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SUMMARY

This report presents the methods and results of a hydroecological classification of 185 unaltered/minimally altered streams in North Carolina. Stream classification is a critical part of a process for developing hydrologic baselines, customized computer software for flow alteration analyses, and development of reach and class specific ecological flow standards (aka environmental flow, instream flow). The Environmental Defense Fund (located in Raleigh, North Carolina) and North Carolina Department of Environment and Natural Resources identified a need to have a process that is applicable statewide for evaluating the hydrologic impact of flow alteration and for developing ecological flow standards for stream and riparian resources. This need is based on the goal to have a long term ecologically sustainable water management process. The hydroecological classification of North Carolina’s streams and development of customized software are critical steps to achieve this goal.

Environmental Flow Specialists, Inc. applied their Hydroecological Process for Environmental Flows for the North Carolina StreamFlow Development Project. Two primary objectives for the project were, (1) to conduct a hydroecological classification of streams, and (2) develop a customized version of EFS’s StreamFlow impact analysis and stream flow management software specifically for North Carolina streams.

Daily stream flow data for 243 stream gages were obtained from US Geological Survey’s National Water Information System internet site. Gages having a daily flow record <18 years were eliminated. The final list of gages suitable for the classification process was 185 for hydrologically unaltered/minimally altered gages and 231 for combined unaltered/altered gages. A priori categorization separated streams into perennial and seasonal groups. Starting with 108 hydrologic indices, principal components analysis was used to derive a reduced set of indices for a k-means cluster analysis. Streams were classified into the following seven classes, six perennial and one seasonal:

- Perennial Class A - Coastal streams.
- Perennial Class B - Small stable streams.
- Perennial Class C - Large stable streams.
- Perennial Class D - Small flashy streams.
- Perennial Class E - Large Piedmont Rivers.
- Perennial Class F - Medium stable streams.
- Seasonal Class G - Small seasonal streams.

Following the classification, a principal components analysis was conducted to identify the best hydrologic descriptors for nine flow components for each of the seven stream classes.

Finally, Environmental Flow Specialist’s, Inc. StreamFlow© software was customized and has the following features and capabilities for 231 stream gages in North Carolina:
• A database with daily flow records for 231 gages.
• A predictive stream classification tool for classifying unclassified streams.
• Tools to identify a baseline and altered time period (if present).
• Ability to identify and integrate hydroecological processes and timing events present for the baseline time period.
• Ability to characterize pre- and post-hydrologic conditions for magnitude, frequency, duration, timing, variability, and rate of change at multiple temporal (daily, monthly, annual) scales and six flow states using 108 indices and nine class specific indices.
• Ability to develop class and reach specific ecological flow standards.
• Identification of gages in each stream class for conducting class specific flow unaltered and altered - ecological response relationships.
• Ability to evaluate current and proposed alterations for planning and regulatory ecological flow standards.
INTRODUCTION

This report addresses the methods and results of a hydroecological classification of streams in North Carolina as part of a process for developing ecological flows. Ecological flows and ecological integrity are defined in North Carolina General Assembly’s Water Allocation Study Report as: "the ability to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat. A living system exhibits ecological integrity if it recovers from a disruption and continues to provide natural goods and services that normally accrue from that system. Ecological integrity includes biological, chemical and physical components. Flow regime encompasses the following characteristics of stream flow and their interactions: magnitude, timing, frequency, duration and rate of change.”

The Environmental Defense Fund (EDF) (located in Raleigh, North Carolina) and North Carolina Department of Environment and Natural Resources (DENR) identified a need to have a process that is applicable statewide for developing ecological flow standards and evaluating the impact of flow alteration on stream and riparian resources. This need is based on the goal to have a long term ecologically sustainable water management process. The hydroecological classification of North Carolina’s streams and the ability to establish and apply ecological flow standards are critical steps to achieve this goal.

EDF and DENR subsequently developed a consulting agreement titled “North Carolina StreamFlow Development Project” with Environmental Flow Specialists, Inc. (EFS) (located in Fort Collins, Colorado). Two primary objectives in the agreement were (1) to conduct a hydroecological classification of streams within the State of North Carolina, and (2) develop a customized version of EFS’s StreamFlow software specifically for North Carolina streams. The customized North Carolina StreamFlow software contains the following features derived in part from the stream classification process:

- A database with baseline and altered hydrologic time periods for 231 stream gages.
- Identification of the stream class for each stream gage currently in or added to the database in the future.
- Identification of nine class specific indices that address magnitude, frequency, duration, timing, variability, and rate of change for each stream class and reach in the database.
- Ability to classify an unclassified gage using a daily flow record.
- Ability to develop class and reach ecological flow standards.

Background

There is a large body of literature that documents the effects of altering hydrologic variability and the ecological consequences (see articles and references in Poff et al., 1997; Arthington et al., 1991; and Poff et al., 2010 for examples). The Natural Flow Regime paradigm (Poff et al., 1997) synthesizes this literature and puts forth the premise that long-term physical characteristics of flow variability have strong ecological consequences at local to regional
scales, and at time intervals ranging from days (biological) to decades (ecological). Furthermore, flow variability plays a critical role in sustaining native biodiversity and ecosystem integrity. The structure and function of riverine ecosystems, and adaptations of freshwater and riparian species, are determined by patterns of intra and inter-annual variation in river flows. Understanding patterns of hydrology in time and space and the associated ecological consequences of altering these patterns of flow variability has become fundamental to the assessment and management of environmental water allocations for river systems, and environmentally sustainable water management planning.

