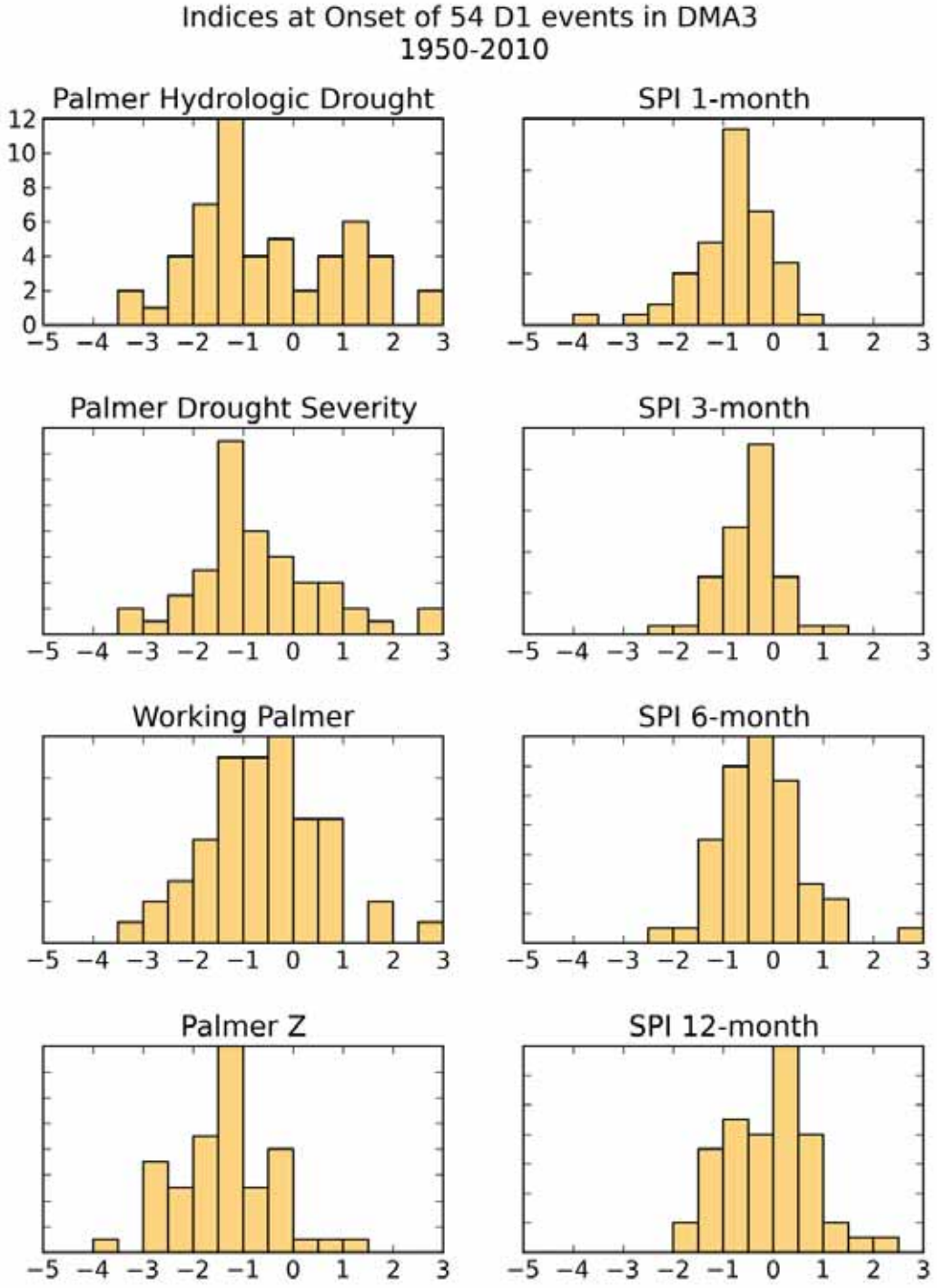


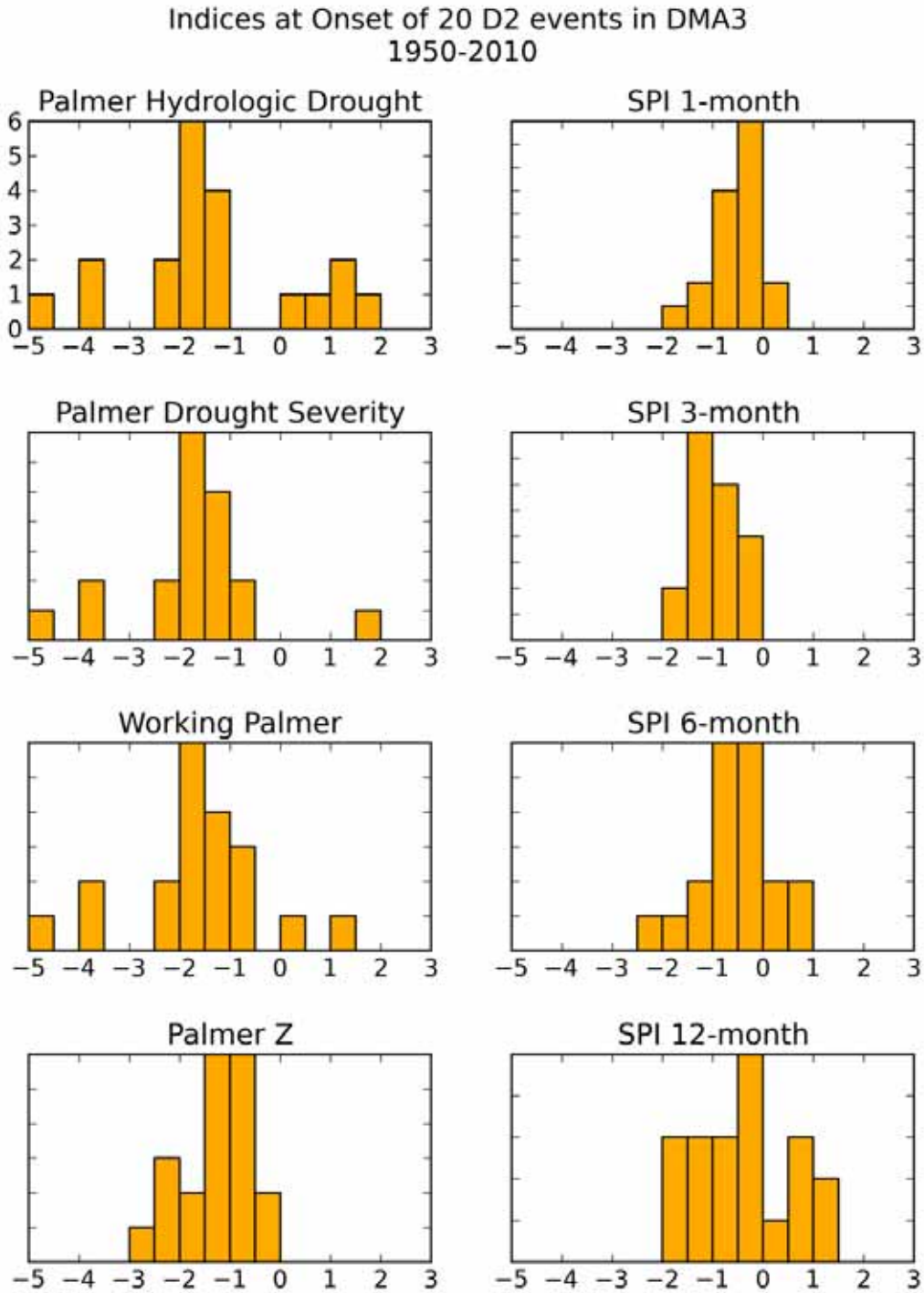

Indices at Onset of 22 D2 events in DMA2
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month

