# Virginia Flow-Ecology Modeling Results: An Initial Assessment of Flow Reduction Effects on Aquatic Biota

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Prepared in cooperation with the Virginia Department of Environmental Quality

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# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | **Area** | |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | **Flow rate** | |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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# Abbreviations

| | |
|---|---|
| B | y-intercept of the regression line |
| EPT[1] | Ephemeroptera Plecoptera Tricoptera |
| HWI | Virginia Healthy Watersheds Initiative |
| IHA | indicators of hydrologic alteration |
| M | slope of the regression line |
| N | number of samples in a linear regression |
| p | measure of statistical significance |
| $r^2$ | estimate of the amount of variability described by the linear regression model |

[1] See ScienceBase (Rapp and Reilly, 2017) for abbreviations of bio metric and hydro metric terms: https://doi.org/10.5066/F7ZW1J42.

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# Contents



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# Background

- The U.S. Geological Survey (USGS), in cooperation with the Virginia Department of Environmental Quality (DEQ), reviewed a previously compiled set of linear regression models to assess their utility in defining the response of the aquatic biological community to streamflow depletion.
- As part of the 2012 Virginia Healthy Watersheds Initiative (HWI) study conducted by Tetra Tech, Inc., for the U.S. Environmental Protection Agency (EPA) and Virginia DEQ, a database with computed values of 72 hydrologic metrics, or indicators of hydrologic alteration (IHA), 37 fish metrics, and 64 benthic invertebrate metrics was compiled and quality assured (Tetra Tech, Inc., 2012). Hydrologic alteration was represented by simulation of streamflow record for a pre-water-withdrawal condition (baseline) without dams or developed land, compared to the simulated recent-flow condition (2008 withdrawal simulation) including dams and altered landscape to calculate a percent alteration of flow (Tetra Tech, Inc., 2012). Biological samples representing the existing populations represent a range of alteration in the biological community today (see Tetra Tech., 2012, for details).
- For this study, all 72 IHA metrics, which included more than 7,272 linear regression models, were considered. This extensive dataset provided the opportunity for hypothesis testing and prioritization of flow-ecology relations that have the potential to explain the effect(s) of hydrologic alteration on biological metrics in Virginia streams.

# Objectives

- Describe the process used to evaluate and identify significant hydro metrics and associated bio metrics from the HWI study dataset.
- Describe flow-alteration gradients that indicate potential ecological degradation in Virginia streams and place into context of similar published investigations.
- Present the significant flow-ecology regression relations in summary figures that illustrate the general pattern of decrease or degradation of the biological community coincident with modeled flow alteration.
- Develop flow-ecology hypotheses about flow-regime influences on biological change within Virginia streams and suggest areas for future additional study.

# Purpose and Scope

- This report describes the current state of understanding from the first year of collaboration with DEQ as USGS reviewed and analyzed the HWI study outputs (Tetra Tech, Inc., 2012) to highlight relations that may be significant and useful in future study. The IHA (hydro metrics in this report) from modeled baseline and recent-condition streamflow simulations were associated with biological responses (bio metrics) represented by median values from historical biological samples at each location.
- The report identifies any linear regression models that describe the effects of decreasing hydro metrics on biological endpoints in Virginia streams. These linear regression models are most pertinent to building understanding for the water-supply permitting process because they represent flow depletion by various management means (withdrawals, reservoir storage, etc.).
- This report documents data and methods used for analysis and details the significant flow-ecology relations presented in the resulting data tables. The ecological mechanism(s) potentially affected by modeled flow alterations also are summarized.
- This report also describes the data-classification schemes used to examine the role of geographic distribution in flow-ecology relations.

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# Study Area, Datasets, and Maps

Study Area: Watersheds throughout the Commonwealth of Virginia for which simulated flow conditions were available represent drainage areas from 7.3 to 7,879 square miles ($mi^2$), with the majority of sites ranging from 112 to 680 $mi^2$. The sites were classified as statewide or by region. The three regions in Virginia were defined by major drainage and physiographic boundaries as the Ohio River drainages, Atlantic non-Coastal Plain, and Atlantic Coastal Plain.

Previous Data, Analysis Methods, and Summaries: All data used for this study were part of a larger dataset developed by Tetra Tech, Inc., for VA DEQ in 2012. Biological sample locations close to the outlet points of watersheds in the VA DEQ water-supply model (Virginia Department of Environmental Quality, 2016) were associated with hydro metrics for each respective watershed. Bio metric data, as they were originally compiled, represent median values of all multiyear sample data (including replicates) for each site that was associated with the outlet point. Dates range from 1972 to 2010 for fish and 1993 to 2010 for benthic invertebrates. At present (2017), raw-data summaries are available through the VA DEQ Water Supply Planning Program.

# Study Area, Datasets, and Maps

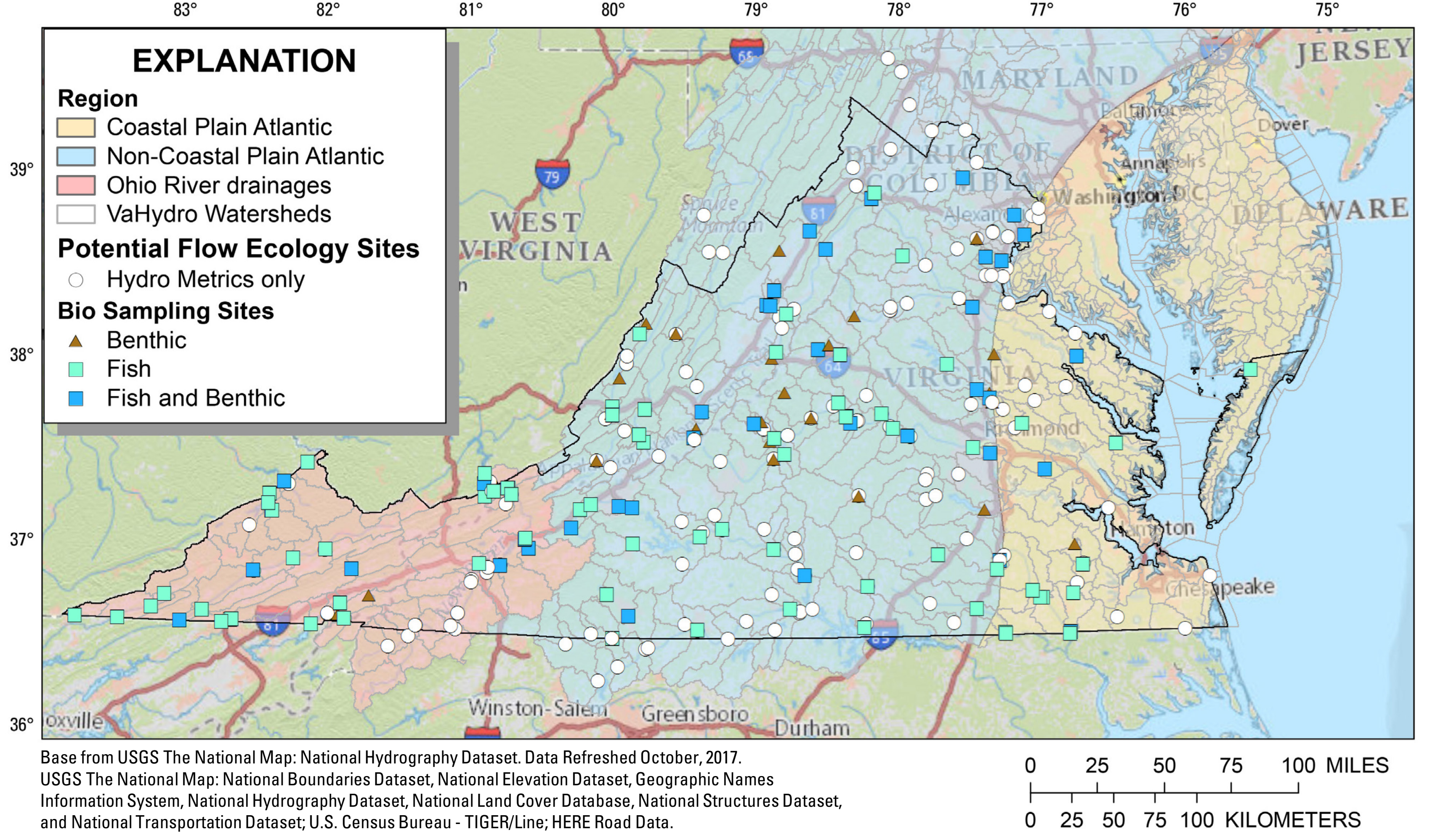
## Datasets used in this evaluation:

- Hydro metrics represented a percent change or percent flow alteration: 304 watersheds (Tetra Tech, Inc., 2012; Virginia Department of Environmental Quality, 2016).
- Fish metrics: 137 watersheds with paired streamflow and fish data (Tetra Tech, Inc., 2012). Data representing the effects of decreasing hydro metrics on fish metrics resulted in linear regression models with:
  - 68 data points statewide,
  - 19 data points in the Ohio River drainages,
  - 30 data points in the Atlantic non-Coastal Plain, and
  - 15 data points in the Coastal Plain.
- Benthic metrics: 77 watersheds with paired streamflow and benthic data (Tetra Tech, Inc., 2012). Data representing the effects of decreasing hydro metrics on benthic metrics resulted in linear regression models with:
  - 32 data points statewide (The small number of data points limited the analyses to statewide classification only).

(For regression-specific n-values, see results tables in supplemental information in ScienceBase https://doi.org/10.5066/F7ZW1J42.)

# Study Area, Datasets, and Maps

## Bio monitoring and hydro modeling sites in Virginia




Base from USGS The National Map: National Hydrography Dataset. Data Refreshed October, 2017.
USGS The National Map: National Boundaries Dataset, National Elevation Dataset, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; U.S. Census Bureau - TIGER/Line; HERE Road Data.

Watersheds from Krstolic and others (2005).
Regions from the Healthy Watershed Investigation (Tetra Tech, Inc., 2012).
Monitoring sites from the Ecological Data Application System (Virginia Department of Environmental Quality).
Albers equal area projection, North American Datum of 1983.

# Study Area, Datasets, and Maps
## Ecological Data Application System (EDAS) in Virginia

A primary effort of the HWI study (Tetra Tech, Inc., 2012) included checking locations, checking duplicate records, and compiling multiple-source data in EDAS.

- Virginia's EDAS database has eight sources:
  - DEQ Probabilistic Monitoring (ProbMon) database,
  - Virginia Department of Game and Inland Fisheries Virginia Fish and Wildlife Information Service (VaFWIS) database,
  - Two EPA sources: Medical Advocates for Healthy Air (MAHA) and Mid Atlantic Integrated Assessment (MAIA) databases,
  - USGS National Water Quality Assessment (NAWQA) biological database (BioData),
  - Virginia Commonwealth University INteractive STream Assessment Resource (INSTAR) database,
  - Multistate Aquatic Resources Information System (MARIS) including Tennessee, and
  - Virginia Department of Conservation and Recreation Natural Heritage database.

# Study Area, Datasets, and Maps
## Ecological Data Application System (EDAS) in Virginia

- Tetra Tech, Inc. (2012), noted that fish data were identified to species; however, the level of taxonomic identification varied among benthic datasets. Although database functions were created to implement Operational Taxonomic Units (OTUs) to reconcile differences in taxonomy among sources, it does not appear that the OTUs were fully implemented to derive family-level consistency across all agency collections.

- Efforts were made by Tetra Tech, Inc. (2012), to resolve issues of ambiguous taxa following Cuffney and others (2007), but were confounded by differing levels of taxonomic identification across agencies. It does not appear that harmonization of taxonomic groups was conducted among all eight sources to ensure that each characterized the same groups of organisms.  A range of 1 to 30 taxa for midges (nt_Chiro), with the majority of sites having 1-2 midge taxa, indicates that a mix of family-level and genus-level data may have been used for this compilation.

- It is for these reasons that only percent-composition results are presented for benthic data.  The percent-abundance metrics were less affected by data source than the number-of-taxa metrics.

# Study Area, Datasets, and Maps

## Limitations:

- Various decisions were made, per Virginia DEQ's request at the onset of the study, to work with the data "as is" without transformations or resampling of the bio metric data and hydro metric data.
- Samples were not subsampled, standardized, or adjusted to account for different sample sizes. Number of individuals for fish ranged from 4 to 4,000, and for benthic invertebrates ranged from 71 to 580.
- Samples were not transformed to reduce the magnitude of difference that rare species may have.
- For the first year of collaboration, no new implementations of OTUs to standardize the benthic data and remove ambiguous taxa were completed.
- Hydro metrics were not log-transformed to develop better fit log-linear distributions. It was beyond the scope of this initial study to further examine nonlinear relations observed within the flow-ecology plots.
- Bio metric data, as they were originally compiled, represent median values of all replicate or multiyear sample data for each site. Dates range from 1972 to 2010 for fish and 1993 to 2010 for benthic invertebrates.

# Approach and Methods

- A systematic approach was developed to evaluate the 7,200+ correlations of hydrologic-change metric to biological response in order to isolate significant relations.
- Separate flow-ecology regressions were developed for hydrologic change that was positive or negative, indicating increasing or decreasing hydro metrics, respectively.
- Summary statistics for the flow-ecology regressions were exported to tabular form and those with significant p-values (alpha = 0.1) were identified.
- Significant summary statistic tables were sorted by the regression slope to isolate various cases of hydrologic change. This study focused on decreasing hydro metrics and the corresponding bio metric responses.
- Scatter plots of these relations were developed and visually evaluated.
- Summary figures that illustrate the general pattern of degradation of the biological community coincident with multiple hydro metrics were developed to illustrate magnitude of degradation and collinearity of various metrics.

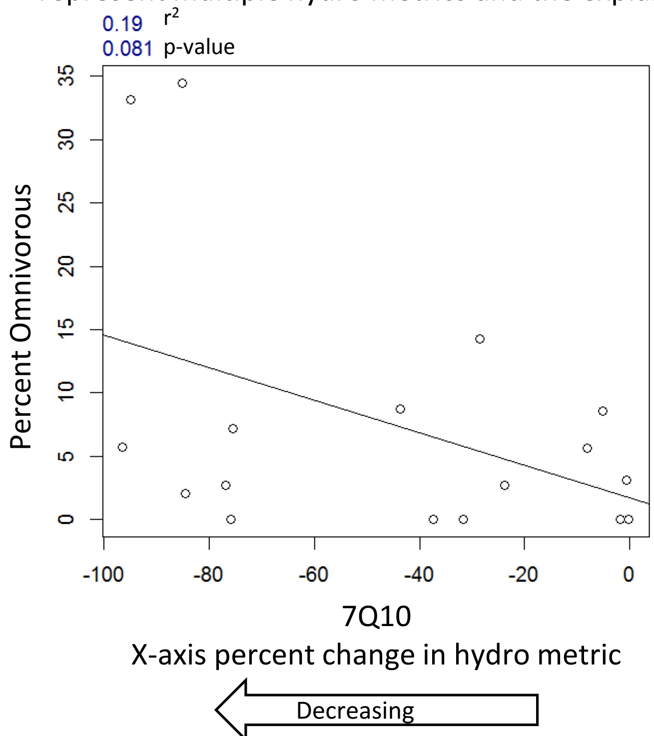
# Approach and Methods

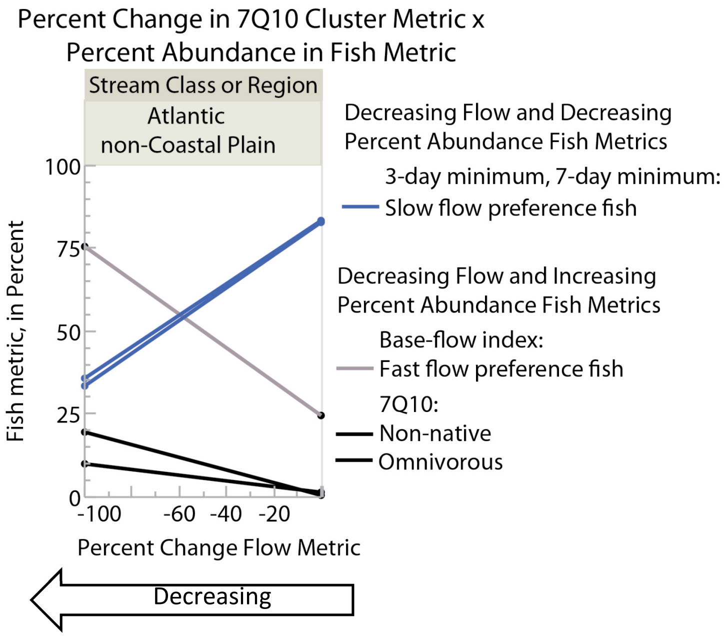
## Key to the regression scatter plots:

Linear regression scatter plots were created using an open-source statistics package RStudio version 0.99.482 (2009–2015 RStudio, Inc.), and represent the "left side" of the regression, or the sites with decreasing percent change in hydro metrics (bottom left graph). For further analysis, separate lines described by the regression equations were plotted together for the highly correlated, clustered hydro metrics (bottom right graph, page 35) to show multiple responses in one figure.