**Why Classify Streams?**

Hydrologic classification of streams is a process of systematically arranging streams, rivers or catchments into classes that are similar with respect to characteristics of their flow regime. By classifying streams according to ecologically meaningful streamflow characteristics (e.g., Poff & Ward, 1989; Henriksen et al., 2006; Kennard et al., 2010) groups of hydrologically similar streams can be identified. Within each stream class there is a range of hydrologic and ecological variation that can be considered the baseline time period. Thus, stream class and the baseline time period is a basis for establishing ecological flow standards based on either hydrological variability and/or flow alteration-ecological response relationships.

A recent publication, *Ecological Limits of Hydrological Alteration* (ELOHA) (Poff et al., 2010) also recognizes that hydrologic variability is important for shaping biophysical attributes and functioning of riverine ecosystems, and that rivers that have similar hydrological characteristics (classes) should also have similar assemblage composition, species traits and community functioning ecological responses to a given anthropogenic change in the baseline flow regime.

The primary purpose of the ELOHA article is to present a framework based on the importance of hydrologic variability that leads to developing ecological flow standards. These standards are potentially developed from a synthesis of existing hydrologic and ecological databases from classes of rivers to develop scientifically defensible and empirically testable relationships between flow alteration and ecological responses. These relationships serve as the basis for the process of developing class based flow standards. This can be achieved by first using hydrologic modeling to build a ‘hydrologic foundation’ of baseline and current hydrographs for stream and river segments. Second, using a set of ecologically relevant flow variables, stream segments within the region are classified into a few distinctive flow regime types that are expected to have different ecological characteristics. Third, the deviation of current-condition flows from baseline-condition flow is determined. And finally, flow alteration-ecological response relationships are developed for each river class, based on a combination of existing hydroecological literature, expert knowledge and field studies across gradients of hydrologic alteration.
METHODS

Hydroecological Process for Ecological Flows
EFS applied their process - **Hydroecological Process for Ecological flows (HPEF)** - for the North Carolina StreamFlow Development Project. Five major steps for HPEF are:

1. Develop a hydrologic foundation initially using US Geological Survey (USGS) historic daily stream flow data. In addition, EDF and DENR intend to utilize OASIS, a water management model, to synthesize supplement flow data by modeling historic flows and future alternative operational options at locations of interest.
2. Conduct a hydroecological classification of streams within a geographic area (the State of North Carolina) using baseline unaltered/minimally altered periods of record. (Note: for brevity when the phrase unaltered is used in this report it represents the phrase unaltered/minimally altered).

Once streams were classified, EFS’s StreamFlow software was customized by developing a stream gage database that identifies the stream class for each gage and nine class specific aspects of flow - magnitude, frequency, duration, timing, and rate of change for each stream class. StreamFlow allows the user to apply the last three steps of the HPEF process:

3. Hydrologically characterize of each stream class and stream reach.
4. Develop ecological flow standards.
5. Conduct alternative impact analyses.

Details of each step of the HPEF that were undertaken for the North Carolina StreamFlow Development Project are shown in Appendix A.

Hydrologic Data

Daily stream flow data were obtained from USGS’s National Water Information System (NWIS) internet site - [http://waterdata.usgs.gov/nc/nwis/sw](http://waterdata.usgs.gov/nc/nwis/sw). The entire daily flow record for 243 gages with a period of record equal to or greater than 15 years were downloaded from this site. This initial list of gages was examined for missing data and evaluated for flow alteration, urbanization, and geographic distribution; staffs with the USGS Raleigh, North Carolina, Water Resources office and DENR were involved in the review. After examining the data, and giving consideration to a statistical need to utilize as many gages as possible for the classification analyses, a minimum period of record of 18 years for unaltered gages was agreed upon. This length of record was considered adequate to ensure representative estimates of long term streamflow statistics. Applying this criterion resulted in eliminating 12 gages. The remaining 231 were then evaluated for flow alteration.
Baseline Determination

Natural baseline flow conditions are considered to be the period of record when flow is unaltered due to water management activities such as dam and reservoir operations, withdrawals, diversions, additions, or long term landscape alterations. This baseline is associated with the Natural Flow Regime Paradigm. However, under some situations an altered flow condition can be declared as the functional baseline because the altered historic (and current) conditions are deemed acceptable, even desirable, since stream resources are considered to be in a desirable state (e.g., a valued tail water fishery resource). It is, of course, recognized that water management activity is of high human value (e.g., water supply reservoir, hydropower) and large scale water management changes are not always achievable. While minor modifications to water management operations might be possible, mimicking the natural baseline may not be realizable. In both cases the purpose for identifying the ‘baseline’ period of record is to use it as a reference condition for comparing existing or proposed water management actions and predicting hydrological and ecological changes. EFS established only the natural baseline and altered time periods. No decision was made by EFS to identify a functional baseline.

Indications of hydrologic alteration were ascertained by first examining four cumulative sum plots - annual coefficient of variation, annual standard departure of the median flow, annual standard departure of the maximum flow, and annual standard departure of the minimum flow - for each gage for the entire period of record. An example of a cumulative standard departure for the annual minimum flow with a flow alteration starting in 1953 is shown in Figure 1. The trend line has a discernable inflection indicative of a flow alteration. In addition to the cumulative sum plots, USGS North Carolina Water Resources Division office and DENR staff
familiar with the NWIS gage records reviewed each gage and identified gages with a known alteration or potentially influenced indirectly by extensive urban development. Consequently, 185 gages have an adequate length of record for a natural baseline condition where identified. In addition, 46 gages were identified with an adequate length of record for an altered baseline condition. Out of 46, 13 gages had an adequate length of record to have both a natural baseline and an altered baseline condition. Appendix B contains the station name, identification number, class, drainage area, start year, ending year, and number of years for the 231 gages.

