OWRRI Project
Final Report
An Assessment of Environmental Flows for Oklahoma

Start Date: February 29, 2008

End Date: February 28, 2009

Congressional District: 3

Focus Categories: ECL, HYDROL, MET, SW, WQN, WU

Submitted by:

Co-PIs:

Dr. Don Turton
Associate Professor
Oklahoma State University
Department of Natural Resource Ecology and Management

Dr. Bill Fisher
USGS, NY Coop Research Unit
206F Fernow Hall, Cornell Univ
Ithaca, NY 14850

And:

Titus S. Seilheimer, Ph.D.
Postdoctoral Fellow
OK Cooperative Fish and Wildlife Research Unit
404 Life Sciences West
Oklahoma State University

Rachel A. Esralew
Hydrologist
U.S. Geological Survey
Oklahoma Water Science Center
202 NW66th
Oklahoma City 73116

Publications: none to date

Table of Contents

List of Tables

List of Figures

Problem and Research Objectives:

Background:

The state of Oklahoma is in the process of updating the Oklahoma Comprehensive Water Plan. The water plan was last updated in 1995, and water demand projections for the current plan will be for the next 50 years (http://www.owrb.ok.gov/supply/ocwp/ocwp.php, accessed on 27 May 2009). The water plan will focus on development of system-level plans to provide the most water to the majority of Oklahomans. Assessment of current and projected water demands and water supply and availability will be made by 2011 prior to implementation of the water plan. Development of the plan will proceed through three phases. Phase one will focus on developing water demand projections by county and region through year 2060 and a comprehensive inventory and analysis of the state's water supplies. Phase two will identify local and regional problems and opportunities related to the use of water for public supply, agricultural, industrial, recreational, and environmental uses. Phase three will involve implementation of planning initiatives and tools derived from the issues, problems and needs identified in phase two. Technical studies will be needed to identify environmental uses of water, particularly the flows required for fish and other aquatic biota, to aid in planning for Oklahoma's future water needs.

Previous Oklahoma water plans have not recognized environmental flows or made provisions for protecting them. Assessment of current and projected water demands and water supply and availability will be made by 2011 prior to implementation of the water plan. Oklahoma has four fish species and three mussel species that are federally-listed as threatened or endangered and sensitive to alterations in streamflow. It is imperative that environmental flows be assessed and considered in the development of the updated Oklahoma comprehensive water plan to aid in sustaining aquatic life and protecting federally threatened and endangered and state species of greatest conservation concern in Oklahoma.

Alteration of the hydrologic regime of rivers from impoundments and flow diversions modifies the structure and function of river ecosystems (Poff et al. 1997, Rosenberg et al. 2000, Postel and Richter 2003, Poff et al. 2007). Hydrologic alterations such as flow stabilization, prolonged low flows, loss of seasonal flow peaks, rapid changes in river stage, and low or high water temperatures downstream disrupt life cycles of aquatic plants, invertebrates, and fishes resulting in a reduction in species diversity and modifying reproduction and growth rates that oftentimes lead to local extinctions of native species and the invasion and establishment of exotic species (Poff et al. 1997). Large water diversions deplete streamflows, sometimes to damaging levels that affect aquatic and floodplain habitats, aquatic biodiversity, sport and commercial fisheries, natural floodplain fertility, and natural flood control (Postel and Richter 2003). The development of water resources to meet the demands of urban population centers is growing and threatens the ecological integrity of many freshwater ecosystems (Fitzhugh and Richter 2004).

Water management goals in the new millennium have broadened from traditional societal goals of water supply, flood control, channel maintenance, power production and commerce to include maintenance and enhancement of natural aquatic communities and ecosystem services. This has resulted in a paradigm shift from the simple question of "How much water can be taken from streams and lakes for human use?" to the more complex question of "How much water needs to be left in streams and lakes to sustain critical water-dependent natural resources?" (USFWS and USGS 2004). Evaluation of water use and development projects now requires consideration of effects at multiple scales, including consideration of the whole hydrograph and not simply minimum flows, the dynamic river channel rather than the static channel, the linkage between surface and ground water, and ecological communities rather than single species.

Assessment of environmental flows, traditionally referred to as instream flows, for Oklahoma is needed to aid planners, policy makers and the public in developing of the Oklahoma Comprehensive Water Plan. An initial step in assessing environmental flows for Oklahoma is characterizing and classifying streams and rivers based on their flow regimes. There are currently over 200 methods for evaluating environmental flows, which range from those that determine "minimum" flows to those that mimic the "natural flow regime" (Arthington et al. 2006). Scientists and many managers are now in general agreement that a regulated river needs to mimic the five components of the natural flow regime, including the magnitude, timing, frequency, duration, and rate of change and predictability of flow events, plus the sequence of these conditions (Olden and Poff 2003, Arthington et al. 2006). These more complex methods go beyond developing simple hydrological "rules of thumb" to more comprehensive environmental flow assessment. HIP is a tool developed by the USGS that identifies 10 non-redundant hydrologic indices that are ecologically relevant, specific to stream classes, and characterize the five components of the natural flow regime (Figure 1) (http://www.fort.usgs.gov/Resources/Research_Briefs/HIP.asp, accessed on 27 May 2009). The HIP process can be developed for a state (e.g., Massachusetts, Missouri, New Jersey, Pennsylvania, and Texas, are using HIP), but also can be applied at the stream reach level.

Objectives:

We used the Hydroecological Integrity Assessment Process (HIP) approach developed by the U. S. Geological Survey to assess environmental flows in Oklahoma's perennial streams. The HIP is a modeling tool that identifies 10 non-redundant hydrologic indices that are ecologically relevant, specific to stream classes, and characterize the five components of the natural flow regime. These components are the magnitude, timing, frequency, duration, and rate of change and predictability of flow events, plus the sequence of these conditions. Information derived from the HIP analysis will be used to make environmental flow recommendations for incorporation into the Oklahoma Comprehensive Water Plan and for future water permitting and planning.

The HIP is a process consisting of four development and two application steps (Figure 1). The objectives of this work were to complete the first 3 steps:

1. Obtain baseline data and identify appropriate streams for classification.
2. Calculate 171 hydrologic indices using the Hydrologic Index Tool (HIT).
3. Classify streams and identify the 10 primary flow indices.

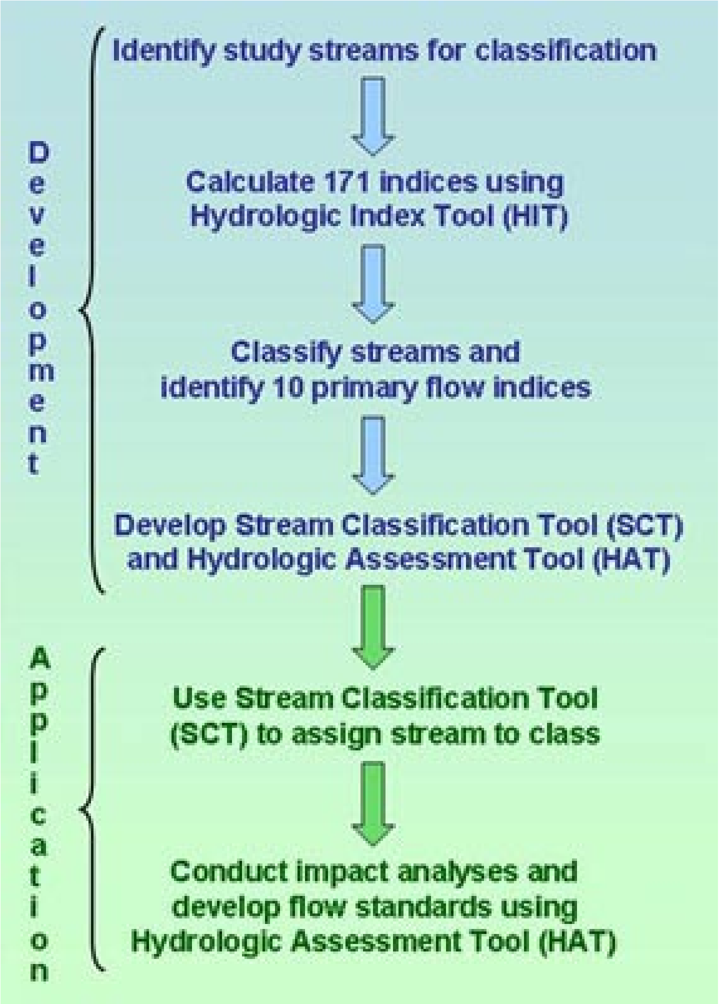


Figure 1. The development and application steps of the Hydroecological Integrity Assessment Process (HIP).

Methods and Results of HIP Development Steps 1,2 and 3

Step 1: Baseline Period of Record and the Identification of Streams for Classification

This section of the report was prepared by the U.S. Geological Survey

Ideally, a HIP classification suite should include long-term continuous streamflow record from the most natural state of streamflow available. This allows for the HIP classification to represent the most “natural” conditions of the basin which can be used as a hydrologic foundation for future assessment of ecological impairment with respect to anthropogenic alteration of the flow regime. Usage of the most natural (or least-altered) streamflow record in the HIP classification also reduces the likelihood that the records will be statistical outliers in the cluster analysis.

In addition to selecting streamflow data from a least-altered period, streamflow records need to be sufficient in length to ensure that typical variations in climate are observed during the selected period. Due to potentially limited gaging record and increasing development of the stream over time, the least-altered period of record for some gages may be relatively short. A sufficient record length would increase the probability that intra-annual variability of the daily hydrograph, which may be affected by recurrent climate cycles, is encompassed by the period chosen for classification. This pre-condition will help to minimize statistical bias and random error in the cluster analysis.

For each USGS streamflow-gaging station with continuous streamflow record selected for use in the HIP classification, a minimum optimal baseline period of record was determined. The baseline period of record can be defined as a period which is both “least altered” by anthropogenic activity and has sufficient record length to represent the extremes of climate variability. By this definition, there is a possibility for streams with continuous streamflow data not to have a period of record that could be considered baseline. For this study, if a streamflow-gaging station had data that either was substantially altered by human activity or did not have a minimum of 10 years of least-altered, then that record was either omitted from use in the HIP classification or downgraded in quality.

In Oklahoma, substantial streamflow alteration can be caused by a variety of human activities. Irrigation with both surface water and groundwater and other consumptive water uses are common throughout Oklahoma and represent the single largest use of water (Tortorelli 2002). Most irrigation water comes from groundwater, primarily from the High Plains aquifer in the panhandle as well as from other parts of western Oklahoma. Surface-water withdrawals, primarily used for consumptive water supply and livestock, are also common throughout the state. Many surface-water diversions in Oklahoma are withdrawn from reservoirs or other impoundments (Tortorelli 2002).

Flood peak reduction, from numerous flood-water retarding structures that serve to decrease main-stem flood peaks and regulate runoff recession of single storm events, also affects streamflow for large areas of Oklahoma (Tortorelli and Bergman 1985; Bergman and Huntzinger 1981).

Few if any streams in or near Oklahoma have been completely free of anthropogenic activity during the last century. Therefore, an allowable amount of anthropogenic alteration must be permitted in order to include sufficiently long-term record in the HIP classification. Long-term record is desired for the classification in order to provide a representative sample of streamflow during variable climate conditions. By accepting some alteration, the goal of the baseline period determination process is to select, for each gage, a sufficiently long period that is “least altered”. The selection of a least-altered period of record includes eliminating the period of streamflow data where the degree of alteration is substantially high and that the streamflow record is unacceptable for use in the HIP classification. The degree of anthropogenic alteration varies over time and over a spatial extent. Determining if a period is “natural” or “altered” may require some subjective judgement. In addition, the effects of anthropogenic activity in a stream basin may not occur over the course of one year, but may take many years. Examples would be increasing irrigation development over a period of time, construction of numerous small flood retarding structures in the stream basin, or gradual urban development in a watershed.

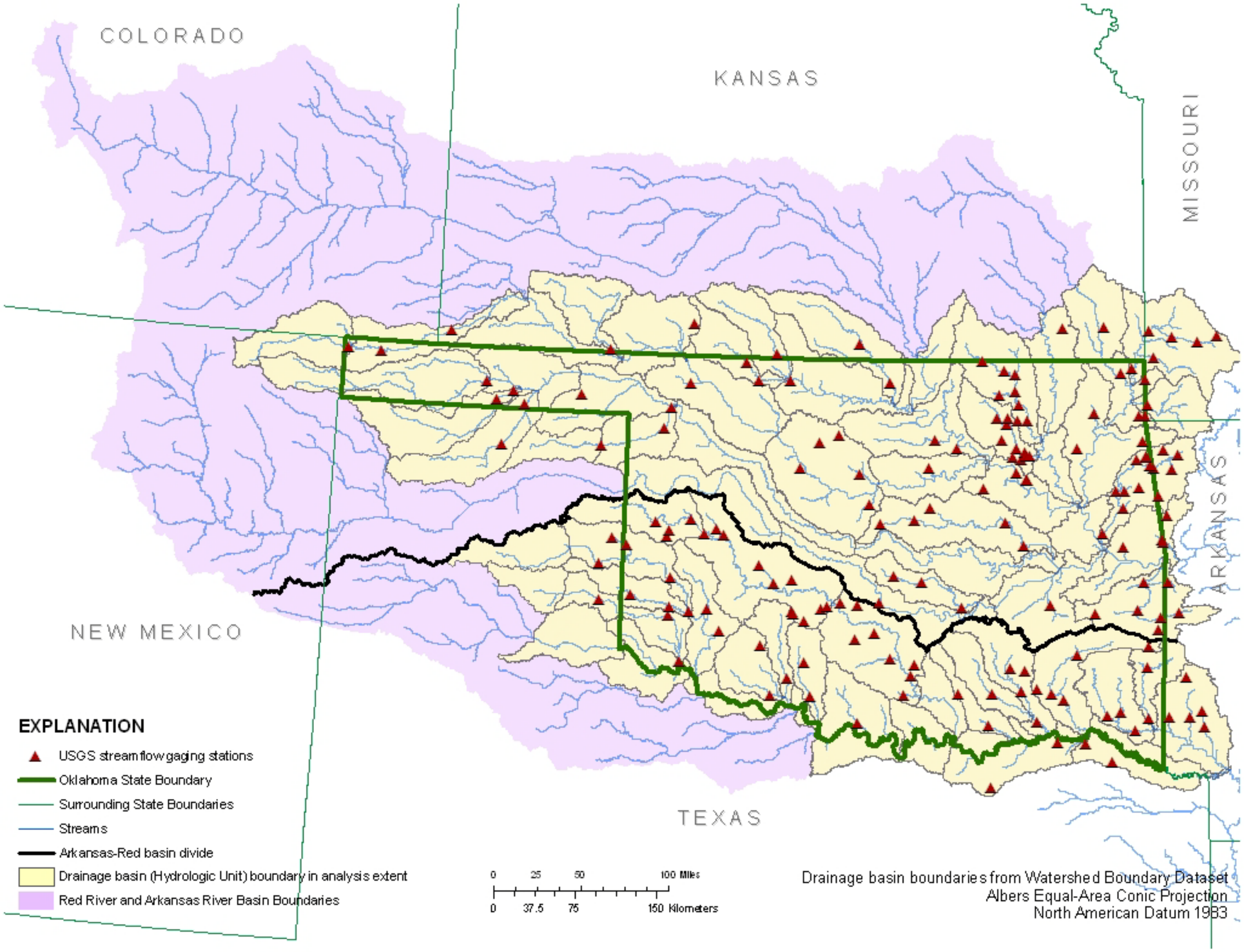
Streamflow data have been collected for streams in and near Oklahoma over periods ranging from a few years to nearly a century (U.S. Geological Survey National Water Information System, http://waterdata.usgs.gov/nwis, accessed June, 2008). Shorter periods of record may coincide with aberrant climate conditions and streamflow patterns that are not representative of typical conditions. Longer periods of record are more likely to provide a representative sample of central tendencies and variability of streamflow. However, as population increases and agricultural, industrial, and urban development increase in Oklahoma over the course of a century, longer periods of record and more recent periods of record are likely to contain streamflow data that are affected by human activity in the basin.

Based on the potential sources of subjectivity involved with selection of baseline periods for gages as described above, baseline periods of some gages may be more complete than others. Quality assurance and examination of outliers in the HIP classifications may require a qualitative assessment of the data used to develop the model. In order to reduce the subjectivity of selecting a baseline period and enable comparison of the baseline periods from one gage to another, a quality ranking was assigned to each baseline period. The terms in the quality ranking of the baseline period are “excellent”,” good”, “fair”, “poor”, or “unusable” and are based on the relative degree of anthropogenic activity, severity of climatic bias for the period with the least anthropogenic activity, and length of the record. The goal of the baseline analysis was to select a period for each stream that had the most favorable quality ranking based on these criteria. Streams where the period of record was determined to be “poor” or “unusable” were entirely omitted from use in the HIP classification.