- The y-axis represents the bio metric response in percent abundance of species or biologic grouping. Each metric abbreviation is described in the supplemental material at https://doi.org/10.5066/F7ZW1J42.

- The x-axis represents the <u>percent change</u> in hydro metric, or percent flow alteration. The clustered metric plots (right) represent multiple hydro metrics and the explanation defines the specific x-axis variables.




Example of scatter plot of bio metric response to the lowest 7-day flow in a 10-year period (7Q10) (left), and summary figure with numerous regressions illustrated (right).

# Approach and Methods
## Visual Assessment and Review Decision Process and Documentation

- The sorted, significant summary statistics tables were assessed to determine whether the data conform to linear regression assumptions of normality and constant variance.
- The number of data points, distribution of points, and linear nature of the regression models were evaluated.
- Both linear and potentially valid nonlinear patterns of biological response were noted.
- Each plot was examined and designated as keep, out, or needs further review.
- During this process, thresholds or gradients that need further investigation were documented.

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# Approach and Methods
## Visual Assessment and Review Decision Process and Documentation

- Classify each flow-ecology plot as Keep | Out | Review.
- Document metrics within summary tables at https://doi.org/10.5066/F7ZW1J42 on the basis of the strength of the regression.
  - Document as "Keep" if the linear regression assumptions are generally met, or if a nonlinear pattern exists that could be addressed with transformation.
    - Describe increasing or decreasing hydro metric and increasing or decreasing bio metric.
  - Document as "Out" if the data do not meet linear regression assumptions in gross ways.
  - Document as "Review" if further examination of leverage points would elucidate the quality of relations.
    - For example, nonlinear, outlier, examine classification, examine left side only (x-axis range restricted in original plot).
  - Document as "Keep Quantile" if the data appear categorical but the decrease or increase in the bio metric appears valid, yet nonlinear.

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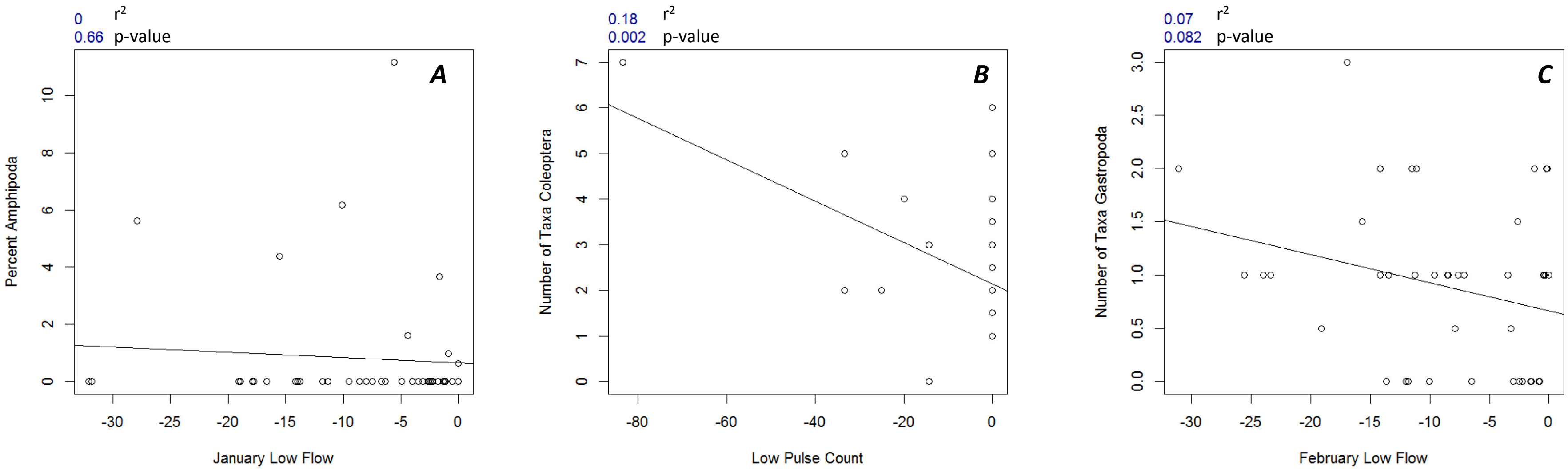
# Approach and Methods

## Scatter plots reviewed to determine if they represent significant and valid linear regressions

Ideally, Y is linearly related to X, data are representative, variance of residuals is constant, and the residuals are independent and normally distributed (Helsel and Hirsch, 2002).




The graphs above represent pathologies noted in the Virginia dataset that resulted in exclusion from the final dataset. *A*, zeros dominate the bio metric values with few other values scattered; *B*, few data points make up the regression and an outlier determines the slope, and *C*, values are distributed at each y-axis category across a wide range of hydro metric percent change.

# Approach and Methods
## Example of tabular results

| | | | Regression Summary Statistics: Decreasing Hydro Metric | | | | | | Regression Summary Statistics: Increasing Hydro Metric | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hydro metric | Bio metric | Stream class or region | $R^2$ | P | B | M (Slope) | N | | $R^2$ | P | B | M (Slope) | N | Total N | Evaluation | Keep / out / review |
| July | nt_benthic | Atlantic non-Coastal Plain | 0.147 | 0.071 | 16.673 | 0.481 | 23 | | 0.048 | 0.130 | 8.446 | -0.063 | 49 | 72 | decrease in July mean = decrease in NT benthic fish | keep |
| July | nt_Cent | Atlantic non-Coastal Plain | 0.147 | 0.070 | 3.685 | 0.146 | 23 | | 0.007 | 0.571 | 2.371 | -0.008 | 49 | 72 | decrease in July mean = decreasein NT centrarchids | keep |
| X3.day.minimum | nt_Cent | Atlantic non-Coastal Plain | 0.342 | 0.022 | 3.193 | 0.036 | 15 | | 0.027 | 0.219 | 2.580 | -0.002 | 57 | 72 | decrease in 3 day min = decrease in NT centrarchids; plot left, looks sparse | keep |
| X7.day.minimum | nt_Cent | Atlantic non-Coastal Plain | 0.324 | 0.054 | 2.729 | 0.030 | 12 | | 0.027 | 0.210 | 2.643 | -0.003 | 60 | 72 | decrease in 7day min = decrease in NT centrarchids; sparse | keep |
| Extreme.low. duration | nt_darter | Atlantic non-Coastal Plain | 0.071 | 0.092 | 1.636 | 0.020 | 41 | | 0.014 | 0.633 | 1.073 | 0.009 | 19 | 70 | decrease in extreme low duration = decrease in NT darters; keep, lots of zeros | keep |
| August....Low.Flow | nt_flow_fast | Atlantic non-Coastal Plain | 0.187 | 0.045 | 6.816 | 0.241 | 22 | | 0.096 | 0.029 | 3.584 | -0.043 | 50 | 72 | decrease or increase in August Low flow = decrease in nt flow fast fish | keep |

- Each row represents two linear regression models between a percent change in a hydro metric and the response of a bio metric. Decreasing and increasing hydro metrics (negative or positive percent change) were regressed and summarized separately in RStudio version 0.99.482 (2009-2015 RStudio, Inc.) with R version 3.2.3 (2015-12-10) "Wooden Christmas-Tree" (The R Project for Statistical Computing, https://www.r-project.org/).
- All decreasing hydro metrics were documented in the 'Evaluation' column, whereas only some of the increasing hydro metrics were evaluated for possible use in future work.
- The tables include statistical significance of each relation, direction of change, and evaluation comments describing reasoning for including or excluding the relation. For example, "leverage resulting from outliers" or "distribution of points that do not meet assumptions of linear regression" was noted.

# Approach and Methods
## Clustering of Hydro Metrics to Characterize the Flow Regime

- Principal Components Analysis (PCA) clustering was conducted with JMP 12 statistical software (SAS Institute Inc., 2015) to identify groups of similar, correlated hydro metrics using 304 sites statewide. The clustering was done with percent change in hydro metric from simulations of hydrologic alteration during the study period from withdrawals, impoundments, and land-cover change.
- Clusters represent groups of hydro metrics that have similar magnitudes of percent change and represent seasonal flows or describe particular components of the flow regime, such as the size of floods or the duration of high flows. The members of each cluster are potentially interchangeable in their relation to bio metrics because they are highly correlated with each other. Novak and others (2015) suggest that multiple flow metrics may be relevant to a particular relation, but provide guidance for obtaining appropriate nonredundant flow indicators.
- It was an important step in the first year of this collaborative study to report all the hydro metrics within each cluster even if they exhibited collinearity to build a common understanding about the dataset. An appropriate next step would include the selection of representative hydro metrics from each cluster for future investigations.

# Results: Overview
## Stream Classification

The effect of stream classification on flow-ecology regressions:

- The summary of differences between the statewide and classified datasets illustrates the number of significant metrics for fish increases when classification is utilized (see table, page 23).
- For the fish analyses, separating out the Atlantic Coastal Plain and the Ohio River drainages from the Atlantic non-Coastal Plain resulted in a larger number of significant relations.
    - Only two significant relations were identified for decreasing low-flow metrics and decreasing bio metrics statewide; however, when considered separately, 48 significant relations were found for the Atlantic non-Coastal Plain alone.
- The benthic analyses are based on "statewide" classification; however, the majority of data are in the Atlantic non-Coastal Plain, so the classified data closely resemble the statewide results for benthic invertebrates.
- Atlantic non-Coastal Plain data represent the majority of samples for both fish and benthic invertebrates, and therefore have the majority of significant relations.

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# Results: Overview

Summary table of significant relations for fish and benthic invertebrate flow-ecology pairs.

[D:D, decreasing hydro metric and decreasing bio metric; D:I, decreasing hydro metric and increasing bio metric]

| Bio metric class | Number of significant relations | Count of decreasing low-flow statistics and decreasing bio metrics [ D:D] | Count of decreasing high-flow statistics and decreasing bio metrics [ D:D] | Count of decreasing low-flow statistics and increasing bio metrics [ D:I] | Count of decreasing high-flow statistics and increasing bio metrics [ D:I] |
|---|---|---|---|---|---|
| **Fish, Statewide** | | | | | |
| Number of taxa (richness) | 52 | 0 | 50 | 2 | 0 |
| Percent of individuals | 57 | 2 | 15 | 8 | 32 |
| Number of individuals | 7 | 0 | 7 | 0 | 0 |
| Indices | 11 | 0 | 8 | 1 | 2 |
| **Classified: Fish, Atlantic Coastal Plain** | | | | | |
| Number of taxa (richness) | 26 | 0 | 1 | 16 | 9 |
| Percent of individuals | 17 | 0 | 3 | 0 | 14 |
| Number of individuals | 2 | 0 | 0 | 2 | 0 |
| Indices | 6 | 0 | 5 | 0 | 1 |
| **Classified: Fish, Atlantic non-Coastal Plain** | | | | | |
| Number of taxa (richness) | 57 | 28 | 28 | 0 | 1 |
| Percent of individuals | 81 | 15 | 15 | 25 | 26 |
| Number of individuals | 1 | 0 | 1 | 0 | 0 |
| Indices | 9 | 5 | 4 | 0 | 0 |
| **Classified: Fish, Ohio River drainages** | | | | | |
| Number of taxa (richness) | 36 | 0 | 31 | 0 | 5 |
| Percent of individuals | 29 | 2 | 15 | 5 | 7 |
| Number of individuals | 2 | 0 | 2 | 0 | 0 |
| Indices | 21 | 0 | 3 | 16 | 2 |
| **Benthic Invertebrates, Statewide** | | | | | |
| Number of taxa (richness) | 100 | 23 | 14 | 45 | 18 |
| Percent of individuals | 191 | 41 | 20 | 81 | 49 |
| Number of individuals | 1 | 0 | 0 | 0 | 1 |
| Indices | 47 | 20 | 15 | 7 | 5 |

# Results: Overview
## Data Tables

Results tables detailing flow-ecology regressions relevant to this investigation are available from ScienceBase (Rapp and Reilly, 2017).

- Regression summary statistics and results of fish flow-ecology regression evaluations for statewide data in the Commonwealth of Virginia are available at https://doi.org/10.5066/F7ZW1J42.

File Name: FishFlowEco_State_Results_04212017.csv

- Regression summary statistics and results of fish flow-ecology regression evaluations for classified data including Atlantic non-Coastal Plain, Atlantic Coastal Plain, and Ohio River drainages regions of the Commonwealth of Virginia are available at https://doi.org/10.5066/F7ZW1J42.

File Name: FishFlowEco_Region_Results_04212017.csv

- Regression summary statistics and results of benthic invertebrate flow-ecology regression evaluations for statewide data in the Commonwealth of Virginia are available at https://doi.org/10.5066/F7ZW1J42.

File Name: BenthicFlowEco_State_Results_04212017.csv

- Selected abbreviations for hydro metrics and bio metrics (Tetra Tech, Inc., 2012) are available at https://doi.org/10.5066/F7ZW1J42.

File Name: Hydro_Bio_Key.pdf

# Results: Overview
## Hydro Metric Clusters

Development of clusters resulted in five main groups that compose the majority of decreasing hydro metrics relevant to this study and represent various hydrologic-alteration scenarios. The clusters closely resemble the primary flow components used to describe the IHA parameters (The Nature Conservancy, 2009).

1. August Low-Flow Cluster representing Summer/Fall low flows (magnitude and duration)
2. 7Q10 Cluster representing extreme low flows (magnitude)
3. Winter-Spring Flow Cluster (magnitude of seasonal flows)
4. Annual High-Flow Cluster (magnitude and duration)
5. Peak-Flow Frequency and Rate-of-Change Cluster (frequency, duration, rate of change)

Key hydro metrics that were of interest for management purposes were used as cluster names where applicable. Although they are members of each cluster, they may not have the highest $r^2$ value representing cluster membership.

Gido and others (2013) utilized a similar approach using PCA to differentiate between core flow attributes for fish investigation in the Southwest. They identified summer coefficient of variation, Base Flow Index, Mean Spring Discharge, High Pulse Duration, and High Pulse Count as key groupings.