**Hydrologic Indices**

Four criteria guided the development of EFS’s unique set of 108 hydrologic indices initially used for the hydroecological classification. These criteria include: 1) capture the diverse features of the five components of flow – magnitude, frequency, duration, timing, and rate of change; 2) capture aspects of six flow states (percentile ranges) – zero flow, very low flow, low flow, average flow, high flow, and very high flow; 3) be ecologically relevant (known and/or potentially), and 4) be understandable and interpretable. Table 1 lists the number of indices in each flow component category. Definitions for the 108 indices are given in Appendix C.

**Table 1. Number of hydroecological indices in 10 flow component groups – total number of indices 108.**

<table>
<thead>
<tr>
<th>Flow Component Categories</th>
<th>Number of Indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Magnitude</td>
<td>8</td>
</tr>
<tr>
<td>Low Magnitude</td>
<td>13</td>
</tr>
<tr>
<td>High Magnitude</td>
<td>13</td>
</tr>
<tr>
<td>Frequency</td>
<td>12</td>
</tr>
<tr>
<td>Duration</td>
<td>6</td>
</tr>
<tr>
<td>Monthly Timing</td>
<td>14</td>
</tr>
<tr>
<td>Seasonal Timing</td>
<td>14</td>
</tr>
<tr>
<td>Rate of Change</td>
<td>4</td>
</tr>
<tr>
<td>Variability</td>
<td>17</td>
</tr>
<tr>
<td>Distribution of Annual Flow</td>
<td></td>
</tr>
<tr>
<td>Among Six Flow States</td>
<td>7</td>
</tr>
</tbody>
</table>

The percentile ranges for the six flow states are:
- Zero flow - state where no flow occurs.
- Very low flow - state where flow > 0 and <= 10th percentile.
- Low flow - state where flow > 10th and <= 25th percentile.
- Average flow - state where flow > 25th and <= 75th percentile.
- High flow - state where flow > 75th and <= 90th percentile.
- Very High flow - state where flow > 90th percentile.

Nine indices are calculated for each flow state including:
- Median number of flow events per year falling within a flow state.
- Median number of days per year falling within a flow state.
- Median duration of an event falling within a flow state.
- Month with the most days falling within a flow state.
- Degree of monthly concentration for flows falling within a flow state.
- Season with the most days falling within a flow state.
- Degree of seasonal concentration for flows falling within a flow state.
- Variability for flow events falling within a flow state.
- Average percentage of daily flows falling within a flow state.

Two hundred thirty one sets of stream flow records were used to calculate values for the 108 indices. The data matrix for these index values is available by contacting the North Carolina Division of Water Resources and also at http://www.ncwater.org/Data_and_Modeling/eflows/. Descriptive statistics, including number of missing values, minimum, maximum, median, mean, variance, standard deviation, and coefficient of variation, were calculated for these data. No missing values or aberrant values were found.

**Statistical Strategy**

The goal for classifying streams in North Carolina was to identify hydrologically similar groups (clusters) based on hydrologic variability by addressing the five major components of flow – magnitude, frequency, duration, timing, and rate of change. The premise being that hydrologic variability is the master driver in shaping biophysical attributes and functioning of riverine ecosystems, and that rivers that have similar hydrological characteristics (classes) will also have similar assemblage composition, species traits and community functioning ecological responses to a given anthropogenic change in the baseline flow regime.

A critical question is which indices should be used to capture the hydrological variability of stream flow from gages across the entire state using highly variable daily flow data collected over a long period of time? The general answer is to use a large number (initially 108) of hydrologic indices that capture diverse aspects of the five major flow components. This included four sub-components of flow - low magnitude, high magnitude, overall variability, and six flow states. Therefore, 108 index values were calculated from mean daily flow values collected from gages distributed across the state with a minimum of 18 years of record (>6570 values), thus, capturing hydrologic variability over both time and space (location of the gages).

Cluster Analysis is an established multivariate analysis statistical technique that seeks to organize information about variables (i.e., hydrologic indices) so that relatively homogeneous classes, or "clusters," can be formed. Multi-dimensional clusters formed with this family of statistical methods should be homogenous (members are similar to one another) and heterogeneous (members are not like members of other clusters). The clustering method used for North Carolina stream classification is known as K-means. K-means assigns objects (stream gages) into clusters in which each object belongs to the cluster with the nearest means. This
technique was used because it maximizes the difference between classes, i.e., groups of gages, while it minimizes the differences within each class. It should be recognized that using different indices can result in objects being assigned to different classes. Also, different periods of time for the flow record can result in objects switching classes.

The next strategic step after cluster analysis was to identify indices that best explained variation in each class for each of the five major flow components (magnitude, frequency, duration, timing, and rate of change) and four sub-components (low magnitude, high magnitude, overall variability, and flow state volumes). This was accomplished using principal component analysis (PCA), also a multivariate analysis technique. PCA is a procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. In this application only the first principal component was selected and the index with the highest loading value was identified as the best descriptor for each flow component.

The final step was to develop a stream classification tool (SCT) for classifying a stream not used in the original classification and also for classifying a stream that has an altered flow time period. The statistical method used to develop the predicative SCT was discriminate function analysis. In this application, by necessity, predicative coefficients were derived for each class from the cluster analysis results. Consequently, SCT could not be tested using streams not used in the classification; the classifications of such streams are not known. Instead, a test was conducted using the already classified streams and the percent error was determined.