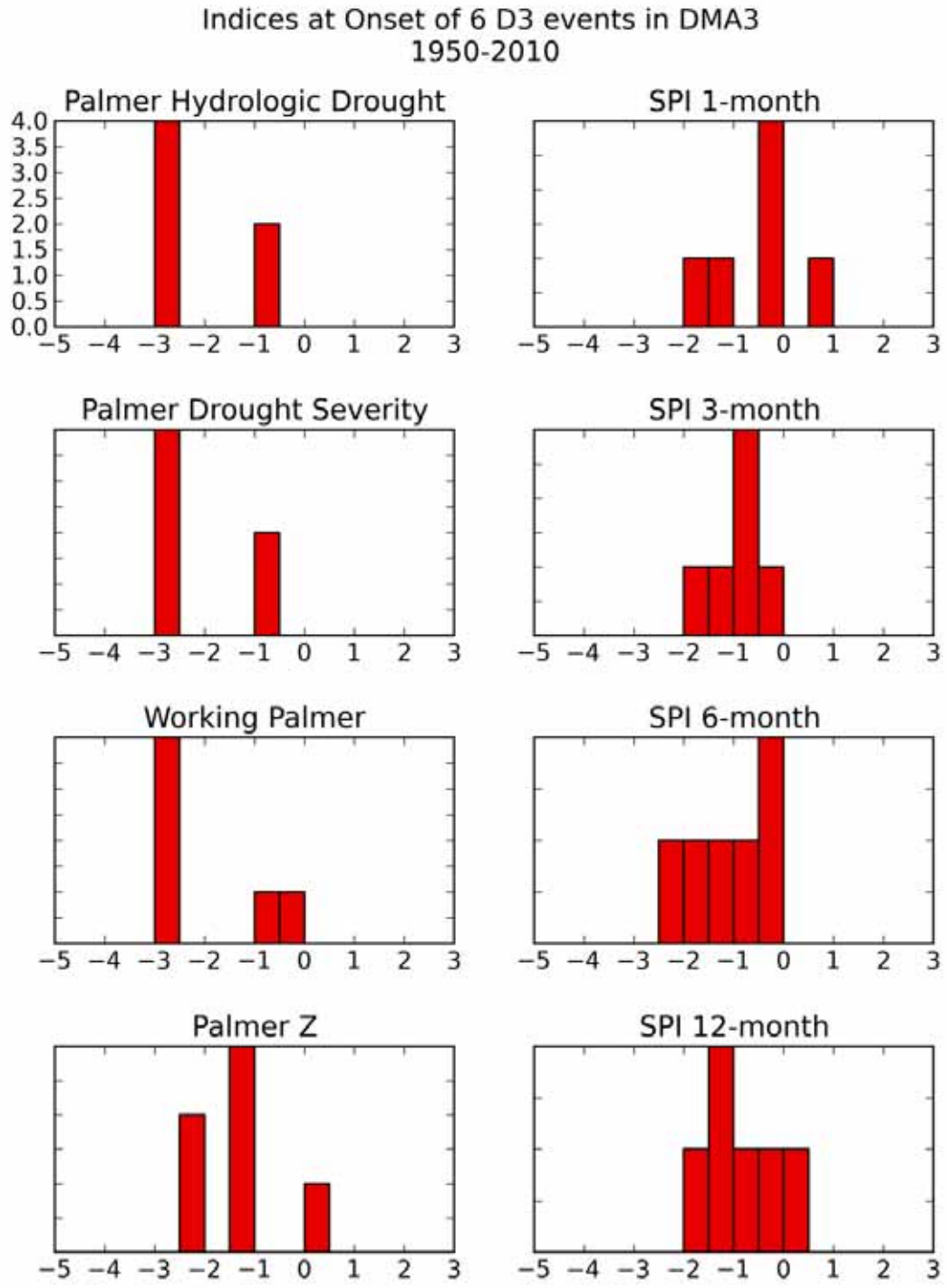

Indices at Onset of 4 D3 events in DMA2
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
2.0
1.5
1.0
0.5
0.0
−5 −4 −3 −2 −1 0 1 2 3