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# Results: Overview

## Hydro Metric Clusters

| 7Q10 | August Low Flow | Winter-Spring Flow | Annual High Flow | Peak-Flow Frequency and Rate-of-Change |
|---|---|---|---|---|
| 1-day minimum | 30-day minimum | November | Mean Annual Flow | Fall Rate |
| 3-day minimum | 90-day minimum | November Low Flow | April | High-Flow Fall Rate |
| 7-day minimum | July | December | May | High-Flow Frequency |
| 7Q10 | July Low Flow | December Low Flow | May Low Flow | High-Flow Rise Rate |
| Base-Flow Index | August | January | June | High Pulse Count |
| Extreme-Low Peak | August Low Flow | January Low Flow | June Low Flow | Large Flood Fall Rate |
| | September | February | 1-day maximum | Low Pulse Count |
| | September Low Flow | February Low Flow | 30-day maximum | Number of Reversals |
| | October | March | 3-day maximum | Rise Rate |
| | October Low Flow | March Low Flow | 7-day maximum | Small Flood Fall Rate |
| | Low-Pulse Threshold | April Low Flow | 90-day maximum | Small Flood Peak |
| | | High-Flow Peak | High Pulse Duration | Small Flood Rise Rate |
| | | | High Pulse Threshold | High-Flow Duration * |
| | | | | Large Flood Peak * |
| | | | | Large Flood Rise Rate * |

*These hydro metrics were members of their own cluster, but were combined with this cluster because they represent similar metrics.

The hydro metric clusters above represent similar metrics that have within-cluster $r^2$ values typically between 0.6 and 0.9. See the introductions for each cluster type for details (pages 27, 34, 40, 47, and 54, respectively).

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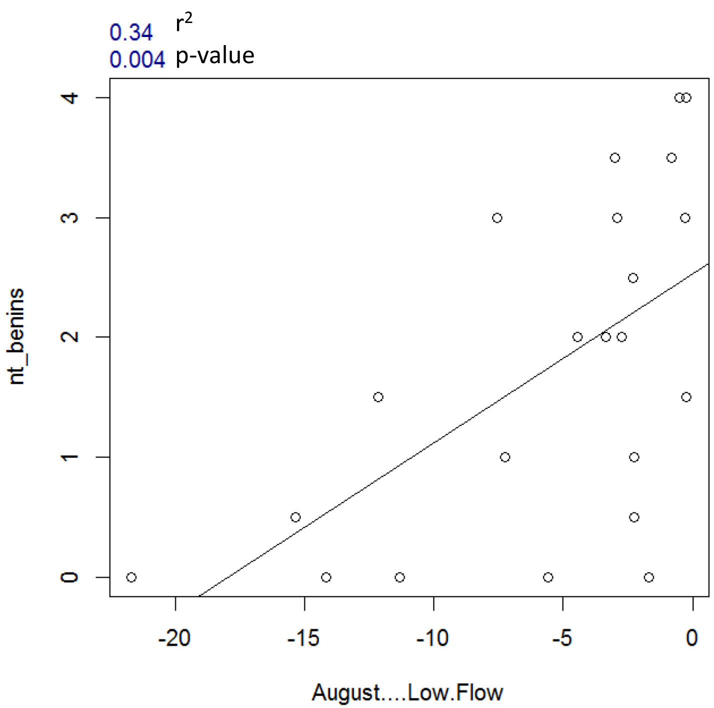
# Results: August Low-Flow Cluster Introduction

The August Low-Flow Cluster is composed of statistics that represent seasonal low-flow magnitude and duration likely to occur in the summer or fall. The magnitude of alteration in this group ranged from 0% to 30% change in hydro metric from baseline scenario to recent-conditions scenario (2008).

- July, August, September, and October mean monthly streamflow conditions
- Minimum flows (monthly, 30-, or 90-day windows)
- Monthly low-flow condition representing the day with the lowest flow during the month

| August Low Flow | Within-Cluster $r^2$ |
|---|---|
| 30-day minimum | 0.752 |
| 90-day minimum | 0.812 |
| July | 0.62 |
| July Low Flow | 0.912 |
| August | 0.929 |
| August Low Flow | 0.93 |
| September | 0.946 |
| September Low Flow | 0.826 |
| October | 0.661 |
| October Low Flow | 0.725 |
| Low-Pulse Threshold | 0.91 |




**Left:** Regression plot of the number of taxa for benthic insectivore fish in response to decreasing percent change in August low flow. See Approach and Methods section for an explanation of the regression scatter plots.

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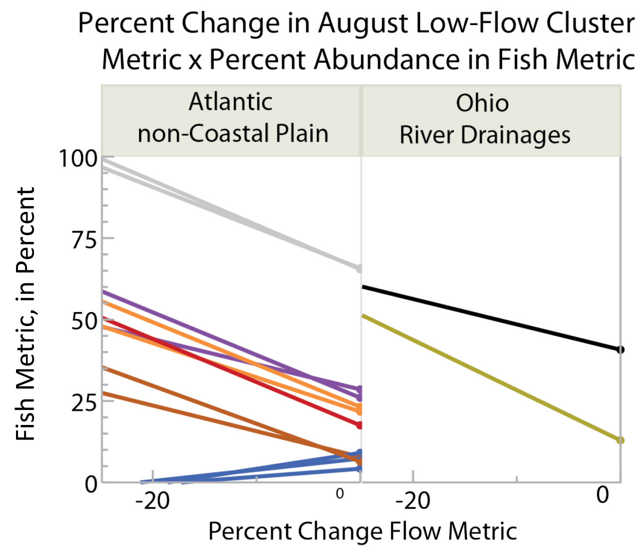
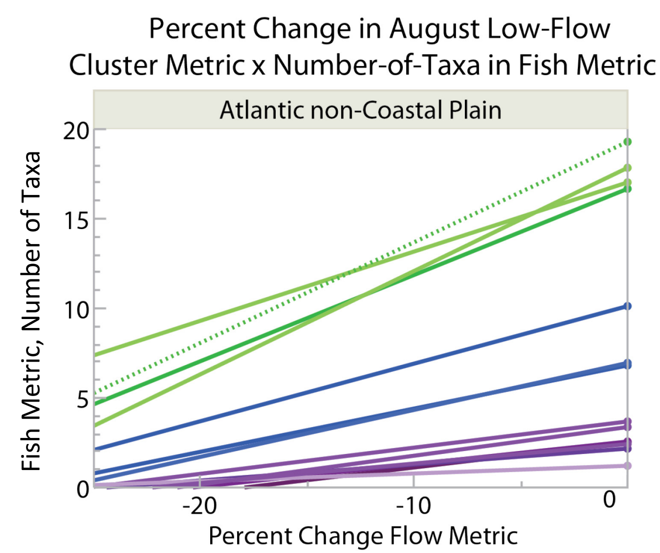
# Results: August Low-Flow Cluster Fish Responses

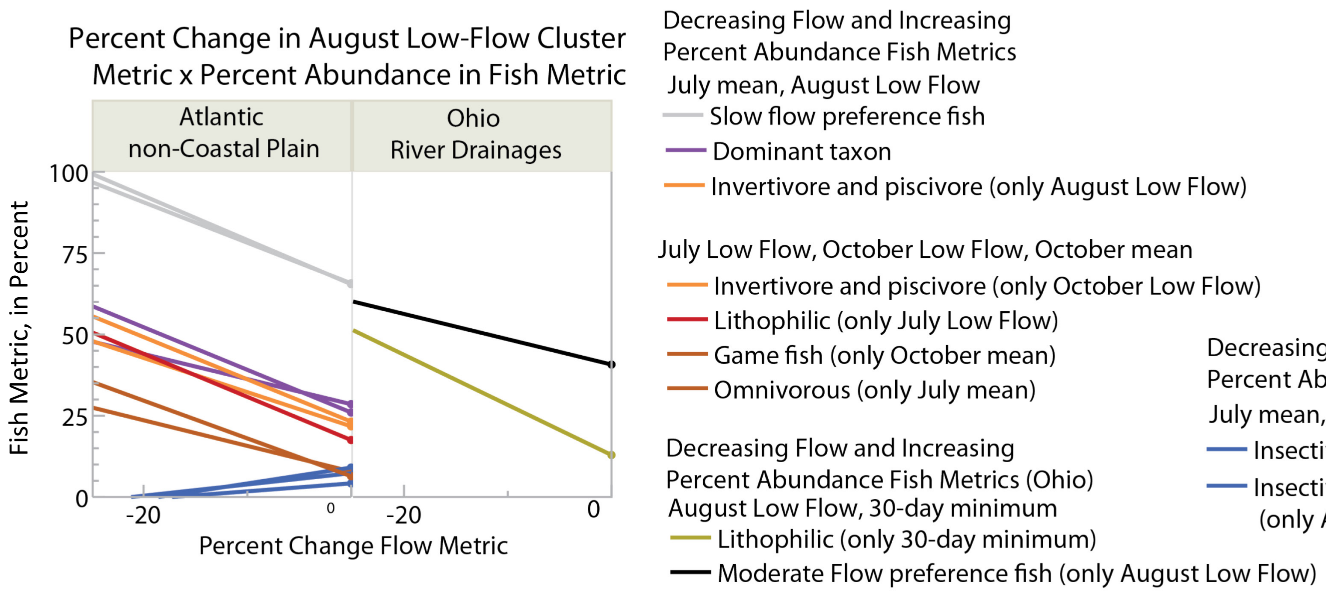
- The predominant response to a reduction of flows in this cluster was a decrease in insectivorous species from Cyprinidae such as emerald shiners. This response is paired with an increase in generalist omnivorous fishes such as sunfish.
- The percent abundances (upper graph left side, brown and gray lines) of omnivorous fish like yellow bullhead catfish and other slow-flow preference fishes such as bluegill and largemouth bass increased for numerous regressions with similar slopes. The percent abundance of generalist fish may shift from 5–65% assemblage composition to 27–100% with a 25% change in flow metrics.
- Atlantic non-Coastal Plain percent abundances (upper graph left side, blue lines) of insectivorous species from Cyprinidae like the fantail darter and other specialized insectivores declined from 5–10% to 0% with a 25% decrease in flow metrics.
- The number of taxa for native, or benthic, or insectivorous fish (lower graph, green and purple lines) decreased for benthic-insectivorous fish taxa (such as shield darter or glassy darter), native and benthic fish (like blacknose dace and green sunfish), and native species (like torrent suckers, greenside darter, and mottled sculpin).  The number of taxa may decline from 3–18 taxa to 0–7 taxa with a 25% decrease in flow metrics.

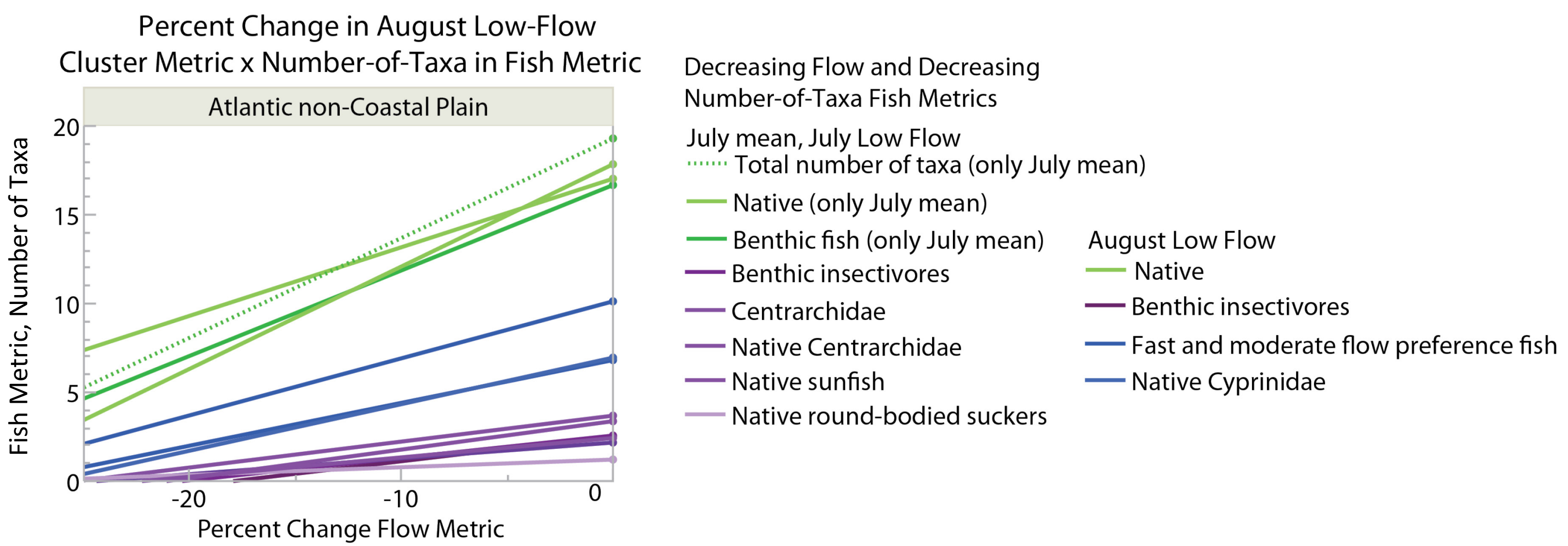



[detailed explanation on page 29]

# Results: August Low-Flow Cluster Fish Responses

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# Results: August Low-Flow Cluster Fish Responses

Decreases in August low-flow cluster metrics were correlated with decreases in native taxa, benthic taxa, insectivorous taxa, and fish that represent combinations of all three bio metrics. These were largely composed of members in the Cyprinidae (minnows) and Centrarchidae (sunfishes) families and taxa that prefer fast-flowing water.

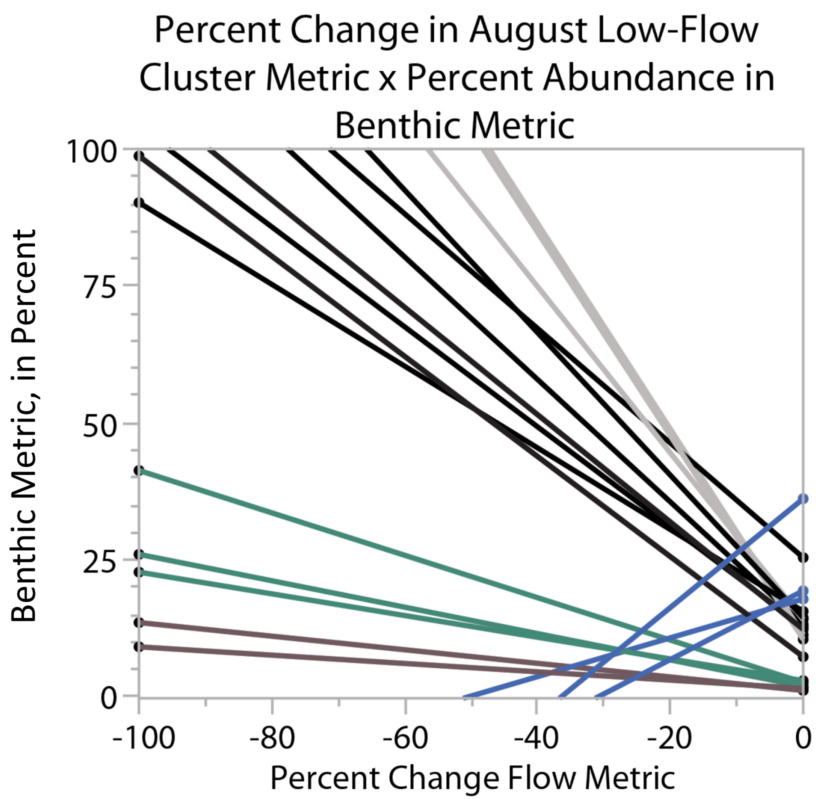
- Other studies have seen a correlation between diminished flows and decreases in taxa with preferences for fast water velocities and gravel-cobble bed substrate (Armstrong and others, 2011; Phelan and others, 2017). Jowett and others (2005) found that native fish densities were adversely affected by flows lower than the mean-annual low flow, with reductions in abundances of fast-water fish in particular. Kennen and others (2012) noted that decreased streamflows tended to support taxa that prefer slower velocities (Jowett, 1997) or taxa that are more tolerant.
- Knight and others (2014) identified decreases in native taxa, riffle-dwelling taxa, and total species richness in association with absolute hydrologic departure–a standardized metric representing increasing or decreasing hydrologic alteration.
- The importance of insectivorous fish was noted by Knight and others (2008) as they represent a middle trophic level, feed on invertebrates, and are prey for predator species.