**Initial Combined Classification**

The HPEF (Appendix A) normally classifies gages using only unaltered daily flow records. Gages with altered flow records are classified post priori using a stream classification predictive analysis and the SCT that places them into one of the defined classes. Prior to conducting the hydrologic classification EDF and DENR questioned if this omission, i.e., altered streams, was necessary and if gages with altered flow records were included would the altered gages fall into a separate class?

A test classification was conducted following the methods described above including the 46 gages with altered time periods. Thirteen of the 46 altered gages had both an unaltered and altered time period, while the remaining 33 gages had only an altered time period. The results yielded the same number of classes as the classification using only gages with unaltered time periods (7 as reported in the results section of this report). Furthermore, the altered gages did not fall into a separate class but several gages occurred in each of the unaltered classes. This was interpreted to mean that the altered gages are hydrologically similar to the unaltered classes and not distinctly different. Consequently, the classification proceeded following the HPEF approach using only gages with unaltered time periods. Only the results for the unaltered classification are presented in this report.
A priori Categorization of Unaltered Gages

The 185 stream gages were categorized a priori as either perennial or seasonal. This initial categorization is based on the ecological importance of flow permanence and impermanence in regulating lotic processes and biological patterns. For North Carolina, perennial streams have continuous discharge based on a zero flow count equal to zero days/year, while seasonal streams have a zero flow duration having greater than zero days/year. A harsh category (>30 zero flow days duration) was considered but no streams meeting this criteria were identified. Based on the criterion of being unaltered and => 18 years of daily flow record 22 seasonal and 163 perennial streams were identified.

Classification of Unaltered Seasonal Streams

Principal components analysis (PCA) was applied to 22 seasonal streams using 108 index values. A scree plot based on the decreasing curve of eigenvalues indicated that four factors should be considered. The cumulative variability explained by the four factors was 71 percent. A criterion for the absolute value of the factor loadings, 0.60, was used to reduce the number of indices. Twenty-nine indices had values below this criterion and were removed; 79 indices were retained for the cluster analyses.

To gain insight into the potential number of seasonal stream classes, agglomerative hierarchical clustering (AHC) was initially examined. AHC, in contrast to k-means clustering, does not require the investigator to establish the number of classes but determines the optimal number of classes based on the AHC algorithm. The Pearson correlation coefficient was used for the similarity coefficient; the unweighted pair-group average was selected for the agglomeration procedure. Two primary classes were indicated by the AHC analysis with 10 gages in one class and 12 in the other.

The 79 indices derived from the PCA were standardized to mean = 0 and variance = 1 prior to being used in k-means clustering procedure. A determinate clustering criterion was applied. Results were initially examined for 2 and 3 classes. No best model was identified. The within class variance was large for the 2 class model while the between class variance was small. The variance for the 3 class model was also questionable. In addition, one class had a small n, only 3. Further examination found that the mean daily flow for these 22 streams ranged from 1 to 74. Due to the small sample size, large variance within classes and small between classes, and the narrow range in mean daily flow, only one class, the seasonal class G, was recognized.

Classification of Unaltered Perennial Streams

Principal components analysis (PCA) was applied to 163 perennial streams using 108 index values. A scree plot based on the decreasing curve of eigenvalues indicated that four factors should be considered. The cumulative variability explained by the four factors was 68 percent. A criterion for the absolute value of the factor loadings, 0.60, was used to reduce the number of
indices. Forty-six indices had values below this criterion and were removed; 61 indices were retained for the cluster analyses.

To gain insight into the potential number of perennial stream classes AHC was initially examined. The Pearson correlation coefficient was used for the similarity coefficient; the unweighted pair-group average was selected for the agglomeration procedure. Three primary and six secondary classes were indicated by AHC analysis.

The 61 indices derived from PCA with the strongest absolute loading (>=0.60) were standardized to mean = 0 and variance = 1 prior to being used in k-means clustering procedure. A determinate clustering criterion was applied. Results were initially examined for 4, 5, 6, and 7 classes. The best model maximized the within class variance while the between class was minimized. Six classes were accepted as the best model.

**Stream Class Specific Flow Components**

Once the seasonal and perennial stream classes were established, a separate PCA was conducted on the two major stream types using 95 indices (a subset of the original 108) categorized into nine flow components. The number of indices in each component category is shown in parentheses - general magnitude (n=8), low magnitude (n=12), high magnitude (n=12), frequency (n=12), duration (n=6), timing (n=24), rate of change (n=4), variability (n=11), and Eflow signature (n=6). The highest loading index in each category collectively provides a set of hydrologic indices that best represents the hydrologic variability for each specific class of stream.

**Stream Classification Tool**

The final analysis for perennial streams was a discriminate function analysis (DFA) to develop a predicative model for classifying unclassified streams. That is, streams not used in the original classification or daily flow records developed from synthesized (modeled) data. A step-wise (backwards) option produced the best model.

**RESULTS**

**Hydrologic Classification of Unaltered Gages**

Cluster analysis identified seven hydrologically similar stream classes in North Carolina, six perennial and one seasonal. The derived classification provides a comprehensive catalogue for North Carolina of small, mid-size, and to a degree large streams that, based on ecological theory, differ in major aspects of their ecological structure and function. Most large rivers are missing from the analysis because they have been altered by reservoir or hydropower projects or are ungaged. The classification captures physical gradients across the State that directly and indirectly affects streamflow. The common names assigned to the seven classes reflect their
perception and their size based on median daily flow (index MDF) and in some cases, their general location in the state.