Methods for Determining the Baseline Period of Record

Streamflow data from gaging stations with a minimum of 10 years of daily streamflow record, and a drainage area that is greater than 1 square mile but less than 2,600 square miles were considered for use in the HIP classification. A minimum period of record of 10 years was assumed to be an adequate minimum record length for determination of the least-altered period. This assumption was based on the use of 10 years of record for the New Jersey statewide HIP classification (Eraslew and Baker 2008 and Kennen et al. 2007). Drainage areas of streams selected for analysis were greater than 1 square mile and less than 2,600 square miles based on drainage area criteria used in previous statistical analysis studies (Tortorelli and Bergman 1985; Tortorelli 1997). Streamgages selected for analysis and contributing drainage area upstream from the streamgage were located within 8-digit hydrologic unit boundaries (based on the 8-digit hydrologic unit codes, or HUC) that were located at least partly in Oklahoma. There were 168 streamgages that met the criteria for analysis. Figure 2 shows the locations of gages that meet these criteria, and were initially included in baseline period determination process.

Streamflow data from substantially altered streams, or periods of streamflow record that were determined to be affected by human alteration, were removed from consideration from the HIP classification after a series of analysis procedures (Figure 1). After this elimination, if the gage did not have at least 10 years of remaining continuous period of record, the streamgage was eliminated from consideration for use in the HIP classification. The methods used to determine a baseline period of record were incorporated from visual and statistical procedures as well as professional judgment.



Drainage basin boundaries from Watershed Boundary Dataset
Albers Equal-Area Conic Projection
North American Datum 1983

Figure 2. USGS streamflow gaging stations, within a selected analysis extent, having 10 or more years of continuous daily streamflow record and a drainage area of less than 2,600 square miles.

Determination of the Least-Altered Period of Record

Determination of a baseline period was conducted in two phases. In the first phase, least-altered periods were selected for gages that had a minimum record length of 10 years. In the second phase, an optimum minimum period of record was determined for gages in each Climate Division (National Oceanic and Atmospheric Administration, 2008) to determine if 10 years of record sufficiently represented long-term climate variability.

In the first step of the process to determine the least-altered period of record, streamgage information was evaluated using previous publications, historical gage record notes, and information gathered from oral and written communication with data-collection staff familiar with selected gages. Known anthropogenic events in the basin were used to reduce the record to a least-altered period with a minimum of 10 years. If the least-altered period of record included streamflow that was affected by anthropogenic alteration, then the quality ranking was reduced accordingly.

In the second step of the determination of the least altered period, gages that had substantial effects from upstream impoundment were identified by evaluating the location and extent of dams in the drainage basin. Impounded areas were delineated using geographic information system (GIS) software in order to estimate the percent of impoundment in the basin, and how much that percentage changed over time. The percentage of the basin that was impounded was used to determine a preliminary quality ranking for the baseline period. If 20 percent or more of the drainage basin was affected by impoundment, it was eliminated from consideration.

In the third step of the determination of the least-altered period, statistical trend analysis was performed for selected streamgages with 20 or more years of record to detect statistically significant changes in baseflow, runoff, total flow, and baseflow index for selected gages where visual trends in the annual hydrograph were observed. Significant trends in streamflow were compared with trends in precipitation, using visual trend observation and analysis of covariance of double-mass curves, in order to determine if the trend was attributable to climate or possible anthropogenic affects. If trends were suspected to be due to anthropogenic affects and not trends in precipitation, an additional Kendall’s tau test was performed for selected datasets to determine if statistically significant trends existed for each of the annual flow parameters (Kendall and Gibbons 1990). If the preliminary baseline period determined from previous steps had a statistically significant trend in the annual hydrograph that was not attributable to climate changes, then the quality ranking was reduced to “poor”.

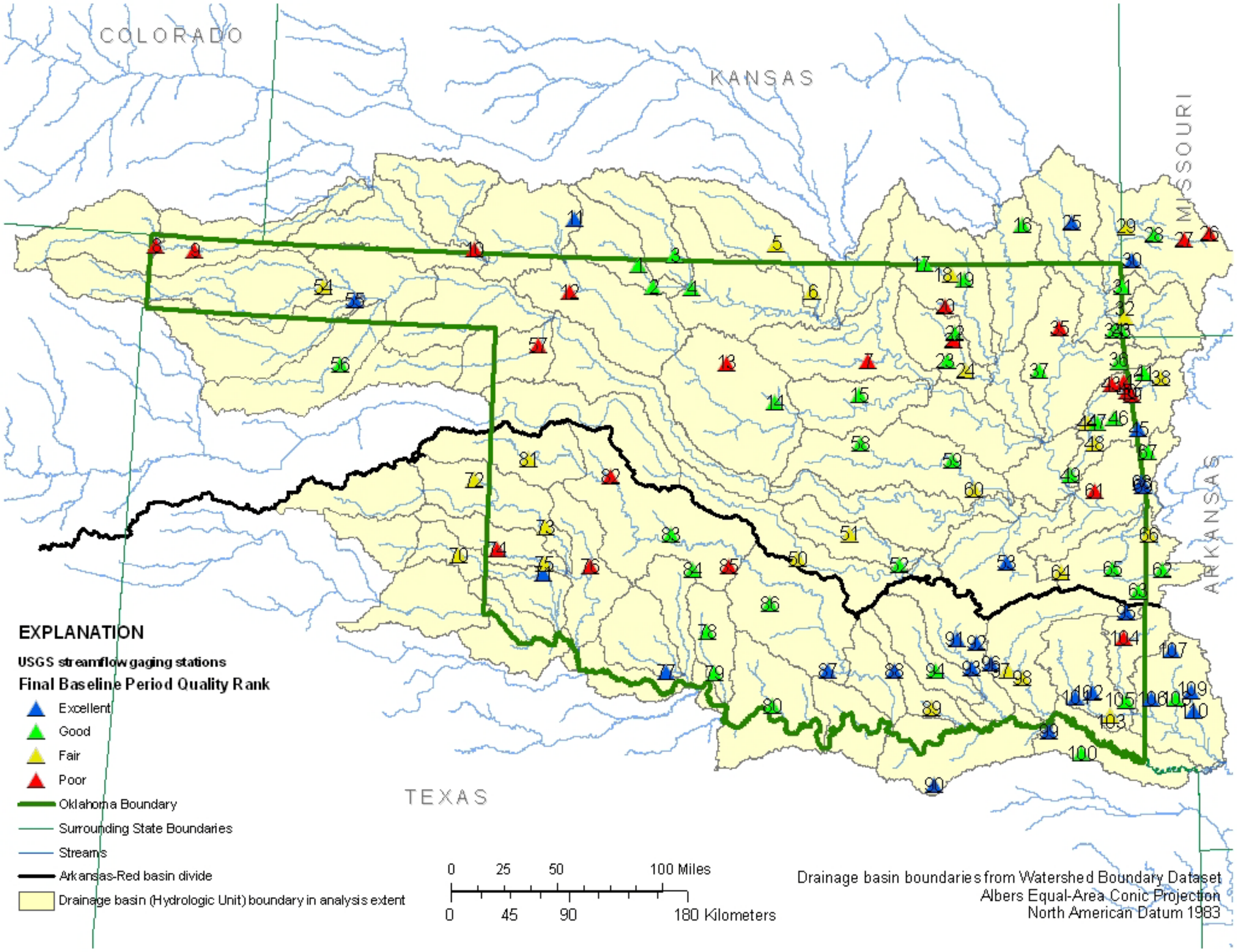
Determination of an Optimum Minimum Period of Record to Encompass Climate Variability

In the second phase, an optimum minimum period of record was determined for each of the least-altered periods to ensure that the selected period had a sufficient record length to provide a representative sample of the extremes of climate variability. An assumption was made in the previous phase that no less than 10 years should be considered for the baseline period. For each climate division that contained gages that were to be used in the HIP classification, an optimum minimum period of 10 years or more were evaluated by using a Wilcoxon rank-sum test. This test was used to analyze the variability of annual precipitation for selected 5-, 10-, 15-, 25-, and 35-year periods. The results from the test were used to determine how many years of annual precipitation were needed for the distribution of annual precipitation for the selected period to be statistically similar to the distribution of annual precipitation for a longer period, 1925-2007. This period was selected because it encompasses all of the years of streamflow record considered in the baseline analysis. In addition, this longer period was compared to the annual precipitation for the least-altered period to determine if the least-altered period was statistically representative of long-term climate variability. Results of the record-length analysis for each gage are listed in Table A.

For purposes of this study, the baseline period was the same as the least-altered period determined from previous steps because least-altered periods were not eliminated from use in the HIP classification if it did not contain an optimal minimum number of years as a result of the second phase of the analysis process. Instead, the quality ranking was reduced for these periods. If the preliminary baseline period determined from previous steps did not have an optimum minimum period of record or was statistically different from the period 1925-2007, the quality ranking was reduced accordingly. Eliminating gages from the HIP classification where the least-altered period of record was less than the optimum minimum period would substantially reduce the number of stations. Instead of eliminating gages from consideration where the least-altered period of record did not meet these criteria, the quality ranking was lowered by one level (for example a “fair” baseline period would be reduced to a “poor” baseline period). Therefore the difference between the baseline period and least-altered period are only due to the quality ranking and not the number of years.

Final Baseline Period of Record

A final baseline period was determined for each gaging station considered for use in the HIP classification. The baseline period for each station was rated as “excellent”, “good”, “fair”, “poor”, or “unusable” by combining the quality rankings determined for the degree of alteration in the basin for the least-altered period of record, and whether or not the least-altered period was long enough to likely be representative of long-term climate variability. The baseline period of record determined for each gage considered for use in the HIP classification, and the associated quality ranking of the baseline period, are presented in Table A and are shown in Figure 3. Gages that were removed from the list because they did not have an adequate baseline period (the baseline period was rated as “unusable”) are not listed in Table A or Figure 3.



Drainage basin boundaries from Watershed Boundary Dataset
Albers Equal-Area Conic Projection
North American Datum 1983

Figure 3. USGS streamflow gaging stations with a baseline period of record of 10 or more years, and the quality ranking of the baseline period for each gage.

Step 2: Calculation of 171 hydrologic indices using the Hydrologic Index Tool (HIT).

We used multivariate statistical analysis on streamflow statistics to describe the variability in the flow regime for reference conditions of Oklahoma rivers (Henriksen et al. 2006; Kennen et al. 2007; Olden and Poff 2003). Classification was completed using data from 88 USGS streamflow stations (Table 1) obtained from the baseline analysis described in the previous section (Table A). The stations were primarily located in Oklahoma (59), along with stations located in bordering states with flows that were relevant to Oklahoma: Kansas (6), Texas (6), Missouri (6), and Arkansas (11).

Flow Regime

Factors such as the quantity of water, the time of the year that high and low flows occur, and how often flow events happen are collectively referred to as the natural flow regime. This set of unique conditions is determined by many factors, such as geology, climate, and vegetation cover (Poff et al. 1997), and can be used to identify groups of streams with similar hydrologic behaviors. In addition to being useful for classification of streams, flow regime is important to biological organisms and the health of aquatic ecosystems, which have adapted over time to those conditions. Impacts to aquatic organisms from flow regime alteration can include the disruption of their life cycle (Scheidegger and Bain 1995), loss of connection and access to wetlands or backwaters (Junk et al. 1989), and change in plant cover types (Auble et al. 1994). Thus to protect ecosystems, the flow regime should be maintained or mimicked to support the natural cycles that species rely on.

The natural flow regime can be described with five categories that cover the natural hydrologic variation that is present in a stream (Poff et al. 1997). Magnitude is a measure of the quantity of water moving past a point per unit time. This category is divided into magnitudes of average (MA), low (ML), and high (MH) flows. Frequency describes how often specified low (FL) and high (FH) flow events occur. Duration describes the length of time that low (DL) and high (DH) flow events occur. Both the frequency and duration categories deal with low (e.g. no flow days) and flood flow events. Timing describes the dates that average (TA), low (TL), and high (TH) flow events occur. The rate of change (RA) describes the rise or fall in streamflow. Streams with high or rapid rate of change can indicate they are “flashy,” while low rates may indicate that a stream has “stable” streamflow.

Software

We used the Hydrologic Index Tool (HIT, Version 1.48; USGS, Fort Collins, CO; http://www.fort.usgs.gov/Products/Software/NATHAT/hitinst.exe) software to calculate indices from all five classes of streamflow. The HIT software calculates a total of 171 indices (Henriksen et al. 2006; Olden and Poff 2003) with 94 describing magnitude, 14 describing frequency, 44 describing duration, 10 describing timing, and 9 describing rate

Table 1: Site code, station ID, and station name of 88 USGS streamflow stations used to classify Oklahoma streams.

Site Code	Station ID	Station Name
CAVC	07157900	Cavalry Creek at Coldwater, KS
LGHT	07184000	Lightning Creek near McCune, KS
SHOL	07187000	Shoal Creek above Joplin, MO
BRND	07196900	Baron Fork at Dutch Mills, AR
GAIN	07232000	Gaines Creek near Krebs, OK
COLD	07233000	Coldwater Creek near Hardesty, OK
LEES	07249985	Lee Creek near Short, OK
LEEV	07250000	Lee Creek near Van Buren, AR
STRM	07300500	Salt Fork Red River at Mangum, OK
DFCK	07311500	Deep Red Creek near Randlett, OK
CADO	07330500	Caddo Creek near Ardmore, OK
BLUM	07332400	Blue River at Milburn, OK
BDRC	07332600	Bois D'Arc Creek near Randolph, TX
CHCS	07333500	Chickasaw Creek near Stringtown, OK
MCGE	07333800	McGee Creek near Stringtown, OK
MBOG	07334000	Muddy Boggy Creek near Farris, OK
KIAC	07335700	Kiamichi River near Big Cedar, OK
TENM	07336000	Tenmile Creek near Miller, OK
LPIN	07336750	Little Pine Creek near Kanawha, TX
LTRW	07337500	Little River near Wright City, OK
GLOV	07337900	Glover River near Glover, OK
ROLL	07339500	Rolling Fork near DeQueen, AR
COSV	07340300	Cossatot River near Vandervoort, AR
SALD	07341000	Saline River near Dierks, AR
SALL	07341200	Saline River near Lockesburg, AR
SLTW	07148350	Salt Fork Arkansas River near Winchester, OK
SLTA	07148400	Salt Fork Arkansas River near Alva, OK
MEDL	07149000	Medicine Lodge River near Kiowa, KS
SLTC	07149500	Salt Fork Arkansas River near Cherokee, OK
SKEL	07160500	Skeleton Creek near Lovell, OK
CNCL	07163000	Council Creek near Stillwater, OK
BHIL	07170700	Big Hill Creek near Cherryvale, KS
CNYE	07172000	Caney River near Elgin, KS
LCAN	07174200	Little Caney River below Cotton Creek, near Copan, OK
CNDY	07176800	Candy Creek near Wolco, OK
HMNY	07177000	Hominy Creek near Skiatook, OK

Table 1, continued.

Site Code	Station ID	Station Name
SPRC	07185765	Spring River at Carthage, MO
LOST	07188500	Lost Creek at Seneca, MO
CVSP	07189540	Cave Springs Branch near South West City, MO
HONY	07189542	Honey Creek near South West City, MO
SPAV	07191220	Spavinaw Creek near Sycamore, OK
PRYR	07192000	Pryor Creek near Pryor, OK
FLTS	07195800	Flint Creek at Springtown, AR
PECH	07196973	Peacheater Creek at Christie, OK
BRNE	07197000	Baron Fork at Eldon, OK
ILRG	07198000	Illinois River near Gore, OK
LTRS	07231000	Little River near Sasakwa, OK
PALO	07233500	Palo Duro Creek near Spearman, TX
DRYC	07243000	Dry Creek near Kendrick, OK
DFKB	07243500	Deep Fork near Beggs, OK
POTC	07247000	Poteau River at Cauthron, AR
BLFK	07247250	Black Fork below Big Creek near Page, OK
POTW	07248500	Poteau River near Wister, OK
COVE	07249500	Cove Creek near Lee Creek, AR
LBEA	07313000	Little Beaver Creek near Duncan, OK
BVCK	07313500	Beaver Creek near Waurika, OK
MUDC	07315700	Mud Creek near Courtney, OK
COBB	07326000	Cobb Creek near Fort Cobb, OK
LWSC	073274406	Little Washita River above SCS Pond No 26 near Cyril,OK
RUSH	07329000	Rush Creek at Purdy, OK
CBOG	07335000	Clear Boggy Creek near Caney, OK
PCAN	07336800	Pecan Bayou near Clarksville, TX
MTNE	07339000	Mountain Fork near Eagletown, OK
COSD	07340500	Cossatot River near DeQueen, AR
CHCC	07151500	Chickaskia River near Corbin, KS
CHCB	07152000	Chickaskia River near Blackwell, OK
CNYH	07173000	Caney River near Hulah, OK
BRDS	07177500	Bird Creek near Sperry, OK
SPRW	07186000	Spring River near Waco, MO
ELKR	07189000	Elk River near Tiff City, MO
OSAG	07195000	Osage Creek near Elm Springs, AR
ILRT	07196500	Illinois River near Tahlequah, OK
CNYC	07197360	Caney Creek near Barber, OK

Table 1, continued.