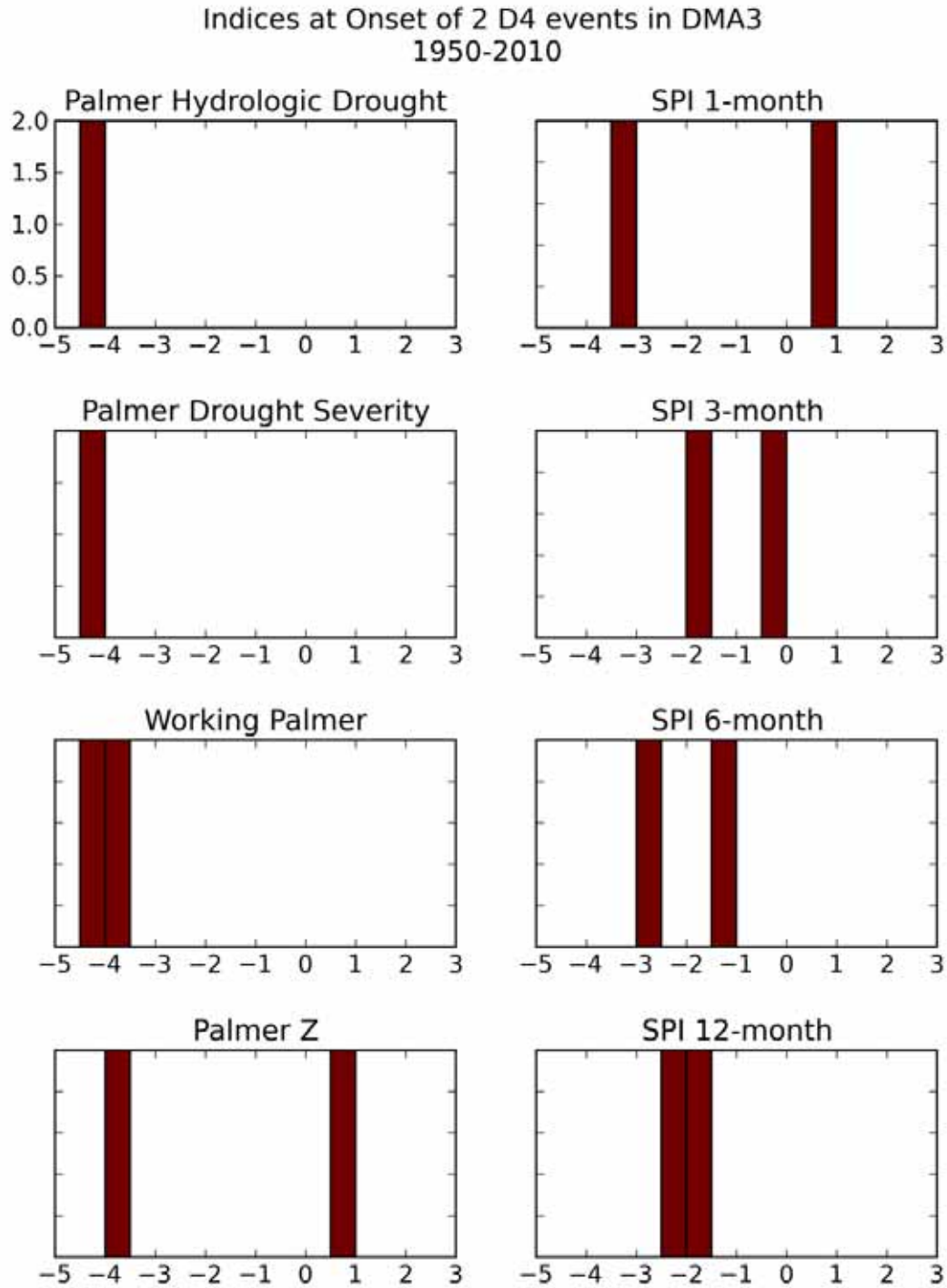

Indices at Onset of 1 D4 events in DMA2
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
1.0
0.8
0.6
0.4
0.2
0.0
−5 −4 −3 −2 −1 0 1 2 3