This study also found that decreases in August low-flow cluster metrics were correlated with increases in game fish, ominvorous fish, invertivore-piscivorous fish, and lithophilic fish taxa and displayed preference for slow-flowing water.

- The increase in percent of individuals categorized as lithophilic spawners is counter to findings of Knight and others (2014) and Grabowski and Isely (2007), who found that a decrease or dewatering of riffle nesting sites results in a decrease in lithophilic breeders.

# Results: August Low-Flow Cluster Benthic Responses

- The predominant response to a reduction of flows in this cluster was an increase in tolerant benthic organisms such as midges and other filter feeders, and tolerant collectors such as net-spinning caddisflies (Hydropsychidae) or moderately tolerant mayflies in the Baetidae family (black and gray lines at right).
- This response is paired with a decrease in intolerant benthic organisms, such as sensitive mayflies and other scrapers (blue lines at right).
- These flow-ecology regressions indicate that percent abundance of tolerant benthic organisms may dramatically increase in assemblage composition with a 50% change in flow metric. Percent abundance of intolerant benthic organisms, shown with blue lines, frequently makes up a greater percentage of assemblages when no hydrologic alteration is evident. However, sharp declines are described with a 30% decrease in flow metrics. Few regressions supported this decline, but additional support is presented with the 7Q10 cluster.
- The number-of-taxa regressions for benthic organisms are not presented because of some sampling inconsistencies between agencies that were unresolved at the publication of this report (see Limitations section).




[detailed explanation on page 32]

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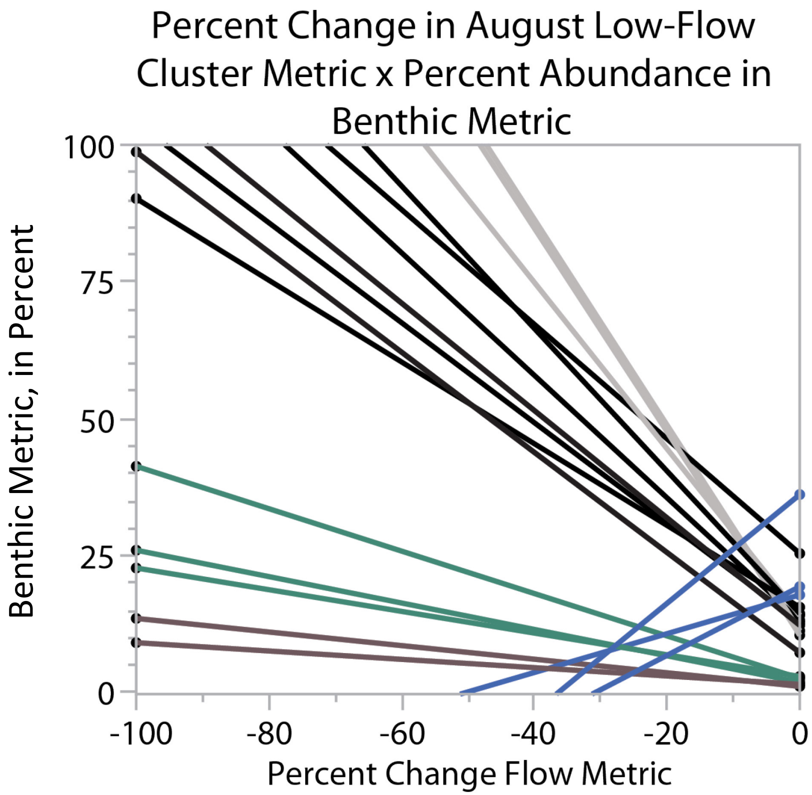
# Results: August Low-Flow Cluster Benthic Responses




Decreasing Flow and Increasing Percent Abundance Benthic Metrics

30-day minimum:
- Percent Bivalve
- Percent filterer
- Hydropsychidae 2 EPT

90-day minimum:
- Percent Baetidae to Ephemperoptera
- Percent Collector
- Percent Sprawlers

August Low Flow:
- Percent Baetidae to Ephemperoptera

August mean:
- Percent Baetidae to Ephemperoptera

July Low Flow:
- Percent Hydropsychidae 2 EPT

October Low Flow:
- Percent Baetidae to Ephemperoptera
- Percent Shredders
- Percent Sprawlers

- October mean: Percent Bivalve

September Low Flow:
- Percent Chironomidae
- Percent Diptera

Decreasing Flow and Decreasing Percent Abundance Benthic Metrics

- October Low Flow: Percent Coleoptera

September Low Flow:
- Percent Scrapers
- Percent Ephemeroptera & Trichoptera no Hydropsychidae

# Results: August Low-Flow Cluster Benthic Responses

Decreases in August Low-Flow Cluster metrics result in decreases in the abundance of intolerant benthic organisms and increases in the abundance of tolerant benthic organisms.

- Diminished seasonal low flows have been associated with an increase in tolerant taxa abundance with preferences for slow water velocities, those that prefer fine sediments over riffle habitats, and organisms that can temporarily leave the aquatic environment (Carlisle and others, 2010). Caddisflies in the Hydropsychidae family and mayflies in the Baetidae family tend to be more tolerant of disturbance or degradation.

- Other studies have seen similar responses within the macroinvertebrate community to reductions to low flow due to water abstraction and diversion. Dudgeon (1992) reported declines in macroinvertebrate species richness in a stream in Hong Kong when flow ceased during the dry season because of water withdrawals. Kinzie and others (2006) found that macroinvertebrate density decreased in an Hawaiian stream when surface flow was diverted during low-flow periods.

- Bivalves are rare in most Virginia streams, but they indicate rivers with exceptional water quality.  A few regressions indicate an increase in percent bivalve with a decrease in October mean flow. Observations of this response have been attributed to juvenile mussel persistence in slower water velocity areas with reduced scour ((Jess Jones, U.S. Fish and Wildlife Service, oral commun., 2012).

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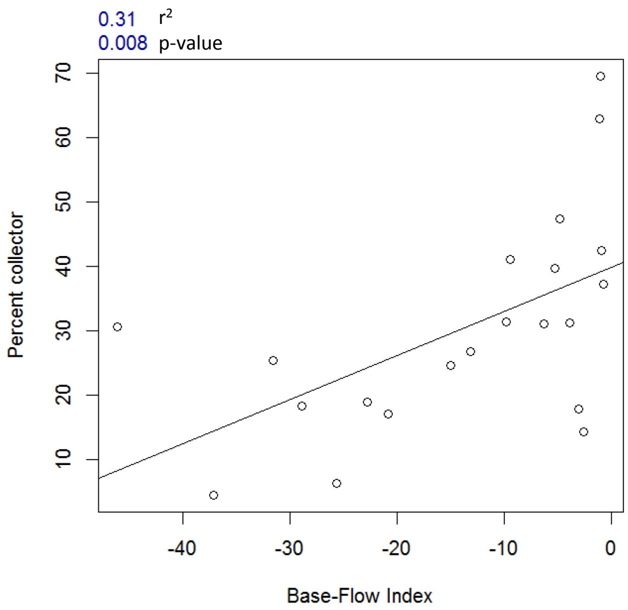
# Results: 7Q10 Cluster Introduction

The 7Q10 cluster is composed of statistics that represent the magnitude of extreme low flows, such as the minimum flow of the year when considering a 1-day, 3-day, or 7-day window.  Hydro metrics that made up the 7Q10 cluster were common among all regions. The magnitude of alteration in this group ranged from 0% to 100% reduction in the hydro metric from baseline scenario to the recent-conditions scenario (2008).

- The 7Q10 statistic is commonly used in water-supply management and represents the lowest 7-day flow in a 10-year period.
- Base-flow index is the ratio of 7-day minimum to the mean flow for the year.
- Extreme-low peak (The Nature Conservancy, 2009) represents the lowest flow during the year.




| 7Q10 Cluster | Within-Cluster $r^2$ |
|---|---|
| 1-day minimum | 0.834 |
| 3-day minimum | 0.865 |
| 7-day minimum | 0.984 |
| 7Q10 | 0.908 |
| Base-Flow Index | 0.931 |
| Extreme-Low Peak | 0.778 |

**Left:** Regression plot of the percent abundance of collector taxa in response to decreasing percent change in base-flow index. [See page 16 for explanation]

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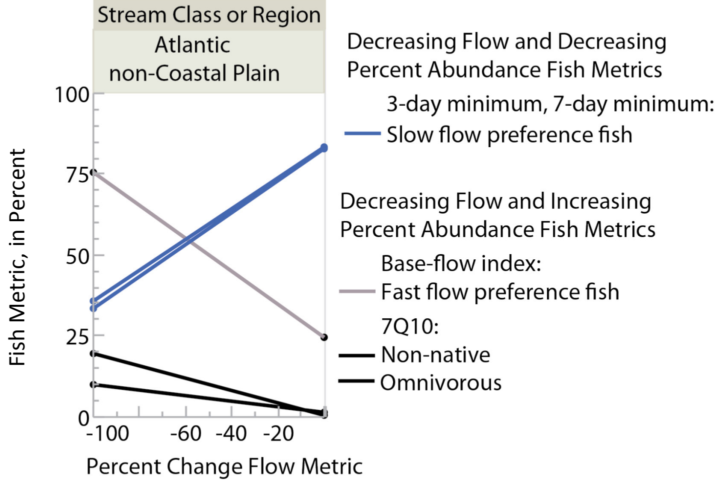
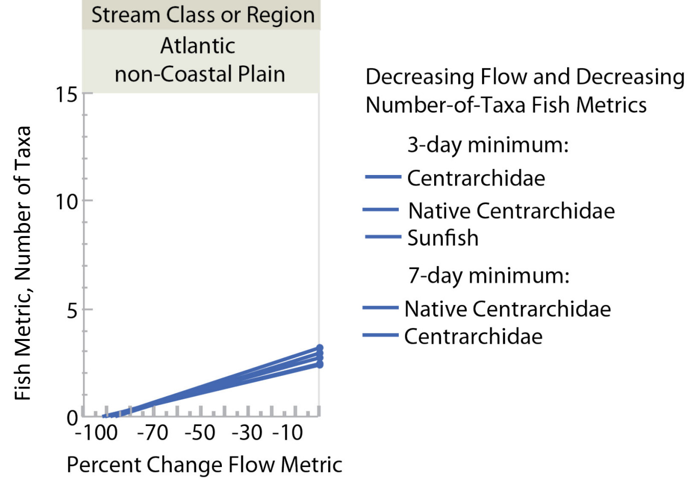
# Results: 7Q10 Cluster Fish Responses

- Percent abundances (upper graph) for slow-flow preference fish such as long ear sunfish, bluegill, or largemouth bass in the Atlantic non-Coastal Plain decreased from 80% to 35% sample composition. This response is paired with an increase in the abundance of generalist, non-native, or omnivorous fish.
- The Atlantic non-Coastal Plain number-of-taxa regressions (lower graph) for diminishing extreme-low flows were significant only for the family Centrarchidae and bio metrics that represent species of sunfish. The number of taxa present may shift from 3 to 0 depending on the percent decrease in flow. This decrease in species like redear sunfish, pumpkinseed, or largemouth bass may indicate impacts to breeding habitat areas, with dewatering of nests or increased siltation contributing to lower survival rates.
- The few significant 7Q10 cluster regressions in the Atlantic Coastal Plain or Ohio River drainages do not present consistent patterns of response from fishes. They are included in the results tables, but no plots are included in this report.

Percent Change in 7Q10 Cluster Metric x
Percent Abundance in Fish Metric




Percent Change in 7Q10 Cluster Metric x
Number-of-Taxa in Fish Metric



# Results: 7Q10 Cluster Fish Responses

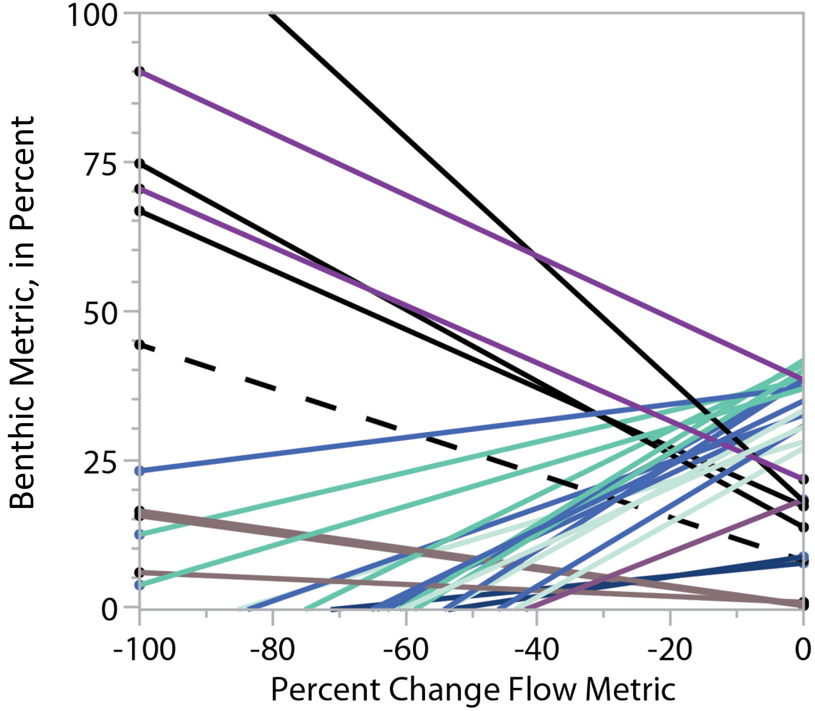
The regressions in the 7Q10 Cluster indicate an increase in the percent abundance of non-native fish and omnivorous fish. Decreases in number of taxa were noted for native fishes within the family Centrarchidae (largely composed of many species of sunfish, largemouth bass, and crappie). The loss of a native species would be reflected in bio metrics representing all sunfishes as well as native sunfishes. The similarity between the number-of-taxa regression relations on the previous slide indicates that native species may be lost with decreases in extreme low flows.

- Variation in frequency of low flow or date of minimum statistics was negatively associated with fish richness for a selected set of large rivers throughout the world (Iwasaki and others, 2012).
- A reduction in the 7Q10 hydro metric could signify a shift to slow water velocities that cause the decline of benthic insect food sources (Rolls and others, 2012).
- Water velocity has been shown to be the most important variable in determining the distribution and abundance of fish and benthic organism community structure (Jowett and Duncan, 1990; Grossman and others, 2010).

# Results: 7Q10 Cluster Benthic Responses

- Percent abundances of intolerant collector taxa such as sensitive Mayflies and caddisflies typically decreased (blue, teal, and pale blue lines) with a reduction in flow metric. This response is paired with a substantial increase in the assemblage abundance composed of the dominant and top two dominant taxa (purple lines), tolerant net-spinning caddisflies (Hydropsychidae; black lines), and noninsects (dashed lines) over the same flow-alteration gradient.
- This example may not indicate the addition of new species to the assemblage, but rather a shift in abundance of previously existing dominant or tolerant taxa.
- The slight increase in abundance shown in brown illustrates a potential positive response from bivalve taxa in response to decrease in the 7Q10 Cluster hydro metrics. This response is similar to the August Low-Flow Cluster response.

