Recommendations for Estimating Flows to Maintain Ecological Integrity in Streams and Rivers in North Carolina



Submitted to the
North Carolina Department of
Environment and Natural Resources
by the
North Carolina Ecological Flows
Science Advisory Board

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DEDICATION

Photo courtesy of Mark Cantrell

The Ecological Flows Science Advisory Board dedicates this report to the memory of Steve Reed in appreciation of his many contributions to the state of North Carolina through his work at the Division of Water Resources.

For more than three decades, Steve led efforts to establish ecological flows in North Carolina, contributing to the science and practice, while leaving a deep impression on all he met with his kindness and professionalism. Steve died suddenly in July, 2012 before the completion of this effort, but his spirit continued to inspire the work behind this report and will inspire the future work of others.

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EXECUTIVE SUMMARY

The Ecological Flows Science Advisory Board (EFSAB) was created to assist the Department of Environment and Natural Resources (DENR) with developing a scientifically defensible approach to establishing flows that protect the ecological integrity of streams and rivers in North Carolina as required under Session Law 2010-143. The EFSAB was tasked with reviewing published and unpublished studies that characterize the ecology of North Carolina rivers, relating ecological conditions to flow alteration, and identifying a scientifically defensible approach to establishing flow requirements for the maintenance of ecological integrity. Per Session Law 2010–143, the EFSAB included representatives from the state (the N.C. Division of Water Resources, the N.C. Division of Water Quality, the N.C. Wildlife Resources Commission, the N.C. Division of Marine Fisheries, and the N.C. Natural Heritage Program), the U.S. Fish and Wildlife Service, the National Marine Fisheries Service, and individuals with expertise in aquatic ecology and habitats from organizations representing agriculture, forestry, manufacturing, electric public utilities, non-governmental organizations, local governments, and other individuals and organizations.

The EFSAB elicited input from a wide variety of state, federal, and local agencies as well as academic and non-governmental organizations in reviewing existing strategies for determining ecological flows and in conducting new analyses within the State. The EFSAB focused on reviewing ecological flow literature, hearing and discussing presentations from ecological flow experts, and reviewing flow-ecology research conducted in North Carolina. In addition, the EFSAB worked through informal subcommittees to analyze flow-ecology relations using data (fish and benthic macroinvertebrate) specific to North Carolina streams and to address flow and ecology issues unique to streams in the coastal plain. The work of these subcommittees helped the EFSAB make recommendations that were more specific to North Carolina streams than was possible by relying solely on recommendations obtained from literature review.

Based on the review of existing work and the detailed analyses conducted by the subcommittees, the EFSAB recommends that DENR use a two-part strategy to establish ecological flows, determine if future conditions support these flows, and assess whether additional review and studies are warranted:

1. **Percentage-of-flow strategy:** establish ecological flows on the basis of 80–90% flow-by (i.e., 80–90% of ambient modeled flow remains in the stream) in combination with a critical low-flow component that identifies when additional actions may be needed to protect ecological integrity. The critical low-flow component is intended to minimize increases in the magnitude and duration of extreme low flows during drought conditions. If the basinwide hydrologic models and critical low-flow component indicate that there is not sufficient water available to meet essential water uses and ecological flows at a given location, further review by DENR is recommended. This strategy of establishing ecological flows is similar to approaches used by other states and countries. The EFSAB has not recommended a specific value for the low-flow component, but recommends that DENR establish these values based on an analysis of typical and extreme low-flow conditions in North Carolina.

2. **Biological-response strategy:** evaluate the effects of ecological flows using models that relate changes in fish and invertebrate communities to current and future flows derived from the percentage-of-flow strategy. The biological-response strategy directly

links the statewide fish and invertebrate data collected by DENR with flow data derived from basinwide hydrologic models to predict biological changes. The EFSAB recommends that DENR use a 5–10% reduction in biological condition—using (A) Shannon-Weaver Diversity Index for fish and (B) number of taxa in the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) for invertebrates—as a threshold for initiating further review by DENR.

The EFSAB recognizes that the science underlying these recommendations will evolve as more research addresses flow-ecology issues at additional spatial and temporal scales. The EFSAB understands that the hydrologic and biologic models on which our recommendations are based may need to be revised as changes in climate and land cover alter patterns in precipitation, temperature (air and water), and runoff across the state. The flow and biological criteria recommended by the EFSAB will need to be reevaluated to determine their efficacy throughout the state and through time. Gaps in available hydrologic and biologic data (headwater, coastal plain and large rivers) will need to be addressed in order to provide a more complete representation of flow effects on biological integrity within the state. Consequently, the EFSAB recommends that DENR take an adaptive management approach to establishing flows that protect the ecological integrity of North Carolina streams. This approach should address the following issues:

1. Collect additional hydrologic and biologic data in headwater, coastal plain and large rivers that are currently underrepresented in DENR datasets. These data will help determine if these streams fit into current models and assumptions.

2. Adopt, design, and develop strategies to:

    a. Validate the efficacy of ecological thresholds and adjust as necessary. Validation should be informed by new data and/or research.

    b. Track the impact of flow changes when and where they occur.

    c. Modify characterizations, target flows, and thresholds based on new data, changing conditions (e.g., land cover, precipitation, hydrology) and lessons learned.

    d. Georeference nodes in each hydrologic model to facilitate analysis.

The recommendations of the EFSAB represent a starting point for developing ecological flows that protect the integrity of North Carolina streams. By adopting an adaptive management approach, DENR can ensure that ecological integrity is protected through the refinement and improvement of the recommendations of the EFSAB over time.

GLOSSARY

7Q10 – the lowest average flow that occurs for seven consecutive days with a recurrence probability of once every 10 years. The 7Q10 value is typically used for determining assimilative capacity for receiving streams when permitting wastewater discharges. Flows equal to the 7Q10 generally occur during drought.

Annual 30-day Minimum Flow – the lowest 30-day mean flow calculated as a moving average for every 30-day period that is completely within the water year.

BEC – Biological Environmental Classification analysis performed by RTI International.

CHEOPS (Computer Hydro-Electric Operations and Planning Software) – simulation package developed by HDR, Inc. to evaluate the costs and benefits associated with a wide range of changes to a hydropower system. CHEOPS was developed for and is currently used to model flows in the Catawba River.

Condition Class – a classification system in which sampling sites are divided into classes on the basis of an ecological attribute or collection of attributes. Classes are ordered by the amount of change in the ecological attribute that occurs along a disturbance gradient that ranges from undisturbed (Excellent condition class) to highly disturbed condition (Poor condition class).

cfs – cubic feet per second (1 cfs = 0.646 million gallons per day).

ecological deficit (ecodeficit) – the total difference between the altered and unaltered flow duration curves, whenever the altered curve falls below the unaltered curve.

ecological flow – "stream flow necessary to protect ecological integrity" [as defined by General Statute 143-355(o)(1)].

ecological integrity – "the ability of an aquatic system to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to prevailing ecological conditions and, when subject to disruption, to recover and continue to provide the natural goods and services that normally accrue from the system" [as defined by General Statute 143–355(o)(1)].

ELOHA (Ecological Limits of Hydrologic Alteration) – a step-wise flow determination process that includes establishing a hydrologic foundation, classifying rivers, and determining flow-ecology relationships before entering a social process to develop flow regime standards (see Poff et al. 2009).

EPT – the insect orders Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies).

EPTr (EPT richness) – total number of taxa collected at a site from the insect orders Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies).

flow duration curve – a cumulative curve that shows the percent of time specified discharges were equaled or exceeded during a given period.

guild – a grouping of species, or species life stages, based on similar habitat requirements.

Index B – habitat metric used during time series analysis, a component of PHABSIM (see below), calculated by averaging all weighted usable area (see WUA) habitat values between the 10th and 90th percentiles on a monthly or seasonal basis for a flow record. Used to compare different flow regimes.

Invertebrate – animals that lack a backbone such as insects, worms, mussels, clams, snails, and crayfish.

Monthly median – In general hydrologic terms the middle flow value for the rank ordered flows for all years of a month (i.e. the 50^{th} percentile).

mgd – million gallons per day (1 mgd = 1.547 cubic feet per second).

NWIS (National Water Information System) – US Geological Survey (USGS) and US Environmental Protection Agency (EPA) work together to provide scientists and policy-makers an easier way to discover and acquire water quality data from their large water quality databases and share water monitoring data via a common format and terminology. A Water Quality Portal is available at www.waterqualitydata.us for downloading monitoring location information and associated water quality results that are automatically linked and integrated from both USGS and US EPA databases.

OASIS (Operational Analysis and Simulation of Integrated Systems) – generalized program for modeling the operations of water resources systems, developed by HydroLogics, Inc., that routes water through a system represented by nodes and arcs. OASIS is the hydrologic model currently used by the Division of Water Resources to model flow and water use in the major river basins.

ORW (Outstanding Resource Water) – a supplemental water quality classification designated by the EMC for special or unique surface waters in NC having excellent water quality and being of exceptional state or national ecological or recreational significance.

p-value – a measure of the probability that an observed value (e.g., slope or intercept in a regression) is the result of random chance. Low p-values (< 0.05) are generally considered to be statistically significant.

PHABSIM (Physical Habitat Simulation) – a specific model designed to calculate an index to the amount of microhabitat available for different organisms and life stages at different flow levels, incorporating two major analytical components: stream hydraulics and organism/life stage-specific habitat requirements.

PNV (potential natural vegetation) – the types of vegetation that would exist under most favorable conditions in the conterminous United States as proposed by A.W. Kuchler (1964).

Prevailing ecological conditions – “the ecological conditions determined by reference to the applicable period of record of the United States Geological Survey stream gauge data, including data reflecting the ecological conditions that exist after the construction and operation of existing flow modification devices, such as dams, but excluding data collected when stream flow is temporarily affected by in-stream construction activity” [from General Statute 143–355(o)(1)].

Q – volumetric flow rate, typically expressed in cubic feet per second.

Quantile Regression – a type of regression analysis that estimates either the conditional median or other quantiles (e.g., 80th or 90th) of the response variable. Quantile regression has been used in ecological studies to uncover predictive relationships between variables where the relationship is weak or obscured by other variables.

SE (standard error) – a statistical term that measures how accurately a sample represents the underlying population. The smaller the standard error, the more representative the sample is of the population.

September Median – the monthly median flow for September (see monthly median). The September median flow has sometimes been used as a minimum flow in the Southeast because September is typically the month with the lowest monthly median flow.

Shannon-Weaver Diversity Index – a quantitative measure that reflects how many different types (such as species) there are in a dataset, and simultaneously takes into account how evenly the basic entities (such as individuals) are distributed among those types.

Tennant method – a hydrologic standard setting approach for minimum flows based on percentage of mean annual flow that varies by month.

Trimmed hydrology dataset – a hydrology dataset that excludes a designated percentage of data at the upper and/or lower ends of the cumulative frequency distribution. For example, a dataset that excludes the highest and lowest 10% contains the central 80% of the data.

WaterFALL™ (Watershed Flow and ALLocation) – watershed modeling tool developed by the RTI International using National Hydrography Dataset (NHDPlus) hydrologic catchments to investigate water availability and allocation at multiple geographic scales.

WUA (weighted usable area) – an amount of habitat determined by PHABSIM, often represented as square feet of habitat per thousand feet of stream (see PHABSIM).

ACRONYMS

APNEP – The Albemarle Pamlico National Estuary Partnership

AWWA – American Water Works Association

BEC – Biological Environmental Classification (see glossary for definition)

CEFWG – Coastal Ecological Flows Working Group

CFS – cubic feet per second

CHEOPS – Computer Hydro-Electric Operations and Planning Software (see glossary for definition)

CHPP – Coastal Habitat Protection Plan

DENR – Department of Environment and Natural Resources

DMF – Division of Marine Fisheries

DO – dissolved oxygen

DWQ – Division of Water Quality (as of 2013, merged with DWR)

DWR – Division of Water Resources

ECU – East Carolina University

EDF – Environmental Defense Fund

EEP – Ecosystem Enhancement Program

EFS – Environmental Flow Specialists, Inc.

EFSAB – Ecological Flows Science Advisory Board

ELOHA – Ecological Limits of Hydrologic Alteration (see glossary for definition)

EMC – Environmental Management Commission

EPT – insect orders of Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies) (see glossary for definition)

ERC – Environmental Review Commission

GIS – Geographic Information System

G.S. – General Statute

MAF – mean annual flow

MFC – Marine Fisheries Commission

MGD – million gallons per day

NCDA&CS – North Carolina Department of Agricultural and Consumer Services

NCFA – North Carolina Forestry Association

NCFS – North Carolina Forest Service

NHD+ – National Hydrography Dataset Plus

NHP – Natural Heritage Program

NMFS – National Marine Fisheries Service

NOAA – National Oceanic and Atmospheric Administration

NWIS – National Water Information System (see glossary for definition)

OASIS – Operational Analysis and Simulation of Integrated Systems (see glossary for definition)

ORW – Outstanding Resource Waters (see glossary for definition)

PHABSIM – Physical Habitat Simulation (see glossary for definition)

RTI – Research Triangle Institute

SALCC – South Atlantic Landscape Conservation Cooperative

SARP – Southeastern Aquatic Resources Partnership

SAS – Statistical Analysis System

SE – standard error

SG – Sea Grant Program

TNC – The Nature Conservancy

UNC IMS – University of North Carolina Institute of Marine Sciences

USFWS – United States Fish and Wildlife Service

USGS – United States Geological Survey

WaterFALL™ – Watershed Flow and ALLocation (see glossary for definition)

WRC – North Carolina Wildlife Resources Commission

WRRI – Water Resources Research Institute

WUA – weighted usable area (see glossary for definition)

1 PREFACE

1.1 The Department (DENR) and Division (DWR)

The North Carolina Department of Environment and Natural Resources (DENR or the Department) is the lead stewardship agency for the preservation and protection of North Carolina's natural resources. The organization administers regulatory programs designed to protect air quality, water quality, and the public's health. The Department, through its Division of Water Resources (DWR), specifically administers water resource planning for the state and has been tasked with convening and providing staff support to the Ecological Flows Science Advisory Board (EFSAB).

1.2 Legislative Background

Session Law 2010-143 (Appendix A) amended portions of General Statute (G.S.) 143, Article 38, which deals with water resources. Specifically, the Session Law added language to G.S. 143-355 requiring DENR to develop basinwide hydrologic models for each of the 17 major river basins in North Carolina to simulate flows for determining if adequate water is available in the future to meet all needs, including essential water uses and ecological flows. Basinwide models are considered a practical approach to water planning because site- and project-specific evaluations require considerable time and money. However, the proposed planning method used by DENR will not replace site-specific studies needed for a specific environmental assessment or permit review. This proposed method will not vary existing permits/licenses or impose additional regulatory requirements on current permittees related to water quality and water quantity. Per the statute, DENR is required to provide status reports to the N.C. Environmental Review Commission (ERC) on the development of basinwide hydrologic models no later than November 1 of each year, beginning in 2011.

The Session Law defines ecological flow as “the stream flow necessary to protect ecological integrity.” Ecological integrity is defined as “the ability of an aquatic system to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to prevailing ecological conditions and, when subject to disruption, to recover and continue to provide the natural goods and services that normally accrue from the system.” The statute directs DENR to “characterize the ecology in the different river basins and identify the flow necessary to maintain ecological integrity.”