South Western

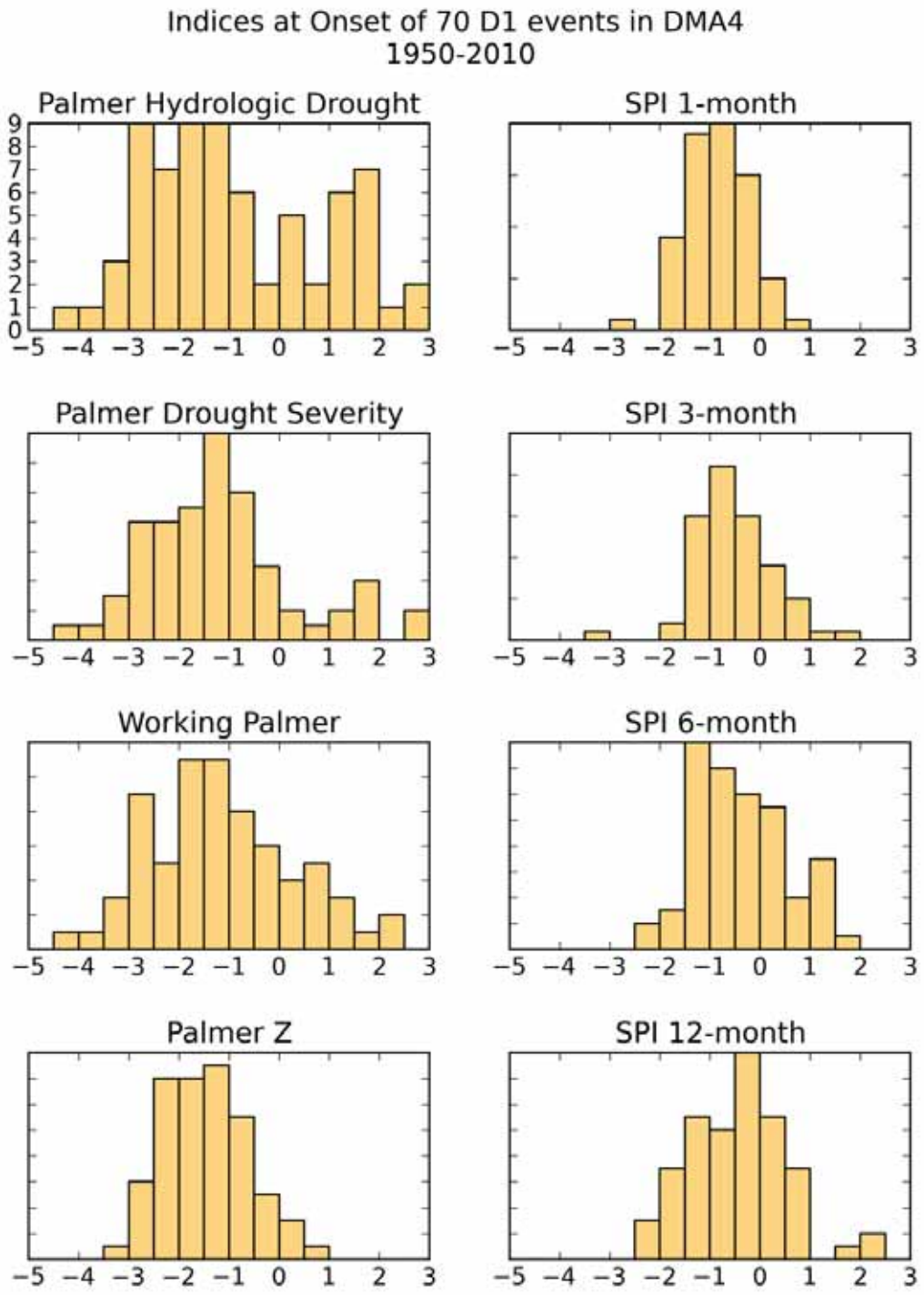


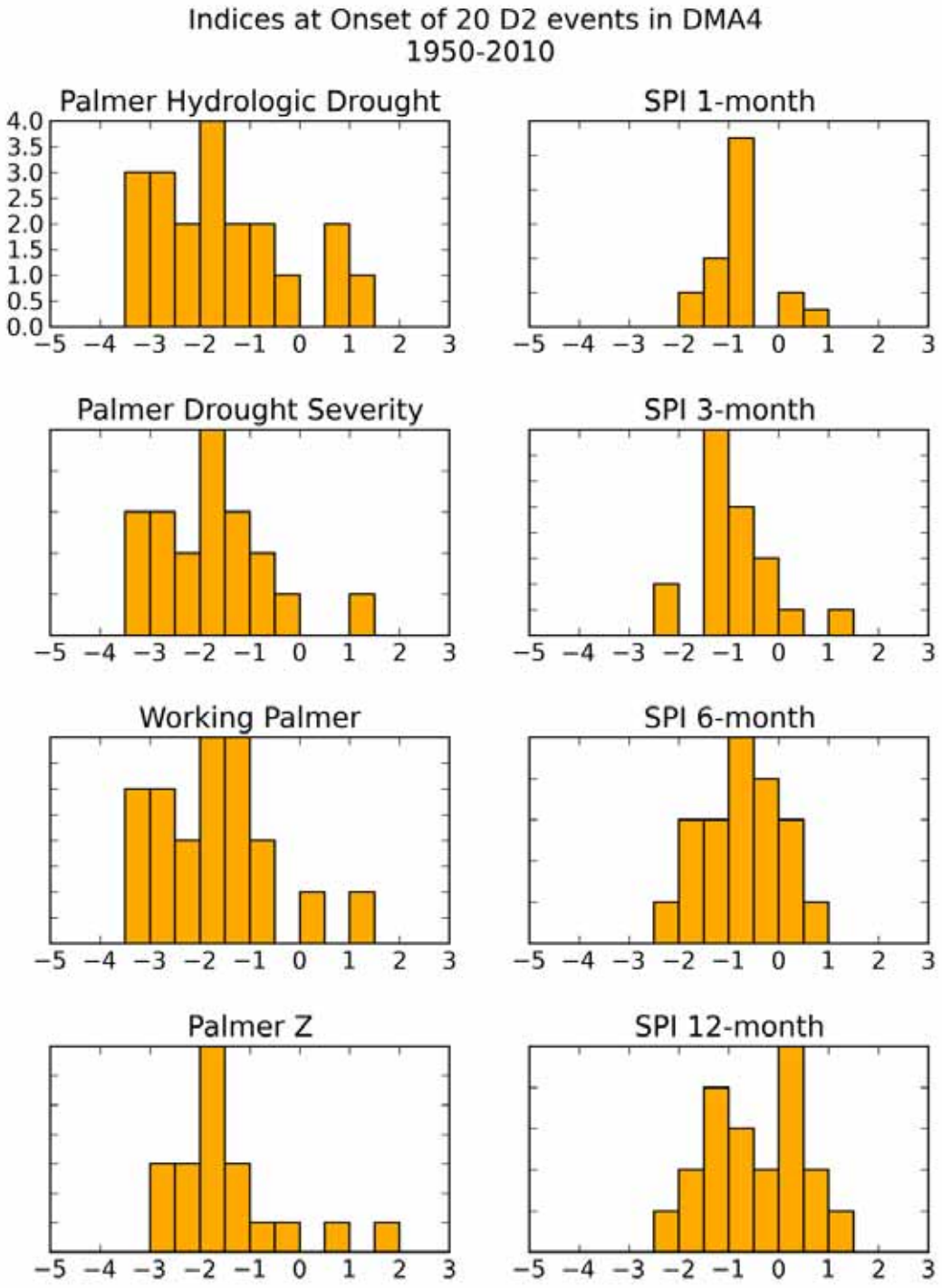

Indices at Onset of 20 D2 events in DMA3
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month