- Perennial class A (coastal streams)
- Perennial class B (small stable streams)
- Perennial class C (large stable streams)
- Perennial class D (small flashy streams)
- Perennial class E (large Piedmont Rivers)
- Perennial class F (medium stable streams)
- Seasonal class G (small seasonal streams)

Figures 2 - 8 show the locations of the seven classes on a major watershed map of the state. These maps indicate stream class distribution and how many different classes are in each major watershed. These maps do not indicate which physical factors (i.e., climate, precipitation, topography, groundwater, and geology) may influence their location based on the array of hydrologic indices used in the classification analysis.

**Figure 2.** Location of Class A streams (n=26) on a map showing 17 major watersheds in the State of North Carolina.
Figure 3. Location of Class B streams \((n=73)\) on a map showing 17 major watersheds in the State of North Carolina.

Figure 4. Location of Class C streams \((n=10)\) on a map showing 17 major watersheds in the State of North Carolina.

Figure 5. Location of Class D streams \((n=36)\) on a map showing 17 major watersheds in the State of North Carolina.
Figure 6. Location of Class E streams \((n=5)\) on a map showing 17 major watersheds in the State of North Carolina.

Figure 7. Location of Class F streams \((n=13)\) on a map showing 17 major watersheds in the State of North Carolina.
Figure 8. Location of Class G streams \( (n=22) \) on a map showing 17 major watersheds in the State of North Carolina.

Four indices are presented below to describe class differences – magnitude of flow (index MDF) in cubic feet per second (cfs); predictability (index TA2) of overall flow variation expressed as a percent that indicates if a stream has, overall, stable flow or flashy flow; a dimensionless baseflow ratio (index BF1) between the median of the 7 day average low flow and mean annual flow that reflects flow stability usually due to groundwater influence; and the month with the most high flows (index HFM - >75th percentile and =<90th percentile). Box plots are used to present these data that show a median value (horizontal bar), the 25\textsuperscript{th} and 75\textsuperscript{th} percentile range (box), and the complete range (’T’ bars) with the exception of HFM that is a single median value, a month with January being month 1.

Median daily flows (index MDF) for the seven perennial stream classes (Figure 9) indicate their most obvious difference, their relative size in terms of the magnitude of flow. Using relative terms, Classes A, B, and D, are small perennial streams with a median daily flow of 126, 97, and 49 cfs respectively. Class G streams are very small seasonal streams with a medium daily flow of 10 cfs. Class F, with a median daily flow of 490 cfs can be considered medium in discharge while Class C is generally considered a large river with a median daily flow of 1294 cfs. And finally, Class E can be considered big rivers with a median daily flow of 2470 cfs.

Predictability (index TA2), expressed as a percent, indicates how stable or how much fluctuation a stream exhibits. For example, a spring fed stream or a ground water influenced stream would be predictable and very stable. A stream influenced by, for example, an impervious soil or surface would be considered ‘flashy’. Classes A, D, and G streams have a
relatively low predictability, 51%, 51%, and 36% respectively (Figure 10) and thus fluctuate with
greater magnitude and frequency and can be considered ‘flashy’ streams. Classes C, E, and F are
more predictable and therefore considered to have stable flow. Class B is intermediate and
could be considered moderately stable or moderately flashy.

Baseflow Index BF1 is the ratio of the median of the 7 day average minimum and the mean
annual flow. This ratio indicates if the stream class has a high or low minimum low flow
compared to its mean annual flow. For example, a stream in Class A with a mean annual flow
of 100 cfs and a 7 day average minimum flow of 4 cfs would have a BF1 of 0.04, that is, 4
percent of the mean annual flow. In contrast, a stream in Class B with a mean annual flow of
100 cfs and a 7 day average minimum flow of 25 cfs would have a BF1 of 0.25, that is, 25
percent of the mean annual flow. Classes A, D, and G all have a low BF1 ratio (Figure 11). The
variability of the ratio is moderate for Classes A and D and small for G the seasonal class. Classes B, C, E, and F have high ratios with Classes B and E having large variability in the data but low variability in the ratio.

The month with the most high flows (index HFM) (Figure 12) occurs in the same month (December) for Classes A, D, and G. The high flow in the remaining four classes occurs during three different months, April for Class B, May for Classes C and F, and June for Class E.

The following seven sections present an example hydrograph for each class using the central object (gage) identified from the K-means cluster analysis. In addition, each class is shown on a state map with 11 major geologic belts, one of several factors such as climate, precipitation,
topography, groundwater, and geology that influence which class they belong to and, subsequently, their location.

**Perennial Class A – Coastal Streams**

The example hydrograph (Figure 13) for the Class A streams ($n=26$) is Northeast Cape Fear River near Chinquapin, West of the city of Jacksonville. The high flows occur in March while the lowest flow occurs in October. Though the high flow period occurs in late winter to early spring, there is an indication of a bimodal aspect with a smaller second high flow occurring during the summer. The low flows occur over an extended time – May through October. In addition, this stream shows a significant drop in the high flow during the month of April. The low flow season is somewhat long, May through October. The coastal streams are, as expected, located the eastern third of the state and influenced by the coastal weather patterns (Figure 14). There are, however, two streams with similar hydrologic regimes located in the extreme western portion of the state.

![Average Annual Hydrograph](image)

**Figure 13.** Example hydrograph for Class A streams - Northeast Cape Fear River near Chinquapin, North Carolina.
Figure 14. Location of Class A streams overlaid on a generalized geologic belt map of North Carolina.