Session Law 2010–143 directs DENR to “create a Science Advisory Board to assist the Department in characterizing the natural ecology and identifying the flow requirements.” The statute directs DENR to ask the EFSAB “to review any report or study submitted to the Department for consideration that is relevant to characterizing the ecology of the different river basins and identifying flow requirements for maintenance of ecological integrity.” Per Session Law 2010–143, the EFSAB shall include representatives from: the N.C. Division of Water Resources (DWR); the N.C. Division of Water Quality (DWQ); the N.C. Wildlife Resources Commission (WRC); the N.C. Division of Marine Fisheries (DMF); and the N.C. Natural Heritage Program (NHP). The statute also directs DENR to invite participation by: the U.S. Fish and Wildlife Service (USFWS); National Marine Fisheries Service (NMFS); and individuals with expertise in aquatic ecology and habitat from organizations representing: agriculture; forestry;

manufacturing; electric public utilities; and local governments; and other individuals or organizations with expertise in aquatic ecology and habitat.

While the role of the EFSAB appeared rather clear from the statutory language, it was subject to early discussion and interpretation by the members. After preliminary discussions and review of the statute, the EFSAB agreed any recommendations regarding ecological flows would be made for the purpose of water resource planning, not water-use permitting. The EFSAB also agreed to recommend scientifically-based methods or approaches, and ecological flow requirements, which may or may not be numerical. Although the EFSAB is charged with developing a statewide approach, this approach does not substitute for site-specific evaluation when that is needed and it does not prevent DENR from requesting a site-specific evaluation. The EFSAB agreed to provide two primary deliverables: 1) characterization of aspects of the ecology in different river basins relevant to ecological flows; and 2) identification of the flow regimes necessary to maintain ecological integrity. The EFSAB is neither responsible for recommending how DENR responds to a water-availability issue nor responsible for advising DENR on how to use the EFSAB recommendations and research products.

1.3 DENR's Actions Establishing the EFSAB

DENR, through DWR, extended invitations to 16 members of the North Carolina scientific and technical community with expertise in aquatic ecology and habitat to serve on the EFSAB. The EFSAB has a total of 16 primary members, as well as alternates, from the following agencies or organizations: DWR, DWQ, WRC, NHP, DMF, Environmental Management Commission (EMC), USFWS, NMFS, USGS, American Water Works Association (AWWA), the N.C. Department of Agricultural and Consumer Services (NCDA&CS), the N.C. Forest Service (NCFS), utilities, local governments, academic institutions, and environmental non-governmental organizations.

In addition, DWR contracted with the N.C. State University's Natural Resources Leadership Institute and program for Watershed Education for Communities and Local Officials to assist in the development of the EFSAB charter, lead development and organization of the agenda for each EFSAB meeting, facilitate the EFSAB meetings, produce written minutes for each meeting, and assist with other process management tasks. DWR produced and hosts an ecological flow website–www.ncwater.org–with pages defining ecological flow and discussing the importance of ecological flows to North Carolina. The website documents the activities of the EFSAB, including presentations, literature reviewed, meeting recordings and minutes.

1.4 Activities of the EFSAB

The EFSAB met 28 times with the first meeting convened November 8, 2010 and the last meeting held October 23, 2013. During the initial meetings, the EFSAB established a charter that included the purpose, goals, procedural rules, and responsibilities for the EFSAB members, DWR and the facilitation team. Decision-making by the EFSAB was based on consensus principles. The EFSAB used small-group break-out sessions, brainstorming, open discussions, and trial balloon techniques to discuss and clarify topics, capture individual member's concerns, and put forth potential methods to achieve the EFSAB's ultimate goal of advising DENR on its charge of characterizing the ecology of the river basins and identifying the flow regime necessary to maintain ecological integrity. To address the latter charge, the EFSAB spent the majority of its time reviewing ecological flow literature, hearing and discussing presentations from ecological flow experts, and reviewing research conducted in North Carolina.

2 STATE OF ECOLOGICAL FLOW SCIENCE

2.1 Characterization of the Ecology of North Carolina Rivers

Physical, biological, and chemical processes determine the presence, absence, abundance and diversity of species, as well as habitat types present within streams. These processes, coupled with hydrology, determine the ecology of streams. In general, the freshwater ecology of the streams of North Carolina is characterized by intermittent and perennial flowing systems with diverse aquatic fauna (depending in part on detrital energy derived from terrestrial plants at the headwaters) and productive larger streams with resident diadromous fishes near the estuaries. North Carolina streams show distinct seasonal patterns and variation in their flow.

The ecology of freshwater streams is as diverse as the landscapes across the state. Streams in North Carolina vary from small tumbling mountain waterfalls and meandering blackwater streams to large piedmont and coastal rivers. North Carolina streams include coldwater communities, mostly in the higher elevations of the mountains where summer water temperatures generally do not exceed 22 degrees Celsius (72°F). Coolwater streams occur in lower elevations in the mountains and piedmont with maximum temperatures between 22-25 degrees Celsius (72-77F).

Warmwater streams are flowing waters with maximum water temperatures typically greater than 25°C (77°F). Outstanding Resource Waters (ORW) are designated in nearly all of the basins in North Carolina and all of the physiographic regions. On the other end of the spectrum, there are impaired streams in all of the basins and each of the physiographic regions. Specific information relative to the streams and watersheds in the state can be obtained from DENR's basinwide plans.

2.1.1 Mountain Streams

The freshwater streams of the mountains are located within the Blue Ridge Physiographic Province of the Appalachian mountains of western North Carolina. These watersheds are characterized by forestland cover, extreme relief and high precipitation resulting in numerous streams with permanently flowing, steep gradient channels, and well-oxygenated waters. These streams provide habitats for diverse aquatic life and complex ecological functions. Much of the land within the mountains is sparsely developed. Major stream systems draining the Blue Ridge Province in North Carolina include the Little Tennessee, Hiwassee, French Broad/Nolichucky, Watauga and New rivers (part of the Mississippi River drainage), and the Savannah, Broad, Catawba, and Yadkin rivers (part of the Atlantic Ocean drainage).

Mountain streams typically have relatively steep gradient in many reaches. Most tributaries are high gradient streams with cold water capable of supporting trout populations in the upper reaches. Some tributaries and upper mainstems have cool water capable of supporting communities characterized by smallmouth bass.

The aquatic communities typically found in mountain drainages are significantly different than those found in drainages of the piedmont and coastal plain. Mountain streams host some of the most diverse aquatic communities within North Carolina. They are home to a variety of rare species, including crayfish, mussels, fish, aquatic insects, and amphibians. For example, the

25-mile reach of Little Tennessee River between the town of Franklin and Fontana Lake has a faunal diversity rivaling any in the state.

The hydrology of most streams and rivers in the mountains is relatively unaltered. However, a number of hydropower projects significantly alter flows, and therefore stream ecology, by operating in a peaking mode or diverting water around long stretches of stream channel. The ecology of mountain streams is also influenced by numerous culverts and barriers that impede the movements of aquatic organisms.

2.1.2 Piedmont Streams

Streams in the Piedmont Physiographic province of North Carolina flow toward the Atlantic Ocean. Many piedmont streams originate in the mountains, eventually transitioning across the Fall Line before reaching the coastal plain. Piedmont streams can be considered as intermediate to the higher gradient, cooler streams of the mountains and the low gradient waters of the coastal plain. In addition, piedmont streams typically lack the large boulders of mountain streams yet have more substrate size diversity than the sand dominated streams of the coastal plain. The majority of aquatic communities in piedmont streams are considered warmwater, although some coolwater communities are present in the foothills portions of some basins.

Increasing nutrient enrichment, stormwater from urban areas, and wastewater are the primary impacts to water quality in the eight basins of the piedmont. Most of these impacts are associated with urban areas. Land conversion from forest and agricultural practices to suburban uses is occurring throughout the piedmont, especially in the area known as the "Piedmont Crescent" which extends from Charlotte to Greensboro to Raleigh, often resulting in impacts to riparian habitats.

Nearly all of the large reservoirs in the state are found in the piedmont. Reservoirs have a significant influence (positive and negative) on the hydrologic regime of the rivers downstream of their dams and transform hundreds of miles of riverine habitat into lakes. This is particularly true in the Catawba, Roanoke and Yadkin basins.

Present in the piedmont region are streams in largely forested areas with comparatively undeveloped catchments and very good water quality. In recent years, streams of the piedmont have experienced recurring moderate to severe drought. The drought conditions have led to acute awareness of the limits of availability of freshwater for drinking, recreation, and assimilation of discharge effluent.

Changes in hydrology and habitat condition have altered the biological communities of many piedmont streams and rivers. For example, many species requiring flowing water and good water quality have been replaced by habitat generalists that can tolerate a variety of conditions. Only a small percentage of piedmont streams, such as the upper Tar and Roanoke, presently support a diversity and abundance of freshwater mussels similar to historic distributions.

2.1.3 Coastal Plain Streams

Freshwater streams of the coastal plain are located within the inner and outer divisions of the Coastal Plain Physiographic provinces. Coastal plain streams are characteristically low to medium gradient, with sandy to muddy substrate that provides habitat to warmwater adapted communities. Groundwater and surface water can be tightly linked in the coastal plain. Further, water quantity and quality are closely linked as flow has important effects on salinity and dissolved oxygen concentrations.

The freshwater and estuarine streams in the coastal plain have different origins. Many freshwater streams in the coastal plain region are non-tidal streams originating in the coastal plain. A very small number of non-tidal stream reaches present along the westernmost boundary of the Inner Coastal Plain Physiographic province originate in one of five piedmont basins and are typically medium gradient streams in the upper reaches. Saline, tidal streams originating in the coastal plain are present along the eastern boundary of the Outer Coastal Plain. Bi-directional flow from wind-driven and astronomical tides may reach into the inner coastal plain rivers and streams.

Natural communities in coastal plain streams include in-channel and floodplain communities that support resident and non-resident migratory fishes, and many species adapted to blackwater and swamp conditions. Riparian floodplains and instream aquatic vegetation associated with coastal plain stream systems influence the aquatic ecology of the coastal plain region. Seasonal hydrologic variations, such as flooding, are important to these flood plain forest communities as well.

The species and ecology in coastal plain streams are often different from those found in inland waters. For example, diadromous fish (fish that migrate between fresh and salt water) require high seasonal flows to cue spawning. Flow in these streams is important during both spawning periods and other times to allow juvenile fish growth within freshwater reaches. Ditching and channelization are extensive, and links between natural and engineered waterways are common with resultant modified flows. Barriers, such as culverts and low head dams, restrict fish movements, particularly diadromous fish and are an issue in many coastal plain and inland watersheds.

Many ecologically and economically valuable estuarine species are dependent on freshwater flows in the coastal plain streams to maintain low-salinity conditions. The position of the salt wedge is a condition critical for transitional communities. Examples of the aforementioned estuarine species include southern flounder, Atlantic croaker, spot, menhaden, bay anchovy, blue crab, white shrimp, and striped mullet. Flows that trigger spawning are also critical for the integrity of these systems. Flows during larval and juvenile growth and development are equally important.

2.1.4 Headwater Streams

The majority of stream miles in North Carolina are classified as headwater streams (drainage area < 10 km^2) (Olivero and Anderson 2008). Headwaters include the smallest parts of streams, are located in the extreme upper portions of a watershed, and are the furthest distance from the stream's mouth. The origin of headwater streams varies per topography and geology, as well as the stream's location within the state. For example, headwater streams in high gradient areas usually contain large rocks and have high velocities, whereas headwater streams in low gradient areas are abutted by large floodplain areas and have low velocities.

Headwater streams originate in almost every type of terrestrial community from undeveloped watersheds to highly developed watersheds containing impervious surfaces and agricultural areas. Headwater streams have small drainage areas, higher elevations, and are more prone to dewatering in comparison to downstream waterways. Headwater streams provide habitat for numerous species and play a significant role in the removal of pollutants, nutrients and sediment, assist in flood control, and provide groundwater recharge.

Headwater streams are narrower and shallower than larger streams and rivers, and the water in headwater streams contacts the streambed and banks more regularly than in larger streams and rivers. The health of and impacts to headwater streams affects the health, water quality, and species composition and abundance of downstream systems. Human alterations, due to agricultural and urbanization, mainly in the more heavily populated areas of the state, have altered or eliminated headwater streams.

There are limited hydrologic data from headwater streams within North Carolina. Based on a GIS evaluation, roughly 8% of the 284 USGS stream gages in North Carolina are located on headwater streams. Discharge estimates for ungaged streams must be derived from mathematical regression equations based upon relationships of drainage area and precipitation. Using these equations, the USGS in cooperation with the state has evaluated low-flow characteristics statewide and for selected streams in several drainage basins in North Carolina including the Roanoke, Neuse and Cape Fear (Geise and Mason 1993, Weaver 1996, Weaver 1998). In addition, discharge estimates can now be generated through the use of sophisticated, proprietary models such as WaterFALL (for further information see Appendix D).

Biological data from headwater streams in North Carolina are also limited. In particular, the biological data used in the RTI/USGS analyses (Appendix D) were generated from the DWQ "Stream Fish Community Assessment" and "Benthic Macroinvertebrate Assessment" datasets. Roughly 10% of the invertebrate sampling sites and 15% of fish sampling sites are located in headwater streams. These percentages are in contrast to nearly 72% of invertebrate and 50% of fish sampling sites located in the next class, Creeks (drainage area ≥ 10km^2 and < 100 km^2) (Olivero and Anderson 2008).

2.2 The Importance of Flow in Riverine Systems

Flow is generally considered the "master variable" of riverine systems, including adjoining riparian areas, because it is always a determinant of water quality, biology, physical habitat, and energy transfer (Poff et al. 1997, Annear et al. 2004). All components of the flow regime (magnitude, duration, frequency, timing, and rate of change), including natural variability, are important to maintaining ecological integrity. Natural variability of flows includes intra-annual and inter-annual variability and consists of extreme low flows, low flows, high flow pulses, small floods, and large floods. Collectively, these concepts are known as the "natural flow paradigm" (Poff et al. 1997).

Maintaining flow variability benefits native species that have adapted to such variability and inhibits invasive species from flourishing (Poff et al. 1997, Cummins et al. 2011). High flows restructure the channel profile through transport of substrate, bank scour and suspension of organic matter from the riparian zone; benefit reptiles and amphibians by refilling vernal pools; and also function as cues for spawning and migration. Low flows benefit top predators by concentrating prey and plant communities by providing habitat for the establishment of submerged aquatic vegetation and floodplain plant species. Seasonal low flows may also benefit freshwater mussel species by improving spawning and the release of glochidia in the presence of host fish species (DePhilip and Moberg 2010).

Many studies have shown that altering one or more flow regime components can significantly impact biota, including fish, mussels and aquatic insects (Freeman et al. 2001, Freeman and

Marcinek 2006, Knight et al. 2008, DeGasperi et al. 2009, Kennen et al. 2009, Rypel et al. 2009, Carlisle et al. 2010, Kanno and Vokoun 2010, Peterson et al. 2011, Mims and Olden 2012, McManamay et al. 2013). A recent meta-analysis showed that, of the 165 studies reviewed, 92% indicated a reduced ecological condition when flows were altered (Poff and Zimmerman 2010). However, it was noted that the data are often noisy and statistical relationships are not always strong. Many streams and rivers in North Carolina have already been subject to flow alteration.