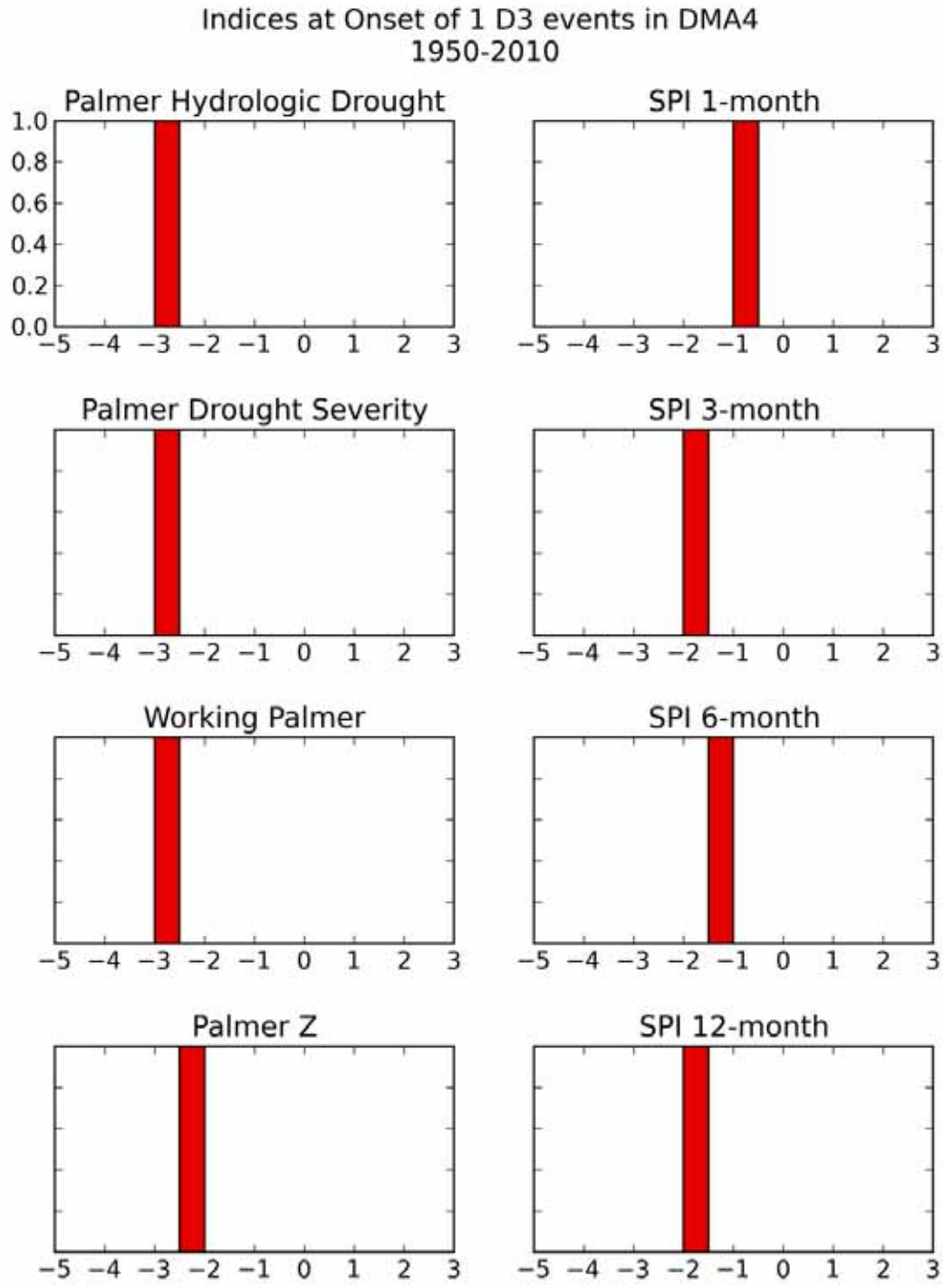

Indices at Onset of 6 D3 events in DMA3
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−5 −4 −3 −2 −1 0 1 2 3


Indices at Onset of 2 D4 events in DMA3
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
2.0
1.5
1.0
0.5
0.0
−5 −4 −3 −2 −1 0 1 2 3