Site Code	Station ID	Station Name
WNUT	07229300	Walnut Creek at Purcell, OK
BVRV	07232500	Beaver River near Guymon, OK
DFKD	07244000	Deep Fork near Dewar, OK
FOMA	07247500	Fourche Maline near Red Oak, OK
JMSF	07249400	James Fork near Hackett, AR
STRW	07300000	Salt Fork Red River near Wellington, TX
SWET	07301410	Sweetwater Creek near Kelton, TX
NFRR	07301500	North Fork Red River near Carter, OK
ELMM	07303500	Elm Fork of North Fork Red River near Mangum, OK
WASC	07316500	Washita River near Cheyenne, OK
BLUB	07332500	Blue River near Blue, OK
KIAA	07336200	Kiamichi River near Antlers, OK
KIAB	07336500	Kiamichi River near Belzoni, OK
LTRI	07338500	Little River below Lukfata Creek, near Idabel, OK

of change of streamflow. Categories with many indices, such as magnitude, had sets indices that were calculated for individual months (e.g. January mean flow, May mean minimum flow), and this resulted in many indices in those categories.

We used data from a reference period recorded at USGS streamflow stations. The analysis used two types of data: daily average flows (mean flow in 24 hours in ft^3/second), and peak flow (instantaneous ft3/sec) data for each gage, which were required for the calculation of six indices. The length of reference period used in the analysis for all stations had a median length of 22 years and ranged from a minimum of 10 to a maximum of 83 years. A set of eleven indices were not able to be calculated for all 88 stations. This was a result of an error in calculation of indices for some sites due to a zero in denominator of the index equation. Ten of the indices had too many zero flow days in their record (MA6, MA7, MA8, ML18, ML21, FL2, DL6, DL7, DL8, DL17), while one had no zero flow days (DL19). After exclusion of the indices, the available dataset was reduced from 171 to 160, but all five components of flow regime were still represented.

Step 3: Classification of streams and identification the 10 primary flow indices

Data Screening and Standardization

We used the two step process called the Hydroecological Integrity Assessment Process (HIP) for classification of streams based on flow regime from hydrological indices (Henriksen et al. 2006; Kennen et al. 2007; Olden and Poff 2003). The first step uses principal component analysis (PCA) to reduce redundancy in the 171 indices and select hydrologic indices that explain the most variation. The selected indices were then used in the second step in a cluster analysis to classify and group streamflow-gage stations based on similarity between flow regime.

Data standardization was required because the indices used different units (e.g. ft^3/second, percent), which can affect the results from the cluster analysis (McGarigal et al. 2000). The standardization procedure we selected was the z-score method, which normalized each column (i.e. hydrologic indices) to have a mean of zero and a standard deviation of one (McCune and Grace 2002). An outlier analysis was also conducted using PC-ORD to remove the confounding influence of multivariate outliers on the principal components analysis and cluster analysis (McCune and Grace 2002). Outliers were defined as indices more than two standard deviations from the mean. The analysis found three indices that were classified as outliers (ML20, FL01, RA08), although they were only slightly over the two standard deviation threshold (2.1, 2.0, and 2.1 respectively). Outliers were flagged and excluded from later analyses. The outliers were not identified as high information variables in the principal components analysis, so no unique information was lost with their exclusion.

Principal Components Analysis

We used principal components analysis (PCA) to identify the hydrologic indices that contained the most information about the flow regime across the region. PCA is an eigenvector method of ordination that is used to reduce a large datasets into a smaller number of synthetic variables that describe the maximum amount of variation in the dataset (McGarigal et al. 2000). The reduced dataset of high information variables can then be used to characterize the flow regime of the selected streams. Variables with high eigenvector values on a principal component (i.e. have high score) contribute more information about the variation in the data than variables with near zero scores. This allows for the heaviest loading variable to be used to explain the ordination of the sites (McGarigal et al. 2000).

We used a PCA on a correlation matrix (PC-ORD) to ordinate 88 stations and 160 hydrologic indices. The first two principal components explain over 50% of the total variation in the dataset. A site's location on the PCA plot represents the centroid of all the hydrologic variables for that site on each plotted principal component (PC; Figure 4a). Stations like SPRC and BRNE both are found on the far left negative end of the first axis, but they do not have high scores on the second axis. The opposite is true for stations like GLOV and MBOG, which have low scores on the first axis but high scores on the second axis. The PCA also produced eigenvectors for the hydrologic indices for each principal component (Figure 4b). Indices with high loadings on an axis indicate that the index is explaining a larger amount of variation (e.g. high positive on PC1 MA3 in Figure 4b) in the dataset than index scores that are near zero (e.g. DH23 in Figure4b). Both the lower left and lower right quadrants of the graph have large groups of indices with high loadings on one or both of the first two principal components.

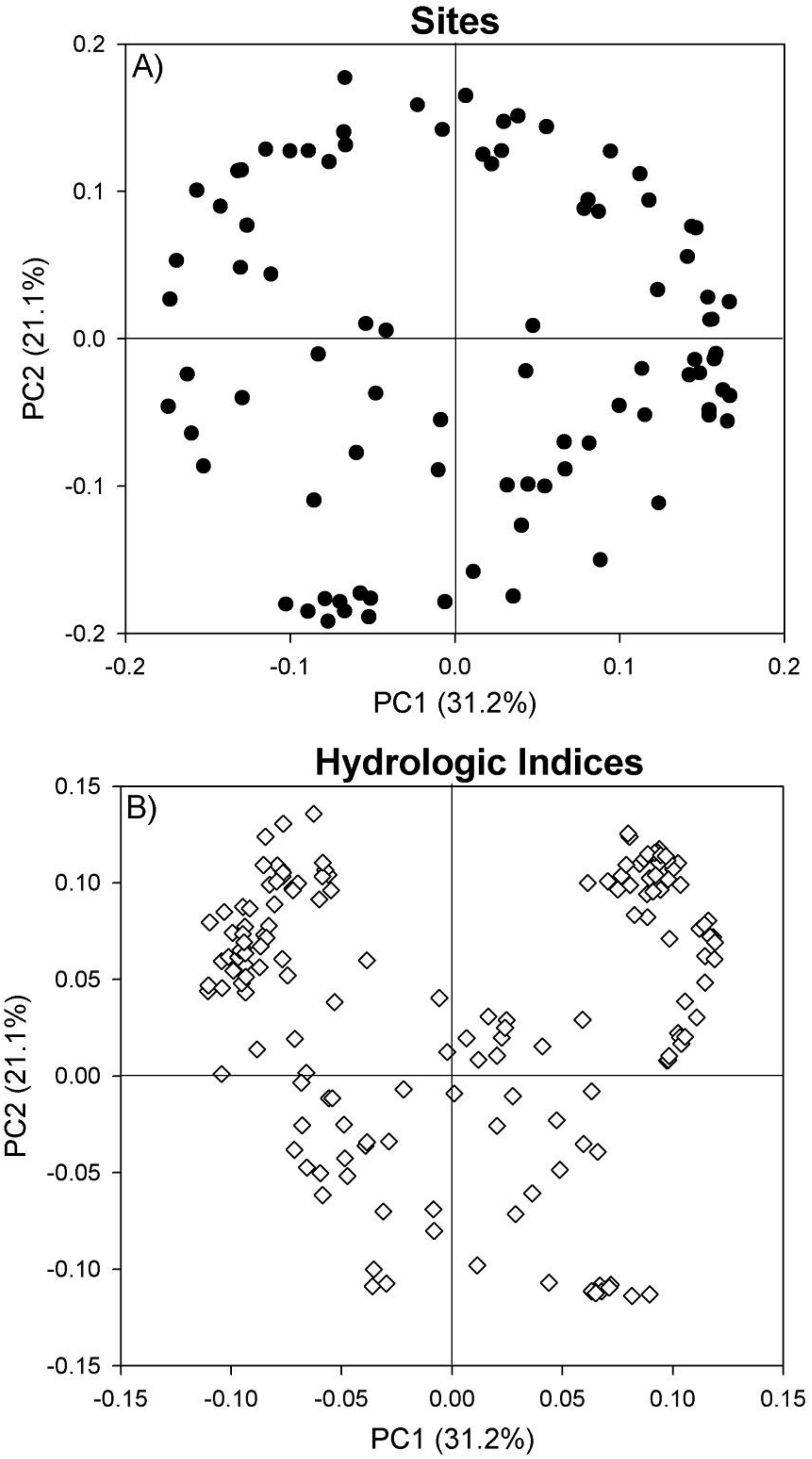
We used the first six principal components as the source for the selection of high information indices. The first two axes explain 52.2% of the variation in the dataset (Table 2). The total variation explained by the first six principal components was 77% (Table 2). We identified the first six principal components as important axes using the brokenstick eigenvalues. Brokenstick eigenvalues are an estimation of the eigenvalues that would be expected from the PCA by chance alone (Jolliffe 1972; King and Jackson 1999). Thus, when the actual eigenvalues are higher than brokenstick eigenvalues, then the patterns observed in the PCA are not random. The first six PC had higher real eigenvalues than brokenstick values and could be used in the selection of the most important hydrologic indices for describing Oklahoma streams (Table 2).

Table 2: Eigenvalues, percent variance explained, cumulative percent variance, and broken-stick eigenvalues for the first six principal components from the principal components analysis of 160 hydrologic indices and 88 stream gages.

Axis	Eigenvalue	Percent Variance	Cumulative Percent Variance	Broken-stick Eigenvalue
1	49.9	31.2	31.2	5.7
2	33.7	21.1	52.2	4.7
3	15.4	9.6	61.8	4.2
4	12.6	7.9	69.7	3.8
5	6.8	4.3	74.0	3.6
6	4.9	3.0	77.0	3.4

The process of index selection seeks to identify indices that contain the maximum amount of information about the flow regime, while removing redundant indices that are highly correlated with each other. One target in the reduction of the number of variables to maintain a 3:1 ratio of sites to indices for the cluster analysis (McGarigal et al. 2000). Based on the number of sites in the dataset (88), we used the target number of 29 hydrologic indices for selection into the cluster analysis. Another guideline was that the selected variables would include each of the ten components of the flow category, in order to include a picture of the entire flow regime in the classification process.

Figure 4: Principal components analysis plots. (A) site scores of streamflow stations and (B) eigenvectors of hydrologic indices for the first and second principal components. Percentages indicate proportion of total variation in dataset that is explained by each principal component.



We selected indices on the first six principal components that were within 15% of the highest absolute loading on each axis. This criterion reduced the total number of variables from 160 to 55. The 55 remaining indices were considered to contain a high amount of information that would be useful for classification of the stations (Table 3). In order to reduce the redundancy between the selected indices, we used a nonparametric correlation analysis (Spearman rho) for indices within each flow category. Indices that were highly correlated (e.g. May and June mean flows) were identified and the least correlated (i.e. most non-redundant) hydrologic indices were selected to be included in the classification portion of the analysis. The subset of 55 variables was further reduced to 27 indices, which was near our target of 29 variables for the 3:1 ratio (Table 4). The five flow components are represented in this set of variables with 8 describing magnitude (3 average magnitude, 2 low magnitude, and 3 high magnitude), 4 describing frequency (1 low flow frequency and 3 high flow frequency), 9 describing duration (3 low flow duration and 6 high flow duration), 3 describing timing (1 in timing of average, low, and high flows), and 3 describing rate of change (Table 4). With this set of variables, we can represent the natural flow regime at the stations and group them based on similarities in streamflow patterns.

Table 3: Eigenvector loading on the first six principal components for the 27 hydrologic indices used to classify Oklahoma streams. Bold indicate the principal component was selected from.

	Eigenvector on Principal Component					
	1	**2**	**3**	**4**	**5**	**6**
MA01	**-0.1023**	-0.1104	-0.0178	-0.0466	0.0104	0.0437
MA04	0.0845	**-0.1239**	-0.0105	-0.0053	-0.0052	0.0342
MA28	**0.1043**	-0.0596	0.0291	-0.0770	-0.0979	-0.1007
ML01	**-0.1119**	-0.0764	-0.0392	-0.0151	-0.0169	-0.0798
ML09	**-0.1039**	-0.0167	-0.1226	0.0055	-0.0532	-0.1487
MH04	-0.0918	**-0.1157**	-0.0025	-0.0454	0.0169	0.0504
MH14	**0.1012**	-0.0617	-0.0895	0.0043	-0.0853	0.0208
MH20	-0.0224	-0.0199	-0.0096	0.0838	-0.0275	**-0.1808**
FL03	**0.1032**	-0.0850	0.0084	-0.0914	-0.0105	-0.0116
FH01	0.0533	-0.0383	0.1126	-0.1385	**-0.1875**	-0.0603
FH04	0.0764	**-0.1307**	-0.0117	0.0472	0.0066	0.0590
FH05	0.0392	0.0360	0.0457	**-0.1871**	-0.2018	0.0487
DL03	-0.0984	-0.0104	-0.1276	0.0129	-0.0666	**-0.1606**
DL05	**-0.1191**	-0.0693	-0.0655	-0.0258	-0.0312	-0.0612
DL18	**0.1041**	-0.0456	-0.0698	0.0023	0.0275	-0.1287
DH02	-0.0937	**-0.1175**	-0.0175	-0.0634	0.0092	0.0581
DH07	0.0474	0.0517	**-0.1512**	-0.1307	0.0636	-0.0131
DH10	0.0678	0.0254	-0.1121	**-0.1646**	0.0997	-0.0216
DH15	-0.0632	0.0079	-0.0566	**0.1627**	0.1177	0.0524
DH21	-0.0119	-0.0085	-0.0777	0.1016	**0.2081**	0.0192
DH23	-0.0164	-0.0309	-0.0516	-0.0595	0.1116	**0.1778**
TA01	-0.0661	0.0391	**-0.1504**	0.0121	-0.1354	-0.0533
TL01	-0.0247	-0.0290	**-0.1030**	0.0737	0.0331	0.0289
TH01	0.0385	0.0342	-0.1024	**-0.1718**	0.0862	0.0494
RA03	-0.0797	**-0.1256**	0.0215	-0.0657	0.0128	0.0725
RA05	-0.0488	0.0485	0.0130	-0.1388	-0.1305	**0.1567**
RA07	**0.1097**	-0.0797	-0.0244	-0.0403	-0.0630	-0.0568

Table 4: Names and definitions of the 27 hydrologic indices used to classify Oklahoma streamflows grouped primarily by flow category.

Code	Hydrologic Index	Units	Definition
	Magnitude		
MA01	Mean daily flows	ft^3/second	Mean daily flows
MA04	Variability in daily flows 2	Percent	Coefficient of variation of the logs in daily flows corresponding to the {5th, 10th, 15th, . . . , 85th, 90th 95th} percentiles
MA28	Variability in May flows	Percent	Coefficient of variation in monthly flows for May
ML01	Mean minimum January flows	ft^3/second	Mean minimum monthly flow for January
ML09	Mean minimum September flows	ft^3/second	Mean minimum monthly flow for September
MH04	Mean maximum April flows	ft^3/second	Mean of the maximum monthly flows for April
MH14	Median of annual maximum flows	Dimensionless	Median of the highest annual daily flow divided by the median annual daily flow averaged across all years
MH20	Specific mean annual maximum flows	ft^3/second /$mile^2$	Mean annual maximum flows divided by catchment area
	Frequency		
FL03	Frequency of low flow spells	Events per year	Total number of low flow spells (threshold equal to 5% of mean daily flow) divided by the record length in years
FH01	High flood pulse count 1	Events per year	Mean number of high pulse events, where the 75th percentile is the high pulse threshold
FH04	High flood pulse count 2	Days per year	Mean number of days per year above the upper threshold (defined as 7 times median daily flow), and the value is represented as an average instead of a tabulated count
FH05	Flood frequency 1	Events per year	Mean number of high flow events per year using an upper threshold of 1 times median flow over all years
	Duration		
DL03	Annual minima of 7-day means of daily discharge	ft^3/second	Magnitude of minimum annual flow of 7-day mean daily discharge
DL05	Annual minima of 90-day means of daily discharge	ft^3/second	Magnitude of minimum annual flow of 90-day mean daily discharge

Table 4, continued.