2.3 Strategies to Determine Ecological Flows

There are two general strategies that have been used to determine ecological flows: habitat response models and biological response models. A habitat response model is one in which the quantity and quality of available habitat is measured relative to variation in flows. A biological response model is one in which the composition and structure of the biological community is measured relative to variation in flows. Traditional efforts to understand the impacts of altering hydrology often focused on the relationship of flow to habitat availability (Stalnaker et al. 1995, Washington Department of Ecology 2010). Although such habitat response models are an indirect and intermediate measure of expected biological response, they are useful when time and money limit the implementation of biological studies. Often, habitat models utilize habitat use or preference curves for guilds of species to ensure that all types of habitat are represented in the analysis (Vadas and Orth 2000, Persinger et al. 2010).

North Carolina has relied heavily on habitat response models, such as PHABSIM (Physical Habitat Simulation), when conducting site-specific flow studies. PHABSIM is a specific model designed to calculate an index to the amount of microhabitat available for different life stages of aquatic organisms at different flow levels, incorporating two major analytical components: stream hydraulics and life stage-specific habitat requirements. DWR, at the request of the EFSAB, conducted additional analysis of PHABSIM sites in the piedmont and mountain portions of North Carolina in an effort to better demonstrate how flow and habitat availability (response) impact biological communities.

Additionally, a new framework to determine ecological flow regimes for large geographic areas was examined. The Ecological Limits of Hydrologic Alteration (ELOHA) approach outlines a step-wise process that involves establishing a hydrologic foundation, classifying rivers, and determining flow-ecology relationships before entering a social process to develop flow regime standards (Poff et al. 2009). The classification step has been used elsewhere by several researchers, including those using only hydrologic parameters (Henriksen et al. 2006, McManamay et al. 2011a) and those using other basin characteristics (Olivero and Anderson 2008, Liermann et al. 2011, McManamay et al. 2011b, Olden et al. 2011). Other basin characteristics often include metrics such as water temperature, gradient (also referred to as slope), stream size, and geology.

Many other states and regions have undertaken efforts to determine ecological flow standards. The EFSAB reviewed many reports and policies, including:

- Alberta (Locke and Paul 2011; also Clipperton et al. 2003)
- Canada (Department of Fisheries and Oceans 2013; Linnansaari et al. 2013)
- Connecticut (Connecticut Department of Environmental Protection 2009)
- Georgia (Evans and England 1995)
- Michigan (Hamilton and Seelbach 2011)
- Potomac River Basin (Cummins et al. 2011)

- Nine case studies (Kendy et al. 2012)
- Pennsylvania (Apse et al. 2008)
- South Carolina (de Kozlowski 1988; Bulak and Jobsis 1989)
- Susquehanna River Basin (DePhilip and Moberg 2010)
- Texas (Texas Commission on Environmental Quality et al. 2008)

This literature review revealed that a variety of approaches have been used to determine ecological flows and the flow standards can be categorized into three basic types–minimum-flow thresholds, statistically-based standards, and percentage-of-flow standards. Minimum-flow thresholds include 7Q10, September median, and monthly median. Other minimum-flow thresholds are based on the Tennant method, which is a percentage of mean annual flow, varying by month (Tennant 1976). Statistically-based standards consist of a series of metrics designed to mimic various flow components (e.g., low flows, high flows, flood pulses) within a range determined from a statistical analysis of the past hydrograph. This type of flow recommendation typically consists of a set of target flow magnitudes, durations and frequencies for each month or season. The percentage-of-flow standard allows only a certain percent of flow to be extracted for off-stream use; the remainder is left in the stream. Minimum-flow thresholds do not retain intra- and inter-annual variability like percentage of flow approaches.

Literature on flow requirements for coastal systems was also reviewed because low-gradient and tidally-influenced streams function differently from other inland streams. In coastal systems, flow may play a secondary role to other factors including tides, salt concentration, and community structure and function (Jassby et al. 1995, Adams et al. 2002, Alber 2002, Mattson 2002, Powell et al. 2002). General approaches to estuarine inflow management fall into three categories–inflow-based, condition-based, and resource-based. The inflow-based approach keeps flow within selected prescribed bounds under the assumption that taking too much away is bad for the resources. A condition-based approach is one in which inflow standards are set in order to maintain a specified condition (e.g., salinity) at a given point in the estuary. Finally, a resource-based approach sets inflow standards based on the requirements of specific resources (e.g., shrimp). A separate section is presented on the assessment of ecological flows within the coastal plain (Appendix C).

2.4 Advancing the Science of Ecological Flows

In addition to reviewing the literature and input from experts who gave presentations to the group, the EFSAB analyzed the results of new research and analyses specific to North Carolina. Certain analyses were undertaken by DWR, and others were commissioned by EFSAB members to support the board's efforts. Additional research was conducted to meet the objectives of individual organizations which also proved beneficial and informative to the EFSAB. During the course of the EFSAB's tenure, it became clear that the multiple research efforts should be coordinated to maximize outcomes and avoid duplication. Thus, an Ad-Hoc Water Research Coordination Group was formed by those entities conducting and/or funding the research. This group was not a formal part of the EFSAB, although it was instrumental in advancing the science of ecological flows and keeping the EFSAB informed. The Coastal Ecological Flows Working Group (CEFWG) was formed to assess ecological flows in the coastal plain.

2.4.1 Flow-habitat Relationships

Over the past several decades, DWR has conducted or assisted in numerous site-specific studies to evaluate the effect of water resource projects on stream flows and aquatic habitat. The types of projects have included federal hydropower relicensing, water supply reservoirs, new or expanded water supply withdrawals, and water resource planning studies.

DWR updated nine PHABSIM study sites from the piedmont and 10 sites from the mountains to analyze the influence of different flow scenarios on habitat for a variety of species, species life stages and guilds (Table 1 and Figure 1). While this analysis included streams from across the state, they were typically clustered in just a few areas. The 19 sites shown are about half of the studies in which DWR has participated. The studies are clustered because of their association with multi-site hydropower projects (mountains), water supply projects (piedmont), or the age of the study that allowed a quick update of the computational platform.

Table 1. DWR PHABSIM sites used for ecological flow analysis.

Piedmont Stream	Drainage Area (mi^2)	Mountain Stream	Drainage Area (mi^2)
Buckhorn Creek	76	Davidson River	14
Buffalo Creek	127	'East Fork' Tuckasegee River	82
Eno River	99.4	Jonathan Creek	14
First Broad River - upper	145	Nantahala River - upper	101
First Broad River - middle	202	Nantahala River - lower	143
First Broad River - lower	230	North Fork Mills River	10
Rocky River	55	Tuckasegee River	287
Tar River	437	West Fork Tuckasegee River - upper	53
West Fork Eno River	11	West Fork Tuckasegee River - lower	56
		Whiteoak Creek	14

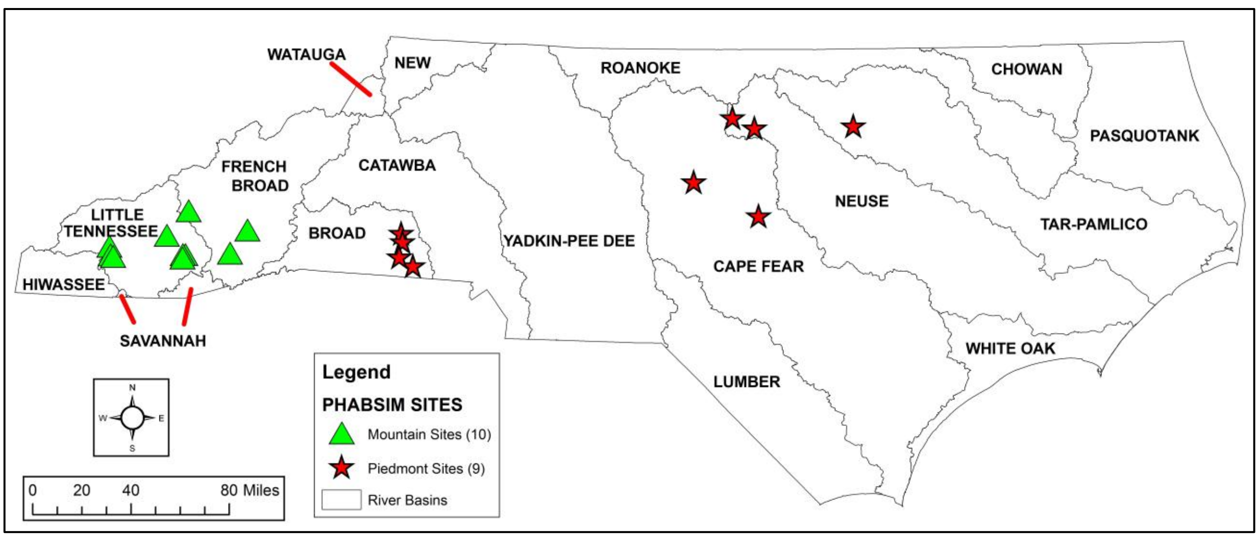

Figure 1. Location of 19 DWR PHABSIM sites analyzed for the EFSAB report.

PHABSIM involves evaluating the suitability of habitat in the stream reach at a variety of stream flow levels. Individual cross-sections, or transects, are selected to represent the range of habitat types available at each site. Data are collected during at least three different stream flow conditions, and PHABSIM files are calibrated using these data to allow simulation of the physical conditions over a wide range of flows. Each study involves the collection of site-specific data for the stream channel, including cross-section profiles, depths, velocities, substrate, and cover objects. Stream velocity, depth, substrate and cover at each stream flow level are assessed relative to the habitat needs and preferences of the species or guild.

PHABSIM modeling combined with time-series analysis is a two-step approach to evaluating the availability of habitat to support a species or guild. Habitat versus flow relationships are determined by PHABSIM, and the frequencies of occurrence for different levels of habitat can then be compared for different flow regimes using time-series analysis.

The aquatic species or representative guilds selected for modeling depends upon the proposed project location, identified problem, or management goals. Table 2 list the guilds and species modeled in the piedmont and mountains for the EFSAB. Each guild or species modeled has a set of habitat suitability indices that represents how the organism responds to different stream velocities, depths, substrates, and cover objects. The suitability indices may also be referred to as preference curves (Figure 2).

Table 2. The guilds and species used for the piedmont and mountain PHABSIM analyses.

Piedmont Sites	Mountain Sites
Shallow Guild	**Shallow Guild**
shallow slow, young of year	blacknose dace spawning
shallow slow, aquatic vegetation cover	blacknose dace fry
shallow slow, woody debris cover	blacknose dace juvenile
shallow slow, coarse substrate	brown trout fry
shallow slow, fine substrate, no cover	brown trout juvenile
shallow fast lower velocity	creek chub young-of-year
shallow fast moderate velocity	creek chub adult
shallow fast higher velocity	longnose dace adult/juvenile/spawning
mayfly	northern hog sucker juvenile
stonefly	rainbow trout fry
caddisfly	mayfly
	stonefly
Deep Guild	**Deep Guild**
deep slow, cover	brown trout adult
deep slow, cover version 2	brown trout spawning
deep slow, no cover	mottled sculpin adult/juvenile
deep fast, fine substrate	northern hog sucker adult
deep fast, gravel/cobble substrate	rainbow trout adult
deep fast, coarse substrate	rainbow trout spawning
golden redhorse adult	caddisfly
golden redhorse juvenile	

PHABSIM simulates the physical conditions that would result from the range of stream flows for the selected cross-sections within a stream reach. The habitat suitability indices are correlated to the physical conditions simulated by PHABSIM in order to produce a set of values indicating the amount of habitat available for the species or guild assessed at each stream flow level for the study site. The set of values are weighted relative to the suitability of the habitat and are expressed in terms of the area per 1,000 feet of stream length. The values are referred to as the weighted usable area (WUA) (Figure 3).

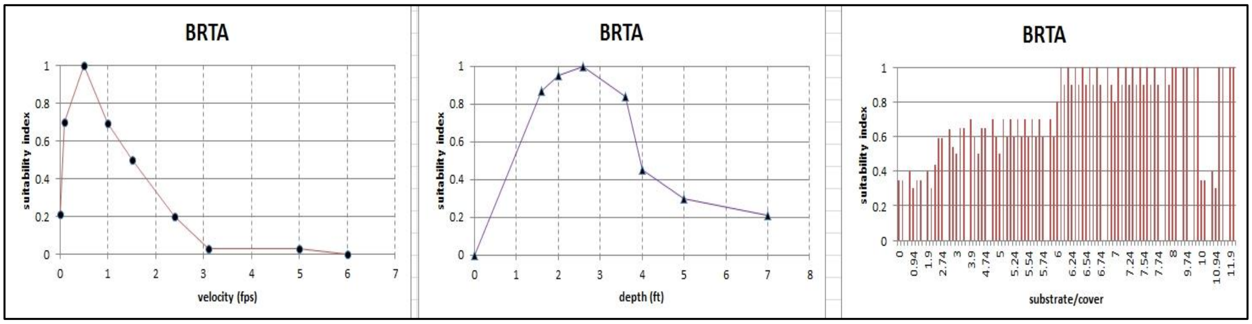

Figure 2. Example of habitat suitability curves (brown trout adult: velocity, depth, substrate-cover) used in PHABSIM modeling.

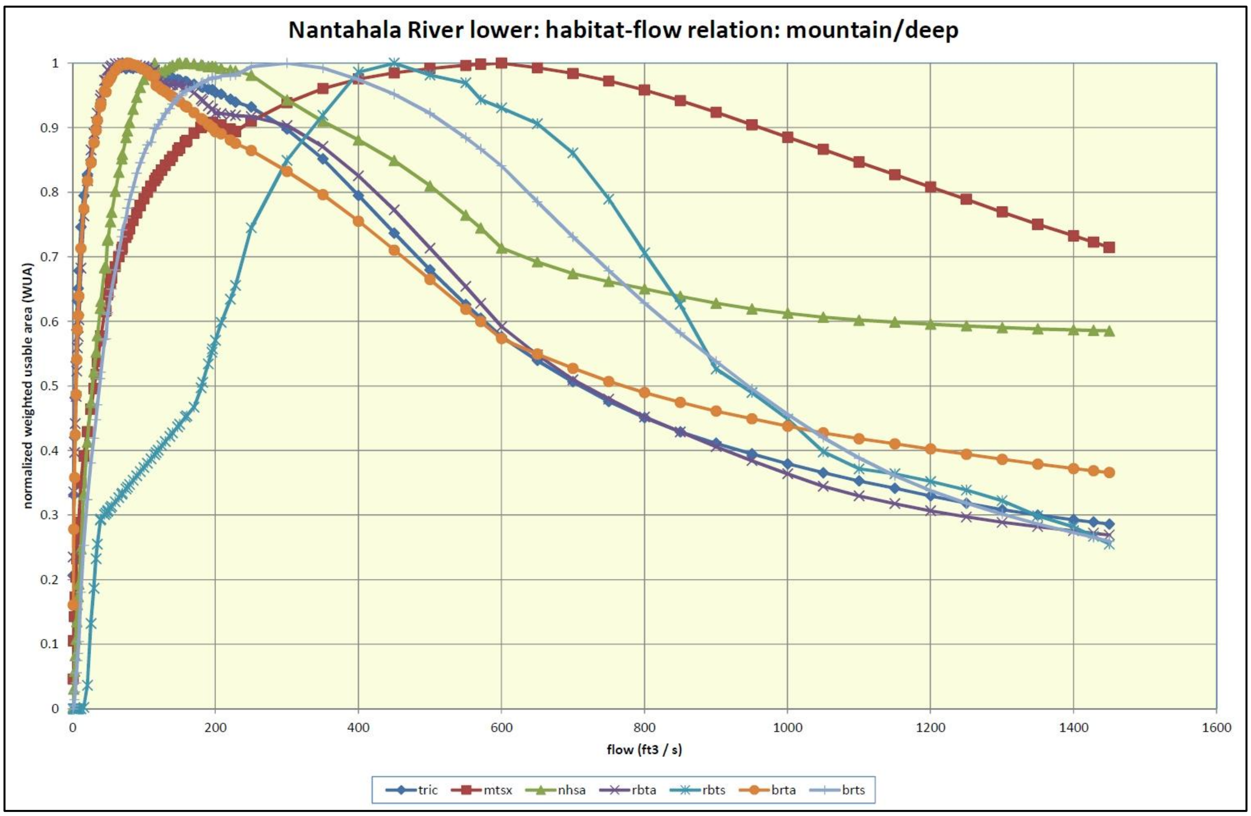

Figure 3. Example of WUA habitat-discharge relation (mountain-deep species/life stages) output from PHABSIM modeling.