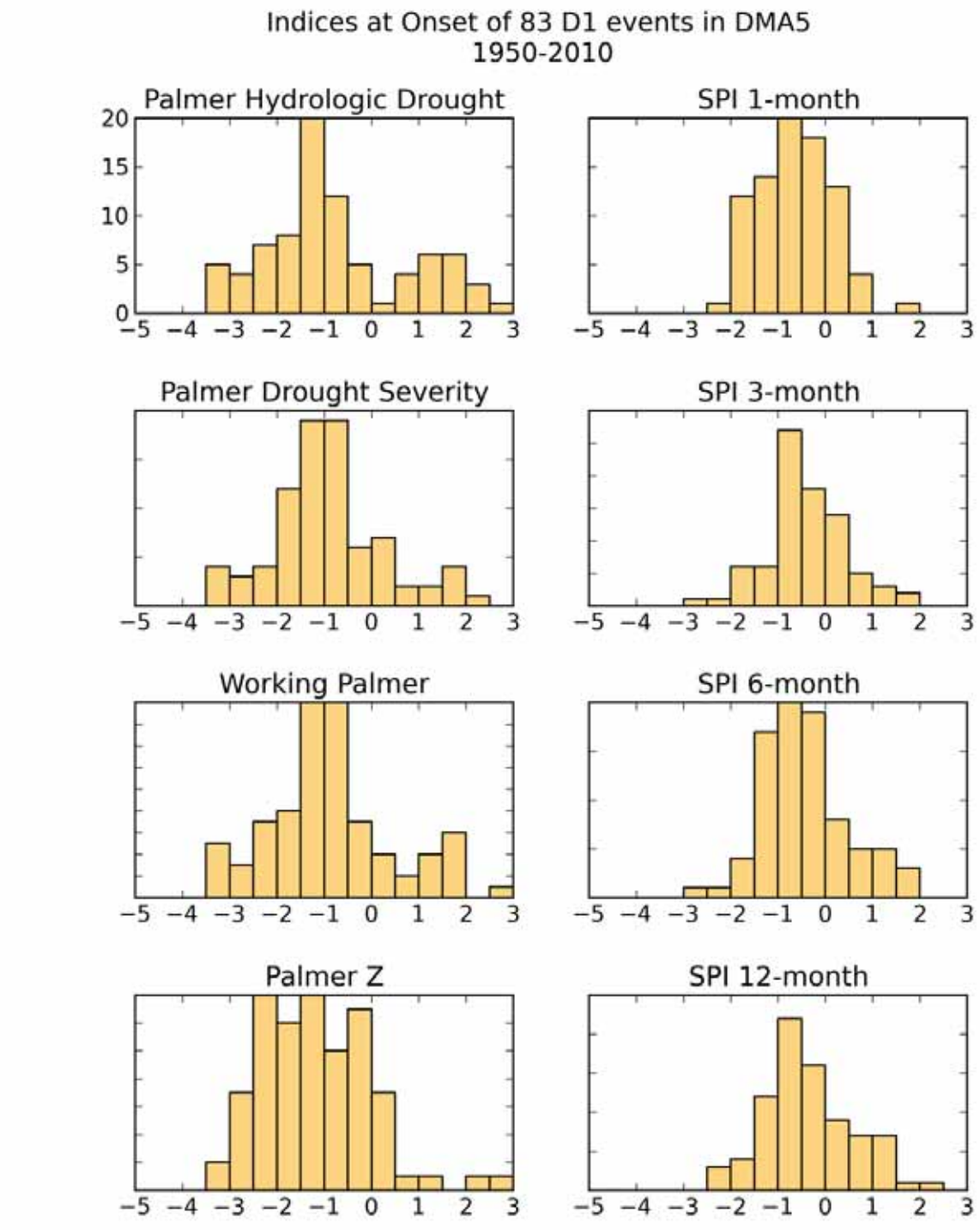
White Mountains

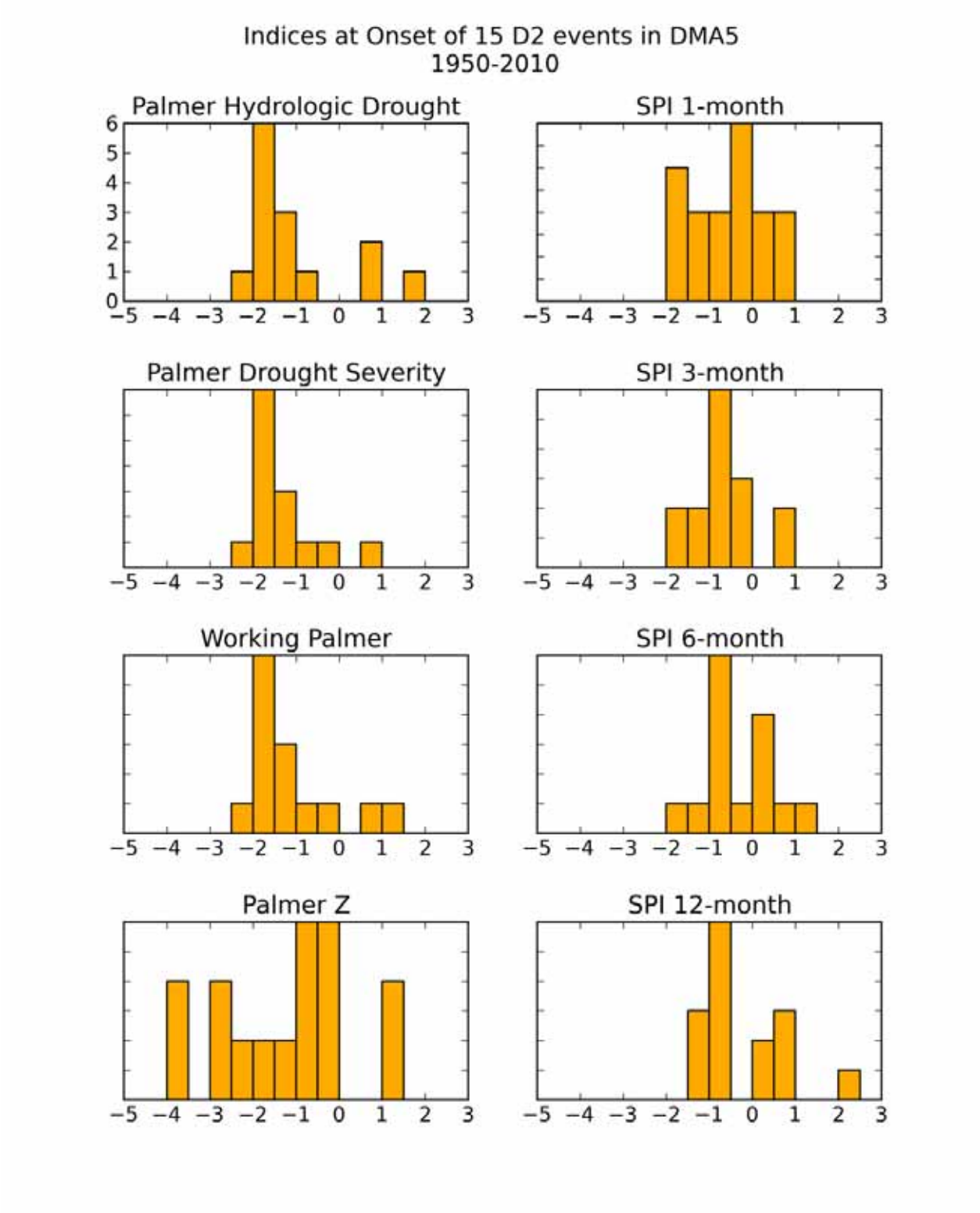


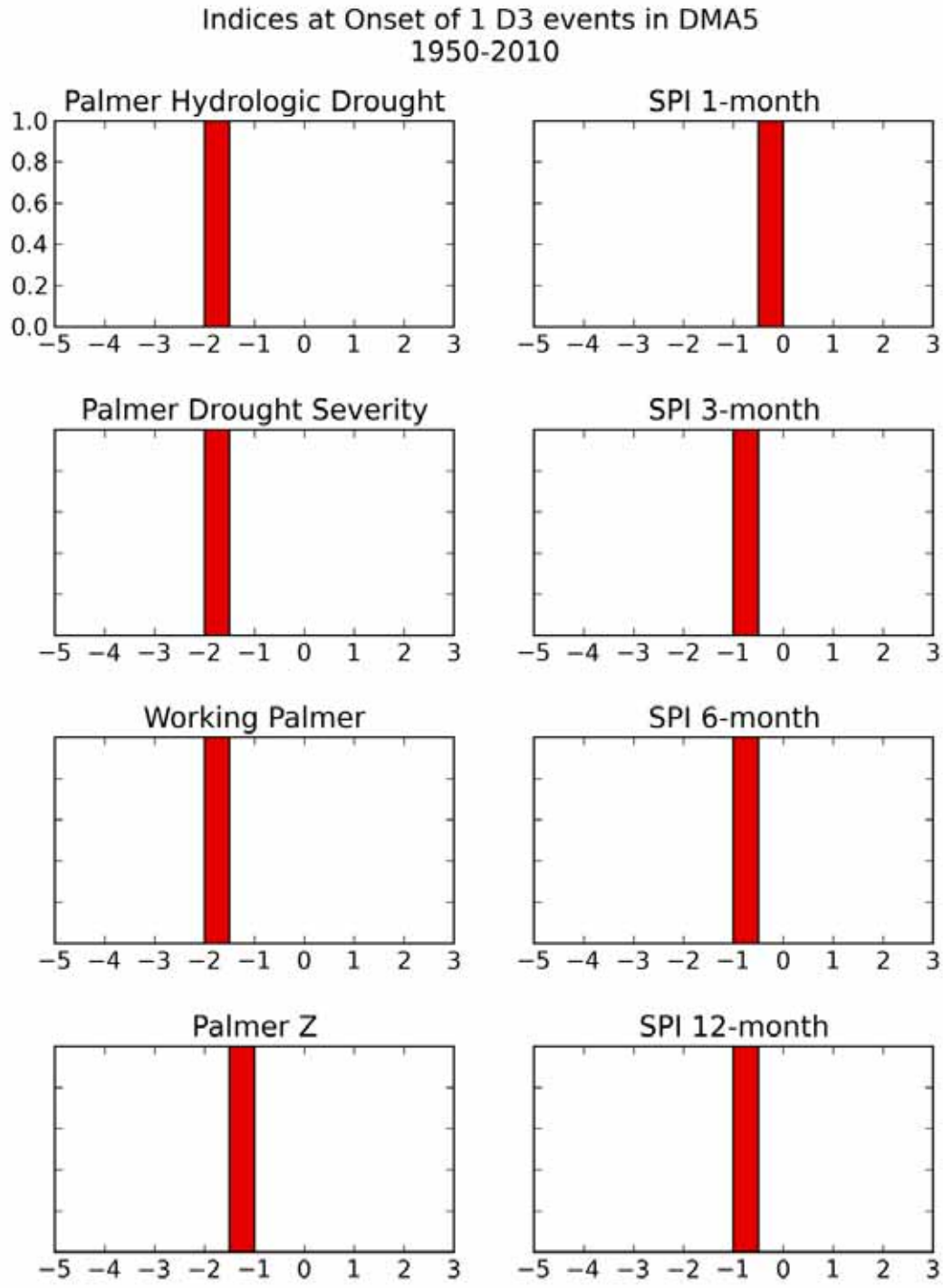

Indices at Onset of 20 D2 events in DMA4
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−5 −4 −3 −2 −1 0 1 2 3


Indices at Onset of 1 D3 events in DMA4
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
1.0
0.8
0.6
0.4
0.2
0.0
−5 −4 −3 −2 −1 0 1 2 3

North Country




Indices at Onset of 15 D2 events in DMA5
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month


Indices at Onset of 1 D3 events in DMA5
1950-2010