**Perennial Class B - Small Stable Streams**

The example hydrograph for this class ($n=73$) is Davidson River near Brevard (Figure 15). This gage has a high base flow and a lengthy (6 months) high flow season that occurs from December through May. The low flow season is from July through September. Overall this hydrograph has a gradual rise and gradual fall pattern to it. Class B streams are located predominately in the western third of the state (Figure 16) ranging from the northern boundary to the southern boundary. A small number (7) of gages are located in the central portion, again ranging from the southern boundary to almost the northern boundary.

Figure 15. Example hydrograph for Class B streams - Davidson River near Brevard.
Figure 16. Location of Class B streams overlaid on a generalized geologic belt map of North Carolina.

**Perennial Class C - Large Stable Streams**

The example hydrograph for the class (n=10) is the French Broad River at Marshall (Figure 17).

![Figure 17. Example hydrograph for Class C streams - French Broad River at Marshall, North Carolina.](image_url)

The high flow for this stream occurs in late March or early April. The lowest flow occurs sometime during September, or October. The higher flows can start in December and end mid April, rather abruptly. The low flow season is short, September through October. Class C streams are apparently hydrologically similar regardless of where they are located and, consequently, are found throughout the State from East to West (Figure 18).
Perennial Class D - Small Flashy Streams

The example hydrograph for this class \((n=36)\) is Abbotts Creek at Lexington (Figure 19). The high flow for this example occurs at the very end of February or very early March. The lowest flow can occur over an extended period of time, July through November. High flow can occur from November to May. Note also the small difference between the 25\(^{th}\) and the 50\(^{th}\) percentile range and even the 75\(^{th}\) percentile at times during the year. These streams are predominately located in the central portion of the State with a few exceptions being found in the coastal plain (Figure 20).
Perennial Class E - Large Piedmont Rivers

This class represents a small number \((n=5)\) of rivers because it contains the largest rivers in the State. In addition, many of the large rivers were not included in the analysis because they have been altered by water development projects. The example hydrograph is the Cape Fear River at William O Huske Lock near Tarheel (Figure 21). The high flow for this stream occurs typically in February. The locations of the five large Piedmont streams are shown in Figure 22.
Perennial Class F - Medium Stable Streams

The final perennial class \((n=13)\) is one of two stable stream classes, small and medium. The example hydrograph for the Class F is the Pigeon River near the city of Hepco (Figure 23).

The high flow occurs in March while the lowest flow in September or October. While this class represents stable streams there is more variability apparent on the rising limb than on the falling limb. Note as with the other stable stream class (B) the range between the 25\(^{th}\) and 75\(^{th}\) percentile is narrow. The locations of the Class F streams are shown in Figure 24. They are predominately in the western half of the State.
Seasonal Class G – Small Seasonal Streams

The seasonal class \((n=22)\) is primarily defined by zero flow duration being greater than zero days/year. An example hydrograph for this class is shown in Figure 25. The high flow generally occurs in February and zero flow can occur from June to November. High flows occur typically during January through March. The 22 seasonal stream gages are mostly located in the central and eastern part of the state except for one that occurs in the Broad watershed (Figure 8).

Figure 24. Location of the Class F streams overlaid on a generalized geologic belt map of North Carolina.

Figure 25. An example hydrograph for a Class G seasonal stream - Big Bear Creek near Richfield, North Carolina.
Figure 26. Location of Class G streams overlaid on a generalized geologic belt map of North Carolina.

Stream Class Specific Flow Components

The class specific indices identified as the best descriptors for nine flow components associated with the seven stream classes identified in North Carolina are listed in Table 2. These indices

Table 2. Nine class specific flow components for the seven stream classes in North Carolina.

<table>
<thead>
<tr>
<th>FLOW COMPONENT</th>
<th>Perennial Class A Coastal Streams</th>
<th>Perennial Class B Small Stable Streams</th>
<th>Perennial Class C Medium Runoff</th>
<th>Perennial Class D Small Flaschy</th>
<th>Perennial Class E Large Piedmont</th>
<th>Perennial Class F Medium Stable</th>
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<td>BF2</td>
<td>MDF</td>
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<td>AFD</td>
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<td>LFD</td>
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<td>VHFMR</td>
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<td>LFIS</td>
<td>VHFIS</td>
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<td>HFIS</td>
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uniquely describe nine hydrologic aspects of each stream class independently. The primary
index in each flow component for each class best explains the variance among the indices in
each component. These class indices can be used as class standards to maintain hydrological
variability and the hydrologic characteristics of each stream class. Flow alteration–ecological
response relationships developed for a class or sub-classes based on other geological or
biological criteria can supplement class standards.

Stream Classification Tool

The overall predicative accuracy of the SCT for the six classes was derived from a confusion
matrix. The accuracy was overall 95% with a range of 85% to 100%. A daily flow record is
required as input to assign an unclassified stream to one of the six perennial stream classes or
the seasonal steam class identified in North Carolina.