The end result of PHABSIM is a habitat versus flow relationship for each guild or species that covers the range of flows evaluated. The next step–time-series analysis–uses the habitat versus flow relationship to convert a record of daily stream flows to a record of daily habitat availability. A record of daily habitat for each species or guild can be generated using records from a nearby USGS gage station or results of hydrologic modeling where daily flow records are not available. Time-series analysis can thus be combined with different hydrologic model simulations (e.g., existing withdrawals or future water use projections). The end result of time-series analysis is a comparison of habitat availability under different flow scenarios, often represented as a table or curve showing the frequency of habitat levels occurring across a range of flows for various hydrologic scenarios. The output of the time-series analysis is reported by month and by season with the seasons being defined as follows. Fall includes October and November, and Winter extends from December through March. Spring represents April through June, and Summer is July through September.

For the ESFAB, the studies assessed the effects of 15 flow records, separated into three groups of scenarios, which were generated using SAS software and routines. The three groups of stream flow approaches that were evaluated in time-series analysis were: (1) minimum flows (annual 7Q10, monthly 7Q10, September median, and monthly median); (2) percent of mean annual flow (MAF) (10 to 60 percent MAF in increments of 10 percent); and (3) percent of inflow (70 to 90 percent of inflow in increments of 5 percent). The 7Q10 value is typically used for determining the assimilative capacity of a receiving stream when permitting wastewater discharges. The September median flow is the lowest monthly median flow in most years and has been used by some states as a minimum flow requirement for projects.

The unregulated, or baseline, flow records used for the piedmont sites were generated by DWR from OASIS basin models for a period from 1928 to 2008 with no reservoirs or flow alterations other than that associated with changes in land cover. Due to the lack of an OASIS model for the Little Tennessee and French Broad basins, the unregulated flow records used for the mountain sites were produced by the WaterFALL program for the period from 1967 to 2006 with no reservoirs or flow alterations, and a 1970's land cover.

One method of reporting and comparing the WUA for each guild or species from the time-series analysis is a habitat metric termed Index B. The Index B value is the average of all habitat values in a month across all years of the analysis that are between the 10^{th} percentile and the 90^{th} percentile of habitat values for the selected month. The outlier values that fall below the 10^{th} percentile and above the 90^{th} percentile are not included in the calculation of Index B.

Index B values were calculated for each guild/species on a monthly basis for each flow scenario. Project alternatives were assessed by computing the ratio of the Index B value for a particular flow scenario (numerator) to the Index B value for the unregulated flow record (denominator). Index B ratios between 0.80 and 1.20 were considered to be within the preferred habitat range. Ratios < 0.80 or > 1.20 were considered to represent a substantial change to the stream ecosystem. Index B ratios based on a denominator value less than 1,000 WUA were considered separately because small changes in the numerator cause disproportionately large changes in the ratio.

Analysis and reporting of Index B ratios was presented in tabular and graphic form. The graphs are summarized by seasons, as defined in the time-series analysis output, for either all 19 guilds/species combined or for the deep water guilds/species and the shallow water guilds/species.

All three flow scenario groups (i.e., minimum flow, percent of MAF, and percent of inflow) for the piedmont and mountain sites generally exhibited a trend of more guilds/species failing to meet the 0.80 ratio criterion as the flow regimes departed from the unregulated baseline condition (Figures 4 and 5). In terms of the percentage of guilds exceeding the 1.20 ratio criterion, the three flow scenario groups showed differing responses in the piedmont. Most of the nine piedmont sites exceeded the 1.20 ratio criterion for all of the minimum flow and percent of MAF flow scenarios. This was also true for the percent of inflow group, except for the 85% and 90% inflow scenarios. Most of the mountain sites also generally exhibited a trend of more guilds/species exceeding the 1.20 ratio criterion as the flow regimes departed from the unregulated baseline condition (Figure 6). All of the 10 mountain sites exceeded the 1.20 ratio criterion for all of the percent MAF scenarios. The majority of the mountain sites exceeded the 1.20 ratio criterion for all of the minimum flow and percent of inflow scenarios, except for the monthly median, 85% inflow and 90% inflow scenarios.

In general, 12 of the 19 PHABSIM sites in the piedmont and mountains showed a habitat response in the preferred range for all seasons under one or more of the following three flow scenarios: monthly median, 85% inflow and 90% inflow. Four of nine sites in the piedmont and eight of 10 sites in the mountains had all seasons within the preferred habitat range for one or more of the three flow scenarios. In the piedmont, the lower First Broad River site was within the preferred range for the monthly median flow scenario and the 90% inflow scenario. Buffalo and Buckhorn creeks and Tar River were within the preferred range for the 90% inflow scenario. Tar River was also within the preferred range for the 85% inflow scenario. In the mountains, the monthly median flow maintained the Tuckasegee and lower Nantahala rivers within the preferred range for all seasons. Davidson and upper Nantahala rivers and Jonathan Creek were within the preferred habitat range for the 85% inflow scenario, while the 90% inflow scenario maintained seven of the 10 sites within the preferred range.

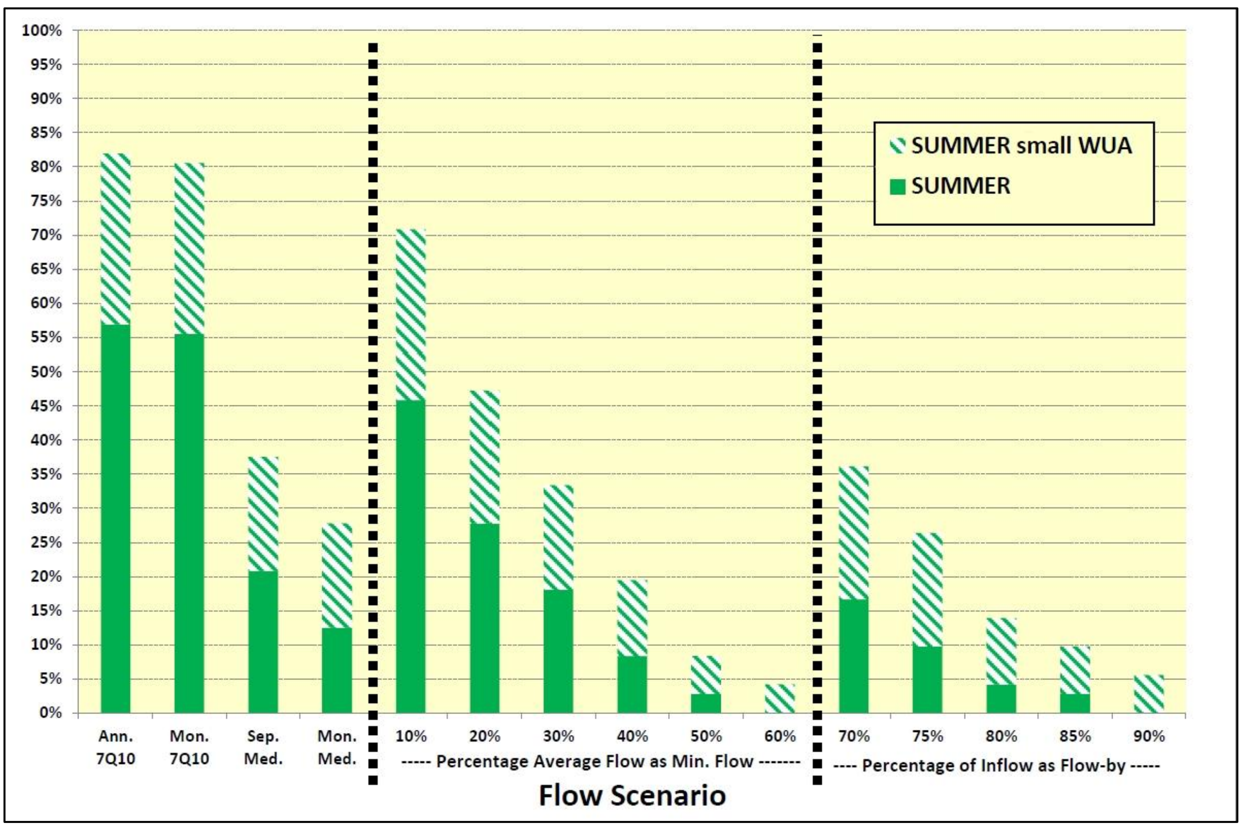

Figure 4: Total percent of eight piedmont deep guilds/species not meeting the 0.80 habitat criterion under 15 flow scenarios at nine piedmont sites in Summer. Visit the DWR ecological flow web site for a complete set of habitat response graphs.

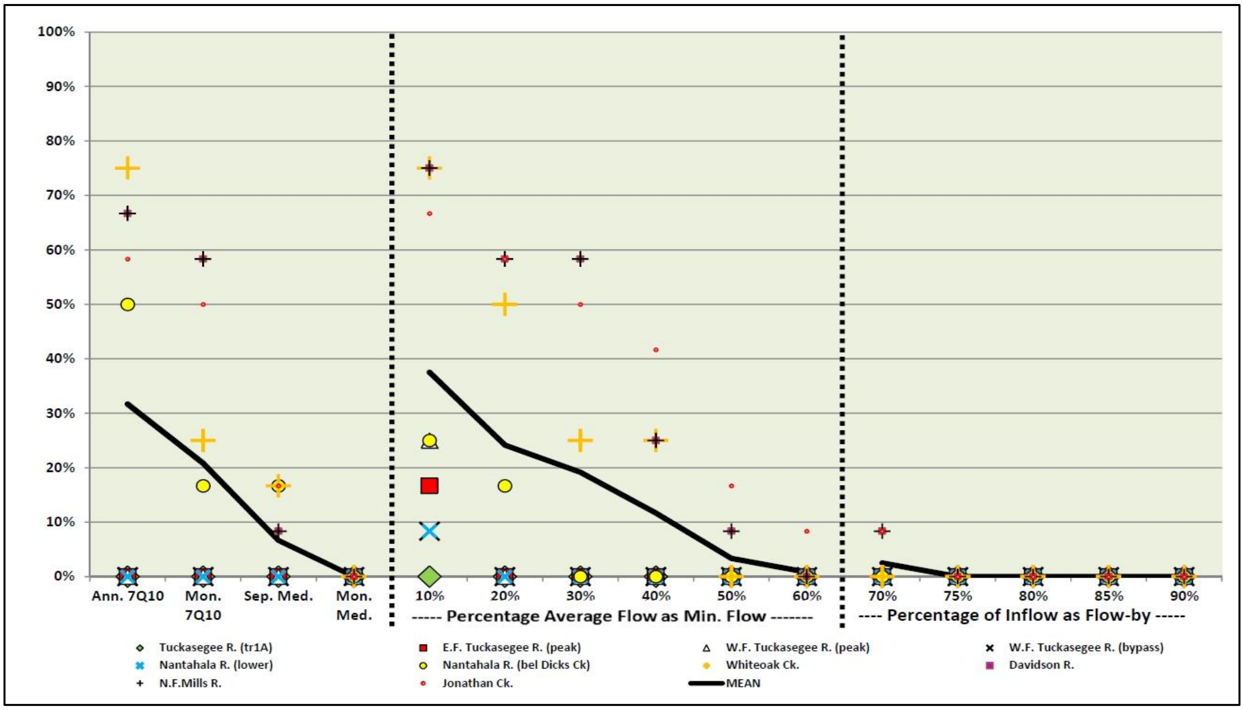

Figure 5. Total percent and associated mean of 12 shallow guilds/species not meeting the 0.80 habitat criterion under 15 flow scenarios at 10 mountain sites in Spring. Visit the DWR ecological flow web site for a complete set of habitat response graphs.

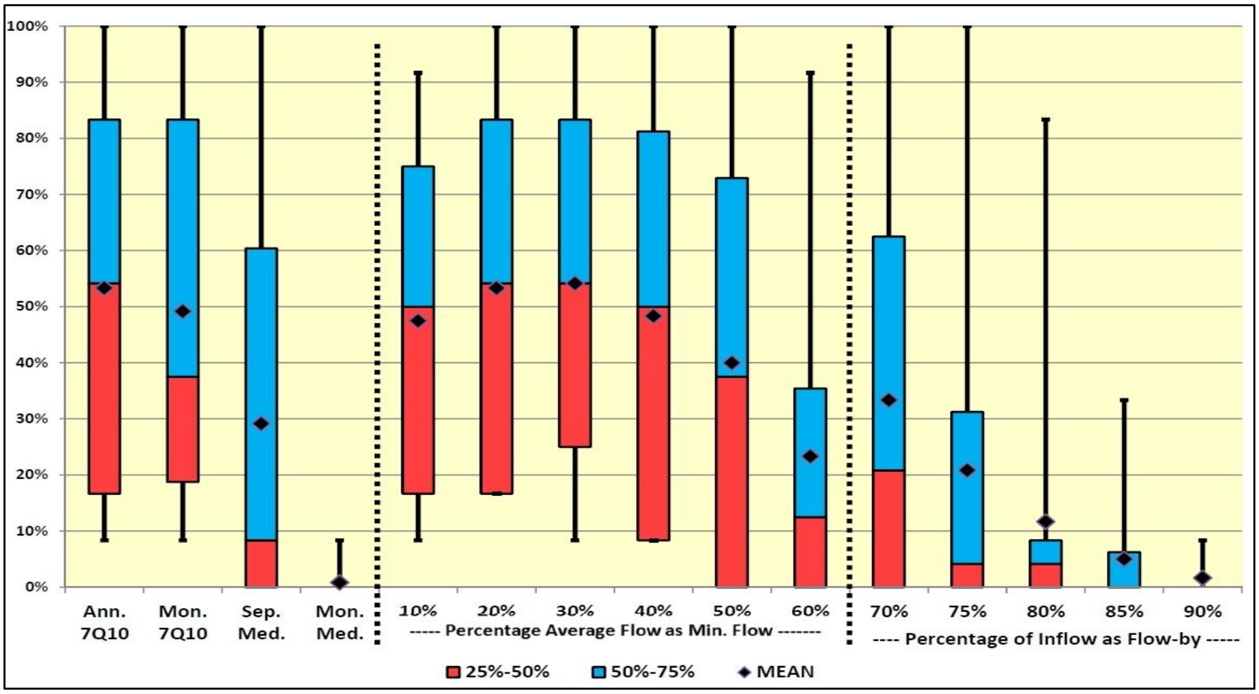

Figure 6: Mean, range, and quartiles of the percentage of 12 shallow guilds/species exceeding the 1.20 habitat criterion under 15 flow scenarios at 10 mountain sites in Spring. Whiskers represent the range of values and the boundary between the red and blue boxes represents the median value. Visit the DWR ecological flow web site for a complete set of habitat response graphs.