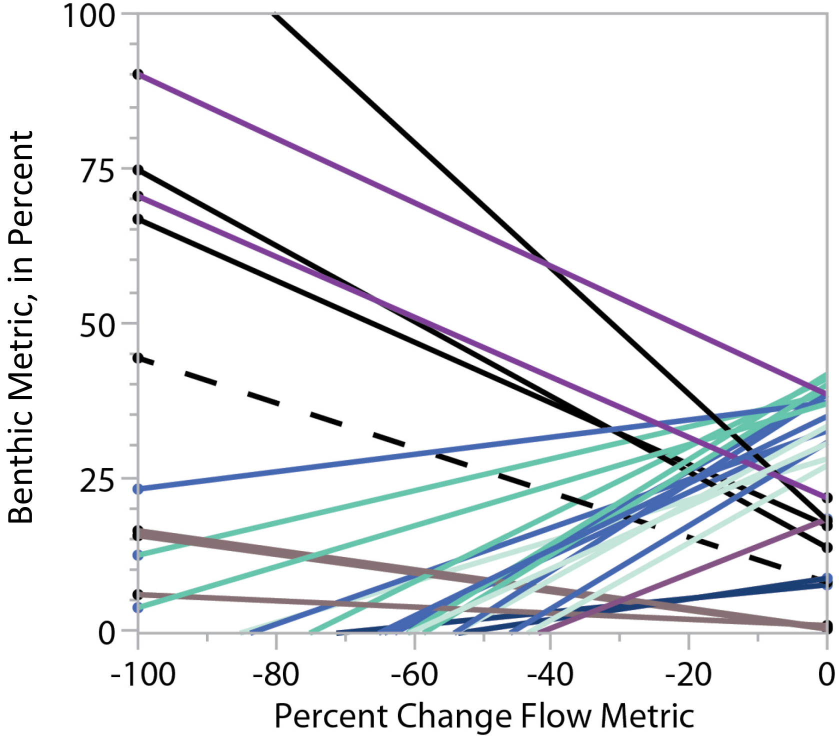
Percent Change in 7Q10 Cluster Metric x Percent Abundance in Benthic Metric




[detailed explanation on page 38]

# Results: 7Q10 Cluster Benthic Responses

Percent Change in 7Q10 Cluster Metric x
Percent Abundance in Benthic Metric




## Decreasing Flow and Decreasing Percent Abundance Benthic Metrics

1-day minimum, 3-day minimum, 7-day minimum, Extreme-Low Peak, Base-Flow Index:

- Percent collector
- Percent Ephemeroptera
- Percent Ephemeroptera and Trichoptera, no Hydropsychidae

1-day minimum and 3-day minimum:

- 7Q10: Percent Ephemeroptera and Trichoptera, no Hydropsychidae
- Base-Flow Index: Percent Coleoptera

## Decreasing Flow and Increasing Percent Abundance Benthic Metrics

- 3-day minimum: Percent noninsects

3-day minimum, 7-day minimum, 7Q10:

- Percent Bivalve

1-day minimum, 3-day minimum, Base-Flow Index:

- Percent Hydropsychidae 2 EPT

Extreme-low peak:

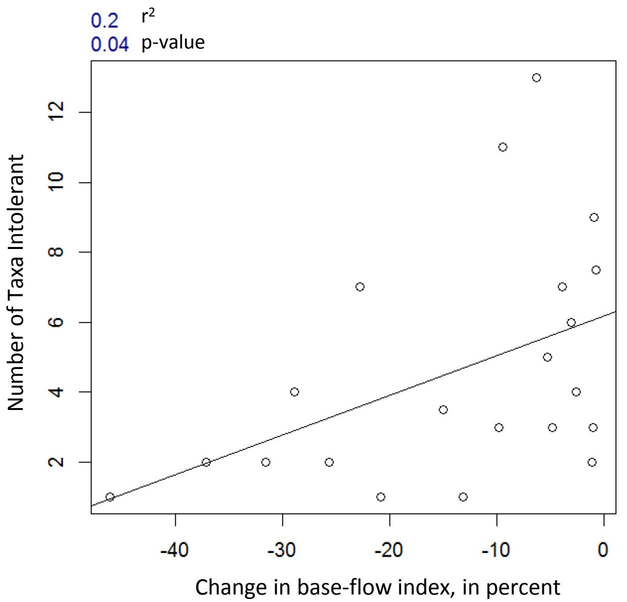
- Percent dominant taxa
- Percent top 2 dominant taxa

# Results: 7Q10 Cluster Benthic Responses

Reductions in the 7Q10 Cluster hydro metrics (that is, drier river conditions) are correlated with decreases in the intolerant benthic invertebrate community, as well as shifts in ratios of intolerant-to-tolerant organisms favoring tolerant-organism dominated assemblages.

- The benthic invertebrate response appears to be patterned after those hypothesized by Knight and others (2008). Decreases in the 7Q10 cluster metrics represent a reduction in extreme low-flow conditions, which may particularly affect smaller streams by reducing available habitat area for invertebrate colonization.
- Rolls and others (2012) support these conclusions and also suggest the decrease in intolerant taxa may result from reduction of food, temperature increase, and/or potentially adverse water-quality conditions associated with reduced flow.

Graph to the right indicates a decrease in number of intolerant benthic invertebrate taxa with a reduction in base-flow index, or the ratio of 7-day minimum flow to the mean flow for the year. As the percent-change values become more negative it indicates less consistent streamflow conditions.




- An important consideration for many regressions in the 7Q10 clustered dataset is that very few data points exist below -10% change in flow. There may be a threshold at -10% but more data are needed to determine whether these few data points represent a valid decrease.

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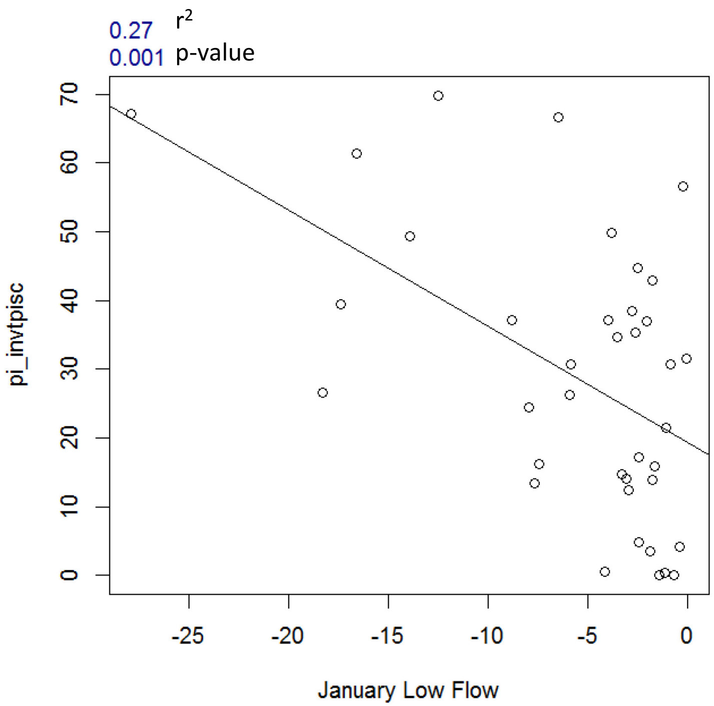
# Results: Winter-Spring Flow Cluster Introduction

The winter-spring flow cluster is composed of statistics that represent the variability in the magnitude of seasonal high flows. These decreasing hydro metrics consist of mean monthly flows and low-flow conditions during the winter and spring months. The months of November through February are typically high-streamflow, groundwater-recharge months for Virginia. For the month of May, hydro metrics were significant only for Coastal Plain fish relations. The magnitude of alteration in this group ranged from 0% to 50% reduction in the hydro metric from the baseline scenario to the recent-conditions scenario (2008).



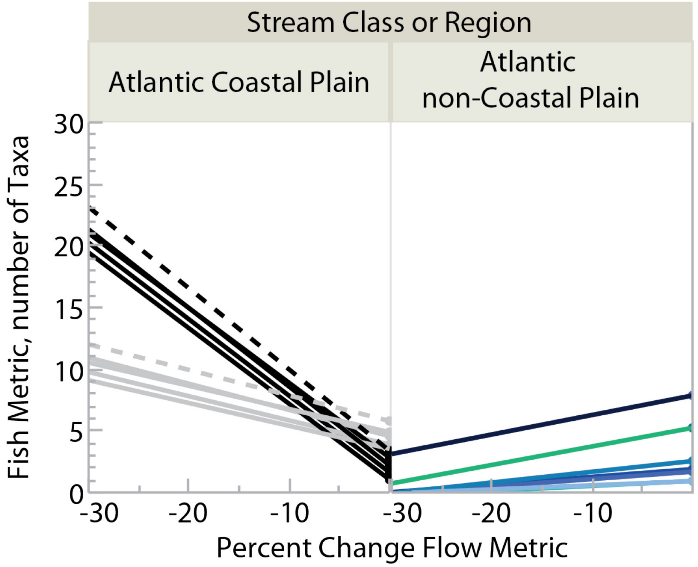

**Left:** Regression plot of the percent abundance of invertivore-piscivore fish taxa in response to decreasing percent change in January Low Flow.

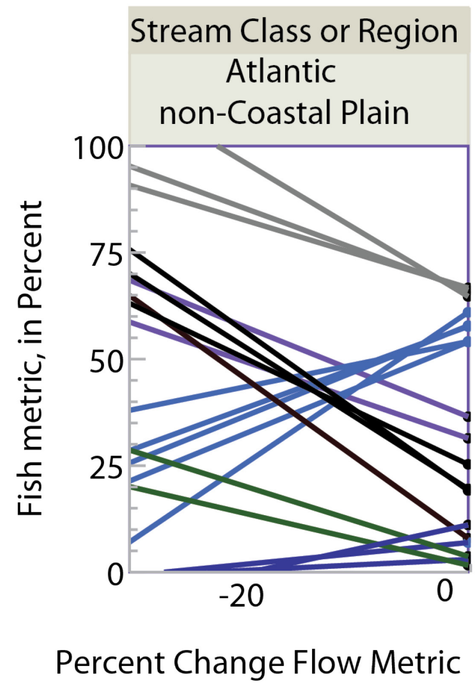
| Winter-Spring Flow | Within-Cluster $r^2$ |
|---|---|
| November | 0.681 |
| November Low Flow | 0.537 |
| December | 0.612 |
| December Low Flow | 0.738 |
| January | 0.701 |
| January Low Flow | 0.593 |
| February | 0.733 |
| February Low Flow | 0.644 |
| March | 0.712 |
| March Low Flow | 0.59 |
| April Low Flow | 0.714 |
| High-Flow Peak | 0.272 |

USGS

# Results: Winter-Spring Flow Cluster Fish Responses

- The predominant response to a reduction in flows in Atlantic non-Coastal Plain (upper graph, right side) was a decrease in insectivorous and native species from Cyprinidae or native Centrarchidae (emerald shiner or redbreast sunfish, respectively) as well as benthic-insectivorous fish taxa (such as shield darter or glassy darter). Many of the darters are also fast-flow preference fish.
- In the Atlantic Coastal Plain (upper graph, left side) the opposite response was observed. Slow-flow preference fish (such as tessellated darters, golden shiners) increased along with native fish and benthic fish species (white catfish, redbreast sunfish) with reductions in May (black lines) or November (gray lines) mean flows.
- The percent abundance increased (lower graph: black, green, or purple lines) for omnivorous game fish like redbreast sunfish or green sunfish and top carnivores like largemouth and smallmouth bass in the Atlantic non-Coastal Plain.
- Changes associated with feeding traits were most apparent when invertivore-piscivore species (black lines) shifted from 10-40% assemblage composition to 60-75%. This response was coupled with a decrease in insectivorous fish like emerald shiner and other minnows (dark blue lines) and moderate-flow preference fish like fallfish (blue lines).



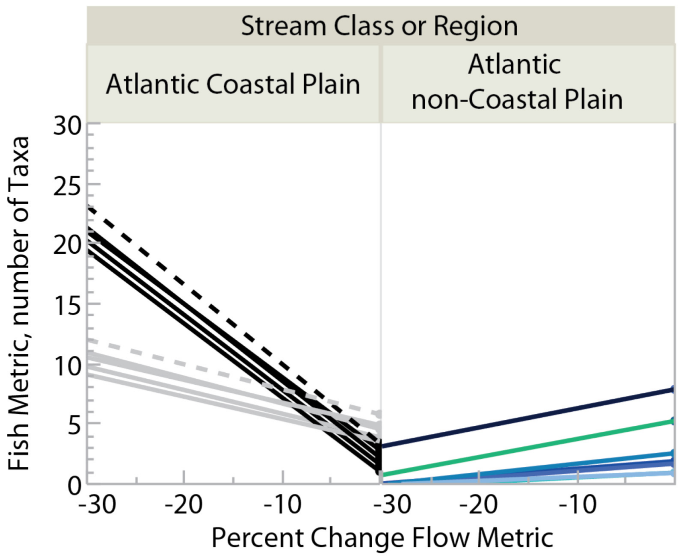




[detailed explanation on page 42]

USGS

# Results: Winter-Spring Flow Cluster Fish Responses

Percent Change in Diminishing
Winter-Spring Flow Cluster Metric x
Number-of-Taxa in Fish Metric




Decreasing Flow and Increasing Number-of-Taxa Fish Metrics

May mean
- Benthic fish
- Slow flow preference fish
- Native benthic
- Native
- Total number of taxa

November mean
- Benthic fish
- Slow flow preference fish
- Native benthic
- Native
- Total number of taxa

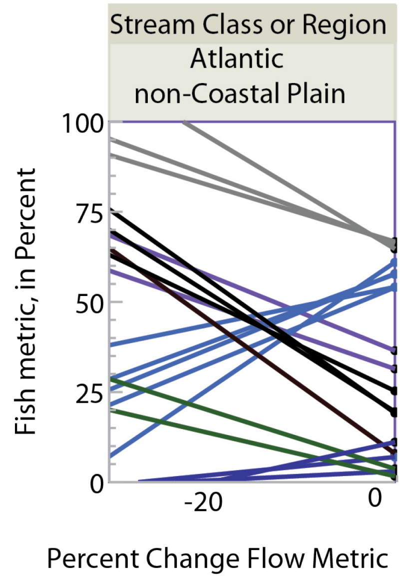
Decreasing Flow and Decreasing Number-of-Taxa Fish Metrics

January mean
- Native Centrarchidae

February Low Flow:
- Benthic insectivores
- Moderate flow preference fish
- Native insectivorous Cyprinidae

March Low Flow:
- Benthic insectivores
- Fast flow preference fish
- Intolerant suckers

Percent Change in Diminishing
Winter-Spring Flow Cluster Metric x
Percent Abundance in Fish Metric




Decreasing Flow and Decreasing Percent Abundance Fish Metrics

February mean, February Low Flow, March Low Flow, April Low Flow, November mean
- Moderate flow preference fish

February Low Flow:
- Insectivorous Cyprinidae

- March Low Flow: Insectivore

Decreasing Flow and Increasing Percent Abundance Fish Metrics

January mean
- Dominant taxon
- Invertivore and piscivore

January Low Flow
- Invertivore and piscivore

January mean and February mean
- Top carnivores

February mean
- Game fish
- Non-native
- Slow flow preference fish

February Low Flow
- Dominant taxon
- Slow flow preference fish
- Invertivore and piscivore

March Low Flow
- Slow flow preference fish

USGS

# Results: Winter-Spring Flow Cluster Fish Responses

Diminished winter-spring mean or low flows may represent a reduction in groundwater recharge and subsequent diminished low-flow conditions in the summer.

- Mean streamflows during winter months (November through February) can be used to predict probability and likelihood of drought for June, July, August, and September (Austin, 2014).
- The increase in game species, top carnivores, non-native fishes, and omnivorous fishes observed with the winter-spring cluster might result because these species are typically opportunistic individuals who can survive drier summers with low base flow.

A reduction in the winter-spring streamflow in Virginia may contribute to lower native densities.