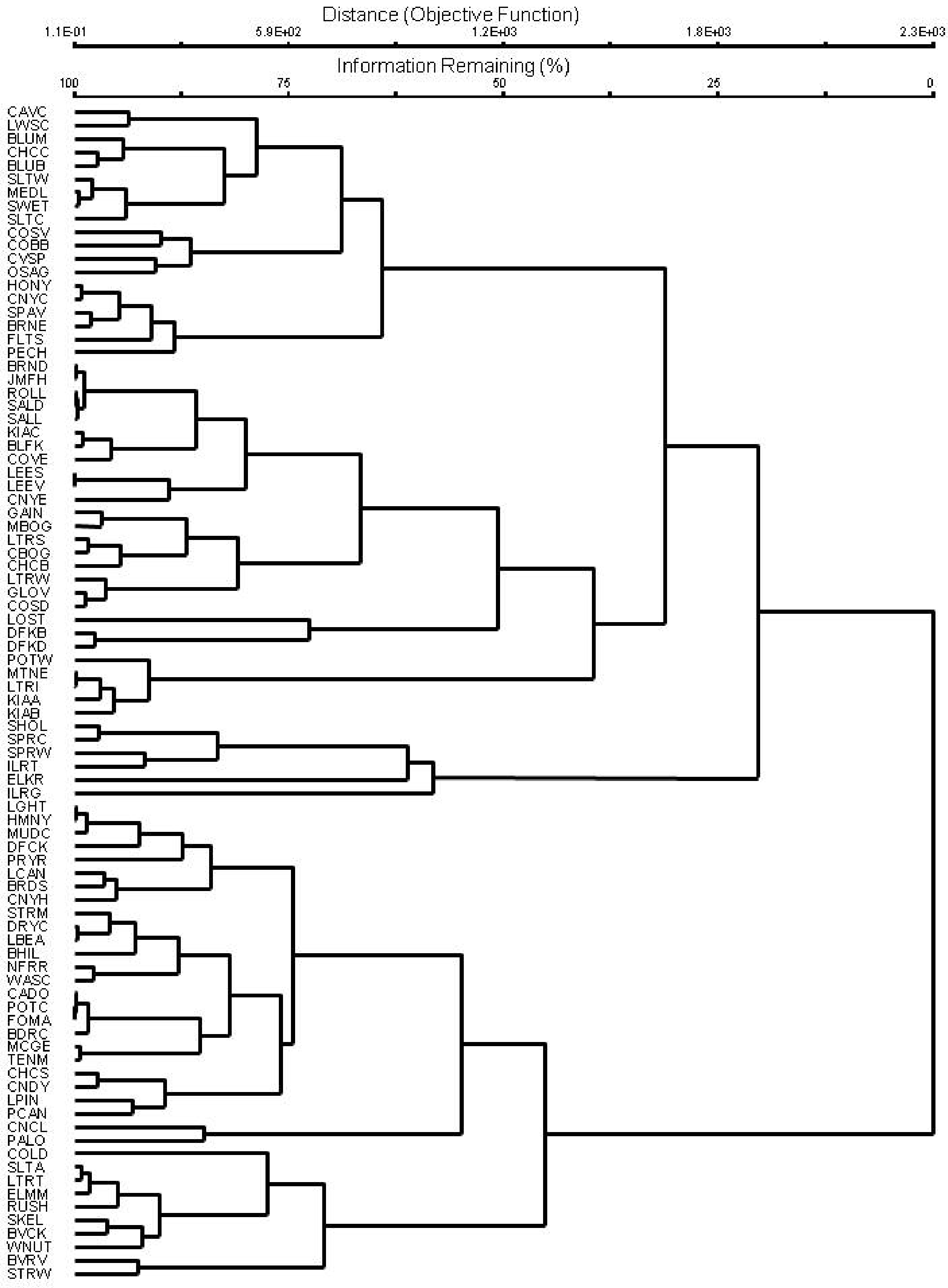
Code	Hydrologic Index	Units	Definition
DL18	Number of zero-flow days	Days per year	Mean annual number of days having zero daily flow
DH07	Variability in annual maxima of 3-day means of daily discharge	Percent	Coefficient of variation in the 3-day moving average flows
DH10	Variability in annual maxima of 90-day means of daily discharge	Percent	Coefficient of variation in the 90-day moving average flows
DH15	High flow pulse duration	Days per year	Mean duration of FH1 (high flood pulse count 1)
DH21	High flow duration 2	Days	Average duration of flow events with flows above a threshold equal to the 25th percentile value for the entire set of flows
DH23	Flood duration 2	Days	Mean annual number of days that flows remain above the flood threshold averaged across all years
	Timing		
TA01	Constancy	Dimensionless	See Colwell (1974)
TL01	Julian date of annual minimum	Julian day	The mean Julian date of the 1-day annual minimum flow over all years
TH01	Julian date of annual maximum	Julian day	The mean Julian date of the 1-day annual maximum flow over all years
	Rate of Change		
RA03	Fall rate	ft^3/second /day	Mean rate of negative changes in flow from one day to the next
RA05	No day rises	Dimensionless	Ratio of days where the flow is higher than the previous day
RA07	Change of flow	ft^3/second /day	Median of difference between natural logarithm of flows between two consecutive days with decreasing flow

Cluster Analysis (CLA)

Cluster analysis is a multivariate statistical method that can be used to identify patterns between many sites using many variables. This study uses a polythetic agglomerative hierarchical clustering that first calculates a dissimilarity matrix with sites and indices. Then, a clustering algorithm is used to group the most similar sites together. In this study, we used Euclidean distance as the measure of dissimilarity and Ward's method (Ward 1963) for the clustering algorithm. This method produced clusters that we were able to classify the stations in a useful and interpretable fashion. The length of the lines on the dendrogram that connect any two stations or groups of stations, indicate the relative similarity of the streamflow, where shorter lines are more similar (CAVC to LWSC) and longer lines are less similar (CAVC to STRW; Figure 5). The selection of clusters was done at levels of information remaining that were the most interpretable for the study. We can divide the cluster dendrogram (Figure 5) in different places to create many combinations of group numbers. The distance function on the top of the graph is measure of the amount of information remaining while the clustering process is being complete (Figure 5; McCune and Grace 2002). The most useful groups produced two clusters at 20% of information remaining, four clusters at 45% of information remaining, and six clusters at 54% of information remaining. These three classification schemes are discussed in the following sections.

We used two nonparametric tests to determine significant differences between the groups identified by the cluster analysis. The Mann-Whitney test was used to compare pairs of groups (i.e. 2 cluster group) and the Kruskal-Wallis with a post-hoc test was used for multiple groups (i.e. 4 cluster group). The Kruskal-Wallis test is similar to the commonly used analysis of variance (ANOVA), but is nonparametric and compares the rank of data in a group rather than actual values (Conover 1999). While the Kruskal-Wallis test can be used to determine if any significant differences were present between the groups. The post-hoc test was used to find the groups that differed between each other, which is similar to the Tukey-Kramer post-hoc test (Conover 1999). The small size of some groups in the 6 cluster classification made statistical analysis not as powerful to compare all the groups, but we did use the Mann-Whitney test to differences in pairs of interest.

Figure 5: Cluster analysis dendrogram made by using Euclidian distance measure and Ward's method for classification of 88 streams in Oklahoma. Station codes are shown in Table 1.



Two-Cluster Classification

The two cluster classification (Figure 6) has a larger cluster (21) with 52 stations and a smaller cluster (22) with 36 stations. The distribution of the sites from both groups are mixed together throughout the region and there is not a clear geographic pattern (Figure 7), although there does appear to be more stations from group 21 in the eastern part of the area. The only stations in the panhandles of Oklahoma and Texas are from group 22, and this area is not well represented in the number of available stations in the analysis.

Statistical analyses with the Mann-Whitney test found that all but 5 indices (MH20, DH21, DH23, TL01, and RA03) were significantly different between groups (Table 5). The stations in group 21 had higher mean flow (MA01) with higher flow during low flow periods (ML01, ML09; Figure 8). The stations in group 22 had more flood events (FH01, FH04, FH05), more days with zero flow (DL18), and more variable flows (TA01; Figure 8).

The cluster analysis shows that 21 had higher flows that were more stable (i.e. perennial streams). The stations in group 22 had lower low flows that stay low for longer and even long periods of zero flows (i.e. intermittent streams). Group 22 also had a greater number of high flow pulses compared to group 21. In general, the streams of group 21 are perennial streams with stable flow, while the streams of group 22 are more intermittent and flashy (Figure 8).

Table 5: Mean and standard deviation for two cluster classification using 27 hydrologic indices. Significant differences (α = 0.05) between groups was tested with the Mann-Whitney test and are indicated by different letters.

Index	**Unit**	**21**			**22**		
		Mean	**SD**		**Mean**	**SD**	
MA01	ft^3/second	482.7	507.2	a	115.6	98.9	b
MA04	Percent	140.0	44.7	a	206.0	45.5	b
MA28	Percent	119.2	34.9	a	209.8	34.2	b
ML01	ft^3/second	109.9	133.0	a	10.4	8.6	b
ML09	ft^3/second	26.9	42.5	a	2.2	2.6	b
MH04	ft^3/second	4671.0	4870.3	a	1604.6	1733.6	b
MH14	Dimensionless	93.5	65.6	a	489.3	333.0	b
MH20	ft^3/second/mile^2	34.0	58.3		24.6	17.3	
FL03	Events per year	3.4	2.6	a	8.3	2.1	b
FH01	Events per year	2.5	10.2	a	1.8	12.6	b
FH04	Days per year	36.6	21.4	a	62.7	25.8	b
FH05	Events per year	8.4	2.3	a	10.2	3.0	b
DL03	ft^3/second	18.3	34.4	a	0.9	1.4	b
DL05	ft^3/second	73.6	76.2	a	12.1	10.2	b
DL18	Days per year	8.5	12.5	a	57.4	39.7	b
DH02	ft^3/second	8315.0	8491.9	a	3289.0	2570.6	b
DH07	Percent	67.9	17.6	a	84.5	27.4	b
DH10	Percent	57.3	15.5	a	79.2	19.4	b
DH15	Days per year	8.4	2.3	a	6.2	1.4	b
DH21	Days	85.0	28.0		80.3	25.4	
DH23	Days	2.3	1.3		2.3	0.8	
TA01	Dimensionless	0.35	0.11	a	0.28	0.06	b
TL01	Julian day	257.9	11.8		253.8	15.2	
TH01	Julian day	114.5	47.2	a	147.8	36.1	b
RA03	ft^3/second /day	168.1	156.4		92.1	61.8	
RA05	Dimensionless	0.23	0.04	a	0.22	0.04	b
RA07	ft^3/second/day	0.12	0.05	a	0.24	0.08	b

Figure 6: Cluster analysis dendrogram (Euclidean distance and Ward's method) showing two cluster classification of 88 Oklahoma streamflow stations. Station codes are shown in Table 1.

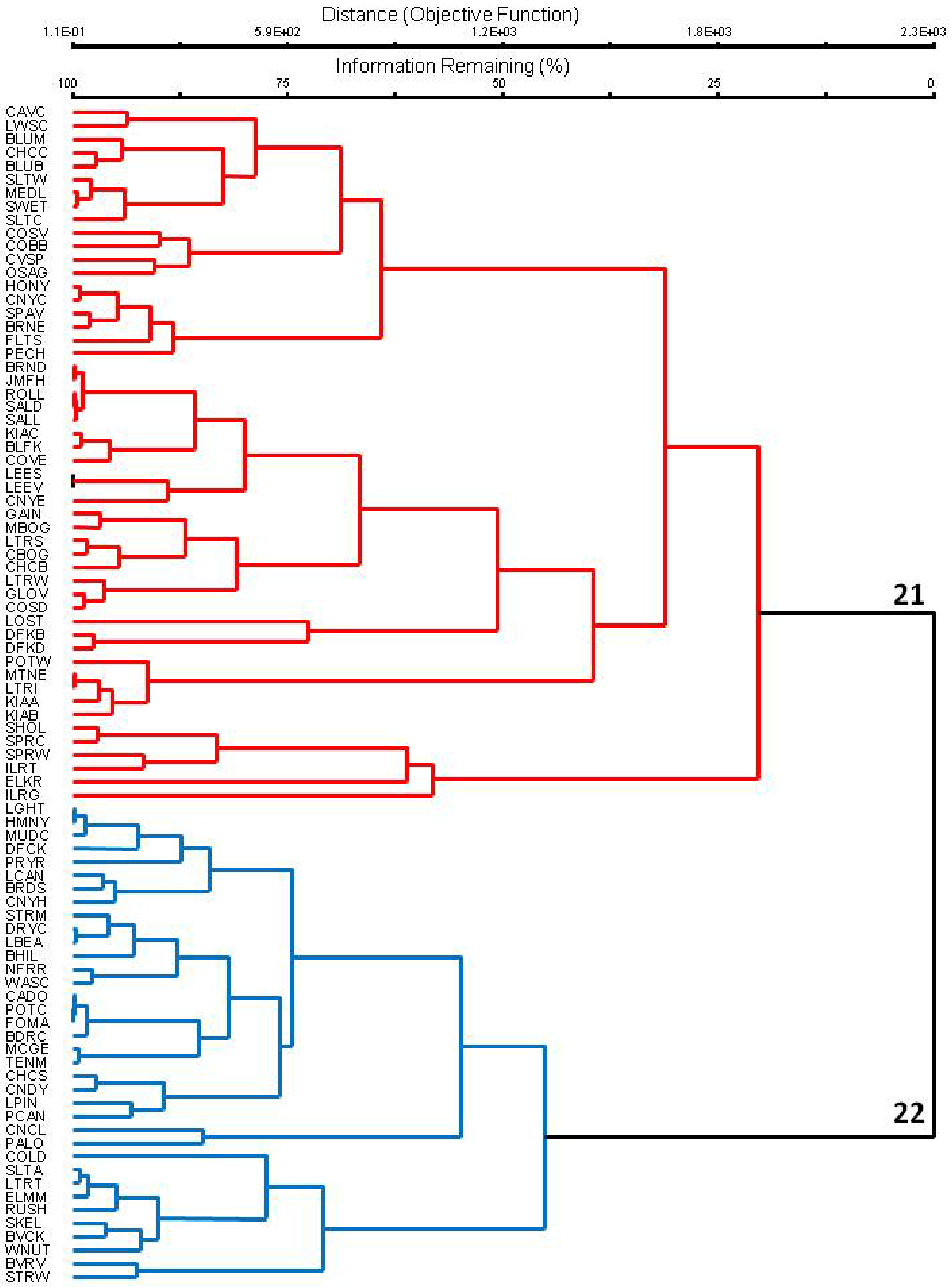


Figure 7: Map of 88 streamflow station in Oklahoma classified by two group cluster analysis. Red triangles are members of group 21 and blue circles are members of group 22.

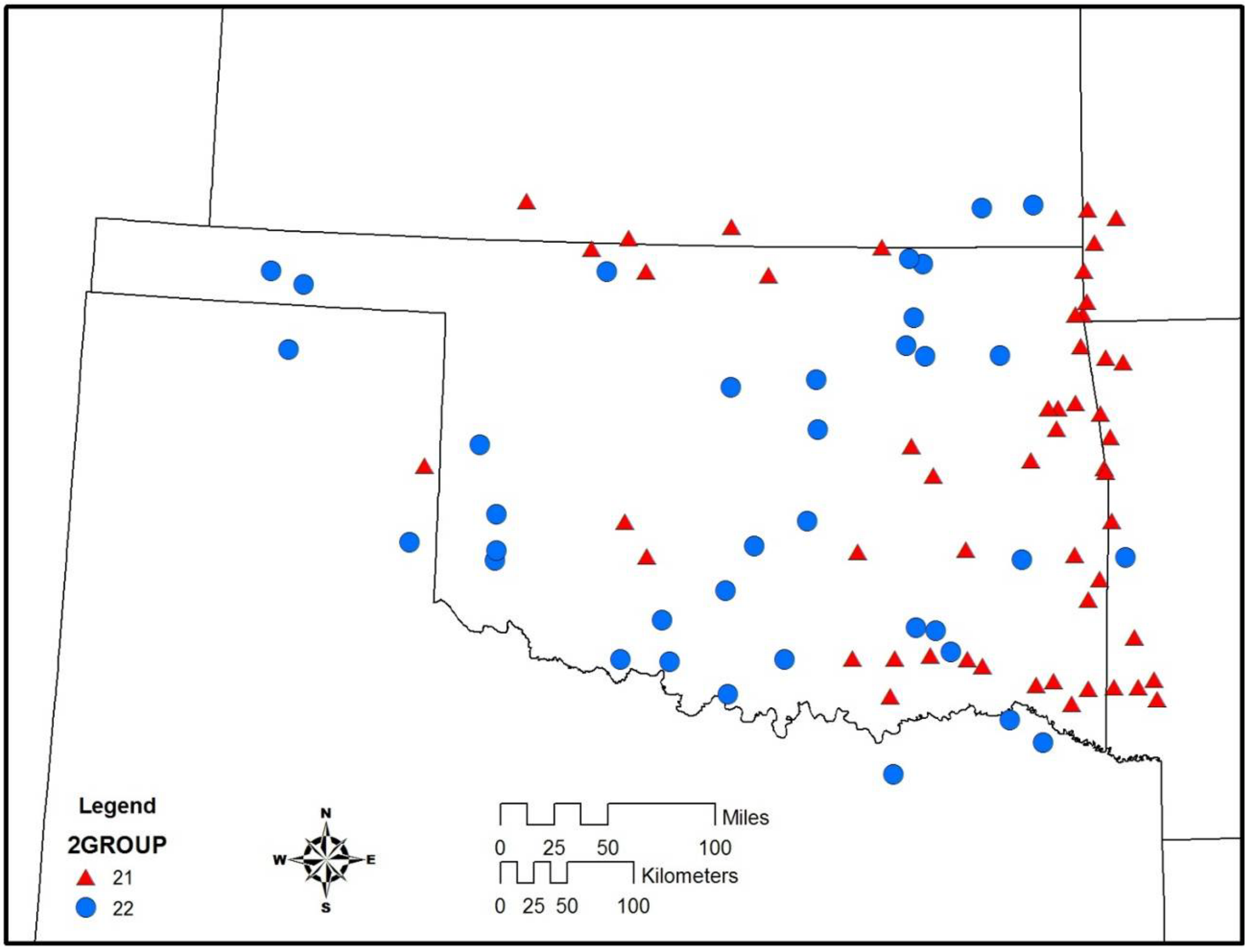


Figure 8: Boxplots of hydrologic indices for the two cluster classification of streamflow-gaging stations in Oklahoma. See Table 4 for hydrologic index names and Figure 6 for groups.