Palmer Hydrologic Drought
SPI 1-month
Palmer Drought Severity
SPI 3-month
Working Palmer
SPI 6-month
Palmer Z
SPI 12-month
1.0
0.8
0.6
0.4
0.2
0.0
−5 −4 −3 −2 −1 0 1 2 3

Appendix E: SPIs for DMAs and Climate Divisions

Comparison of Standardized Precipitation Indices for the Southern Climate Division as obtained from the National Climate Data Center (NCDC) with those computed using precipitation data for each Drought Management Area.

Southern Climate Division

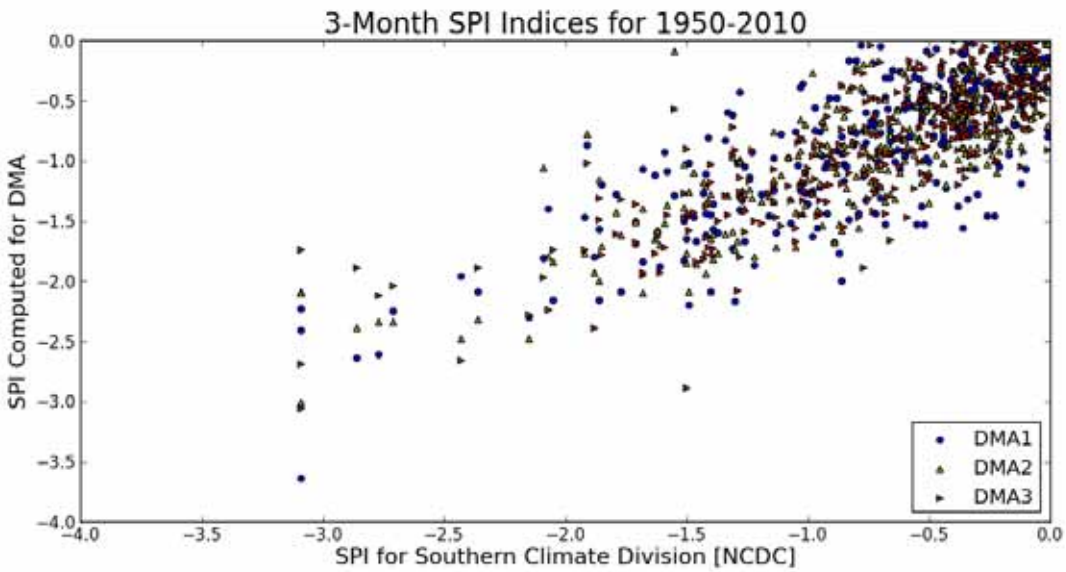


Figure E1. 3 month SPIs for Southern Climate Division.