North Carolina Customized StreamFlow Software

EFS’s StreamFlow software was customized for the North Carolina stream classes and has the
following capabilities:

- Classify unclassified streams.
- Identify a baseline and altered time period (if present) for unclassified streams.
- Identify and integrate hydroecological processes and timing events present for the
  baseline time period.
- Characterize pre and post hydrologic variation of magnitude, frequency, duration,
  timing, variability, and rate of change at multiple temporal (daily, monthly, annually)
  scales using the nine class specific indices and 108 indices.
- Develop class and reach specific ecological flow standards.
- Identify stream class reaches for conducting flow unaltered and altered - ecological
  response relationships.
- Evaluate current and proposed alterations to planning and regulatory ecological flow
  standards.
References Cited


EFS, INC.
HYDROECOLOGICAL PROCESS FOR ENVIRONMENTAL FLOWS (HPEF)

1. HYDROLOGIC FOUNDATION
   Historic Daily Stream Flow Data (USGS)
   Determine Baseline and Altered Time Period(s)
   Database for Gage/Modeled Time Periods in StreamFlow Software
   User Developed Modeled Daily Stream Flow Data

2. STREAM CLASSIFICATION
   A priori Classification of Streams
   Perennial Streams Zero Flow count
   Intermittent Streams Zero Flow Duration
   Intermittent Harsh Streams Zero Flow Duration
   Classification of Perennial Streams
   Classification of Intermittent Streams
   "X" Perennial Classes ID Nine Class Specific Indices for Six Flow Components (MFDTVR)
   "X" Intermittent Classes ID Nine Class Specific Indices for Six Flow Components (MFDTVR)

3. STREAM CHARACTERIZATION
   StreamFlow Software Daily Flow Database
   Baseline and Altered Time Periods
   Getting to Know Your Stream
   Recurrence Interval, Flood Frequency
   12 Annual and Monthly Flow Statistics, Exceedence Plots
   - Hydrograph - Baseflow, 20 Percentiles Ranges, Three Time Steps
   Five Flow States, Nine Flow State Indices, 10 Component Group Indices
   Eflow Signature for 5 Flow States

Stream Classification Tool
## APPENDIX B

REVISED AND CORRECTED MAY 2, 2010 (CLASS "G" = INTERMITTENT)

<table>
<thead>
<tr>
<th>STATION NAME</th>
<th>NUMBER</th>
<th>UNALTERED OR ALTERED</th>
<th>CLASS</th>
<th>DRAINAGE AREA (Sq. Miles)</th>
<th>START YEAR</th>
<th>END YEAR</th>
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## Appendix C. Index Definitions