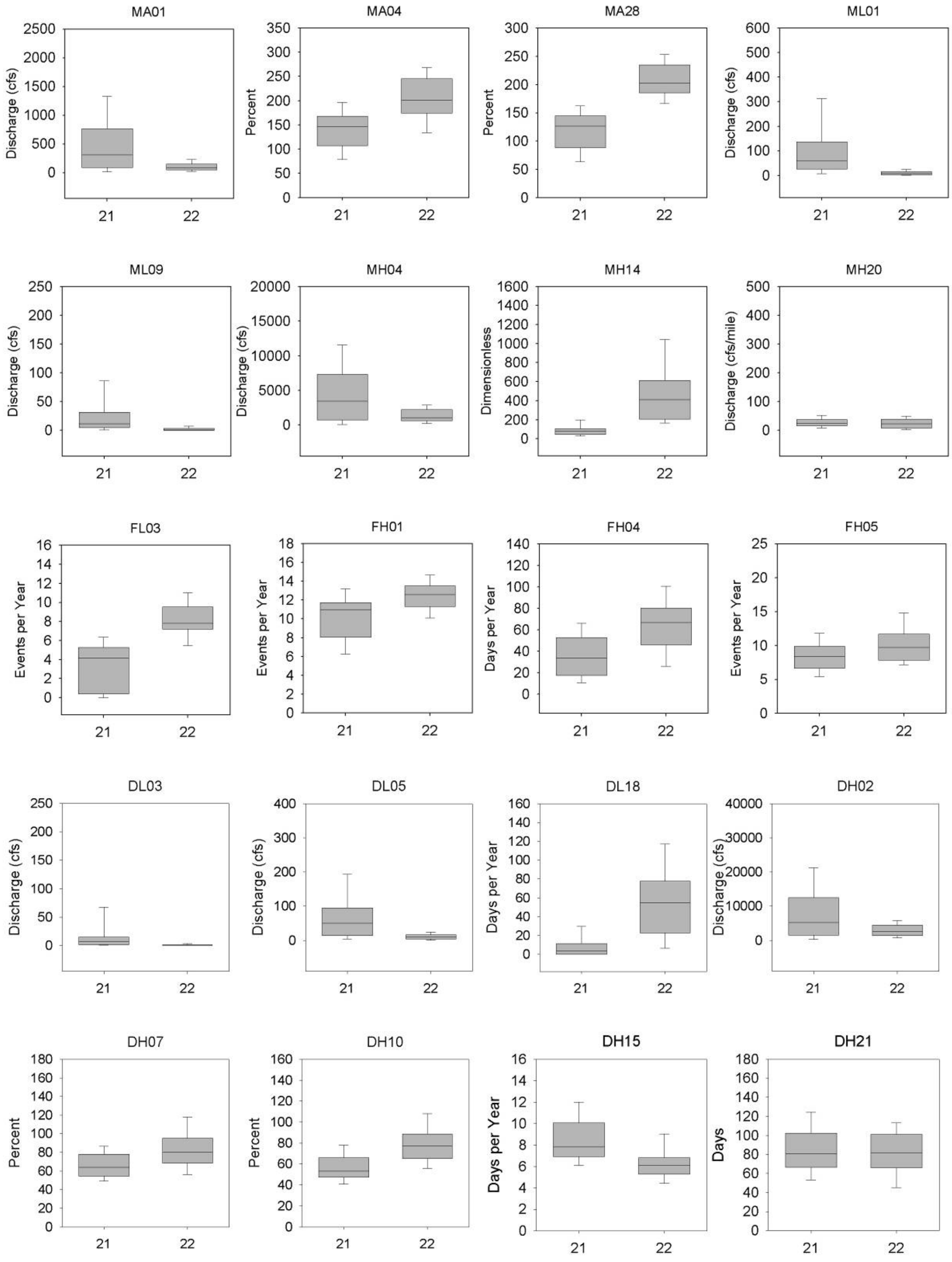
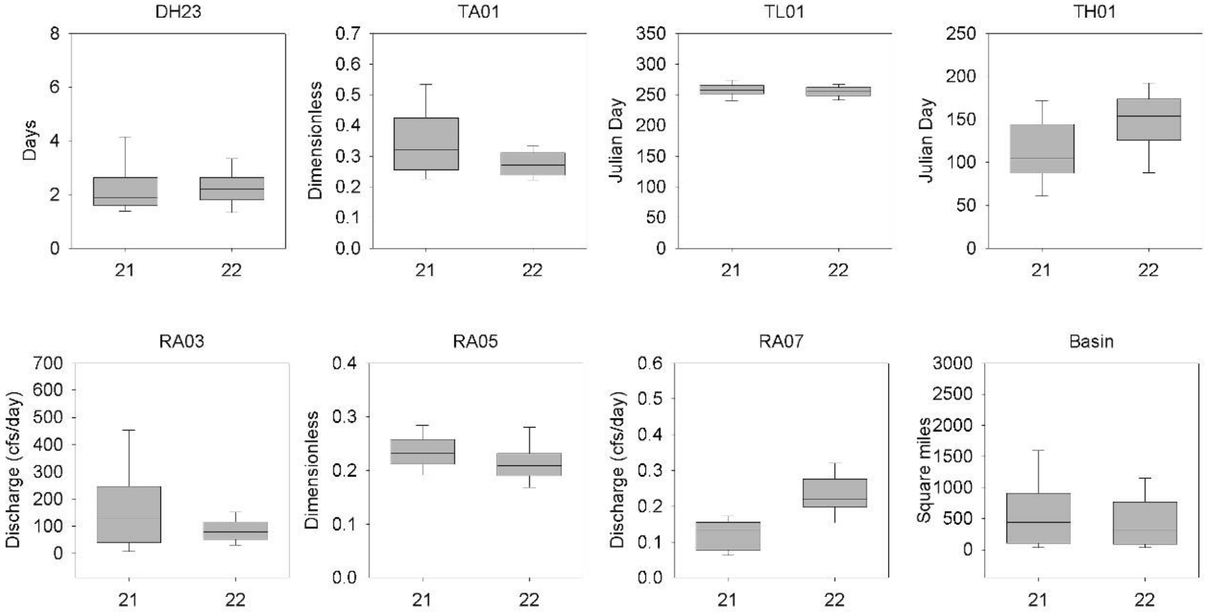


Figure 8, cont.



Four-Cluster Classification

The 4 group dendrogram (Figure 9) is divided with 45% of the information remaining and divided the two cluster classification group 21into three groups, numbered 41,42 and 43. Group 41 had 19 stations, group 42 had 27 stations, and group 43 had 6 stations. Group 44 contained 36 stations and is the same as group 22. Group 43 was more dissimilar (longer distance away on the dendrogram) from groups 41 and 42 than the differences between groups 41 and 42. There was a more regional distribution of the sites in the four group classification (Figure 10) than in the two group classification. The group 41 stations were found throughout the study area. Group 42 stations are concentrated in the southeastern part of the region but it also has some stations in the northeast. Group 43 has the fewest number of stations, which are located only in the northeastern part of the region (i.e. Ozark Highlands). The stations in group 44 were the same as group 22 and were located throughout the region.

A statistical comparison of the stations in the four group classifications with the Kruskal-Wallis test and post test show that there were significant differences between groups for all the hydrologic indices (Table 6). Group 41 stations had lower mean flows (MA01) with relatively stable flows (MA04, TA01; Figure 11). Group 42 stations had more frequent (FH01, FH04) and less variable (DH07) high flow events (Figure 11). Group 43 had the highest stability of flows (TA01) with high baseflows (ML01, DL03, DL05), and no zero flow days in the entire record (DL18). There were also similarities for the stations in groups 42 and 43, which had significantly higher mean flows (MA01) with a higher magnitude of maximum flows in April (MH04) than the other groups. When high flow events did occur at these stations, the flows fell quickly (RA03; Figure 11). The stations of group 44 are the same as group 22, so similar patterns are present with a high number of flood events (FH01) and a high number of zero flow days (DL18; Figure 11).

Based on the trends observed between the four groups, we can classify group 41 as perennial run-off streams, while group 42 stations are perennial flashy streams. The stations in group 43 are stable groundwater streams. Group 44 has streams that have many zero flow days and can be classified as intermittent.

Table 6: Mean and standard deviation for the four cluster classification using 27 hydrologic indices. Significant differences ($\alpha = 0.05$) between groups was tested with the Kruskal-Wallis test with post-hoc test to differentiate between groups. Significant differences between groups is indicated by different letters.

		41			**42**			**43**			**44**		
		Mean	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	
MA01	ft^3/second	122.2	119.5	a	643.3	519.6	b	901.1	570.4	b	115.6	98.9	a
MA04	Percent	101.8	30.2	a	173.1	29.0	b	112.0	18.8	a	206.0	45.5	c
MA28	Percent	98.7	28.5	a	142.4	23.4	b	79.9	17.4	a	209.8	34.2	c
ML01	ft^3/second	38.2	31.9	a	118.5	135.4	b	298.6	136.9	c	10.4	8.6	d
ML09	ft^3/second	16.4	15.5	a	11.9	10.5	a	127.4	57.0	b	2.2	2.6	c
MH04	ft^3/second	1098.6	1250.1	a	6562.0	4811.6	b	7473.8	6220.6	b	1604.6	1733.6	a
MH14	Dimensionless	57.1	22.8	a	131.6	69.6	b	36.8	12.1	a	489.3	333.0	c
MH20	ft^3/second/mile^2	18.7	13.5	a	32.6	15.2	b	88.6	168.3	ab	24.6	17.3	ac
FL03	Events per year	1.5	1.7	a	5.3	1.7	b	0.6	0.9	a	8.3	2.1	c
FH01	Events per year	9.7	3.0	a	11.1	1.8	b	7.9	1.7	a	12.6	1.8	c
FH04	Days per year	17.3	8.8	a	53.5	14.4	b	21.1	8.3	a	62.7	25.8	b
FH05	Events per year	9.3	2.9	ab	8.3	1.5	a	6.0	0.9	c	10.2	3.0	b
DL03	ft^3/second	11.2	12.3	a	5.3	5.5	a	99.6	48.6	b	0.9	1.4	c
DL05	ft^3/second	32.1	27.6	a	70.9	59.7	b	216.8	81.9	c	12.1	10.2	d
DL18	Days per year	6.7	11.1	ab	11.6	13.8	a	0.0	0.0	b	57.4	39.7	c
DH02	ft^3/second	2185.4	2282.5	a	11245.0	8162.3	b	14540.8	11605.9	b	3289.0	2570.6	a
DH07	Percent	75.0	20.1	ab	61.0	14.3	d	76.7	9.4	ac	84.5	27.4	bc
DH10	Percent	59.8	19.7	a	55.4	13.8	a	58.2	3.7	a	79.2	19.4	b
DH15	Days per year	8.1	2.7	a	8.1	1.8	ab	10.2	2.1	b	6.2	1.4	c
DH21	Days	75.1	26.5	ab	87.5	28.8	ac	105.3	16.8	d	80.3	25.4	bc
DH23	Days	1.8	0.5	ac	2.6	1.7	ab	2.7	0.8	bd	2.3	0.8	cd
TA01	Dimensionless	0.40	0.11	a	0.28	0.05	b	0.54	0.03	c	0.28	0.06	b
TL01	Julian day	253.0	11.8	a	258.7	10.9	a	269.7	6.5	b	253.8	15.2	a
TH01	Julian day	128.8	55.9	ab	104.5	43.4	a	114.4	19.3	ab	147.8	36.1	b
RA03	ft^3/second /day	51.3	53.4	a	238.3	161.7	b	222.6	146.4	b	92.1	61.8	c
RA05	Dimensionless	0.24	0.04	a	0.23	0.03	ab	0.24	0.02	ab	0.22	0.04	b
RA07	ft^3/second/day	0.09	0.03	a	0.16	0.03	b	0.06	0.01	a	0.24	0.08	c

Figure 9: Cluster analysis dendrogram (Euclidean distance and Ward's method) showing four cluster classification of 88 Oklahoma streamflow stations. Station codes are shown in Table 1.

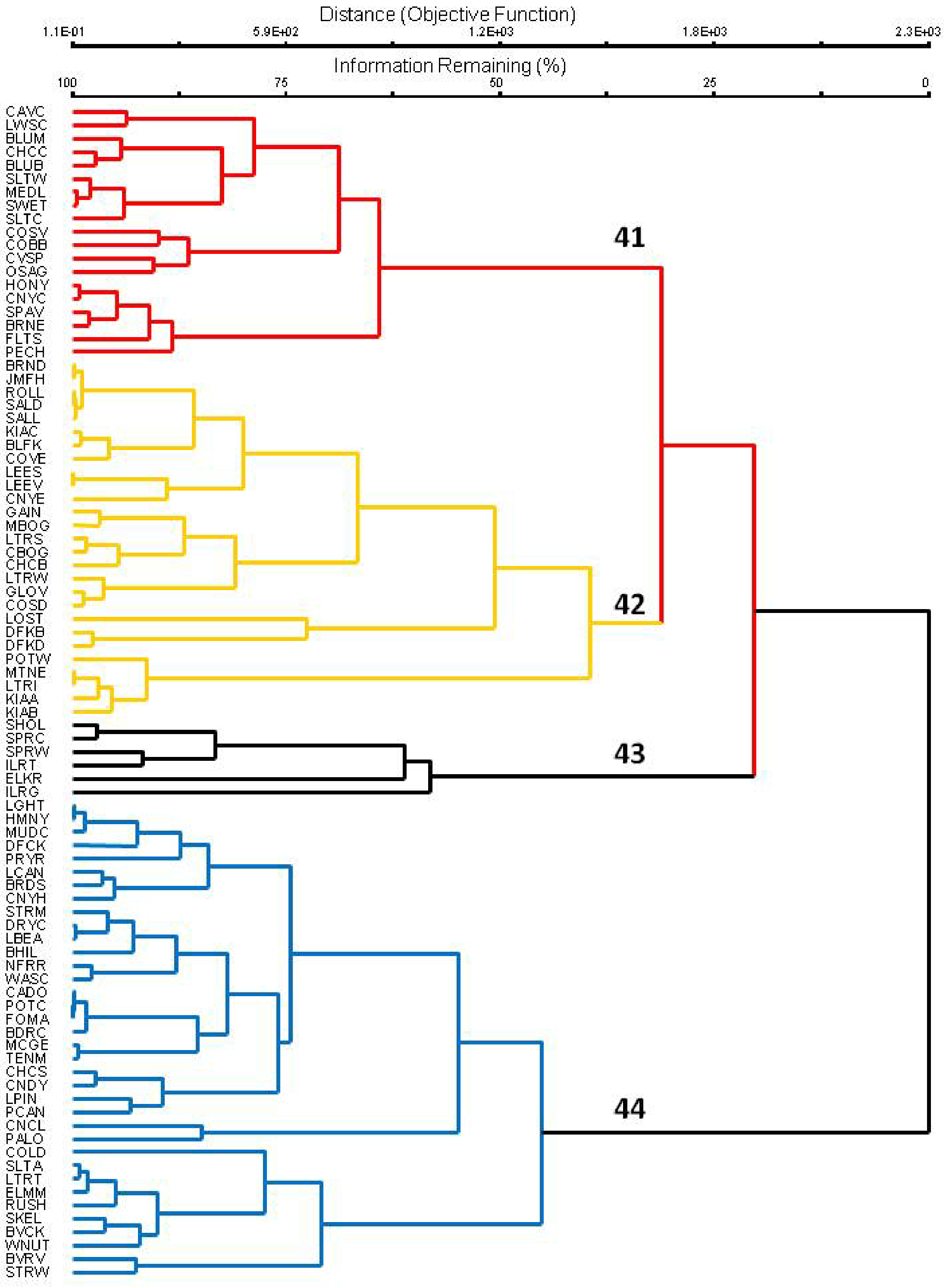


Figure 10: Map of 88 streamflow stations in Oklahoma classified by four group cluster analysis. Red triangles are members of group 41, yellow pentagons are members of group 42, black diamonds are members of group 43, and blue circles are members of group 44.