2.4.2 Flow-ecology Relationships

Ecological flow regime recommendations specific to North Carolina can be developed by determining how biota in streams respond to changes in flow. One approach involves relating biological conditions to flow across a range of flow conditions (space for time approach) or by changes in biological conditions at a site over time. Another approach is to track biotic conditions over time to changes in flow. Organizations outside of the EFSAB tried both approaches and reported their results to the Board. The primary biotic conditions considered for both approaches are related to community structure of fish or macroinvertebrates. The most information is on community structure of fish and benthic invertebrates. Ecosystem condition and ecological integrity are inferred from fish and benthic communities in most cases.

Ecological integrity involves the interplay of both ecosystem structure and function and the ability to respond to environmental perturbations. Functional indicators of ecosystems are particularly difficult to measure directly, and structural indicators have had a long history of defining function in environmental management (Brinson and Rheinhardt 1996). Without statewide data on ecosystem structure and function, the EFSAB relied on fish and invertebrate community composition to infer ecological integrity.

Fish and benthic macroinvertebrates were evaluated as indicators of ecological integrity. Two components of the ecology of these assemblages were assessed: (1) habitat availability and (2) species distribution. Habitat availability of both assemblages was used in the PHABSIM approach (above). Species distribution approach was assessed by RTI International (RTI) and USGS. Sensitive indicators for the latter approach were designated as the Shannon-Weaver Diversity Index of the riffle-run fish guild and the taxa richness of the EPT benthos (the number of mayfly, stonefly, and caddisfly taxa). These indicators are correlated with ecodeficits, a measure of flow deficiency over the period of evaluation (typically the period of record), so the species' responses reflect recovery (or lack of it) from environmental perturbations.

RTI and USGS conducted numerous statistical analyses to find meaningful relationships between several fish and aquatic insect metrics and various flow metrics. They used the space for time approach with 649 fish and 1,227 benthos sites deemed wadeable from nearly all major river basins in North Carolina. Although wadeable streams include some larger rivers, there was a lack of information from the largest rivers and many coastal systems.

Initially, the efforts attempted to include other explanatory factors, such as stream size and basin characteristics, but these were unsuccessful. Ultimately, significant relationships were found between six flow metrics and Shannon-Weaver Diversity Index of the riffle-run fish guild and richness of benthic (Ephemeroptera, Plecoptera, Trichoptera) species. The six flow metrics included the annual and seasonal (winter, spring, summer, and fall) ecodeficits and reductions in the average 30-day minimum flow. Figure 7(A and B) presents responses of riffle-run fish guild diversity (Figure 7(A)) and benthic EPT richness (Figure 7(B)) responses to summer ecodeficit. Refer to Appendix D for additional information regarding the methods and results of the project that developed the flow-ecology relationships for fish and benthos in North Carolina.

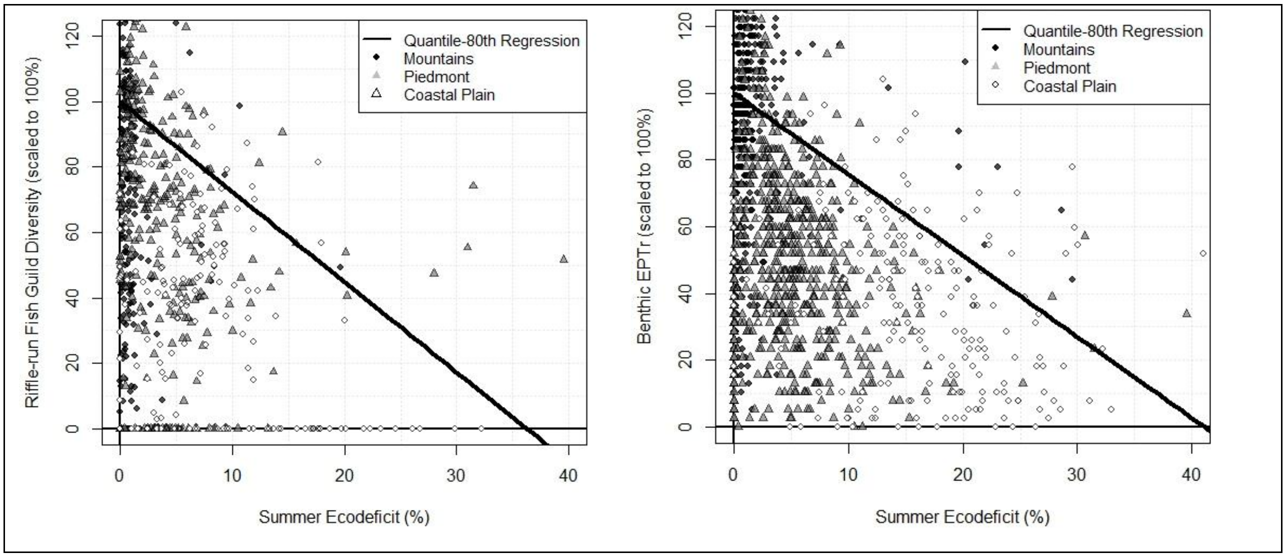

Figure 7. Flow-ecology relationships for: (A) the Shannon-Weaver diversity of the riffle-run fish guild (n = 649) and (B) benthic EPT richness (n = 1,227) in response to summer ecodeficits in wadeable streams in North Carolina.

The Nature Conservancy (TNC) analyzed spatial-temporal patterns of changes in flow and biota over time and explained how they are relevant to ecological flow guidelines. While the primary project purpose was to assist TNC in prioritizing conservation areas, it also was designed to provide meaningful information to the EFSAB to develop ecological flows.

Fish diversity and abundance at 141 sites in four North Carolina river basins (Roanoke, Cape Fear, Tar, and Little Tennessee) were compared to flow for the period of 1992 to 2009. These sites were in wadeable portions of streams and rivers, so data are lacking from large rivers. Many sites saw relatively little change in fish diversity and abundance over time. However, fish abundance and diversity declined in portions of the Cape Fear and Tar basins.

To understand the direct influence of water withdrawals, only sites located downstream of known water withdrawals were analyzed further. While only 14 data points fit this criterion, they showed a negative relationship between fish diversity and the relative size of the water withdrawal. While the relationship was statistically significant, the explanatory power of the relationship was small due to the small sample size. With that caveat in mind, the analysis showed a 5–10% decline in species diversity relative to a withdrawal equivalent to 10% of the mean annual flow. A withdrawal of 50% of the mean annual flow resulted in a 25–30% decline in species diversity.

2.4.3 Attempts at Stream Classification

DWR worked closely with Environmental Flow Specialists Inc. (EFS) on efforts to characterize and classify North Carolina streams based on flow characteristics from USGS gage data. The effort resulted in a classification scheme comprised of seven stream classes that generally reflected stream size and flow stability, and was similar to a classification produced by McManamay et al. (2011a) that had eight classes. However, further analysis by RTI comparing the two classifications found that they were not similar enough to be used interchangeably.

Analysis by RTI also found that classes generated from hydrology derived from USGS gages often differed from hydrology created from the WaterFALL rain-runoff model. This was true for both the EFS and McManamay classification frameworks. Therefore, it was concluded that neither classification approach should be extrapolated beyond the USGS gages to ungaged sites. Because of the uncertainty associated with the classes generated from either framework, it was agreed that developing flow recommendations for these different stream classes is not appropriate at this time.

3 RECOMMENDATIONS OF THE EFSAB

3.1 Statewide Ecological Flow Evaluation

To evaluate flow scenarios in most North Carolina streams, the EFSAB recommends the following two strategies to assess whether ecological flows are maintained:

1. *The percentage of flow strategy using 80–90% flow-by combined with a critical low flow component as the ecological flow threshold. If the basinwide hydrologic models indicate that there is insufficient water available to meet all needs, essential water uses and ecological flows at a given location, then further review by DENR is recommended.* [Flow-by is defined as "the percentage of ambient modeled flow that remains in the stream."]

2. *The biological response strategy should be used to determine the current and future modeled biological condition of locations in the basinwide hydrologic models. DENR should evaluate the change in current and future biological condition as a decision criterion. A 5–10% reduction in biological condition is suggested as a threshold for further review by DENR.*

The EFSAB recommends a statewide approach to establishing ecological flows based on the simultaneous use of these two strategies:

3.1.1 Percentage of Flow Strategy

Natural flow regimes are important in maintaining instream, riparian, and floodplain ecosystem diversity and resilience (Poff et al. 1997). The natural flow paradigm postulates that natural ecosystems are best protected by maintaining flow regimes close to their unaltered state in terms of the five flow components (magnitude, duration, frequency, timing, and rates of change), including intra- and inter-annual variability. The most effective mechanism for resembling a natural flow regime in altered river systems is to use a percentage of flow approach (Richter et al. 2011), also known as a "flow-by" approach. It is conceptually simple and relatively easy to implement.

As an ecological flow standard, the flow-by approach works by requiring a percentage of the "instantaneous" natural flow to remain in the river (Figure 8). The flow-by approach is being used in the US, Canada, and Europe (Richter et al. 2011, Locke and Paul 2011). The percentages typically range from 80–90%. **In the North Carolina basinwide hydrologic models, the EFSAB recommends that the ecological flow should be 80–90% of the instantaneous modeled baseline flow.**

The EFSAB recommends a flow-by range of 80–90% for several reasons. Based on results of PHABSIM analyses for North Carolina, there was no apparent threshold in the data indicating a decline in predicted habitat, and flow-by percentages greater than 80% were most consistently protective of all guilds and species modeled. Furthermore, there was no consensus on a single flow-by percentage by the EFSAB. A range of 80–90% is common in the literature and other jurisdictions. Therefore, the EFSAB recommends a range of 80–90% as protective for North Carolina streams. The EFSAB is not recommending using different values for different kinds of streams, but suggesting that DENR use its discretion to select the most appropriate value for planning purposes.

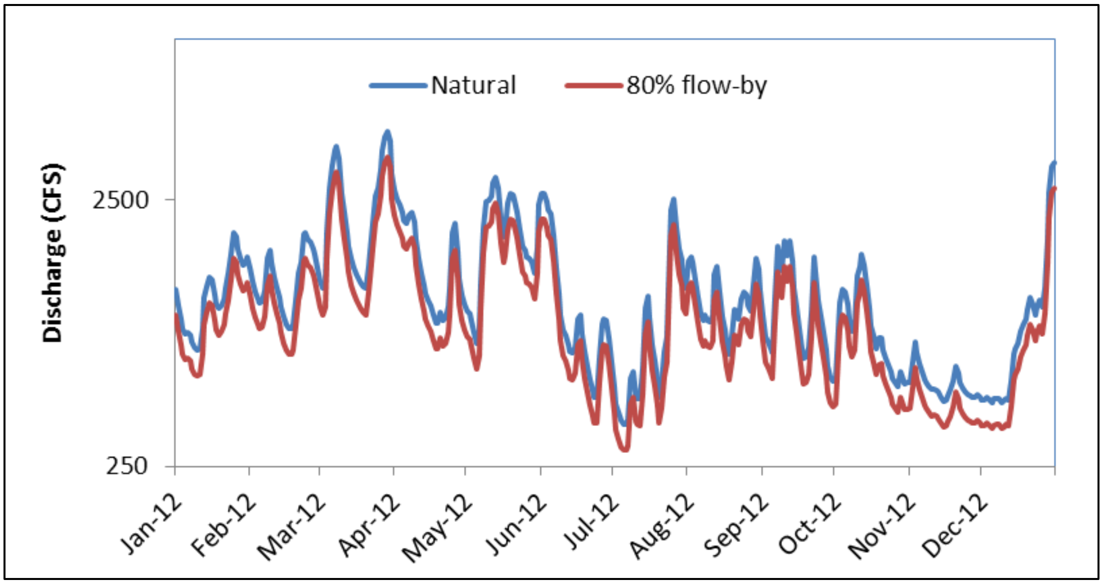

Figure 8. Example of a percentage flow-by approach.

The definition of "instantaneous" depends on how the flow-by approach is implemented. In a hydrologic planning model, instantaneous would be set at the normal time step of the model. For example, in a model that uses daily average flow, the flow-by value would be 80% of the daily flow for each day in the model's period of record. On the other hand, if a model uses a time-step of 15 minutes, the flow-by value would still be 80%, adjusted every 15 minutes. In any model, the flow-by calculation is simply the baseline flow multiplied by the flow-by percentage. In a real world implementation, the time step might be daily or every three days. Another difference in a practical application is that the flow-by might be based on the flow from the previous day, because, unlike a model, the flow for the current day is unknown. **Because the North Carolina basinwide hydrologic models use daily average flow, the flow-by value should be calculated on a daily time step.**

To the extent possible, flow regimes representing natural conditions (flow regimes without withdrawals or returns), baseline conditions (flow regimes incorporating current withdrawals and returns), and projected conditions (flow regimes incorporating current and future withdrawals and returns) should be estimated by basinwide hydrologic models. Baseline conditions will be compared with natural and future conditions to assess how much hydrology has been altered and to determine the effects of future withdrawals and returns. DENR should use this information to identify areas that have undergone substantial hydrologic change and that warrant additional attention when considering further water withdrawals. **As the hydrologic models are updated with new withdrawals and returns, baseline conditions should continue to be used as a benchmark to avoid comparisons to a continually shifting "current" condition. The recommended baseline should be the management regime extant when the legislation was passed in 2010.**

Another consideration of the flow-by approach is that it should consider cumulative effects; otherwise, multiple withdrawals could result in an overall reduction in flow below the flow-by threshold (Figure 9). Therefore, **the cumulative net upstream withdrawals at any point in the basin established after 2010 should not result in flows that are predicted to fall below the flow-by criterion.**

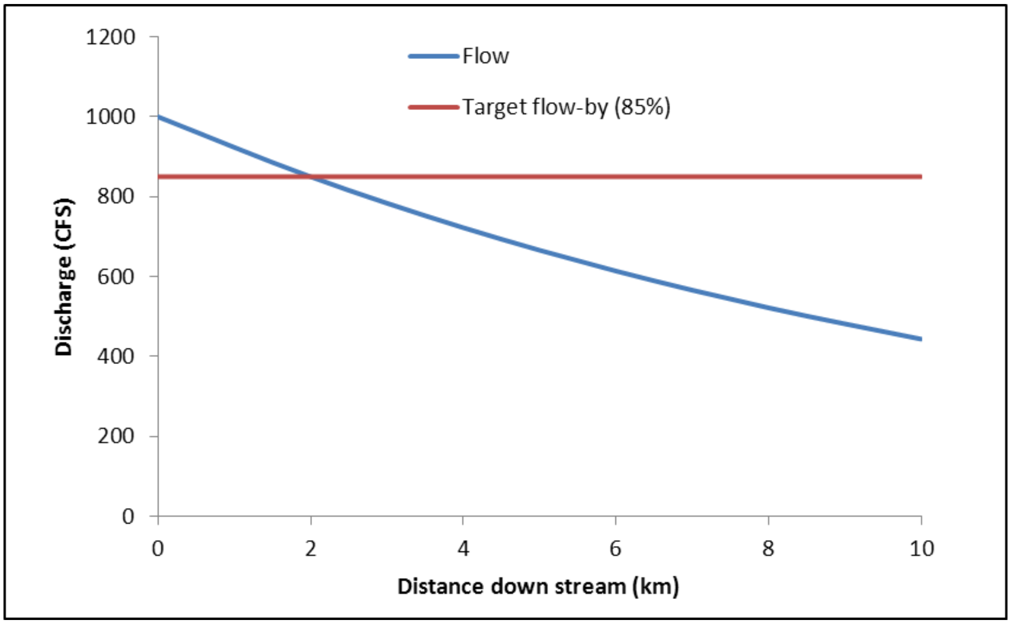

Figure 9. A percentage flow-by criterion must take into account the cumulative effects of water use along each stream. This example shows how quickly five withdrawals each adhering to an 85% flow-by criterion for incoming flows can result in a large cumulative loss in flow (56% reduction between 0 and 10 km) for a section of stream with no inflows (e.g., tributaries or return flows).