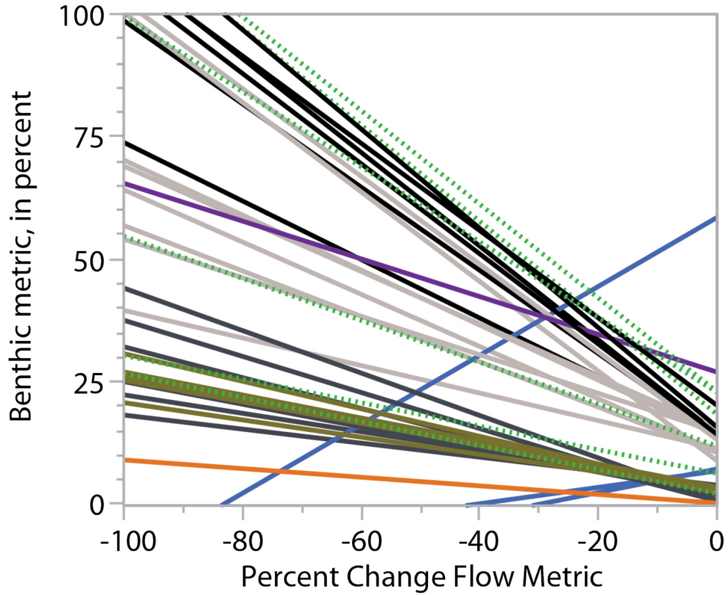
- Decreases in native benthic species in response to decreases in the winter-spring flow cluster may occur because these species are less tolerant to changes in the natural flow regime of the river to which they are adapted.
- Gido and others (2013) observed native species densities were generally higher and non-native species densities were lower in years with higher mean spring flows, supporting their prediction that higher spring flows support recruitment. Other research in the Gila River reported increases in non-native fish in reduced spring flow years (Propst and others, 2008; Stefferud and others, 2011).

USGS

# Results: Winter-Spring Flow Cluster Benthic Responses

- The predominant response to a reduction in winter-spring flows was an increase in the percent abundance of tolerant benthic organisms. Increases in the tolerant taxa such as midges and blackflies as well as shifts in the abundance ratios of tolerant mayflies to intolerant mayflies or net-spinning caddisflies to EPT are common within this cluster.
- Some regressions for December, February, and March hydro metrics do not solely fit the response discussed above. Along with the increase in tolerant organisms, there is a concurrent increase in the percent abundance of intolerant organisms such as mayflies, stoneflies, and caddisflies. As of the writing of this report (2017), it is uncertain whether these are true responses or reflect small sample sizes, outliers affecting the relation, statewide grouping of regional datasets, or problems with taxonomic ambiguities that obscure the results.
- Only a few regressions identified decreases in the percent abundance of Gastropoda or snails.

Percent Change in Diminishing Winter-Spring Flow Cluster Metric x Percent Abundance in Benthic Metric




[detailed explanation on page 45]

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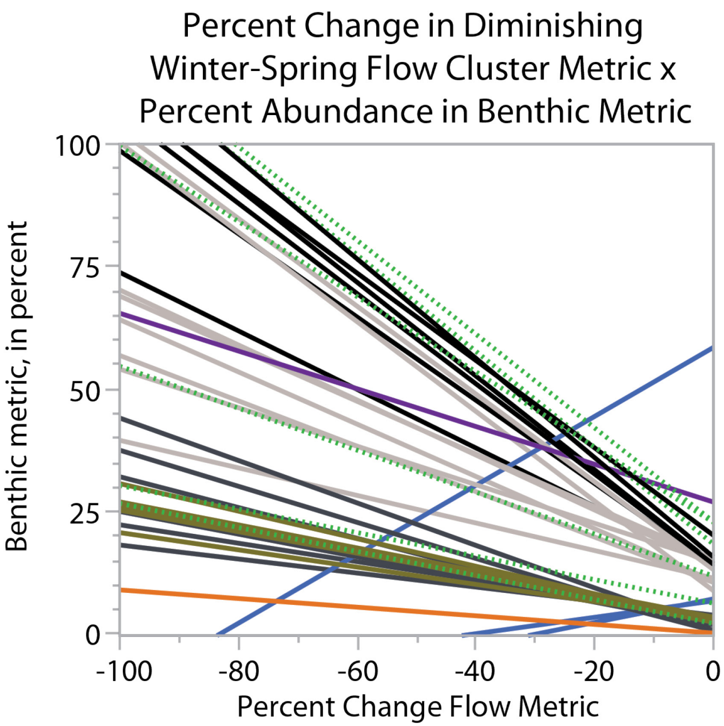
# Results: Winter-Spring Flow Cluster Benthic Responses




Decreasing Flow and Decreasing Percent Abundance Benthic Metrics

November Low Flow, April Low Flow, January mean (clinger only)
- Percent clinger
- Percent Gastropoda

Decreasing Flow and Increasing Percent Abundance Benthic Metrics

February mean
- Percent Ephemeroptera and Trichoptera, no Hydropsychidae
- Percent Ephemeroptera
- Percent Intolerant

March mean or March Low Flow
- Percent Trichoptera
- Percent Plecoptera

December Low Flow
- Percent Plecoptera and Trichoptera, no Hydropsychidae

December mean, January mean, March Low Flow
November (Chironomidae only), April Low Flow (filterer)
- Percent Chironomidae
- Percent Diptera
- Percent filterer

November Low Flow, February Low Flow, March Low Flow
- Percent Baetidae to Ephemeroptera

December mean, January mean, and March mean
- Percent Hydropsychidae 2 EPT

November Low Flow, December Low Flow, March Low Flow, March Mean
- Percent shredders
- Percent climber (March Low Flow and December Low Flow only)

January mean
- Percent dominant taxa

November mean, December Low Flow, December mean, January mean, January Low Flow, April Low Flow
- Percent sprawlers

February Low Flow
- Percent swimmers

USGS

# Results: Diminishing Winter-Spring Flow Cluster Benthic Responses

There is a shift in the macroinvertebrate assemblage in the winter-spring cluster, with differing responses to decreases in winter flows.

- Other studies have noted similar responses and have similarly attributed varied responses to taxa movement ability, tolerance to flow and/or water-quality conditions, and habitat modification caused by streamflow alteration (Poff and Zimmerman, 2010; Carlisle and Hawkins, 2008; Carlisle and others, 2010; Brooks and others, 2011; Dewson and others, 2007).

Relative to other winter-spring months, streamflow alteration during December, February, and March may be unique at a given stream.

- Water management strategies may transition to water storage to prepare for the upcoming water needs, including streamflow regulation and human use. Also, some February and March flow statistics may be altered from increased groundwater pumpage (lowered base flows).

- Although these linear regression models do not reveal the underlying mechanisms for diminishing flows within the study basin, future work can provide a better understanding of the effects of decreased winter flows by further characterizing certain variables (stream size, class, climate, catchment controls on runoff and water extraction) with macroinvertebrate family composition.

USGS

# Results: Annual High-Flow Cluster Introduction

The Annual High-Flow Flow cluster is composed of statistics that represent decreases in the magnitude and duration of annual high flows. The magnitude of alteration in this group ranged from 0% to 40% reduction in the hydro metric from baseline scenario to the recent-conditions scenario (2008).

The decreasing hydro metrics in this group consist of high-flow metrics for the continuous streamflow period of record, along with mean flow metrics from spring or summer months that typically have higher cumulative precipitation and streamflow.

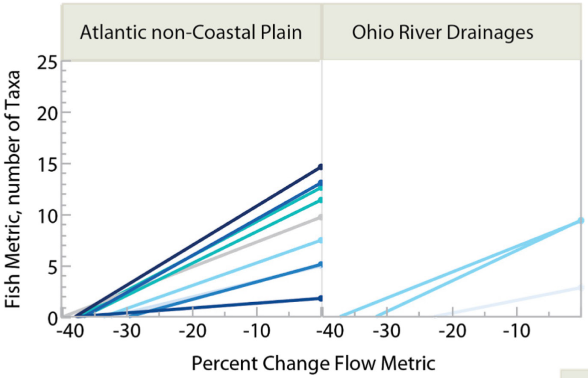
- Mean Annual Flows are heavily affected by high flows during the year, so their grouping with the 1-, 3-, 7-, 30-, and 90-day maximum flow was expected.
- April, May, and June hydro metrics represent mean monthly metrics.
- High pulse duration is the length of time floods of a certain magnitude persist.

| Annual High Flow | Within-Cluster $r^2$ |
|---|---|
| Mean Annual Flow | 0.992 |
| April | 0.987 |
| May | 0.986 |
| May Low Flow | 0.875 |
| June | 0.986 |
| June Low Flow | 0.889 |
| 1-day maximum | 0.603 |
| 30-day maximum | 0.993 |
| 3-day maximum | 0.855 |
| 7-day maximum | 0.985 |
| 90-day maximum | 0.99 |
| High Pulse Duration | 0.815 |
| High Pulse Threshold | 0.973 |

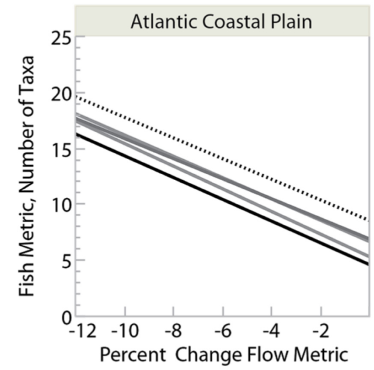
USGS

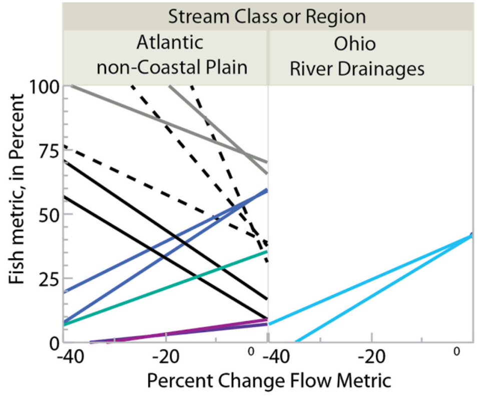
# Results: Annual High-Flow Cluster Fish Responses

- The predominant response to a reduction in maximum flows in this cluster is a decrease in native taxa and benthic fish taxa (madtoms, suckers, and darters) in the Atlantic or Ohio River drainages (upper graph, blue lines). Declines may occur in native benthic fish like blacknose dace and green sunfish; native species like torrent suckers, fantail darter, and mottled sculpin; and benthic fish taxa such as emerald shiners. Specific to the Ohio River drainages, greenside darter or gilt darter may decline.
- An opposite response was observed in the Atlantic Coastal Plain (middle graph, black and gray lines) with an increase in native and benthic fish taxa with 10% reduction in flow metrics. No decreasing fish metrics were observed in the Coastal Plain.
- The percent abundances (lower graph) of specialized feeders (purple lines) and lithophilic fish (turquoise lines), such as madtoms or central stonerollers, decreased in the Atlantic and Ohio River drainages regressions. In the Atlantic non-Coastal Plain, substantial increases in the dominant taxa (dashed lines), slow-flow preference fish (gray lines), and invertivore-piscivore species (black lines) were associated with a 40% change in annual high-flow metrics.



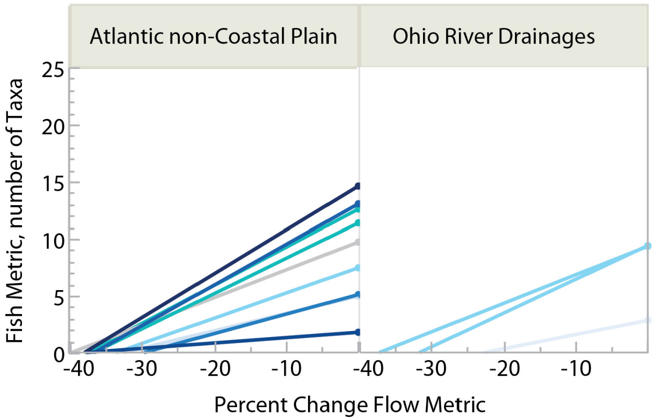

[detailed explanation on page 49]



# Results: Annual High-Flow Cluster Fish Responses

Percent Change in Annual High Flow
Cluster Metric x Number-of-Taxa in Fish Metric

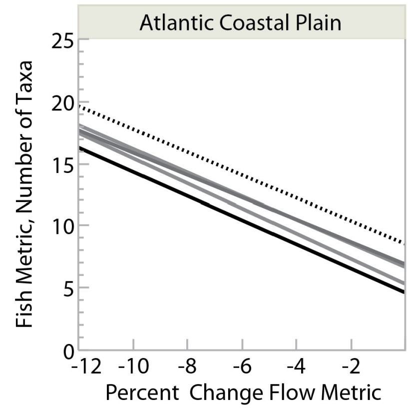



Decreasing Flow and Decreasing
Number-of-Taxa Fish Metrics

Ohio River Drainages
3-day maximum, 1-day maximum
- Darters
- Fast flow preference fish
- Moderate flow preference fish (1-day maximum only)

Atlantic non-Coastal Plain
3-day maximum
- Slow flow preference fish
- Benthic fish
- Native benthic
- Native Cyprinidae
- Native
- Sucker
- Total number of taxa

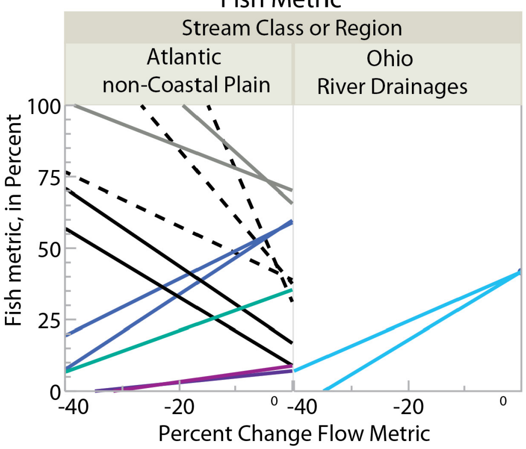
Percent Change in Annual High Flow
Cluster Metric x Number-of-Taxa Fish Metric




Decreasing Flow and Increasing
Number-of-Taxa Fish Metrics

Atlantic Coastal Plain,
Mean annual flow
- Benthic fish
- Native benthic
- Native
- Slow flow preference fish
- Total number of taxa

Percent Change in Annual High Flow
Cluster Metric x Percent Abundance in
Fish Metric




Decreasing Flow and Increasing
Percent Abundance Fish Metrics

30-day maximum, 3-day maximum, 7-day maximum
- Dominant taxon

7-day maximum, April mean
- Slow flow preference fish

1-day maximum, 3-day maximum
- Invertivore and piscivore

Decreasing Flow and Decreasing
Percent Abundance Fish Metrics
1-day maximum, 3-day maximum
- Lithophilic (1-day maximum only)
- Round-bodied suckers (3-day maximum only)
- Fast flow preference fish

June Low-Flow, 3-day maximum
- Insectivore (June Low Flow only)
- Moderate flow preference fish

USGS

# Results: Annual High-Flow Cluster Fish Responses

In the Atlantic Coastal Plain, reductions in various sizes of floods or fall rates resulted in increases in total number of taxa as well as native, benthic, and slow flow preference fish.

- These significant regressions occurred over a small percent reduction (10%) of flows, but could be better defined with additional samples. These responses may reflect stable, consistent flow regimes, lacking extremely large floods.

The increased number of taxa in the Atlantic Coastal Plain with a decrease in the Annual High-Flow Cluster metrics was not supported by other published works.