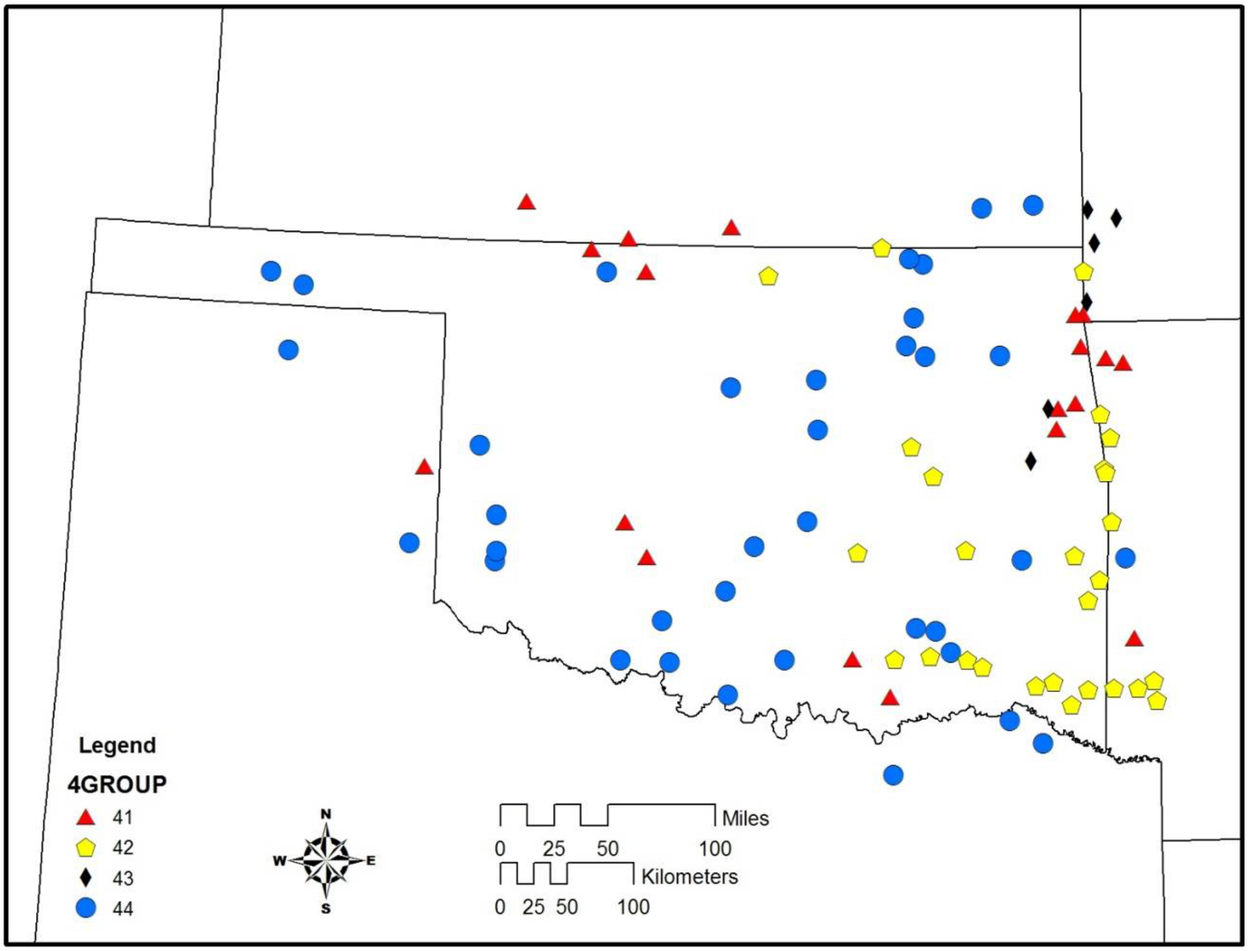


Figure 11: Boxplots of hydrologic indices for the four cluster classification of streamflow-gaging stations in Oklahoma. See Table 4 for hydrologic index names and Figure 9 for groups.

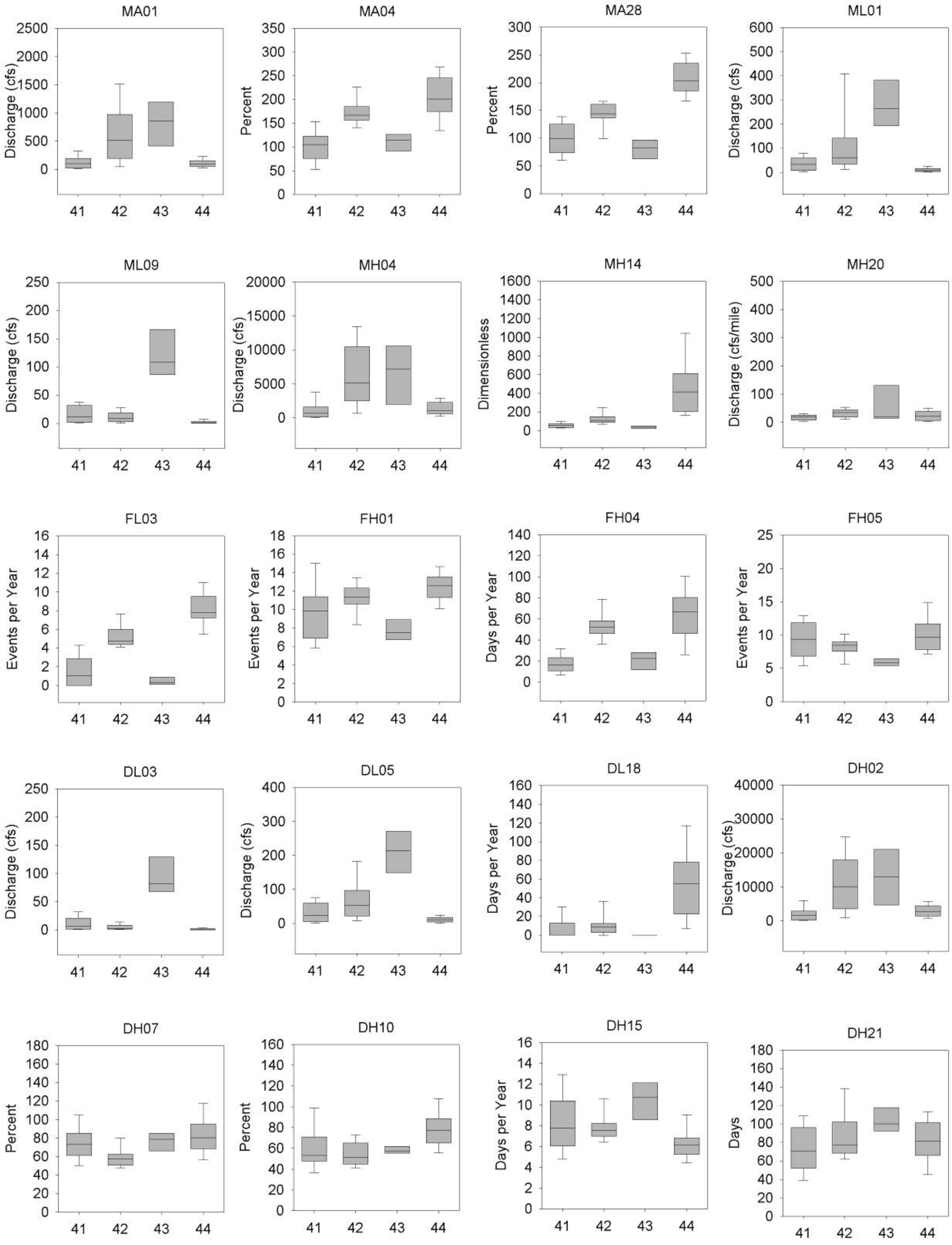
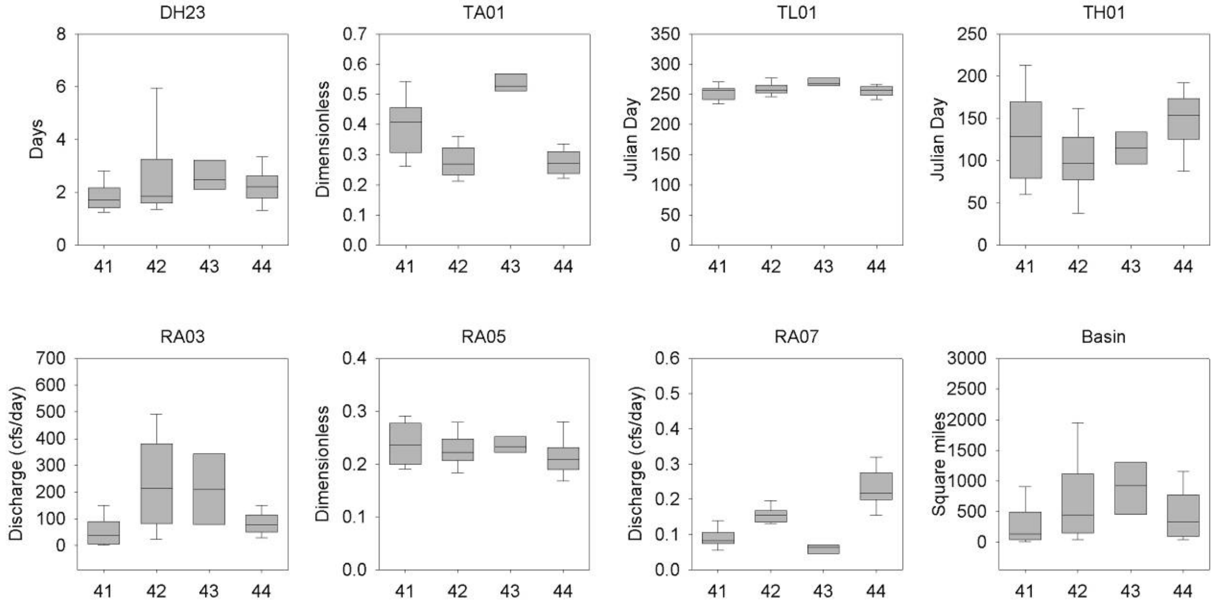


Figure 11, cont.



Six-Cluster Classification

The dendrogram divided at 54% of the information remaining had several smaller clusters compared to the four cluster classification (Figure 12). The group numbers and the number of stations in each group were: 61 (19 stations), 62 (22 stations), 63 (5 stations), 64 (6 stations), 65 (26 stations), and 66 (10 stations). The two changes from the four cluster classification are that group 42 was divided into two groups (62 and 63), and group 44 was divided into two groups as well (65 and 66; Figure 12). We will focus on the differences within groups 62/63 and 65/66 that only occur in the six cluster classification because groups 61 and 64 were discussed in the previous section as 41 and 43, respectively. Group 62 is located primarily in the eastern part of the region, while the five stations of Group 63 are found only in southeastern Oklahoma (Figure 13). The stations of groups 65 and 66 are mixed together around the region (Figure 13). Group 66 stations are mostly in the western part of the region, while stations in group 65 are scattered among the other stations, with a concentration of eight stations in the northeastern part of the region (Figure 13).

Only 10 of the 27 hydrologic indices were significantly different between the groups 62 and 63 when tested with the Mann-Whitney test (Table 7). Group 63 had higher magnitude flows for average (MA01), low (ML01, ML09), and high (MH04) magnitude flows (Table 7). The stations of group 63 had more stable flows (TA01) and a higher fall rate (RA03). There was also a significant difference in basin size (608 miles^2 in group 62 and 1142 miles^2 in group 63), which would be linked to the values of the magnitude and other indices. The stations in groups 65 and 66 have been clustered together in both the two cluster classification as 22 (Figure 6) and the four cluster classification as 44 (Figure 9). There were 17 indices that were significantly different between groups 65 and 66 (Table 7). Group 65 stations had more variable daily flow (MA04) and higher mean annual maximum flows (MH14) than group 66. The group also had more low flow spells (FL03) and twice as many zero flow days per year (DL18). Group 66 stations had more frequent (FH05) and longer floods (DH15). The timing of flows for group 66 stations were earlier in the year for low flows (TL01) and later in the year for high flows (TH01) than station in group 66 (Table 7). The group 66 stations also had more days with no rise (RA05) and a lower rate of change between days (RA07) than group 65.

The analysis of the differences between the groups in the six cluster classification indicate that group 62 are perennial streams with smaller watersheds, while group 63 are stations are perennial streams with larger watersheds. The stations in groups 65 and 66 are both intermittent streams. Group 65 appears to be more intermittent flashy streams and group 66 streams are intermittent run-off streams.

Table 7: Mean and standard deviation for the six cluster classification using 27 hydrologic indices. Letters separate significant differences (α = 0.05) between groups tested with the Mann-Whitney test for groups 62/63 (a/b) and 65/66 (y/z).

		61		**62**			**63**			**64**		**65**			**66**		
		Mean	**SD**	**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	**Mean**	**SD**		**Mean**	**SD**	
MA01	ft^3/second	122.2	119.5	451.7	347.2	a	*1486.4*	176.9	b	901.1	570.4	124.8	112.2		91.6	46.7	
MA04	Percent	101.8	30.2	173.2	31.9		172.9	11.4		112.0	18.8	*225.0*	35.6	y	156.6	27.7	z
MA28	Percent	98.7	28.5	144.2	25.3		134.5	10.4		79.9	17.4	214.0	36.4		198.9	26.3	
ML01	ft^3/second	38.2	31.9	63.1	44.9	a	*362.0*	132.9	b	298.6	136.9	9.2	8.8		13.4	7.5	
ML09	ft^3/second	16.4	15.5	10.0	10.0	a	*20.6*	9.3	b	127.4	57.0	1.3	1.6	y	*4.7*	3.3	z
MH04	ft^3/second	1098.6	1250.1	4885.3	3342.4	a	*13939.3*	2888.4	b	7473.8	6220.6	1828.2	1963.9		1023.2	673.6	
MH14	Dimensionless	57.1	22.8	*142.7*	72.2	a	82.8	20.5	b	36.8	12.1	*592.7*	337.6	y	220.6	59.2	z
MH20	ft^3/second/mile^2	18.7	13.5	33.6	16.5		28.5	6.7		88.6	168.3	*29.4*	17.2	y	12.1	9.8	z
FL03	Events per year	1.5	1.7	5.4	1.8		5.1	1.0		0.6	0.9	*8.9*	2.1	y	7.0	1.7	z
FH01	Events per year	9.7	3.0	10.9	1.9		12.1	1.0		7.9	1.7	12.1	1.5	y	*13.9*	1.7	z
FH04	Days per year	17.3	8.8	53.8	15.9		52.5	4.4		21.1	8.3	*74.0*	20.0	y	33.4	12.2	z
FH05	Events per year	9.3	2.9	8.2	1.7		8.7	0.9		6.0	0.9	9.1	2.2	y	*13.3*	2.8	z
DL03	ft^3/second	11.2	12.3	4.6	5.6		8.3	4.1		99.6	48.6	0.4	0.8	y	*2.4*	1.7	z
DL05	ft^3/second	32.1	27.6	50.2	39.2	a	*162.3*	47.5	b	216.8	81.9	10.8	10.9	y	*15.7*	7.5	z
DL18	Days per year	6.7	11.1	12.2	15.2		9.0	4.6		0.0	0.0	*68.7*	35.3	y	27.8	36.2	z
DH02	ft^3/second	2185.4	2282.5	8368.3	5773.0	a	*23902.4*	3508.2	b	14540.8	11605.9	3478.3	2925.7		2796.7	1244.3	
DH07	Percent	75.0	20.1	*63.6*	14.3	a	49.4	6.7	b	76.7	9.4	79.2	25.3		98.3	29.2	
DH10	Percent	59.8	19.7	56.6	14.7		50.0	6.8		58.2	3.7	74.7	16.8		90.9	21.7	
DH15	Days per year	8.1	2.7	8.3	2.0		7.3	0.7		10.2	2.1	*6.7*	1.2	y	4.9	0.8	z
DH21	Days	75.1	26.5	91.0	30.8		72.0	7.1		105.3	16.8	83.0	23.1		73.2	30.9	
DH23	Days	1.8	0.5	2.6	1.9		2.5	0.7		2.7	0.8	2.3	0.8		2.4	0.8	
TA01	Dimensionless	0.40	0.11	0.27	0.05	a	*0.32*	0.02	b	0.54	0.03	0.28	0.07		0.29	0.03	
TL01	Julian day	253.0	11.8	258.7	11.8		258.5	6.8		269.7	6.5	*258.3*	8.0	y	242.0	22.5	z
TH01	Julian day	128.8	55.9	106.3	48.0		96.7	7.6		114.4	19.3	138.3	37.1	y	*172.5*	17.0	z
RA03	ft^3/second/day	51.3	53.4	178.7	108.6	a	*500.5*	50.3	b	222.6	146.4	97.2	70.2		78.9	30.1	
RA05	Dimensionless	0.24	0.04	0.23	0.04		0.23	0.02		0.24	0.02	0.20	0.02	y	*0.26*	0.04	z
RA07	ft^3/second/day	0.09	0.03	0.16	0.03		0.15	0.02		0.06	0.01	*0.26*	0.08	y	0.18	0.04	z

Figure 12: Cluster analysis dendrogram (Euclidean distance and Ward's method) showing six cluster classification of 88 Oklahoma streamflow stations. Station codes are shown in Table 1.