Percentage flow-by should be combined with a critical low-flow component that is intended to protect the aquatic ecosystem during periods of drought (Figure 10). The critical low flow represents a point at which further human-induced reductions in flow are likely to result in unacceptable levels of risk to the health of aquatic resources. Low-flow events are most critical for contributing to biological impacts. The critical low-flow criteria are derived from historic flow records and represent expected low flows. These criteria are intended to prevent increasing the frequency or duration of extreme low flows (drought conditions) that are damaging to ecosystem health. Other jurisdictions are beginning to use a critical low-flow component for protecting ecological integrity. For example, Alberta, Canada uses the monthly 20th percentile flow as a critical low flow (Locke and Paul 2011). **The EFSAB recommends DENR incorporate critical low flow as a component of the ecological flow threshold.**

Ecological flows are set as the larger of the flow-by or critical low-flow values on a daily time step. If actual flows fall below the criterion for ecological flows, DENR should evaluate current water uses to determine the best path forward/strategy to minimize ecological effects while meeting the basic needs of current water users.

As a means of assessing the potential for ecological impacts based on projections of future water use, the EFSAB recommends DENR use the baseline hydrology dataset defined above and a daily flow record containing only days when flows are between the 10th and 90th percentiles (trimmed hydrology dataset) to avoid assessments based on impacts of extreme low or high flows. The purpose of this recommendation is to assist DENR in identifying basins or nodes which are at higher risk for not maintaining ecological flows. DENR should evaluate potential for adversely impacting ecological flows at all flow nodes.

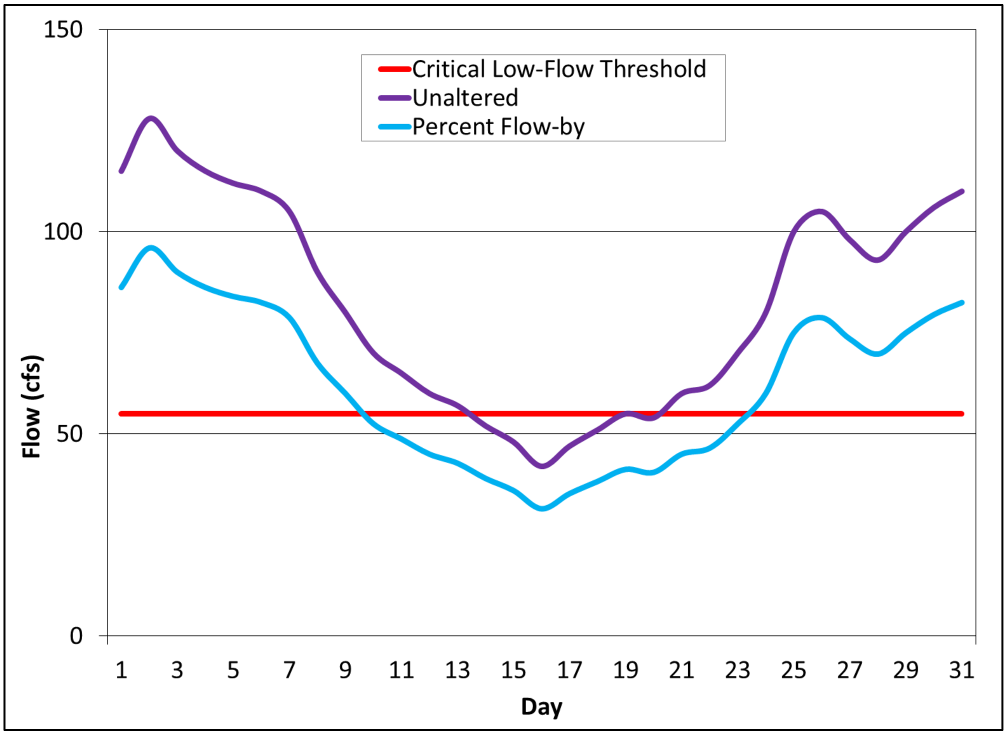

Figure 10. Percentage flow-by is shown with a critical low-flow threshold to protect against increasing the severity and duration of drought periods. The criterion for ecological flow is the larger flow value defined by the daily percentage flow-by or the critical low-flow threshold.

Using the flow records described above, the EFSAB proposes the following approach to evaluate ecological flows at model flow nodes:

1. The ecological-flow threshold should be calculated as the greater of the flow-by and critical low-flow values. If none of the nodal flows from the baseline record fall below this threshold, then the risk of impact relative to ecological flows will be considered to be low and no immediate action is recommended (green flag).

2. If one or more days of the existing or projected daily model flows fall below the ecological-flow threshold but all of the projected flows within the trimmed hydrology dataset remain above the ecological-flow threshold, this should alert DENR to begin further review of water usage that may be contributing to the deviations (yellow flag). Management tools including water shortage and drought response plans should be evaluated for the purpose of maintaining ecological integrity.

3. Stream reaches associated with nodes having one or more days of the trimmed hydrology dataset less than the ecological-flow threshold should be given additional review by DENR (red flag). Management tools including water shortage and drought response plans should be evaluated for the purpose of maintaining ecological integrity. Additional review could include actions such as conducting site-specific evaluations or review and modeling of any biological data that are available.

The establishment of ecological flows based on a combination of percentage flow-by and critical low-flow thresholds represents the best available methodology for the protection of aquatic resources. However, these methods are based on hydrologic models that may not be applicable to all streams across the state since the stream gages needed for model verification may not be available for smaller streams. These models also do not directly address the relationship between flow alteration in the state and biological effects. Fortunately, North Carolina has a well-developed biological assessment program that provides data that can be used to model the effects of flow alteration on biology.

3.1.2 Biological Response Strategy

Biological response models developed by RTI and USGS should be used to evaluate the effects of flow regimes on fish (as measured by the Shannon-Weaver Diversity Index of the riffle-run fish guild) and benthic macroinvertebrates (measured as EPT richness) on the basis of annual and seasonal (winter, spring, summer, fall) ecodeficit, and reductions in the average annual 30-day minimum flow. Ecodeficits are determined by computing the total negative change in flows between altered and unaltered flow duration curves obtained from basinwide hydrologic models (Figure 11; also see Appendix D).

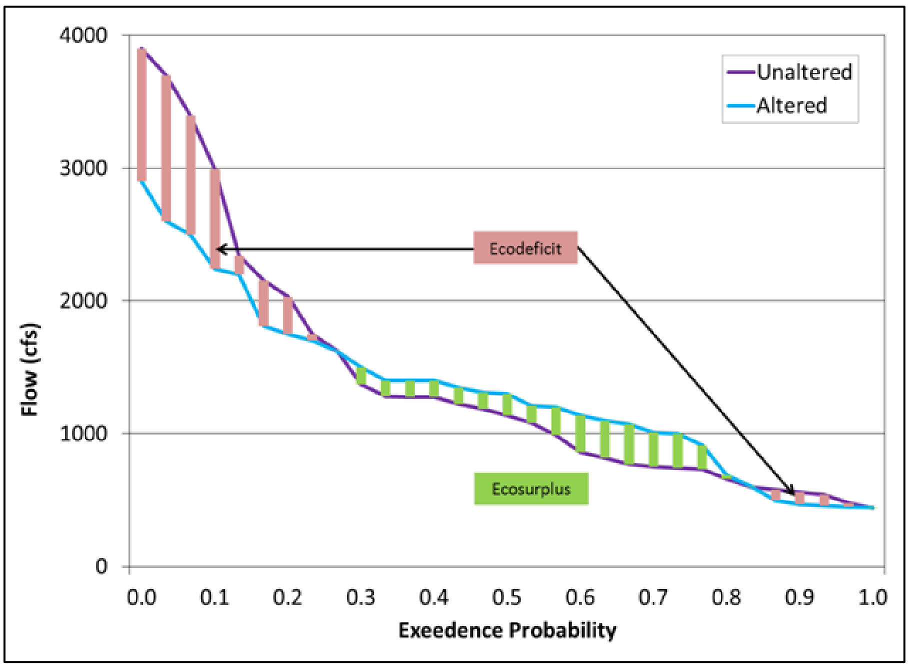

Figure 11. Ecodeficits are calculated by measuring reductions in flow between altered and unaltered flow duration curves.

These fish and benthic macroinvertebrate response models were derived from biological monitoring data collected by DENR at 649 and 1,227 wadeable streams and rivers throughout North Carolina, respectively (NCDENR 2013a and NCDENR 2013b). Quantile regressions were used to develop the relationship between the 0.8 (i.e., 80^{th}) response quantiles of fish and benthos and ecodeficits for the annual, winter, spring, summer and fall seasons (Table 3). Figure 12A presents the 0.8 quantile regression relationship of the riffle-run fish guild Shannon-Weaver Diversity Index and summer ecodeficit and Figure 12B presents the same relationship for benthic EPT richness.

Table 3. Statewide quantile regression models (Y = A + BX) relating ecodeficit (X) to biological responses (Y) for riffle-run fish guild (Shannon-Weaver Diversity Index) and benthic macroinvertebrates (EPT richness).

Riffle-run Fish Guild: Shannon-Weaver Diversity Index						
	Intercept (A)			Slope (B)		
Ecodeficit	Value	SE[1]	p-value[2]	Value	SE	p-value
Annual	100	2.580	<0.001	-1.429	0.429	<0.001
Winter	100	2.383	<0.001	-1.353	0.530	0.011
Spring	100	2.365	<0.001	-1.653	0.332	<0.001
Summer	100	1.797	<0.001	-2.761	0.469	<0.001
Fall	100	2.326	<0.001	-2.093	0.444	<0.001

Benthic macroinvertebrates: EPT richness						
	Intercept (A)			Slope (B)		
Ecodeficit	Value	SE	p-value	Value	SE	p-value
Annual	100	2.210	<0.001	-2.344	0.387	<0.001
Winter	100	2.050	<0.001	-2.427	0.334	<0.001
Spring	100	2.009	<0.001	-2.657	0.307	<0.001
Summer	100	2.005	<0.001	-2.433	0.257	<0.001
Fall	100	1.730	<0.001	-2.341	0.166	<0.001

[1] Standard Error
[2] p-value < 0.05 is considered statistically significant

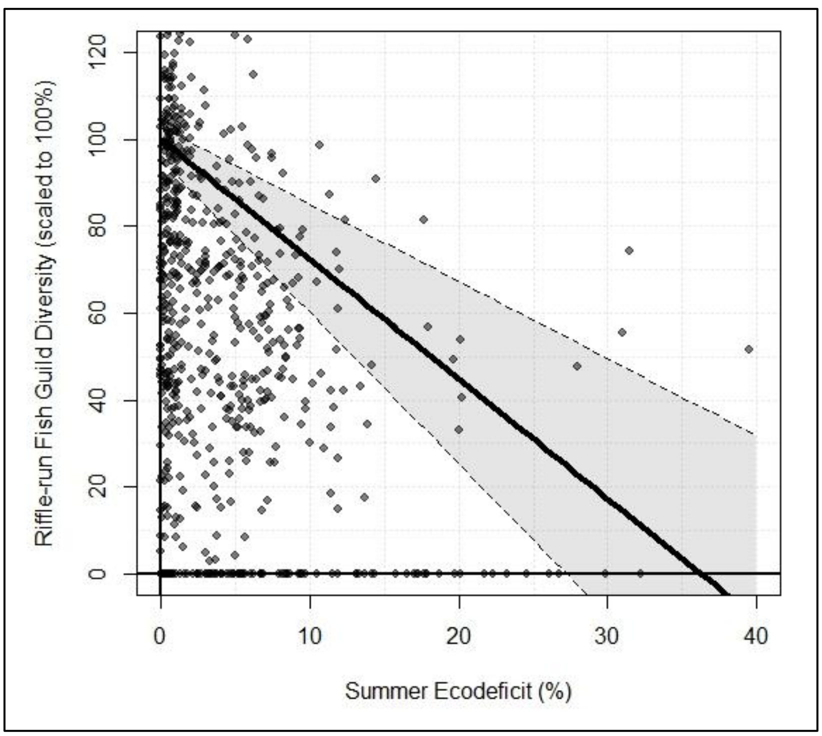

Figure 12A. Quantile regression (0.8 quantile) showing the relation between summer ecodeficit and riffle-run fish guild Shannon-Weaver Diversity Index (greyed area indicates 95% confidence interval).

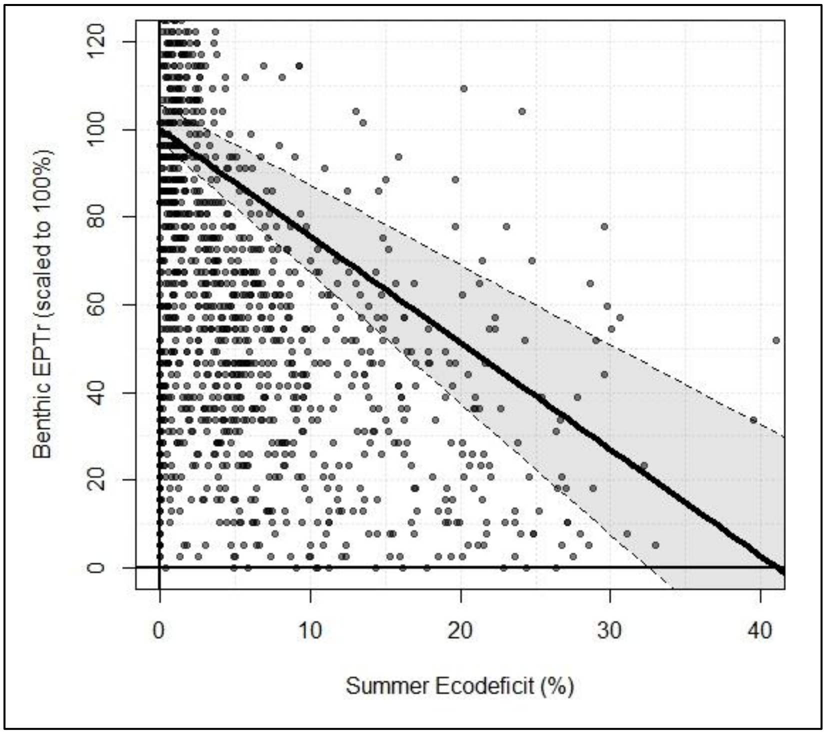

Figure 12B. Quantile regression (0.8 quantile) showing the relation between summer ecodeficit and macroinvertebrate EPT richness (greyed area indicates 95% confidence interval).