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<td>Average flow count. Average number of days per year when flow is &gt; 25th percentile and &lt;= 75th percentile</td>
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<td>Average flow duration. Mean duration of average flow states (Number of days per event)</td>
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<td>Average flow events. Average flow pulse count (Median # events per year &gt; 25th percentile and &lt;= 75th percentile)</td>
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<td>Ratio of the average flow volume for maximum month to volume per month uniformly distributed</td>
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<td>Ratio of the average flow volume for maximum season to volume per season uniformly distributed</td>
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<td>Average flow state variability (Percent)</td>
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<td>Median annual maximum flow</td>
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<td>AMXV</td>
<td>Variability in annual maximum flow</td>
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<td>BF1</td>
<td>Baseflow index 1 (Median of 7 day average minimum/mean annual flow for each year)</td>
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<td>BF2</td>
<td>Median baseflow computed using USGS HYSep algorithm</td>
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<td>Ratio of total baseflow to total flow using BF2</td>
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<td>Ratio of the high flow volume for maximum season to volume per season uniformly distributed</td>
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<td>High flow pulse event variability</td>
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<td>Low flow events. Low flow pulse count (Mean # events per year &gt; 10th percentile and &lt;= 25th percentile)</td>
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<td>LFV</td>
<td>Low flow pulse event variability (Percent)</td>
<td>Percent</td>
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<td>Median flow for the period of record</td>
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<td>MH2</td>
<td>Median maximum monthly flow for February</td>
<td>CFS</td>
</tr>
<tr>
<td>MH3</td>
<td>Median maximum monthly flow for March</td>
<td>CFS</td>
</tr>
<tr>
<td>MH4</td>
<td>Median maximum monthly flow for April</td>
<td>CFS</td>
</tr>
<tr>
<td>MH5</td>
<td>Median maximum monthly flow for May</td>
<td>CFS</td>
</tr>
<tr>
<td>MH6</td>
<td>Median maximum monthly flow for June</td>
<td>CFS</td>
</tr>
<tr>
<td>MH7</td>
<td>Median maximum monthly flow for July</td>
<td>CFS</td>
</tr>
<tr>
<td>MH8</td>
<td>Median maximum monthly flow for August</td>
<td>CFS</td>
</tr>
<tr>
<td>MH9</td>
<td>Median maximum monthly flow for September</td>
<td>CFS</td>
</tr>
<tr>
<td>MH10</td>
<td>Median maximum monthly flow for October</td>
<td>CFS</td>
</tr>
<tr>
<td>MH11</td>
<td>Median maximum monthly flow for November</td>
<td>CFS</td>
</tr>
<tr>
<td>MH12</td>
<td>Median maximum monthly flow for December</td>
<td>CFS</td>
</tr>
<tr>
<td>ML1</td>
<td>Median minimum monthly flow for January</td>
<td>CFS</td>
</tr>
<tr>
<td>ML2</td>
<td>Median minimum monthly flow for February</td>
<td>CFS</td>
</tr>
<tr>
<td>ML3</td>
<td>Median minimum monthly flow for March</td>
<td>CFS</td>
</tr>
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<td>Median minimum monthly flow for April</td>
<td>CFS</td>
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</tr>
<tr>
<td>ML11</td>
<td>Median minimum monthly flow for November</td>
<td>CFS</td>
</tr>
<tr>
<td>ML12</td>
<td>Median minimum monthly flow for December</td>
<td>CFS</td>
</tr>
<tr>
<td>MR50</td>
<td>Median of the fifty percent range (75th 25th) percentile for each year</td>
<td>Count</td>
</tr>
<tr>
<td>MR60</td>
<td>Median of the sixty percent range (80th 20th) percentile for each year</td>
<td>Count</td>
</tr>
<tr>
<td>MR90</td>
<td>Median of the ninety percent range (95th 5th) percentile for each year</td>
<td>Count</td>
</tr>
<tr>
<td>MTV</td>
<td>Median total annual volume</td>
<td>1000 acre feet</td>
</tr>
<tr>
<td>NR</td>
<td>Number of reversals per year</td>
<td>Count</td>
</tr>
<tr>
<td>NRV</td>
<td>Variability in reversals</td>
<td>Percent</td>
</tr>
<tr>
<td>PRC</td>
<td>Percent of record that are rises</td>
<td>Percent</td>
</tr>
<tr>
<td>RR</td>
<td>Rise rate</td>
<td>CFS/day</td>
</tr>
<tr>
<td>RRV</td>
<td>Variability in rise rate</td>
<td>Percent</td>
</tr>
<tr>
<td>TA1</td>
<td>Constancy</td>
<td>Percent</td>
</tr>
<tr>
<td>TA2</td>
<td>Predictability of flow</td>
<td>Percent</td>
</tr>
<tr>
<td>TQM</td>
<td>Fraction of time flows are &gt; annual mean</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>VHFC</td>
<td>Very high flow count. Average number of days per year when flow is &gt; 90th percentile flow</td>
<td>Days/year</td>
</tr>
<tr>
<td>VHFD</td>
<td>Very high flow duration. Mean duration of very high flow pulses (Number of days per event)</td>
<td>Days/event</td>
</tr>
<tr>
<td>VHFE</td>
<td>Very high flow events. Very high flow pulse count (Mean # events per year &gt; 90th percentile)</td>
<td>Events/year</td>
</tr>
<tr>
<td>VHFS</td>
<td>Percentage of daily flow volume for each year that are very high flows (90th&gt;flow)</td>
<td>Percent</td>
</tr>
<tr>
<td>VHFM</td>
<td>Index for month with the most very high flow (90th&gt;flow) volume</td>
<td>1 to 12</td>
</tr>
<tr>
<td>VHFMR</td>
<td>Ratio of the very high flow volume for maximum month to volume per month uniformly distributed</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>VHFS</td>
<td>Index for season (3 month period) with the most very high flow (90th&gt;flow) volume</td>
<td>1 to 12</td>
</tr>
<tr>
<td>VHFMR</td>
<td>Ratio of the very high flow volume for maximum season to volume per season uniformly distributed</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>VHFE</td>
<td>Very high flow event variability ( Percent)</td>
<td>Percent</td>
</tr>
<tr>
<td>VLFC</td>
<td>Very low flow count. Median number of days per year when flow is &lt;= 10th percentile and &gt; 0.</td>
<td>Days/year</td>
</tr>
<tr>
<td>VLFD</td>
<td>Very low flow duration. Median duration of very low flow states (Number of days per event)</td>
<td>Days/event</td>
</tr>
<tr>
<td>VLFE</td>
<td>Very low flow events. Low flow pulse count (Median # events per year &lt;= 10th percentile and &gt; 0)</td>
<td>Events/year</td>
</tr>
<tr>
<td>VLFIS</td>
<td>Percentage of daily flow volume for each year that are very low flows (0&lt;flow&lt;=10th)</td>
<td>Percent</td>
</tr>
<tr>
<td>VLFM</td>
<td>Index for month with the most very low flow (0&lt;flow&lt;=10th) volume</td>
<td>1 to 12</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
<td>Units</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
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<tr>
<td>VLFMR</td>
<td>Ratio of the very low flow volume for maximum month to volume per month uniformly distributed</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>VLFS</td>
<td>Index for season (3 month period) with the most very low flow (0&lt;flow&lt;=10th) volume</td>
<td>1 to 12</td>
</tr>
<tr>
<td>VLFSR</td>
<td>Ratio of the very low flow volume for maximum season to volume per season uniformly distributed</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>VLFV</td>
<td>Very low flow pulse event variability</td>
<td>Percent</td>
</tr>
<tr>
<td>ZFC</td>
<td>Median number of zero flow days per year</td>
<td>Days/year</td>
</tr>
<tr>
<td>ZFED</td>
<td>Average zero flow event duration</td>
<td>Days/year</td>
</tr>
<tr>
<td>ZFE</td>
<td>Average number of zero flow events per year</td>
<td>Events/year</td>
</tr>
<tr>
<td>ZFIS</td>
<td>Percentage of daily flows for each year that are zero flows</td>
<td>Percent</td>
</tr>
<tr>
<td>ZFM</td>
<td>Index for month with the most zero flow days</td>
<td>1 to 12</td>
</tr>
<tr>
<td>ZFMR</td>
<td>Ratio of the number of zero flow days for maximum month to number of days per month uniformly distributed</td>
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<td>Index for season (3 month period) with the most zero flow days</td>
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<td>ZFSR</td>
<td>Ratio of the number of zero flow days for maximum season to number of days per season uniformly distributed</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>ZFV</td>
<td>Zero flow event variability</td>
<td>Percent</td>
</tr>
<tr>
<td>7Q10</td>
<td>Minimum 7 day average flow with a return interval of 10 years</td>
<td>CFS</td>
</tr>
<tr>
<td>7Q2</td>
<td>Minimum 7 day average flow with a return interval of 2 years</td>
<td>CFS</td>
</tr>
</tbody>
</table>