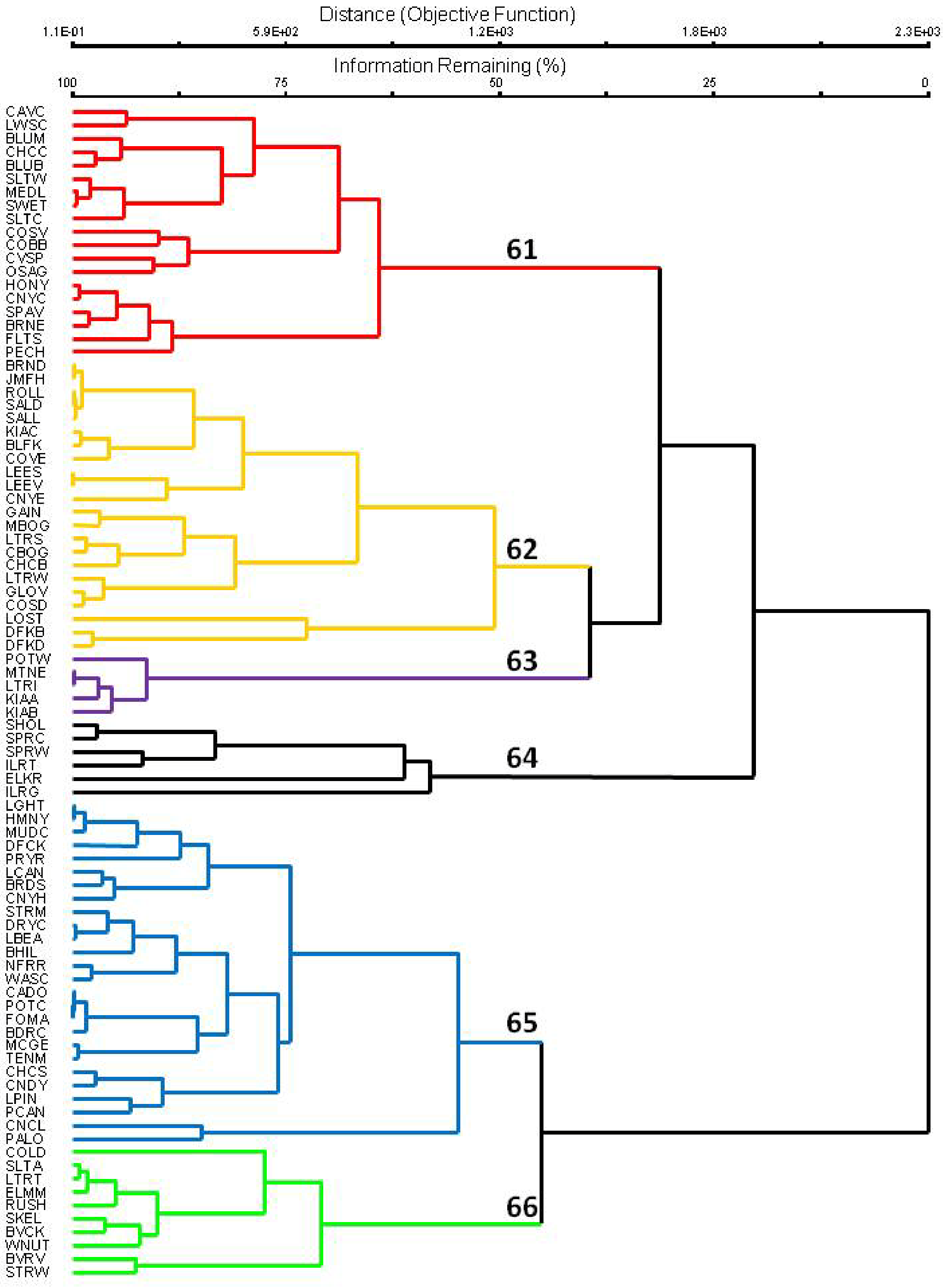
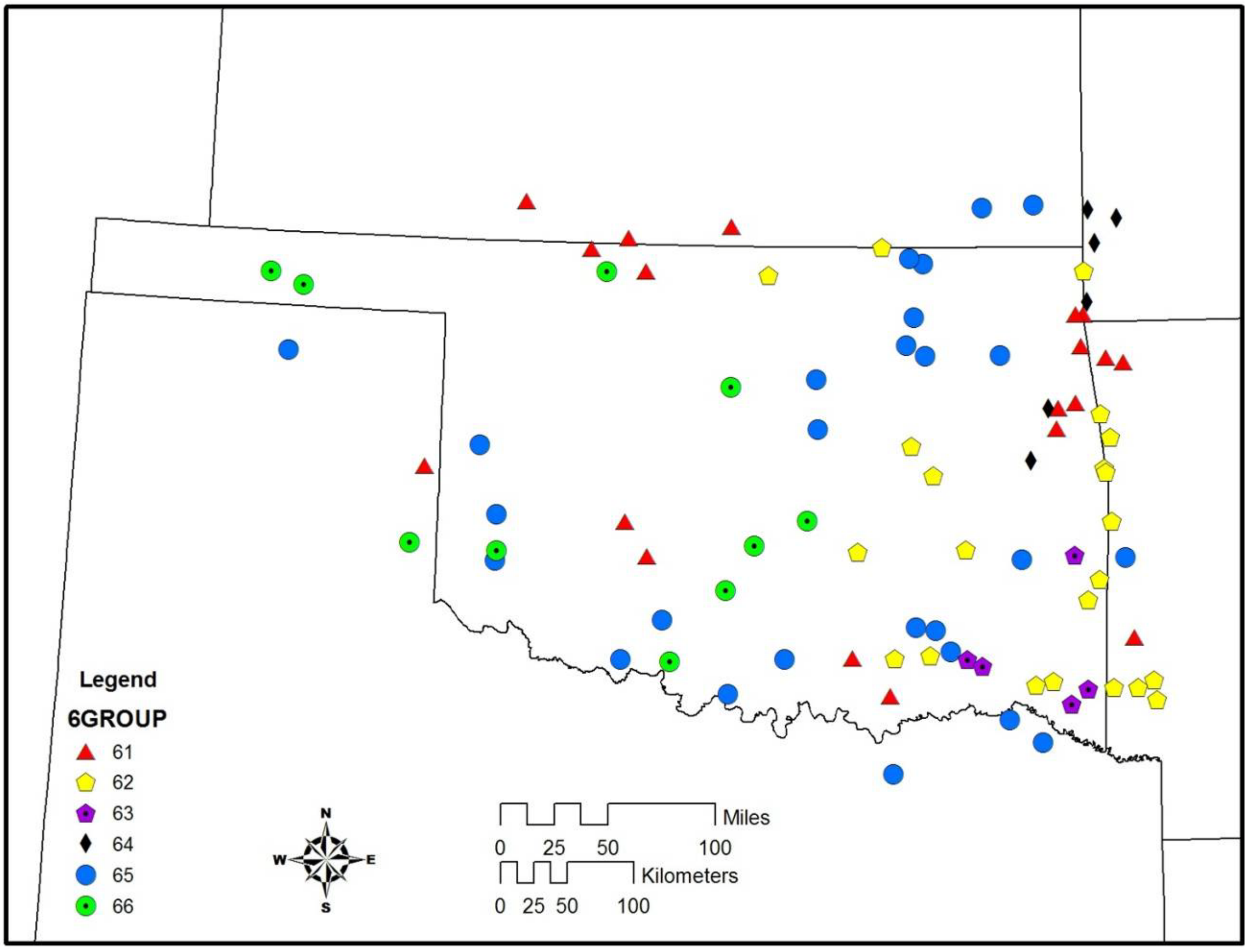


Figure 13: Map of 88 streamflow stations in Oklahoma classified by six group cluster analysis. Red triangles are members of group 61, yellow pentagons are members of group 62, purple pentagons with a dot are members of group 63, black diamonds are members of group 64, blue circles are members of group 65, and green circles with a dot are members of group 66.



Stability of Clusters

We tested how reliable the clusters were using a jackknife method in order to determine if the clusters were dependent on a specific combination of sites and variables (Armstrong et al. 2008; McGarigal et al 2000). Cluster stability was tested by removing individual indices and stations and then running the cluster analysis again. The number of sites that changed cluster membership were then counted. This process was repeated 115 times for each of the 88 sites and 27 indices. The analysis showed that the clusters represent unique groups of stations. The mean stability across all indices and sites was 91% and 94%, respectively. The stability of the clusters from site removal ranged from 73% (with removal of MA04, MA28) to 100%, while the stability of clusters from hydrologic indices ranged from 75% (with removal of SALD, KIAB) to 100%.

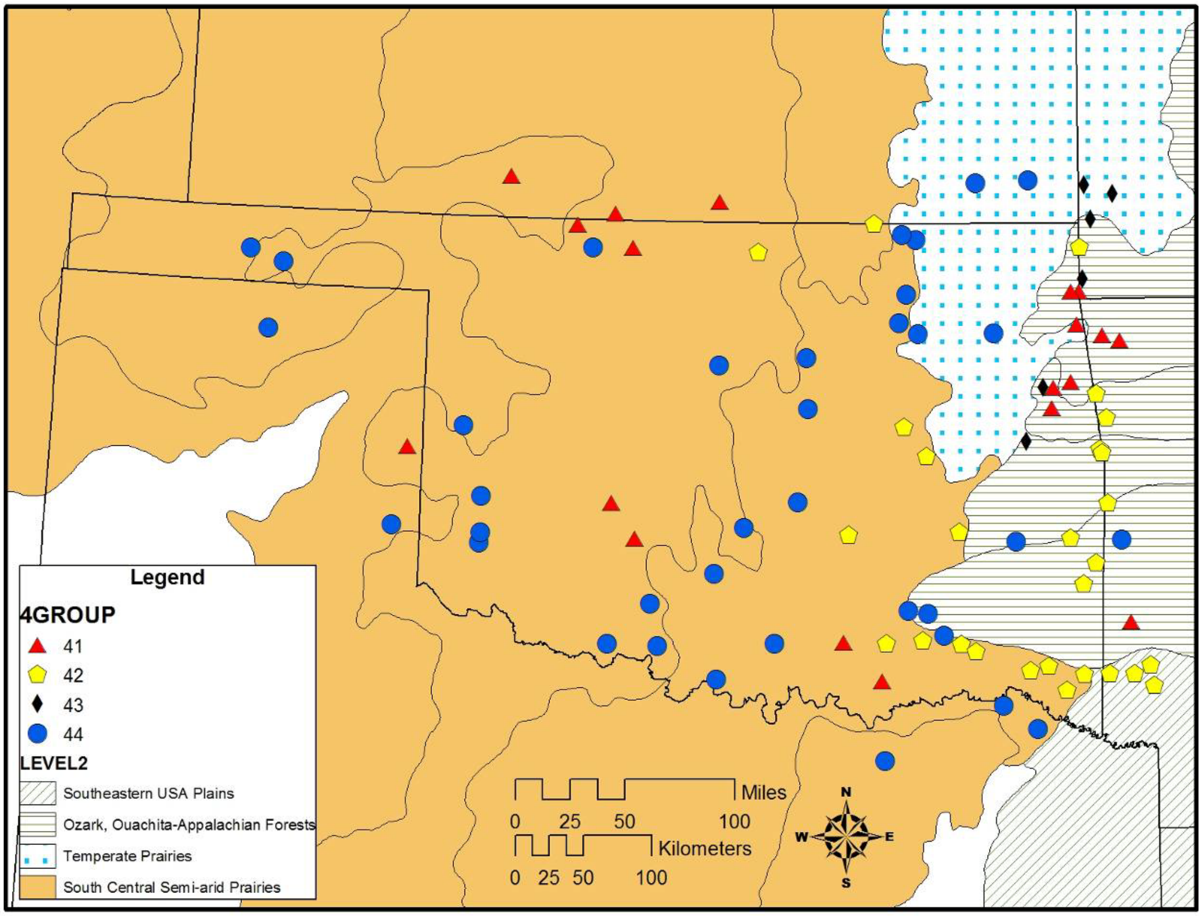
Principal Findings and Significance

This report documents the hydroecological classification of Oklahoma streams based on natural flow regime that incorporates natural flow variability. The classification completes the first 3 development steps of the Hydroecological Integrity Assessment Process (HIP). Completion of the remaining steps of the HIP process will provide tools to water resource managers to include environmental flows to support aquatic life in specific streams as part of Oklahoma's Comprehensive Water Plan.

We calculated 171 ecologically-relevant hydrologic indices for 88 streams across Oklahoma, which described the magnitude, frequency, duration, timing, and rate of change of stream flows. The 27 most non-redundent, high information indices representing all five components of a flow regime were selected for use in the classification of 88 streamflow stations. Cluster analysis was then used to group streamflow stations with similar flow characteristics in two cluster, four cluster, and six cluster groups.

We found that the groupings of streams fell roughly within specific ecoregions of Oklahoma. For example, most of the Group 42 streams (4 cluster analysis) were located in (or the majority of the watershed drained) the Ozark, Ouachita-Appalacian Forests Level II ecoregions (Figure 14). Group 44 streams were located predominately in the Temperate Prairies and South-Central Semi-arid Prairies ecoregions (Figure 14). Ecoregions are based on differences in the inter-related characteristics of climate, geology, soils, and vegetation of a particular location. The hydrologic characteristics of a particular stream (or watershed) are also based on the same characteristics. Therefore we can conclude that the stream groupings generated by the HIT procedure and identification of the primary flow indicies represent "real world" differences in the hydrologic characteristics of the watersheds. From a water resources management perspective, this information is vital to develop environmental flow prescriptions that are stream and organism specific.

Figure 14. A comparison of the four-group cluster analysis stream classifications and Level II Ecoregions of Oklahoma. Note that the symbols represent the location of a gaging station at the watershed outlet. The majority of the watershed drained by the stream may lie in a different ecoregion.



Future Needs

In order to gain the maximum amount of usefulness from this work, the remaining steps of the Hydroecological Integrity Assessment Process (HIP) should be completed. The next development step in the HIP is the development of the Stream Classification Tool (SCT) and the Hydrologic Assessment Tool (HAT) for Oklahoma streams. The SCT development further refines the stream classification and provides water resource managers tools to classify streams that were not included in the baseline analysis performed in this project. The HAT is based on the initial classifications created in this report and the SCT procedure. It is used to provide options for setting environmental flow standards and evaluating past and proposed hydrologic modifications for a specific stream reach.

The baseline stream classification developed in this report and further development of the SCT and HAT will also serve to increase our understanding of the link between natural climate variability, or a changed climate under different climate change scenarios and the variability of the hydrologic characteristics of a stream and populations of various aquatic species. This could include state and federally listed species as well as sportfishes.

Overall, the HIP represents an evolution from simple “rules of thumb” minimum flows to a complex system of hydroecologic flow parameters that support aquatic life throughout the life cycle. The HIP will provide water resource managers with better information with which they can better balance water allocation between human and ecological uses.

References

Auble, G. T., J. M. Friedman, and M. L. Scott. 1994. Relating Riparian Vegetation to Present and Future Streamflows. Ecological Applications 4(3):544-554.

Armstrong, D.S., Parker, G.W., and Richards, T.A., 2008, Characteristics and classification of least altered streamflows in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2007–5291, 113 p.

Arthington, A. H., S. E. Bunn, N. L. Poff, R. J. Naiman. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. Ecological Applications 16:1311-1318.

Bergman, D. L., and T. L. Huntzinger. 1981, Rainfall-runoff hydrograph and basin characteristics data for small streams in Oklahoma: U.S. Geological Survey Open File Report 81-824, 320 p.

Colwell RK. 1974. Predictability, constancy, and contingency of periodic phenomena. Ecology **55**: 1148–1153.

Conover, W. J. 1999. Practical nonparametric statistics, 3rd edition. Wiley, New York.

Esralew, R.A. and R.J. Baker. 2008. Determination of baseline periods of record for selected streamflow gaging stations in New Jersey for determining ecologically relevant hydrologic indicies (ERHI). U.S. Geological Survey Scientific Investigations Report 2008-5077, 83p.

Fitzhugh, T. W., and B. D. Richter. 2004. Quenching urban thirst: growing cities and their impacts on freshwater ecosystems. Bioscience 54:741-754.

Henriksen, J., J. Heasley, J. Kennen, and S. Nieswand. 2006. User's manual for the Hydroecological Integrity Assessment Process software. U.S. Geological Survey Open-File Report 2006–1093:71 p.

Kendall, M. and J.D. Gibbons. 1990, Rank correlation methods (5th ed.): New York, Oxford University Press, 260 p.

Kennen, J.G., J.A. Henriksen, and S.P. Nieswand. 2007. Development of the Hydroecological Integrity Assessment Process for Determining Environmental Flows for New Jersey Streams: U.S. Geological Survey Scientific Investigations Report 2007-5206, 65 p.

Jolliffe, I. T. 1972. Discarding Variables in a Principal Component Analysis .1. Artificial Data. Journal of the Royal Statistical Society Series C-Applied Statistics 21(2):160-&.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems. Canadian Special Publication of Fisheries and Aquatic Sciences 106:110-127.

Kennen, J., J. Henriksen, and S. Nieswand. 2007. Development of the Hydroecological Integrity Assessment Process for determining environmental flows for New Jersey streams. U.S. Geological Survey Scientific Investigations Report 2007-5026. 55 p.

King, J. R., and D. A. Jackson. 1999. Variable selection in large environmental data sets using principal components analysis. Environmetrics 10(1):67-77.

McCune, B., and J. B. Grace. 2002. Analysis of ecological communities. MjM Software Design, Gleneden Beach, OR.

McGarigal, K., S. Cushman, and S. G. Stafford. 2000. Multivariate statistics for wildlife and ecology research. Springer, New York.