These biological response models provide DENR with an estimate of the most probable statewide effect of flow alteration on biological condition. While these models provide a direct link between flow alteration and biological effects for North Carolina streams and rivers, such models are not designed to be highly predictive for specific sites. The uncertainty is high when considering a particular time and place within a stream. Rather they provide expected and statistically significant trends under various scenarios. **Therefore, DENR should evaluate the use of these models to assess changes in biological conditions associated with projected changes in flow with the intent of developing biological criteria for implementing further review of the ecological effects of flow alteration (e.g., implementation of site-specific studies such as PHABSIM). A 5–10% change in biological condition is suggested as an initial criterion for further review.** This criterion is based on the average range of EPT richness within the invertebrate condition classes (Excellent, Good, Good-Fair, Fair, and Poor) as defined by DENR (see Table 17 in Appendix D). The 5–10% criterion represents a change of one-quarter to one-half of the width of a condition class (e.g., Excellent to Good). The 5–10% criterion should be evaluated by DENR as more data are collected.

The RTI/USGS report recommended varying the criteria for acceptable change on the basis of the condition class of the stream or river. A 5% change would be tolerated for sites rated as excellent, 10% for sites rated as good or good-fair, 15% for sites rated as fair, and a minimum flow criterion for sites rated as poor. The rationale for this approach was to provide higher protection for sites with high EPT taxa richness and lower protection for sites with lower EPT taxa richness. The EFSAB decided not to adopt the RTI/USGS variable criteria because (1) it requires that the site condition be known before the criterion can be applied and (2) there was concern that the 15% acceptable change criterion was too large.

The adoption of a range (5–10%) applied statewide carries important implications. For example, EPT taxa richness at the least disturbed sites is known to vary by region (i.e., decreases from mountains to piedmont to coastal plain) and to decrease with diminishing water-quality conditions. Consequently, the amount of change (number of EPT taxa) that will be acceptable using the 5–10% criterion will vary by region (i.e., larger change allowed in the mountains and smaller change allowed in the coastal plain) and by level of disturbance (larger change allowed at sites with excellent conditions, smaller change allowed at sites with poorer conditions). While the EFSAB supports the 5–10% change criterion, it acknowledges that the application of this criterion may result in the reduction of conditions at sites with exceptional quality conditions. The EFSAB encourages DENR to consider additional protection for sites with outstanding biological characteristics.

3.2 Exceptions to Statewide Recommendation

Headwater and coastal plain streams require different criteria for the establishment of ecological flows. The following sections present recommendations for addressing these special situations.

3.2.1 Headwater Streams

There are limited biological and hydrologic data in headwater streams within North Carolina. These streams have a higher vulnerability to disturbance, and the broader statewide approach may not adequately reflect the potential for impact to ecological integrity. **Therefore, for streams with drainage basins < 10 km^2, DENR should conduct additional analyses to determine the potential for impact.**

The EFSAB recommends that DENR conduct additional review, over and above that recommended in the broader statewide approach, for proposed flow alteration of headwater streams. For the purposes of this recommendation headwater streams are defined as streams with drainage areas of < 10 km^2 (3.9 mi^2). This size class threshold for headwater streams has been utilized in recent riverine assessments conducted by TNC for the Northeast (Olivero and Anderson 2008) and Southeast (Olivero-Sheldon and Anderson 2013).

3.2.2 Coastal Streams

The Coastal Ecological Flows Working Group (CEFWG) developed a framework for providing recommendations by introducing four potential approaches to determining ecological flows for coastal streams, depending on the origin of the stream, the gradient or slope of the stream and whether the stream has wind- or tidal-driven flow (Table 4).

Table 4. CEFWG proposed framework to determine ecological flows.

Origin	Gradient	Ecological Flow Approach			
		Statewide Recommendation	Habitat Relationship	Downstream Salinity	Overbank Flow
Piedmont	Medium	X	X	X	
Coastal Plain	Medium	X	X	X	
Coastal Plain	Low		X	X	X
Coastal Plain	Wind or tidally driven flow			X	X

The statewide ecological flow recommendation may be used where discharge and stage are still closely correlated. Water level stations exist within the coastal plain below modeled reaches of streams with piedmont reaches. These water levels could be correlated with the upstream or nearby flows records from USGS gage stations. When correlation meets some criteria of pattern similarity, regression can be used to extend known flows to ungaged reaches.

The low elevation, flat terrain and proximity to tidal, saline water combine to prevent the use of current hydrologic models in the coastal plain that are used to determine the flow-by and ecodeficit recommendations. Different approaches to ecological flows from those described are required, although there is a lack of detailed understanding to offer specific protocols for this region. Thus, a more general framework is recommended that categorizes coastal plain streams and identifies four ecological flow approaches to be considered based on stream category. The approaches include extension of the statewide flow-by criteria; conditions of habitat, primarily for anadromous fish; downstream salinity; and overbank flow. Each stream category may be subjected to more than one, but not all, approaches.

Flow requirements and recommendations for the viability of living aquatic resources have been developed for eastern North Carolina and for specific river basins. The DMF has developed the Coastal Habitat Protection Plan (CHPP) (Deaton et al. 2010) based on the concept of protecting habitat for protection of living marine resources, especially fish and shellfish. The fish and shellfish of concern include both residents of fresh to oligohaline waters and species that live part of their life cycle in saline waters. This approach has goals similar to the efforts of the EFSAB. The DMF should be directly engaged in establishing an approach based on CHPP and other fisheries management plans. This action should also include plans to protect threatened and endangered species.

Salinity is a key water quality factor dependent on flow. Organisms have different physiological tolerances and dependencies for salinity that may vary with life stage. The physiological ranges are directly related to reproductive, developmental and other ecological success of the organisms. Further, salinity distribution is linked to the potential for low dissolved oxygen (DO) conditions, especially in bottom waters. Affected organisms include both animals and plants. Either position of a prescribed salinity or the salinity at a prescribed position has been used by other states to index ecological flows. A recent study on the effects of future water withdrawals in Greenville, NC, used salinity within the Tar River as its indicator of effect. The study should provide insight into how salinity may be used for assessing ecological flow effects.

Overbank flow is dependent on stage with varying dependence on discharge associated with location and elevation of a reach. Riparian, freshwater wetlands are often inundated during colder months and dry or infrequently flooded during warmer months. This pattern is needed to maintain community structure and ecosystem function of these wetlands. Blackwater streams have unique characteristics derived from high dissolved organic matter concentrations and low DO originating from wetlands, combined with slow velocities. Ecological flows within the coastal plain should be sufficient to maintain the seasonal flooding regime in order to protect the ecological integrity of these wetlands, a factor not necessary for streams in the mountains or piedmont.

The framework presented here advances the assessment of ecological flows within the coastal plain but not to the extent of that in other regions. It represents a way forward, but requires further understanding of the relationships that control ecological flows and institution of assessment efforts. Such efforts can be undertaken using resources within North Carolina, but no one program within the state has the expertise or resources to fully advance and refine the framework. It will take coordination and cooperation of the agencies within DENR and the research community.

The EFSAB proposes that DENR continue to work with the CEFWG, and other agencies and organizations as appropriate to further develop this framework. Several agencies within DENR can contribute expertise and effort to CEFWG. The Albemarle Pamlico National Estuary Program (APNEP) has ecological flows as a primary mission within its Comprehensive Conservation and Management Plan (APNEP 2012). The DMF and WRC have expertise on the key species and habitats of coastal North Carolina. The expertise of DWR is essential to extending both ecological condition of coastal ecosystems and the hydrological modeling. The Ecosystem Enhancement Program (EEP) also would have interest and relevant expertise. The Water Resources Research Institute (WRRI) and Sea Grant Program (SG) at NC State University provide a connection to the research community. All of these agencies have an interest and stake in ecological flows within the coastal plain that go beyond the immediate legislative needs directing the EFSAB.

Representatives of state agencies and others should meet to determine (1) general goals and objectives, (2) their needs within this topic, (3) expertise and resources available from each, and (4) a plan to achieve both general and individual goals. Once these agencies can establish their aggregated objectives and general approach, other organizations can be invited to participate. Other contributors should include various willing partners who participated in the EFSAB (e.g., industry and agricultural groups, federal and local government entities, environmental groups). This should include RTI International, which did not have membership on the EFSAB but contributed greatly. Initial leadership should come from someone associated with EFSAB activities, but once a path forward is determined, this requirement may not be necessary.

Coincidental to this activity should be the stimulation of research directed toward ecological flows within the coastal plain. WRRI and SG would be the likely sources of funds for this action, but other agencies may have more directed funding opportunities. (See appendix of CEFWG report for more information.)

3.3 Additional Recommendations

3.3.1 Threatened and Endangered Species

The flow requirements of listed species are often not fully understood. In order to conserve state and federally listed species, the EFSAB recommends that the flow needs of these species should be considered by DENR in addition to the standard recommendations offered in this report. For planning purposes, portions of basins (e.g., nodes) that include listed species should be treated by DENR as needing additional analysis in consultation with the WRC, NMFS and USFWS. When a decision moves beyond planning, then applicable environmental review documents will be sought from appropriate agencies. The EFSAB also encourages DENR and other appropriate agencies to support further research on the flow requirements of listed species.

3.3.2 Ongoing Validation Using an Adaptive Management Approach

There is uncertainty in the science and the existing models, thus a risk averse strategy was used when devising recommendations. Changes in climate and land use are expected to have significant effects on patterns of temperature, precipitation, hydrology and ecology. Monitoring and predicting these changes will be critical for success in maintaining ecological integrity of North Carolina's rivers and streams. An adaptive management approach is required to continually advance the science and reduce areas of uncertainty. Therefore, DENR should:

1. Emphasize new data (hydrologic and biological) collection and evaluation in headwaters, in the coastal plain, and in large rivers, recognizing that current biological models and assumptions may not address these systems.
2. Adopt/design/develop strategies to:
    a. Validate ecological thresholds (strategies should be informed by new data or research);
    b. Track the impact of flow changes when they occur;
    c. Modify characterizations, target flows, and thresholds based on new data, changing conditions (e.g., land cover, precipitation, hydrology) and lessons learned; and
    d. Georeference nodes in each hydrologic model to facilitate analysis.

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APPENDIX A – Session Law 2010-143

GENERAL ASSEMBLY OF NORTH CAROLINA

SESSION 2009

SESSION LAW 2010-143

HOUSE BILL 1743

AN ACT to direct the department of environment and natural resources to develop basinwide hydrologic models, AS RECOMMENDED BY THE ENVIRONMENTAL REVIEW COMMISSION.

The General Assembly of North Carolina enacts:

SECTION 1. G.S. 143-350 reads as rewritten:

"§ 143-350. Definitions.
As used in this Article:

(3) "Essential water use" means the use of water necessary for firefighting, health, and safety; water needed to sustain human and animal life; and water necessary to satisfy federal, state, and local laws for the protection of public health, safety, welfare, the environment, and natural resources; and a minimum amount of water necessary to ~~maintain~~ support and sustain the economy of the state, region, or area.

SECTION 2. G.S. 143-355 is amended by adding a new subsection to read:

"(o) Basinwide Hydrologic Models. - The Department shall develop a basinwide hydrologic model for each of the 17 major river basins in the state as provided in this subsection.

(1) Definitions. - As used in this subsection:

a. "Ecological flow" means the stream flow necessary to protect ecological integrity.

b. "Ecological integrity" means the ability of an aquatic system to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to prevailing ecological conditions and, when subject to disruption, to recover and continue to provide the natural goods and services that normally accrue from the system.

c. "Groundwater resource" means any water flowing or lying under the surface of the earth or contained within an aquifer.

d. "Prevailing ecological conditions" means the ecological conditions determined by reference to the applicable period of record of the United States Geological Survey stream gauge data, including data reflecting the ecological conditions that exist after the construction and operation of existing flow modification devices, such as dams, but excluding data collected when stream flow is temporarily affected by in-stream construction activity.

e. "Surface water resource" means any lake, pond, river, stream, creek, run, spring, or other water flowing or lying on the surface of the earth.

(2) Schedule. - The Department shall develop a schedule for basinwide hydrologic model development. In developing the schedule, the Department shall give priority to developing hydrologic models for river basins or portions of river basins that are experiencing or are likely to experience water supply shortages, where the ecological integrity is threatened or likely to become threatened, or for which an existing hydrologic model has not been developed by the Department or other persons or entities.

(3) Model. - Each basinwide hydrologic model shall:

a. Include surface water resources within the river basin, groundwater resources within the river basin to the extent known by the Department, transfers into and out of the river basin that are required to be registered under G.S. 143-215.22H, other withdrawals, ecological flow, instream flow requirements, projections of future withdrawals, an estimate of return flows within the river basin, inflow data, local water supply plans, and other scientific and technical information the Department deems relevant.

b. Be designed to simulate the flows of each surface water resource within the basin that is identified as a source of water for a withdrawal registered under G.S. 143-215.22H in response to different variables, conditions, and scenarios. The model shall specifically be designed to predict the places, times, frequencies, and intervals at which any of the following may occur:

1. Yield may be inadequate to meet all needs.

2. Yield may be inadequate to meet all essential water uses.

3. Ecological flow may be adversely affected.

c. Be based solely on data that is of public record and open to public review and comment.

(4) Ecological flow. - The Department shall characterize the ecology in the different river basins and identify the flow necessary to maintain ecological integrity. The Department shall create a Science Advisory Board to assist the Department in characterizing the natural ecology and identifying the flow requirements. The Science Advisory Board shall include representatives from the Divisions of Water Resources and Water Quality of the Department, the North Carolina Wildlife Resources Commission, the North Carolina Marine Fisheries Commission, and the Natural Heritage Program. The Department shall also invite participation by the United States Fish and Wildlife Service; the National Marine Fisheries Service; representatives of organizations representing agriculture, forestry, manufacturing, electric public utilities, and local governments, with expertise in aquatic ecology and habitat; and other individuals or organizations with expertise in aquatic ecology and habitat. The Department shall ask the

Science Advisory Board to review any report or study submitted to the Department for consideration that is relevant to characterizing the ecology of the different river basins and identifying flow requirements for maintenance of ecological integrity. The Department shall consider such other information, including site specific analyses, that either the Board or the Department considers relevant to determining ecological flow requirements.