- In Georgia medium-sized Coastal Plain rivers, the predicted number of redbreast sunfish reaching a length of 203 mm was reduced by 19-62% with a 30% increase in water withdrawals during higher flows from April to June (Sammons and Maceina, 2009).
- In the northeast, Coastal Plain studies demonstrated how bluespotted sunfish are highly dependent upon flood magnitude and duration to inundate flood-plain wetlands (Leitman and others, 1991; Light and others, 1998), which would make reductions of high flows detrimental to their persistence.

In the Atlantic non-Coastal Plain, reductions in the Annual High-Flow Cluster metrics resulted in increases in percent individuals with slow flow preference or omnivorous fish.

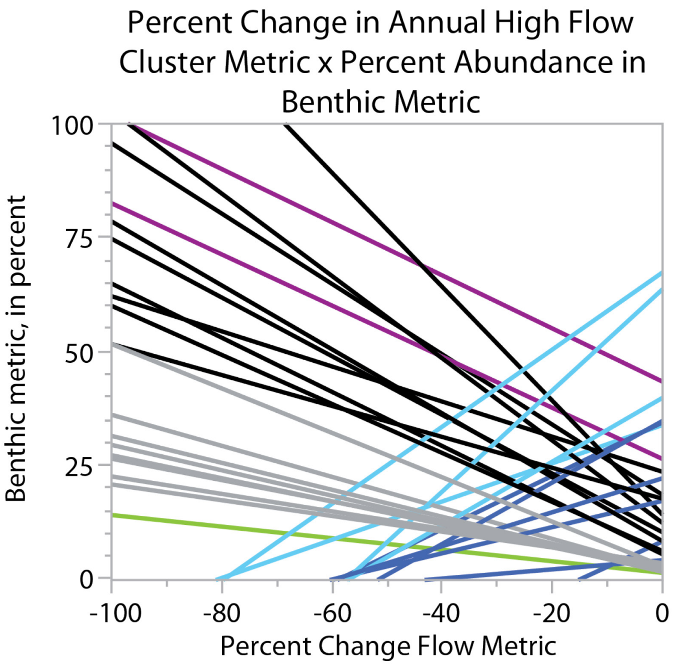
- Gido and others (2013) found increased densities of nonnative species in years with low mean annual discharge and reduced spring flows. Native species densities were generally higher in years with higher mean spring flows, which they hypothesized support recruitment (Gido and others, 2013). Olden and Poff (2003) found changes in community homogenization varied with the initial type and number of nonnative and native species, the historical degree of similarity among the communities, and the richness of the recipient communities.

Also of note for both the Atlantic and Ohio River drainages were decreases in benthic, native, Cyprinidae, suckers, darters, and fast flow preference fish that reflect patterns described by reductions in low-flow statistics in Virginia streams.

USGS

# Results: Annual High-Flow Cluster Benthic Responses

- There are similar responses to reduction in flows in this cluster depending on whether the statistic measures a decreasing magnitude or duration of a flood. The percent abundance of tolerant benthic organisms (black lines) such as midges, net-spinning caddisflies (Hydropsychidae), or organisms in the Baetidae family and noninsects increases with a corresponding decrease in intolerant organisms (EPT taxa, blue lines) in response to reductions in seasonal flow and annual mean and high flows.
- The reduction in high-pulse duration equates to shorter and lower magnitude floods and likely indicates a shift in the natural flow regime. Decreases in the percent abundance of intolerant organisms, such as EPT taxa (light and dark blue lines), typically result when high-pulse durations decrease.
- Increases in the percent abundance of blackfly larvae (Diptera), shredders (such as stonefly larvae, Plecoptera) and sprawlers (gray lines) like midges result from reductions in May and June low flows. Sprawlers live primarily on fine bottom sediments and have modifications for staying on top of substrate to keep respiratory surfaces free of silt. Increases in sprawlers can indicate a change in benthic substrate.

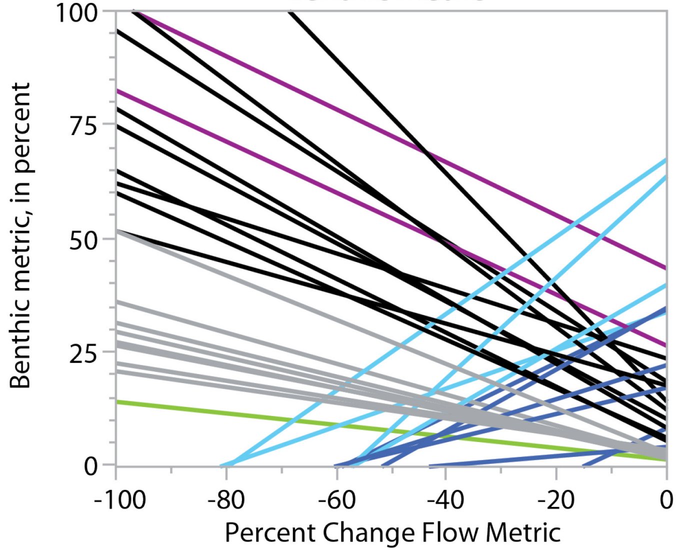



[detailed explanation on page 52]

USGS

# Results: Annual High-Flow Cluster Benthic Responses

Percent Change in Annual High Flow Cluster Metric x Percent Abundance in Benthic Metric




Decreasing Flow and Increasing Percent Abundance Benthic Metrics

7-day maximum
- Percent dominant and Top 2 dominant taxa

High Pulse Duration, April mean, June mean
- Percent Chironomidae (not June)
- Percent Diptera
- Percent noninsects (High Pulse only)

June Low Flow, May Low Flow, June mean, April mean, Mean Annual Flow
- Percent sprawlers
- Percent Plecoptera (May only)
- Percent Shredders (only June and May Low Flow)

1-day maximum
- Percent Bivalve
- Percent intolerant

3-day maximum
- Percent Hydropsychidae 2 EPT

90-day maximum
- Percent Baetidae to Ephemeroptera

Decreasing Flow and Decreasing Percent Abundance Benthic Metrics

1-day maximum, 3-day maximum
- Percent collector

High Pulse Duration
- Percent intolerant, EPT, clinger
- Percent Plecoptera
- Percent Coleoptera
- Percent Ephemeroptera
- Percent scrapers

90-day maximum
- Percent Gastropoda

# Results: Annual High-Flow Cluster Benthic Responses

Decreased high flows coupled with shorter high-flow durations may indicate the departure of flow conditions from the natural flow regime (Poff and others, 1997).

- Artificially lower flows during periods with historically higher scouring flows, such as those during spring-flow runoff, may be the result of streamflow alteration by water abstraction, decreased annual groundwater recharge, water regulation and management, and/or climate change (Carlisle and others, 2012; Castro and others, 2013).

A reduction in the mean annual, high, or mean-monthly flows may have an adverse effect on the biological community; these results have also been seen by Kennen and others (2014), Lytle (2002), Boulton (2003), and Lytle and Poff (2004).

- Kennen and others (2008) simulated the depletion of mean annual flow, which resulted in decreasing EPT and intolerant benthic organisms, plus an increase in tolerant relative abundances. Other work by Kennen and others (2010) suggests the timing of emergence periods can be affected by changes in mean annual streamflow as a mechanism to explain reduced abundance of sensitive taxa.
- Reduced high flows have been shown to enhance fine-sediment retention and reduce dissolved-oxygen concentration within the interstices of coarse streambed material, thereby altering stream habitat and the macroinvertebrate assemblage (Culp and others, 1986; Lisle and Hilton, 1999; Waters, 1995).
- Other studies have demonstrated how taxa favoring slow-moving waters and fine substrates (that is, some tolerant species and sprawler taxa) replaced macroinvertebrates that prefer coarse substrates in streams (such as EPT taxa) (Merritt and Cummins, 1996; Waters, 1995; Lenat and others, 1981; Carlisle and others, 2010).

# Results: Peak-Flow Frequency and Rate-of-Change Cluster Introduction

The peak-flow frequency and rate-of-change cluster is composed of decreasing hydro metrics that measure the streamflow variability during storm events, emphasizing streamflow flashiness and the frequency and magnitude of high-flow events. The magnitude of alteration in this group ranged from 0% to 50% reduction in the hydro metric from the baseline scenario to the recent-conditions scenario (2008).

- Peak-flow metrics in this cluster are grouped as high-flow (bankfull floods not overtopping channel bank), small floods (spilling into the flood plain), and large floods (extreme flooding events).

- The decreasing rise rate or fall rate means the incremental changes in flow from one day to the next during floods are small. This may indicate a smoothing or overall decrease in the flashiness of the system and lowering of the flood size or peak size. Flow alterations of streamflow variability are relatively uncommon except in the case of artificial flow regimes from heavily managed streams, such as those with dam/reservoir releases.

- Hydro metrics with an asterisk* were members of their own cluster, but were combined with this cluster because they represent similar metrics.

| Peak-Flow Frequency and Rate-of-Change | Within-Cluster $r^2$ |
|---|---|
| Fall Rate | 0.742 |
| High-Flow Fall Rate | 0.882 |
| High-Flow Frequency | 0.968 |
| High-Flow Rise Rate | 0.826 |
| High Pulse Count | 0.918 |
| Large Flood Fall Rate | 0.851 |
| Low Pulse Count | 0.811 |
| Number of Reversals | 0.422 |
| Rise Rate | 0.92 |
| Small Flood Fall Rate | 0.96 |
| Small Flood Peak | 0.582 |
| Small Flood Rise Rate | 0.903 |
| High-Flow Duration * | 0.704 |
| Large Flood Peak * | 0.811 |
| Large Flood Rise Rate * | 0.436 |

USGS

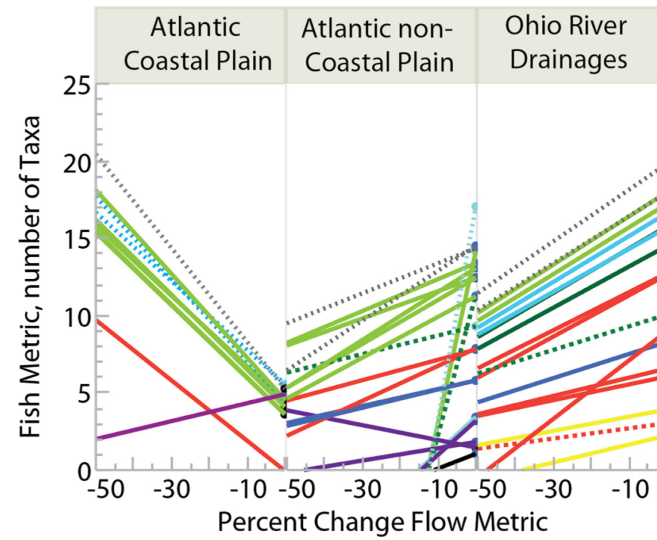
# Results: Peak-Flow Frequency and Rate-of-Change Cluster Fish Responses

- In response to decreasing rise rates and fall rates in the Atlantic and Ohio River drainages (upper graph, middle and right side), native or benthic taxa such as madtoms, darters, sculpins, and stonerollers decreased along with sunfish and the total number of taxa present.

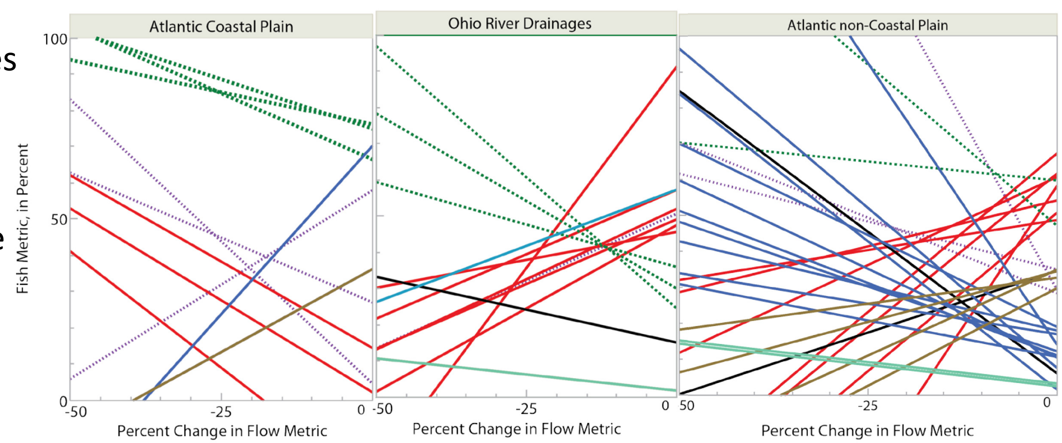
- In the Atlantic Coastal Plain (upper graph, left side) benthic taxa, native taxa, as well as slow flow preference fish such as largemouth bass increased in response to a 50% change in flow metric in this cluster. As the number of taxa increased in the Atlantic Coastal Plain, the percent abundances (lower graph, left side) of dominant taxon (dashed purple lines) and species preferring moderate flow also increased from less than 20% to greater than 50%. Slow flow preference fish (dashed green lines), which already compose the majority of the assemblages, also increased in response to reduced flow metrics.

- In the Atlantic and Ohio River drainages (lower graph, middle and right sides), species that prefer slow moving water and omnivorous diets, such as invertivore-piscivore fish (dashed green and solid blue lines), increased from less than 20% to more than 40%. Percent abundances of fish that prefer swiftly moving water (orange lines), like torrent suckers, sculpins, crescent shiners, darters, and blacknose dace, and lithophilic fish (brown lines) such as madtoms and central stonerollers, decreased.

Percent Change in Peak Flow Cluster Metric x Number of Taxa in Fish Metric



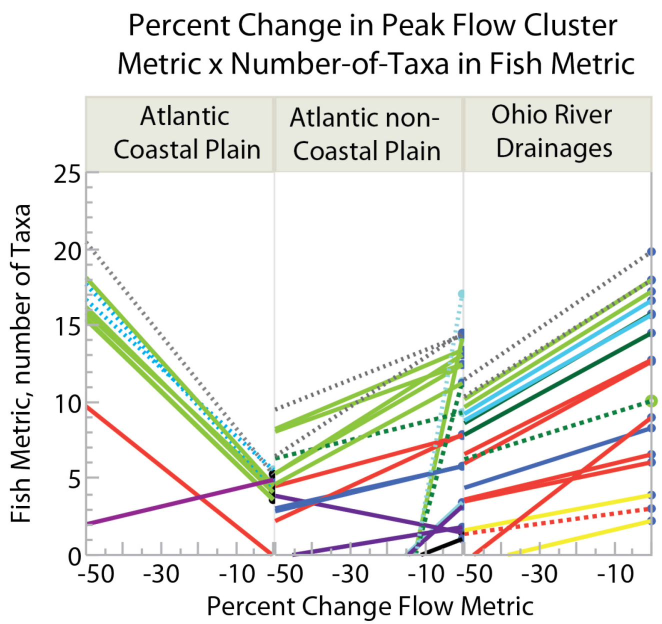

Percent Change in Peak-Flow Cluster Metric x Percent Abundance Fish Metric




[detailed explanation on pages 56 and 57]

USGS

# Results: Peak-Flow Frequency and Rate-of-Change Cluster Fish Responses




Ohio River Drainages
Decreasing Flow and Decreasing Number-of-Taxa Fish Metrics

Large flood Rise Rate, Small Flood Rise Rate
- Total number of taxa
- Benthic fish
- Native benthic
- Native
- Native Cyprinidae (only small Flood Rise Rate)

Large flood Rise Rate
- Darters ( plus Low Pulse Count)
- Benthic insectivores
- Fast and moderate flow preference fish
- Slow flow preference fish
- Moderate flow preference fish (Small Flood Peak)

Atlantic Coastal Plain
Decreasing Flow and Increasing Number-of-Taxa Fish Metrics

High-Flow Rise Rate, Fall Rate
- Total number of taxa
- Native benthic
- Benthic fish
- Slow flow preference fish
- Moderate flow preference fish (Fall Rate only)