National Oceanic and Atmospheric Administration (NOAA), 2008: National Climatic Data Center U.S. Climate Monitoring Reports and Products, database available online at http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html (Accessed July 1, 2008).

Olden, J. D., and N. L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. River Research and Applications 19(2):101-121.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. Bioscience 47:769-784.

Poff, N. L., J. D. Olden, D. M. Meritt, and D. M Pepin. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. Proceedings of the National Academy of Sciences 104:5732-5737.

Postel, S., and B. Richter. 2003. Rivers for life: managing water for people and nature. Island Press, Washington D. C.

Rosenberg, D. M., P. McCully, and C. M. Pringle. 2000. Global-scale environmental effects of hydrological alterations: introduction. Bioscience 50: 746-751.

Scheidegger, K. J., and M. B. Bain. 1995. Larval Fish Distribution and Microhabitat Use in Free-Flowing and Regulated Rivers. Copeia (1):125-135.

Tortorelli, R.L., and D.L. Bergman. 1985, Techniques for estimating flood peak discharges for unregulated streams and streams regulated by small floodwater retarding structures in Oklahoma: U.S. Geological Survey Water Resources Investigations Report 84-4358, 85 p.

Tortorelli, R. L., 1997, Techniques for estimating peak-streamflow frequency for unregulated streams and streams regulated by small floodwater retarding structures in Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 97-4202, 39 p.

Tortorelli, R.L., 2002, Estimated Freshwater Withdrawals in Oklahoma: U.S. Geological Survey circular available online at http://ok.water.usgs.gov/intro.html (Accessed July 1, 2008)

USFWS (U.S. Fish and Wildlife Service) and USGS (U.S. Geological Survey). 2004. Future challenges project: compendium of challenge summaries. USFWS/USGS Future Challenges Project Workshop Report, Shepardstown, West Virginia.

Ward, J.H. 1963. Hierarchical grouping to optimize an objective function. Journal of the American Statistical Association 58: 236-244.

Appendix

Table A: Final baseline period of record for selected streamflow gaging stations in and near Oklahoma that were considered for use in the HIP Classification. *This data was prepared by the US Geological Survey*

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
1	07148350	Salt Fk Arkansas River near Winchester, OK	OK2	848.7	1960-1993	34	Minor Irrigation	Yes	Good
2	07148400	Salt Fork Arkansas River near Alva, OK	OK2	1007.5	1939-1951	13	Minor Irrigation	Yes	Good
3	07149000	Medicine Lodge River near Kiowa, KS	KS8	908	1939-1950, 1960-1968	21	None to note	Yes	Good
4	07149500	Salt Fk Arkansas River near Cherokee, OK	OK2	2420	1941-1950	10	None to note	Yes	Good
5	07151500	Chikaskia River near Corbin, KS	KS8	833.6	1951-1965, 1976-2007	47	Withdrawal, diversion, and irrigation	Yes	Fair
6	07152000	Chikaskia River near Blackwell, OK	OK2	1921.6	1937-1949	13	Withdrawal, diversion, and irrigation	Yes	Fair
7	07153000	Black Bear Creek at Pawnee, OK	OK3	552.3	1945-1960	16	Minor Regulation	No	Poor
8	07154500	Cimarron River near Kenton, OK	OK1	1140.4	1951-1966	16	Irrigation	Yes	Poor
9	07155000	Cimarron River above Ute Creek near Boise City, OK	OK1	2017.6	1943-1954	12	Irrigation, Diversion	No	Poor

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
10	07157500	Crooked Creek near Englewood, KS	KS7	843.3	1943-1963	21	Irrigation	Yes	Poor
11	07157900	Cavalry Creek near Coldwater, KS	KS8	42.6	1967-1980	14	None to note	Yes	Excellent
12	07157960	Buffalo Creek near Lovedale, OK	OK1	411.7	1967-1993	27	Minor Regulation	Yes	Poor
13	07159000	Turkey Creek near Drummond, OK	OK2	261.4	1948-1970	23	Diversion	Yes	Poor
14	07160500	Skeleton Creek near Lovell, OK	OK5	422.7	1950-1993, 2002-2007	58	None to note	Yes	Good
15	07163000	Council Creek near Stillwater, OK	OK5	30.8	1935-1960	26	None to note	Yes	Good
16	07170700	Big Hill Creek near Cherryvale, KS	KS9	37.8	1958-1980	23	None to note	Yes	Good
17	07172000	Caney River near Elgin, KS	KS9	439.6	1940-1964	25	None to note	Yes	Good
18	07173000	Caney River near Hulah, OK	OK3	729.2	1938-1949	12	None to note	No	Fair

Table A, continued

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record[*]	Baseline Years	Human Activities	Climate Variability in Baseline?[†]	Baseline Quality Ranking
19	07174200	Little Caney River below Cotton Cr, near Copan, OK	OK3	516.4	1939-1963	24	None to note	No	Good
20	07174600	Sand Creek at Okesa, OK	OK3	141.4	1960-1993	34	Regulation	Yes	Poor
21	07176500	Bird Creek at Avant, OK	OK3	378.1	1946-1967	22	Regulation	No	Poor
22	07176800	Candy Creek near Wolco, OK	OK3	32.2	1970-1980	11	None to note	No	Good
23	07177000	Hominy Creek near Skiatook, OK	OK3	348.9	1945-1980	36	None to note	Yes	Good
24	07177500	Bird Creek near Sperry, OK	OK3	930.5	1939-1957	20	Diversion	No	Fair
25	07184000	Lightning Creek near McCune, KS	KS9	201	1939-1946, 1960-2007	56	None to note	Yes	Excellent
26	07185500	Stahl Creek near Miller, MO	MO4	4.1	1951-1976	26	None to note	No	Poor
27	07185700	Spring River at LaRussell, MO	MO4	313.5	1958-1973, 1976-1980	21	None to note	No	Poor
28	07185765	Spring River at Carthage, MO	MO4	459.4	1967-1980, 2002-2007	20	None to note	No	Good

Table A, continued

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
29	07186000	Spring River near Waco, MO	MO4	1188.1	1925-2007	83	Minor regulation	Yes	Fair
30	07187000	Shoal Creek above Joplin, MO	MO4	438.5	1942-2007	66	None to note	Yes	Excellent
31	07188500	Lost Creek at Seneca, MO	MO4	41.8	1949-1959	11	None to note	No	Good
32	07189000	Elk River near Tiff City, Mo	MO4	872.7	1940-2007	68	Backwater from Regulation	Yes	Fair
33	07189540	Cave Springs Branch near South West City, MO	MO4	8.2	1997-2007	11	None to note	No	Good
34	07189542	Honey Creek near South West City, MO	OK3	49.9	1997-2007	11	None to note	No	Good
35	07191000	Big Cabin Creek near Big Cabin, OK	OK3	462	1948-2007	60	Effluent, Irrigation	Yes	Poor
36	07191220	Spavinaw Creek near Sycamore, OK	OK3	135	1962-2007	46	None to note	Yes	Good
37	07192000	Pryor Creek near Pryor, OK	OK3	233.3	1948-1963	16	None to note	No	Good
38	07195000	Osage Creek near Elm Springs, AR	AR1	133.3	1966-1975, 1996-2007	22	Effluent, Minor Regulation	Yes	Fair

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
39	07195430	Illinois River South of Siloam Springs, AR	AR1	582.5	1996-2006	11	Minor Regulation	No	Poor
40	07195500	Illinois River near Watts, OK	OK6	646.1	1991-2007	18	Diversion	No	Poor
41	07195800	Flint Creek at Springtown, AR	AR1	15.1	1962-1963, 1965-1979, 1981-2007	44	None to note	Yes	Good
42	07195865	Sager Cr near West Siloam Springs, OK	OK3	19.6	1997-2007	11	Effluent	No	Poor
43	07196000	Flint Creek near Kansas, OK	OK3	118.6	1956-1977	22	Irrigation	No	Poor
44	07196500	Illinois River near Tahlequah, OK	OK6	974.9	1936-1977	42	Minor Regulation	Yes	Fair
45	07196900	Baron Fork at Dutch Mills, AR	AR1	42.2	1959-2007	49	None to note	Yes	Excellent
46	07196973	Peacheater Creek at Christie, OK	OK6	25.5	1993-2003	11	None to note	No	Good
47	07197000	Baron Fork at Eldon, OK	OK6	319.7	1949-2007	59	None to note	Yes	Good
48	07197360	Caney Creek near Barber, OK	OK6	92.5	1998-2007	10	None to note	No	Fair
49	07198000	Illinois River near Gore, OK	OK6	1656.8	1940-1951	12	None to note	No	Good

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
50	07229300	Walnut Creek at Purcell, OK	OK5	207.4	1966-1993	28	Backwater from Regulated Stream	Yes	Fair
51	07230500	Little River near Tecumseh, OK	OK5	474.5	1944-1964	21	Irrigation	Yes	Fair
52	07231000	Little River near Sasakwa, OK	OK5	911.4	1943-1961	19	None to note	Yes	Good
53	07232000	Gaines Creek near Krebs, OK	OK6	600.2	1943-1963	21	None to note	Yes	Excellent
54	07232500	Beaver River near Guymon, OK	OK1	1653.5	1938-1960	23	Minor Regulation	Yes	Fair
55	07233000	Coldwater Creek near Hardesty, OK	OK1	1055.5	1940-1964	25	None to note	Yes	Excellent
56	07233500	Palo Duro Creek near Spearman, TX	TX1	640.9	1946-1969	24	Diversion	Yes	Good
57	07236000	Wolf Creek near Fargo, OK	OK1	1511.1	1943-1956	16	Impoundment	Yes	Poor
58	07243000	Dry Creek near Kendrick, OK	OK5	70.1	1956-1994	39	None to note	Yes	Good
59	07243500	Deep Fork near Beggs, OK	OK6	2056.2	1939-1960	22	Minor Regulation	Yes	Good
60	07244000	Deep Fork near Dewar, OK	OK6	2355.5	1938-1950	13	Minor Regulation	No	Fair

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record[*]	Baseline Years	Human Activities	Climate Variability in Baseline?[†]	Baseline Quality Ranking
61	07245500	Sallisaw Creek near Sallisaw, OK	OK6	185.8	1943-1962	20	Diversion	Yes	Poor
62	07247000	Poteau River at Cauthron, AR	AR4	208.8	1940-1963	29	Minor Regulation	Yes	Good
63	07247250	Black Fork below Big Creek near Page, OK	OK9	96.8	1992-2007	16	None to note	Yes	Good
64	07247500	Fourche Maline near Red Oak, OK	OK9	123.5	1939-1963	25	Impoundment	Yes	Fair
65	07248500	Poteau River near Wister, OK	OK9	1019.4	1939-1948	10	None to note	Yes	Good
66	07249400	James Fork near Hackett, AR	AR4	150.5	1959-2007	19	Diversion/Withdrawal	Yes	Fair
67	07249500	Cove Creek near Lee Creek, AR	AR4	35.7	1950-1970	21	None to note	Yes	Good
68	07249985	Lee Creek near Short, OK	OK6	445.3	1931-1936, 1950-1991, 1993-2007	63	None to note	Yes	Excellent
69	07250000	Lee Creek near Van Buren, AR	OK6	449.3	1931-1936, 1951-1992	48	None to note	Yes	Excellent

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
70	07300000	Salt Fk Red Rv near Wellington, TX	TX2	1029.4	1953-1966	14	Irrigation	Yes	Fair
71	07300500	Salt Fork Red River at Mangum, OK	OK7	1380.4	1938-1966	29	None to note	Yes	Excellent
72	07301410	Sweetwater Creek near Kelton, TX	TX2	305	1963-1978	15	Diversion	Yes	Fair
73	07301500	North Fork Red River near Carter, OK	OK4	2155	1938-1961	25	None to note	Yes	Fair
74	07303400	Elm Fk of N Fk Red River near Carl, OK	OK7	449.3	1960-1979, 1995-2007	33	Diversion/Withdrawal	Yes	Poor
75	07303500	Elm Fk of N Fk Red River near Mangum, OK	OK7	868.3	1938-1976	39	Minor Regulation	Yes	Fair
76	07304500	Elk Creek near Hobart, OK	OK7	563.5	1950-1966	17	Irrigation	No	Poor
77	07311500	Deep Red Creek near Randlett, OK	OK7	619.7	1950-1963,1970-1973	18	None to note	No	Excellent
78	07313000	Little Beaver Creek near Duncan, OK	OK8	160.6	1949-1963	15	None to note	Yes	Good

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
79	07313500	Beaver Creek near Waurika, OK	OK8	579	1954-1976	23	None to note	Yes	Good
80	07315700	Mud Creek near Courtney, OK	OK8	589.3	1961-2007	47	Minor Regulation	Yes	Good
81	07316500	Washita River near Cheyenne, OK	OK4	782.3	1938-1957	18	Irrigation	Yes	Fair
82	07325000	Washita River near Clinton, OK	OK4	1998.8	1936-1955	20	Irrigation, Minor Regulation	Yes	Poor
83	07326000	Cobb Creek near Fort Cobb, OK	OK7	318.8	1940-1950	11	Minor Regulation	No	Good
84	073274406	Little Washita River above SCS Pnd 26 near Cyril, OK	OK7	3.7	1995-2007	13	None to note	No	Good
85	07327490	Little Washita River near Ninnekah, OK	OK5	213.3	1952-1969	18	Irrigation, Minor Regulation	Yes	Poor
86	07329000	Rush Creek at Purdy, OK	OK8	143.3	1940-1953	13	None to note	Yes	Good
87	07330500	Caddo Creek near Ardmore, OK	OK8	304	1937-1950	14	None to note	Yes	Excellent
88	07332400	Blue River at Milburn, OK	OK8	208.5	1966-1986	21	None to note	Yes	Excellent
89	07332500	Blue River near Blue, OK	OK8	489.8	1937-1980	44	Minor Regulation	Yes	Fair

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record[*]	Baseline Years	Human Activities	Climate Variability in Baseline?[†]	Baseline Quality Ranking
90	07332600	Bois D'Arc Creek near Randolph, TX	TX3	74	1964-1985	22	None to note	Yes	Excellent
91	07333500	Chickasaw Creek near Stringtown, OK	OK8	33.5	1956-1968	13	None to note	Yes	Excellent
92	07333800	McGee Creek near Stringtown, OK	OK8	91.1	1956-1968	13	None to note	Yes	Excellent
93	07334000	Muddy Boggy Creek near Farris, OK	OK8	1117.1	1938-1958	21	None to note	Yes	Excellent
94	07335000	Clear Boggy Creek near Caney, OK	OK8	731.8	1943-1960	18	None to note	Yes	Good
95	07335700	Kiamichi River near Big Cedar, OK	OK9	40.7	1966-2007	42	None to note	Yes	Excellent
96	07336000	Tenmile Creek near Miller, OK	OK9	70.1	1956-1970	15	None to note	Yes	Excellent
97	07336200	Kiamichi River near Antlers, OK	OK9	1158.3	1973-1982	10	Diversion	Yes	Fair
98	07336500	Kiamichi River near Belzoni, OK	OK9	1452.6	1926-1972	47	Diversion	Yes	Fair
99	07336750	Little Pine Creek near Kanawha, TX	TX4	77.2	1970-1980	11	None to note	Yes	Excellent
100	07336800	Pecan Bayou near Clarksville, TX	TX4	101.5	1963-1977	15	None to note	Yes	Good
101	07337500	Little River near Wright City, OK	OK9	665	1945-1966	22	None to note	Yes	Excellent

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
102	07337900	Glover River near Glover, OK	OK9	328.6	1962-2007	46	None to note	Yes	Excellent
103	07338500	Little River blw Lukfata Ck, near Idabel, OK	OK9	1260	1930-1968	39	Diversion/Withdrawal	Yes	Fair
104	07338750	Mountain Fork at Smithville, OK	OK9	330.7	1992-2007	16	None to note	No	Poor
105	07339000	Mountain Fork near Eagletown, OK	OK9	820.5	1930-1968	39	None to note	Yes	Good
106	07339500	Rolling Fork near DeQueen, AR	AR7	188.1	1949-1976	28	None to note	Yes	Excellent
107	07340300	Cossatot River near Vandervoort, AR	AR4	91.4	1967-2007	29	None to note	Yes	Excellent
108	07340500	Cossatot River near DeQueen, AR	AR7	370.6	1939-1974	36	None to note	Yes	Good
109	07341000	Saline River near Dierks, AR	AR7	123.3	1939-1974	36	None to note	Yes	Excellent
110	07341200	Saline River near Lockesburg, AR	AR7	259.3	1964-1974	11	None to note	Yes	Excellent

*A water year is the 12-month period beginning October 1 and ending September 30 and is named for the year in which it ends; %, percent; --, did not exceed indicated percentage; "no change" indicates that the baseline period of record did not change as a result of the assessment of impoundment.
†An optimum minimum period of record to encompass climate variability was determined by analyzing variability in annual precipitation for each climate division and determining the minimum number of years where the distribution of annual precipitation in the climate division was similar to the distribution of annual precipitation for a longer period, 1925-2007. If the gage has fewer baseline years than the minimum number of years determined for the climate division that the gage is located in, the quality ranking was reduced.