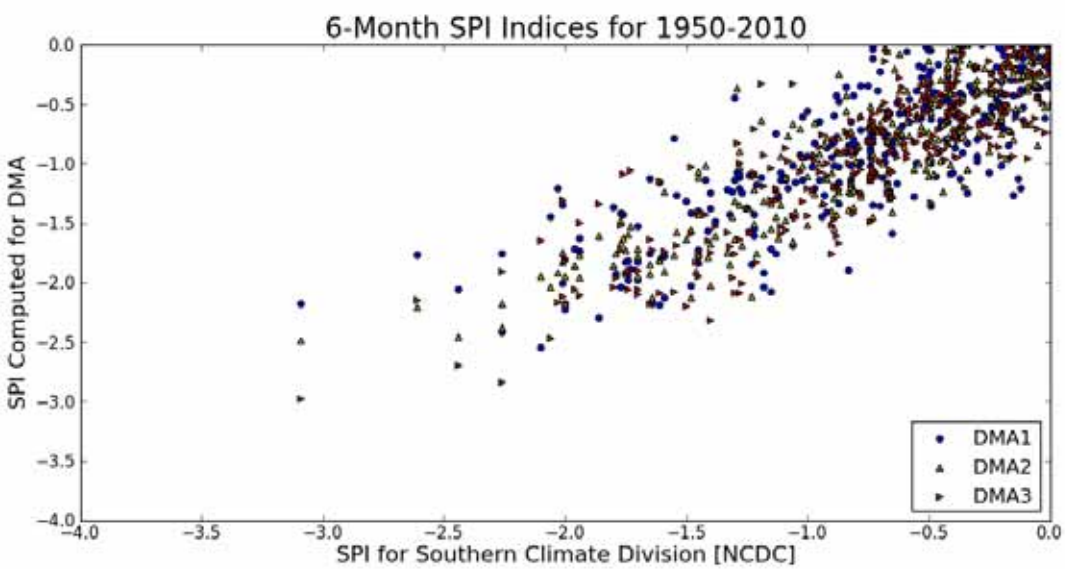


Figure E2. 6 month SPIs for Southern Climate Division.

Northern Climate Division

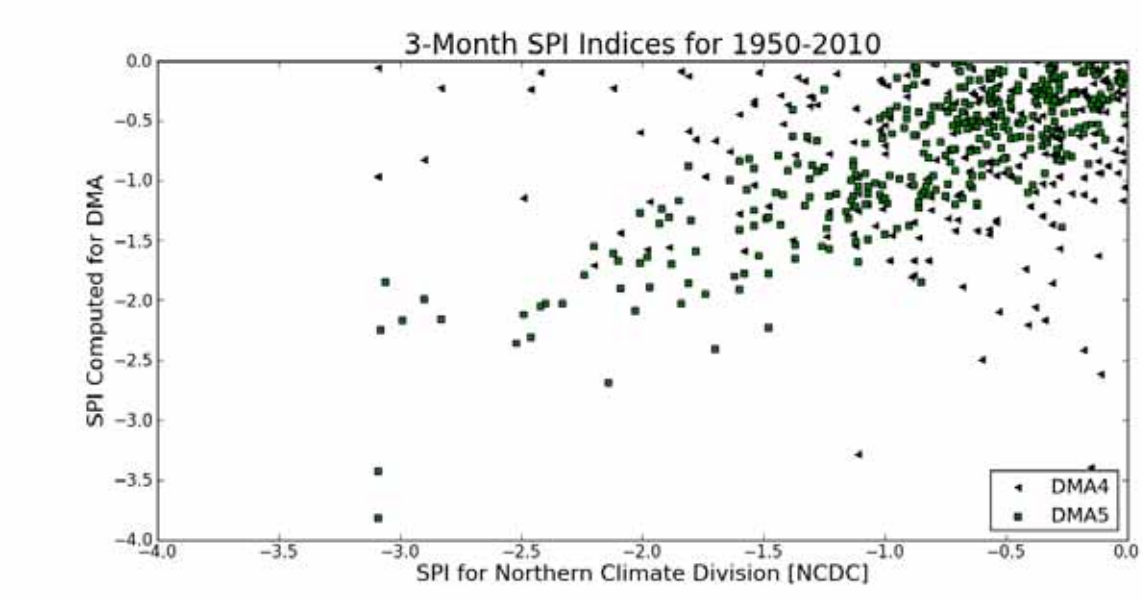


Figure E3. 3 month SPIs for Northern Climate Division

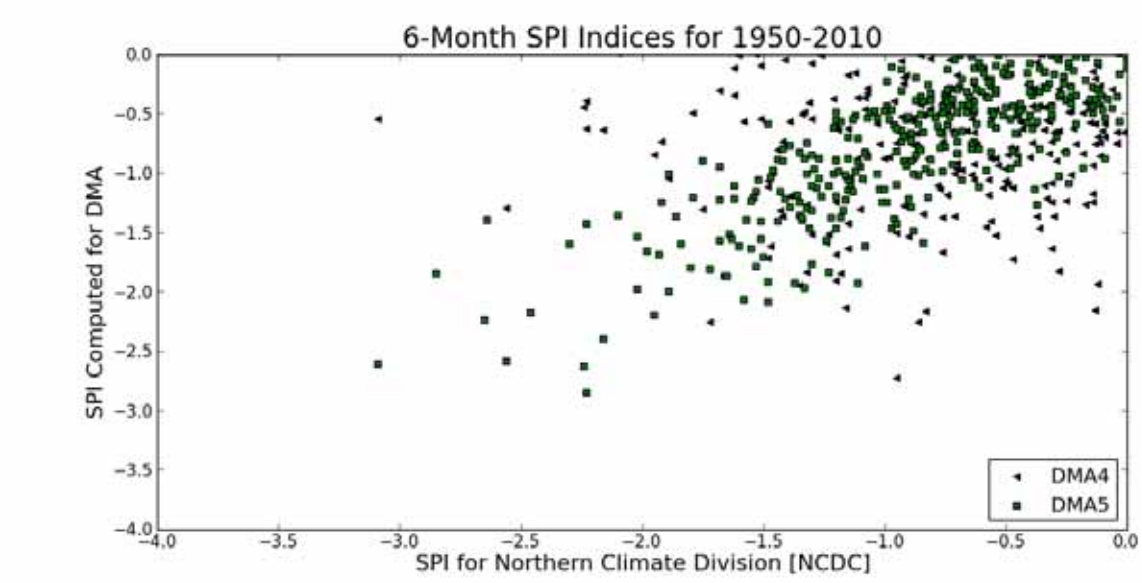


Figure E4. 6 month SPIs for Northern Climate Division