Decreasing Flow and Decreasing Number-of-Taxa Fish Metrics
- Native sunfish (Large Flood Fall Rate)

Atlantic non-Coastal Plain Decreasing Flow and Decreasing Number-of-Taxa Fish Metrics

Small Flood Fall Rate
- Total number of taxa
- Native, native benthic, and benthic fish
- Moderate flow preference fish

Fall Rate
- Total number of taxa
- Benthic fish
- Slow flow preference fish
- Centrarchidae and native Centrarchidae
- Native sunfish (High-Flow Fall Rate)
- Native round-bodied suckers

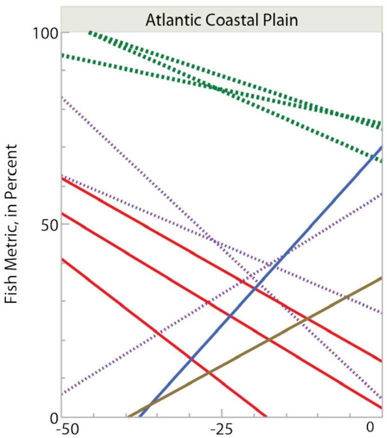
Small Flood Rise Rate
- Slow flow preference fish
- Moderate and fast flow preference fish
- Native Cyprinidae

Atlantic non-Coastal Plain
Decreasing Flow and Increasing Number-of-Taxa Fish Metric

High-Flow Rise Rate
- Centrarchidae

# Results: Peak-Flow Frequency and Rate-of-Change Cluster Fish Responses

Percent Change in Peak-Flow Cluster Metric x Percent Abundance Fish Metric




Decreasing Flow and Increasing Percent Abundance Fish Metrics

High-Flow frequency, Small Flood peak
- pi. dominant taxon

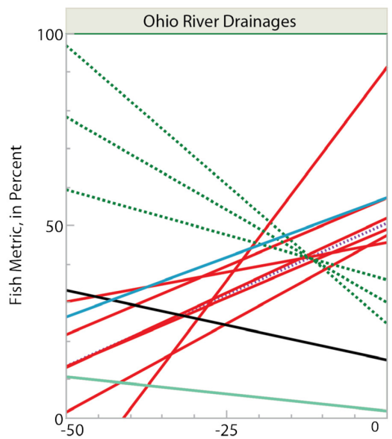
Large flood Fall Rate, Small Flood Fall Rate, Small Flood peak
- pi. Moderate flow preference fish

Large flood peak, RBI, Small Flood peak
- pi. Slow flow preference fish

Decreasing Flow and Decreasing Percent Abundance Fish Metrics

High-flow Rise Rate
- pi. invertivore and piscivore
- pi. lithophilic (High-flow frequency)
- pi. dominant taxon

Percent Change in Peak-Flow Cluster Metric x Percent Abundance Fish Metric



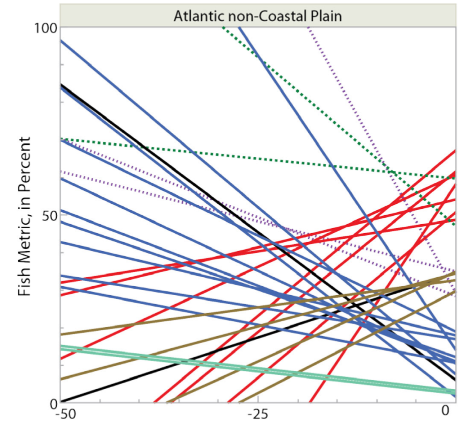

Decreasing Flow and Increasing Percent Abundance Fish Metrics

Small Flood Rise Rate, High Pulse Count & RBI (slow only)
- pi. Slow flow preference fish:
- pi. game fish
- pi. non-native

Decreasing Flow and Decreasing Percent Abundance Fish Metrics

High-Flow Rise Rate, High Pulse Count, Large Flood Rise Rate, Low Pulse Count, Small Flood Fall Rate, RBI
- pi. Fast flow preference fish: Small Flood Fall Rate
- pi. lithophilic (Large flood Fall Rate)
- pi. dominant taxon (High-Flow duration)

Percent Change in Peak-Flow Cluster Metric x Percent Abundance Fish Metric




Decreasing Flow and Increasing Percent Abundance Fish Metrics

Large Flood Rise Rate, Number of Reversals
- pi. Slow flow preference fish
- pi. game fish (Number of reversals only)

Fall Rate, High-Flow Frequency, High-Flow Fall Rate
- pi. invertivore and piscivore

Large flood Rise Rate, High-Flow Rise Rate, Large flood peak, Large Flood Fall Rate
- pi. invertivore and piscivore

Small Flood Peak, Rise Rate, RBI
- pi. invertivore and piscivore

Small Flood Rise Rate, Rise Rate
- pi. non-native
- pi. round-bodied suckers

Fall Rate, High-Flow Frequency, Small Flood Fall Rate
- pi. dominant taxon

Decreasing Flow and Decreasing Percent Abundance Fish Metrics

Small Flood Rise Rate, High-Flow frequency, High-Flow Fall Rate and Small Flood Peak (lithophilic only) Number of Reversals, High-Flow Rise Rate (fast only), Fall Rate (moderate only),
- pi. Fast flow preference fish
- pi. Moderate flow preference fish
- pi. lithophilic
- pi. game fish (High-Flow duration)

USGS

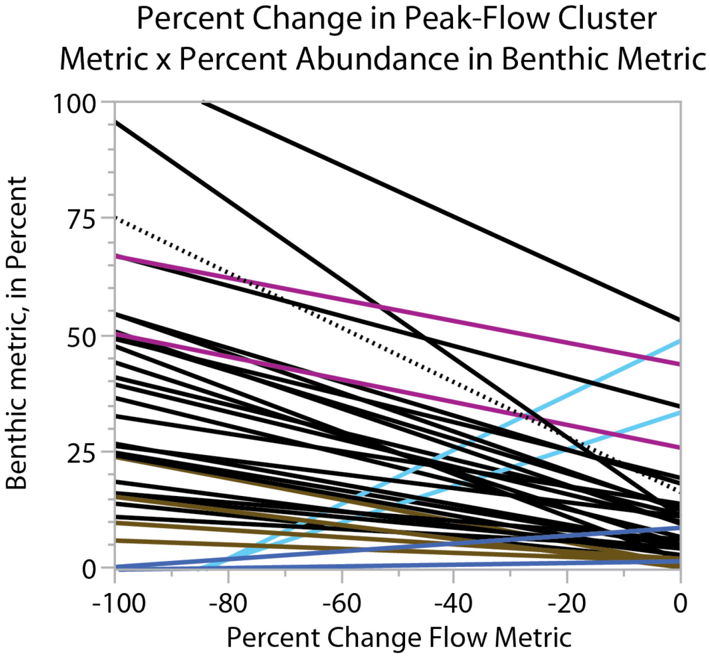
# Results: Peak-Flow Frequency and Rate-of-Change Cluster Fish Responses

Decreasing rise rates and fall rates in the Atlantic non-Coastal Plain and Ohio River drainages contribute to declines in total number of taxa of native, benthic fishes and sunfish present in the populations surveyed.

- Long-term monitoring sites throughout the northeastern United States demonstrated decreases in insectivore and piscivore feeding styles as well as taxa richness, sunfish, and darters (Kennen and others, 2012) in response to changes in rise rate and coefficient of variation (CV) in annual flows. Decrease in insectivore fish may indicate a shift in the benthic community.
- Future work in Virginia ideally would consider the inclusion of CV in summer, monthly, or low flows as an indicator of consistency of the flow regime. Many other studies (Gido and others, 2013; Iwasaki and others, 2012; Kennen and others, 2012; Knight and others, 2008) include CV statistics; however, other than the base-flow index this work has not.
- In their study of 22 streams of various sizes across the United States, Magilligan and Nislow (2005) found that the majority of sites had 40-48% decrease in rise rate or fall rate after upstream impoundment. They also found that high-pulse duration tended to decrease after dams were installed.
- Flow regimes that include reduced peak flows, increased base flows, and altered natural seasonal timing of flow variations are most likely from larger flood-control dams 50 meters (m) high or greater (Petts, 1984; Poff and Hart, 2002); whereas run-of-river hydropower dams 10 m high or less may only occasionally reduce peak flows (Poff and Hart, 2002). Given these findings, the sites in this study with reduced rates of change may be located downstream from large dams.

# Results: Peak-Flow Frequency and Rate-of-Change Cluster Benthic Responses

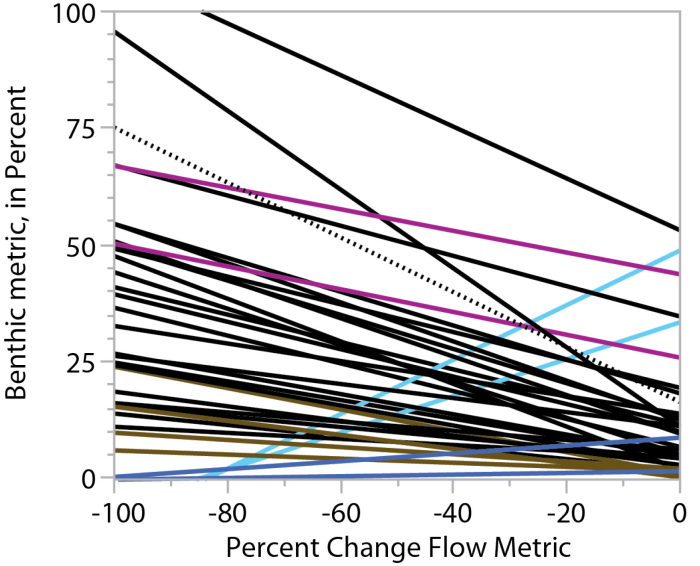
- Decreasing rise and/or fall rates indicate that these streams have slow rates of change in streamflow from one day to the next during high flows and flooding events.
- Decreases in large and small flood peak, rise rate, and fall rate resulted in an increase in intolerant organisms, such as percent of EPT species and stoneflies.
- Conversely, decreases in bankfull high-flow rise rate resulted in increases in tolerant taxa such as Chironomidae, noninsects, Baetidae, and Hydropsychidae.
- There is a mixed response for decreases in bankfull high-flow fall rate, frequency, and duration, as these metrics indicate the ability of some intolerant organisms to persist and increase, along with an increase in the percent abundance of tolerant organisms.




[detailed explanation on page 60]

# Results: Peak-Flow Frequency and Rate-of-Change Cluster Benthic Responses

Percent Change in Peak-Flow Cluster Metric x Percent Abundance in Benthic Metric




Decreasing Flow and Decreasing Percent Abundance Benthic Metrics

Large Flood Fall Rate and Fall Rate

- Percent collector
- Percent Oligochaeta
- Percent Gastropoda

High-Flow Duration

- Percent EPT

Decreasing Flow and Increasing Percent Abundance Benthic Metrics

Fall Rate, Richards Baker Index (RBI), High-Flow Fall Rate

- Percent Bivalve
- Percent climber (not RBI)

Large Flood Fall Rate

- Percent predators
- Percent Trichoptera
- Percent EPT
- Percent filterer

Large Flood Peak, Large Flood Fall Rate, Fall Rate, Large Flood Rise Rate

- Percent Intolerant (not Fall Rate, Large Flood Rise Rate)
- Percent Plecoptera and Trichoptera, no Hydropsychidae

Small Flood Peak

- Percent intolerant
- Percent Trichoptera

High-Flow Rise Rate, RBI

- Percent Baetidae to Ephemeroptera

Fall Rate, Rise Rate

- Percent Chironomidae
- Percent Diptera (Rise Rate only)

Large Flood Rise Rate, Small Flood Fall Rate

- Percent Bivalve

Rise rate

- Percent Hydropsychidae 2 Trichoptera or EPT
- Percent dominant and Top 2 dominant taxa
- Percent Coleoptera (RBI)
- Percent noninsects (High-Flow Frequency)

# Results: Peak-Flow Frequency and Rate-of-Change Cluster Benthic Responses

The slower rates of change and lower peak flows for high and extreme flows suggest streamflow stabilization, or a smoothing of the natural streamflow variability.

- Other studies have seen similar modified flow regimes in streams affected by dams, impoundments, water diversions, levees, and decreases in base flow by groundwater abstraction or diminished infiltration (Magilligan and Nislow, 2005; Miller and others, 2007; Dewson and others, 2007).

Decreasing extreme flooding events may increase species richness and relative abundance of intolerant species in the macroinvertebrate assemblage.

- Many studies (see review by Poff and Zimmerman, 2010) have found that extreme flooding events with increased flashiness and streamflow magnitudes are a major factor in macroinvertebrate life-cycle disruption, reduced species richness, altered assemblages, relative abundance of taxa, and the loss of sensitive species. Diminishing flood magnitude and decreasing flashiness within the study area may have a protective effect, resulting in an increase in intolerant species. These lower magnitude floods regulate numerous ecological processes by flushing fine sediments, reducing temperature, increasing dissolved-oxygen concentration, and altering riparian factors within a stream (Poff and others, 1997; Hart and Finelli, 1999).
- Deleterious effects from extreme flows may be minimized as a result of slower rates of change and lower peak flows. In one managed stream downstream from a dam, ramping restrictions may have reduced the effects of flow magnitude by lessening catastrophic drift during initial stream rise, peaking at a modified flow, and minimizing stranding with a slower fall rate (Patterson and Smokorowski, 2011).

Streams with increased streamflow stabilization and reduced high-flow variability show a mixed response with macroinvertebrate assemblage.

- Other studies have shown that macroinvertebrates exhibit mixed responses to increases or decreases in high flow, and this may result from geomorphic changes or habitat influences of high-flow events (Poff and others, 1997; Poff and Zimmerman, 2010; Richter and others, 2003).
- Both intolerant and tolerant macroinvertebrates can persist in streams with diminished high flows if they possess traits that allow them to adapt to their environment, such as the ability to find refuge in both higher and lower velocity patches or temporarily leave the aquatic environment (Brooks and others, 2011; Brooks and Haeusler, 2016; Carlisle and others, 2010). However, alterations in the natural high-flow variability, magnitude, and duration can substantially affect the most sensitive species of macroinvertebrates that are less resilient (Kennen and others, 2010, 2014).

# Results: Key Findings Summary

- Overall, each flow cluster demonstrated that decreases in flows throughout the flow regime contributed to a shift in the community structure to generalized and less diverse species assemblages.
- The decreasing magnitude of low flows or mean flows during summer or fall periods may result in a shift to a more generalist fish community (omnivorous and slow flow preference), and a more tolerant assemblage of macroinvertebrates (decrease in EPT, decrease in evenness, and increase in Chironomidae and Hydropsychidae).
- The diminished low-flow magnitude and duration could signify a shift to slow water velocities that cause habitat degradation in riffles and fast-run habitats. The decrease in Ephemeroptera and Tricoptera may explain the shift to a generalist fish community resulting from a decline in benthic insect food sources.
- Observance of winter-spring flow-magnitude decrease with an increase in intolerant species of macroinvertebrates (EPT) merits additional study. This response does not follow the patterns of decreasing intolerant organisms with monthly decreasing flows observed during other seasons.
- Decreases in high-flow metrics have varying effects on the aquatic assemblage, depending on the type of high-flow event and overall reduction in flow magnitude and rate of change. These reductions in flow ultimately affect channel geomorphology, water quality, and the aquatic community.
- It is important to reiterate that the flow alterations simulated in this study represent the cumulative hydrologic alteration from water withdrawals, impoundments, and altered landscapes. More work is needed to determine the effect of water withdrawals on biota if other factors were held constant. Future work could focus on reference or exposure streams with minimal landscape alteration and water withdrawal amounts as Chessman and others (2011) found no difference in the benthic community structure in these types of streams with a 0–20% reduction in mean annual flow.

# Acknowledgments

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