(5) Interstate cooperation. - To the extent practicable, the Department shall work with neighboring states to develop basinwide hydrologic models for each river basin shared by North Carolina and another state.

(6) Approval and modification of hydrologic models. -

a. Upon completion of a hydrologic model, the Department shall:

1. Submit the model to the Commission for approval.

2. Publish in the North Carolina Register notice of its recommendation that the Commission approve the model and of a 60-day period for providing comment on the model.

3. Provide electronic notice to persons who have requested electronic notice of the notice published in the North Carolina Register.

b. Upon receipt of a hydrologic model, the Commission shall:

1. Receive comment on the model for the 60-day period noticed in the North Carolina Register.

2. Act on the model following the 60-day comment period.

c. The Department shall submit any significant modification to an approved hydrologic model to the Commission for review and approval under the process used for initial approval of the model.

d. A hydrologic model is not a rule, and Article 2A of Chapter 150B of the General Statutes does not apply to the development of a hydrologic model.

(7) Existing hydrologic models. - The Department shall not develop a hydrologic model for a river basin for which a hydrologic model has already been developed by a person or entity other than the Department, if the Department determines that the hydrologic model meets the requirements of this subsection. The Department may adopt a hydrologic model that has been developed by another person or entity that meets the requirements of this subsection in lieu of developing a hydrologic model as required by this subsection. The Department may make any modifications or additions to a hydrologic model developed by another person or entity that are necessary to meet the requirements of this subsection.

(8) Construction of subsection. - Nothing in this subsection shall be construed to vary any existing, or impose any additional regulatory requirements, related to water quality or water resources.

(9) Report. - The Department shall report to the Environmental Review Commission on the development of basinwide hydrologic models no later than November 1, of each year."

SECTION 3. The first report required by G.S. 143-355(o), as enacted by Section 2 of this act, is due no later than November 1, 2011.

SECTION 4. This act is effective when it becomes law.

In the General Assembly read three times and ratified this the 8th day of July, 2010.

s/ Walter H. Dalton
President of the Senate

s/ Joe Hackney
Speaker of the House of Representatives

s/ Beverly E. Perdue
Governor

Approved 1:52 p.m. this 22nd day of July, 2010

APPENDIX B – NC Ecological Flows Science Advisory Board Members and Other Contributors

Ecological Flows Science Advisory Board Members

1. **Academic Research**
   Amy Pickle, Nicolas Institute for Environmental Policy Solutions, Duke University

2. **Agriculture**
   Dr. Jeff Hinshaw, NC State University
   Alternate – David Williams, NC Division of Soil and Water Conservation

3. **Electric Public Utilities**
   Hugh Barwick, Duke Energy Carolinas
   Alternate – Thomas Thompson, Duke Energy Carolinas

4. **Environmental Non-Governmental Organizations**
   Sam Pearsall, Environmental Defense Fund
   Alternate – Rebecca Benner, The Nature Conservancy

5. **Local Governments**
   Linda Diebolt, Hazen & Sawyer
   Alternate – Rusty Rozzelle, Mecklenburg County Land Use and Environmental Services

6. **NC American Water Works Association (AWWA-WEA)**
   Jaime Henkels Robinson, CH2M HILL

7. **NC Division of Water Resources (DWR)**
   Fred Tarver
   Alternate – Ian McMillan

8. **NC Division of Water Quality (DWQ)** (integrated into NC DWR in August 2013)
   No representation past August 2013

9. **NC Environmental Management Commission (EMC)**
   No representation past August 2013

10. **NC Forestry Association (NCFA)**
    Bill Swartley, Forestry Non-Point Source Branch, NC Forest Service – Department of Agriculture & Consumer Services
    Alternates – Peter Caldwell, USDA Forest Service & Tom Gerow, NC Forest Service - Department of Agriculture & Consumer Services

11. **NC Natural Heritage Program (NHP)**
    Judy Ratcliffe

12. **NC Marine Fisheries Commission (MFC)**
    Dr. Bob Christian, East Carolina University
    Alternate – Kevin Hart, NC Division of Coastal Management

13. **NC Wildlife Resources Commission (WRC)**
    Chris Goudreau
    Alternate – Vann Stancil

14. **US Geological Survey (USGS)**
    Tom Cuffney, USGS - Raleigh
    Alternate – Holly Weyers, USGS - Raleigh

15. **US Fish and Wildlife Service (USFWS)**
    Mark Cantrell, Asheville Field Office
    Alternate – Sarah McRae, Raleigh Field Office

16. **US National Marine Fisheries Service (NMFS)**
    Fritz Rohde

A list of the NC Ecological Flows Science Advisory Board members and alternates who have served in the following capacities but are no longer serving or no longer serving in these roles for various reasons follows. These members are listed here to recognize their contributions:

- Jessi Baker, NC Division of Marine Fisheries (Alternate to Dr. Bob Christian, East Carolina University)
- Donnie Brewer, Environmental Management Commission – Water Quality and Water Allocation Committees
- Cat Burns, The Nature Conservancy (Alternate to Dr. Sam Pearsall, Environmental Defense Fund)
- Scott Chappell, NC Division of Marine Fisheries (Alternate to Dr. Bob Christian, East Carolina University)
- Vernon Cox, NC Dept of Agriculture and Consumer Services (Alternate to Dr. Jeff Hinshaw, NC State University)
- John Crutchfield, Progress Energy Carolinas
- Jim Mead, NC Division of Water Resources
- Amy Pickle, Environmental Management Commission – Water Quality and Water Allocation Committees
- Steve Reed, NC Division of Water Resources (Alternate to Jim Mead, Division of Water Resources)
- Arlene Roman, City of Gastonia (Alternate to Linda Diebolt, Local Governments)
- Jay Sauber, NC Division of Water Quality

EFSAB Working Groups

To further investigate certain topics outside the scheduled meetings of the EFSAB, ad hoc working groups were formed. The EFSAB determined that these topics were worthy of further investigation beyond the scheduled meetings. Another benefit of the working groups was the involvement of outside subject matter experts, such as was accomplished with the formation of the Coastal Ecological Flows Working Group. Each group then reported its findings during the scheduled meetings of the EFSAB; their findings and recommendations are captured in the meeting summaries. Writing teams developed and proposed sections of the EFSAB report to the board in order to ensure a comprehensive and complete report to the NC Division of Water Resources. These working groups and their members are listed here to recognize their contributions.

Ecological Flows Science Advisory Board Report Writing Teams

- Mark Cantrell, US Fish & Wildlife Service
- Dr. Bob Christian, East Carolina University
- Thomas Cuffney, US Geological Survey
- Linda Diebolt, Hazen & Sawyer
- Chris Goudreau, NC Wildlife Resources Commission
- Jeff Hinshaw, NC State University
- Sarah McRae, US Fish & Wildlife Service
- Jim Mead, Environmental Defense Fund
- Sam Pearsall, Environmental Defense Fund
- Amy Pickle, Nicolas Institute for Environmental Policy Solutions, Duke University
- Judy Ratcliffe, NC Natural Heritage Program
- Jaime Robinson, NC American Water Works Association
- Fred Tarver, NC Division of Water Resources
- Tom Thompson, Duke Energy Carolinas

Ad Hoc Research Water Coordination Group

- Thomas Cuffney, US Geological Service
- Mary Davis, Southeast Aquatic Resources Partnership
- Robert Dykes, RTI International
- Michele Cutrofello Eddy, RTI International
- Chris Goudreau, NC Wildlife Resources Commission
- Phillip Jones, RTI International
- Ian McMillan, NC Division of Water Resources
- Jim Mead, EDF Volunteer
- Rua Mordecai, SALCC
- Lauren Patterson, RTI International
- Sam Pearsall, Environmental Defense Fund
- Jennifer Phelan, RTI International
- Fred Tarver, NC Division of Water Resources

Coastal Ecological Flows Working Group

- Dr. Bob Christian, East Carolina University, Chair
- Eban Bean, East Carolina University
- Dean Carpenter, Albemarle-Pamlico National Estuary Partnership
- Scott Ensign, AquACo
- Mike Griffin, East Carolina University
- Kevin Hart, NC Division of Coastal Management
- Mike O'Driscoll, East Carolina University
- Mike Piehler, University of NC Institute of Marine Science
- Judy Ratcliffe, Natural Heritage Program
- Fritz Rohde, National Oceanic and Atmospheric Administration
- Bennett Wynne, NC Wildlife Resources Commission

Threatened and Endangered Species Working Group

- Mark Cantrell, US Fish & Wildlife Service
- Chris Goudreau, NC Wildlife Resources Commission
- Sarah McRae, US Fish & Wildlife Service
- Judy Ratcliffe, NC Natural Heritage Program

Guest speakers

Experts on various topics contributed their time to help the EFSAB learn about ecological flows science. The following people provided educational presentations to the EFSAB at their meetings.

- Mark Anderson, The Nature Conservancy
- Dr. Bob Christian, East Carolina University
- Tom Cuffney, US Geologic Survey
- Michelle Eddy, RTI International
- Mary Davis, Southern Instream Flow Network
- Robert Dykes, RTI International
- Tom Fransen, NC Division of Water Resources
- Mary Freeman, USGS Patuxent Wildlife Research Center
- Chris Goudreau, NC Wildlife Resources Commission
- Philip Jones, RTI International
- Jim Mead, NC Division of Water Resources
- Kimberly Meitzen, The Nature Conservancy
- Brian McCrodden, Hydrologics
- Thomas Payne, Normandeau Associates
- Sam Pearsall, Environmental Defense Fund
- Jennifer Phelan, RTI International
- Fred Tarver, NC Division of Water Resources
- Ty Ziegler, P.E., HDR/DTA

Facilitation Team

A facilitation team, administered by the Natural Resources Leadership Institute, convened in October 2010. Based on the charter of the EFSAB and guidance from the board, the facilitation team managed the meetings of the EFSAB and provided project support to the board and DWR.

- Mary Lou Addor, EdD, NC State University Cooperative Extension – Natural Resources Leadership Institute
- Christy Perrin, NC University Cooperative Extension – Watershed Education for Communities and Officials
- Nancy Sharpless, Natural Resources Leadership Institute

Recognition of a former facilitation team member for his earlier contributions to the process (October 2010–August 2012).

- Patrick Beggs, NC University Cooperative Extension

APPENDIX C – Recommendations for Establishing Ecological Flows in Coastal Waterways

Membership of Coastal Ecological Flows Working Group (CEFWG)

Bob Christian, ECU, chair
Eban Bean, ECU
Dean Carpenter, APNEP
Scott Ensign, AquACo
Mike Griffin, ECU
Kevin Hart, NC DMF
Mike O'Driscoll, ECU
Mike Piehler, UNC IMS
Judy Ratcliffe, Natural Heritage
Fritz Rohde, NOAA
Bennett Wynne, NC Wildlife Resources

(We refer the reader to more detailed summaries of coastal ecological flows activities as part of the EFSAB minutes located on the NC Division of Water Resources website www.ncwater.org.)

Summary

The low elevation, flat terrain and proximity to tidal, saline waters combine to prevent the use of current hydrologic models in the coastal plain. Different approaches to ecological flows from those described are required, although we lack detailed understanding to provide specific protocols for this region. A more general framework is recommended that categorizes coastal plain streams and identifies four ecological flow approaches to be considered based on stream category. The approaches include extension of the state-wide flow-by criteria; condition of habitat, primarily for anadromous fish; downstream salinity; and overbank flow. Each stream category may be subjected to more than one, but not all, approach. We propose that agencies and organizations within and outside of DENR form a joint committee to further develop this framework.

Uniqueness of coastal ecosystems with respect to ecological flows

Progressing from the piedmont to the coast, streams and rivers become more distinct from those in other regions of the state based primarily on their (1) hydrogeomorphology and hydrodynamics, (2) ecology, and (3) human modifications. Key hydrogeomorphic and hydrodynamic features arise from the flat terrain, low elevation, and tidal influence. Flat terrain and low elevation result in the inundation of extensive riparian swamps, while tidal influence disconnects watershed runoff from being the sole factor affecting river stage. Tides influence coastal rivers far upstream from the saline estuary resulting in tidal freshwater reaches whose hydrology is fundamentally different from rivers in the Piedmont and Mountain regions. Tides may be dominated by astronomical conditions or wind with the latter being more important in the enclosed sounds of the Northeast. These factors result in the potential disconnect between stage and flow and the strong link between flow and water quality (i.e., salinity and dissolved oxygen concentration). Modeling approaches used for the rest of the state for ecological flows do not apply in some coastal plain streams. In addition ground water and surface water are more intimately connected than farther inland. Ecology of coastal waterways includes communities highly influenced by nekton that spend much of their life history within estuarine and ocean waters. Also, submerged aquatic vegetation and riparian wetland trees are integral parts of the ecosystem as foundation species. Finally, current and historical industries have altered the hydrology and ecology of the region. Wetlands have been replaced by linear drainage ways for agricultural production, while more recent desalinization and mining have discharged concentrated brine and depleted groundwater levels, respectively. In summary, the combination of these factors necessitates different approaches to modeling ecological flows than are being used in other regions of the state.

Objectives of Coastal Ecological Flows Working Group (CEFWG)

The overall objective of the CEFWG was to assess the general ability to establish an ecological flows approach for coastal streams, recognizing that a formal recommendation of an approach was unlikely. Rather, the CEFWG has provided a framework for establishing an ecological flows approach. The following summarizes the steps to meet the objective:

- Assess applicability of previous coastal work
    - Other states
    - Greenville Study
- Develop stream typology
- Advance spatial modeling and mapping
- Establish relevant ecological and biological dependencies on flow
- Develop frameworks for potential coastal ecological flows criteria and protocols if possible
- Identify factors limiting ecological flows protocols and needed research within coastal systems

Details are provided in the presentation summary at the EFSAB meeting on July 17, 2013.

Stream typology (led by Scott Ensign)

The coastal plain river network exists with gradients of slope, elevation, influences of tides and seawater intrusion, and degree of human alteration. A stream typology was considered necessary to incorporate recognition of these gradients into ecological flows decision making. The typology in Figure 1 was established as a simplification of a more complex one. It is used to classify reaches under consideration for water flow modifications. The typology identifies several major classification factors: origin, slope or gradient, and wind or tidal influence on stage. These factors are presented as a decision tree that has been used to identify approaches to ecological flows assessment. It should be stressed, however, that there may be no clear demarcation between one category and another, but rather a continuum of influences from the different factors.

This typology highlights two important features of coastal plain rivers. First, ecological flow models based on stage-habitat relationships cannot be used in tidal freshwater rivers. Instead of controlling river stage, discharge emanating from upstream primary controls the upstream intrusion of saltwater. Therefore, ecological flow modeling in tidal freshwater rivers should focus on the effects of flow modification on saltwater intrusion, not on flow affecting the availability of submerged habitat within the channel.

Second, stage-habitat relationships like those used in other regions of the state may be modified for use in the non-tidal coastal plain rivers. However, unlike the models used in other regions, it is necessary to account for the habitat provided by riparian wetlands. Riparian wetlands and swamps occupy a large portion of the coastal plain, are inundated for long period of the year, are highly connected with the hydrology of the channel, and are critical to the ecology of coastal plain rivers.

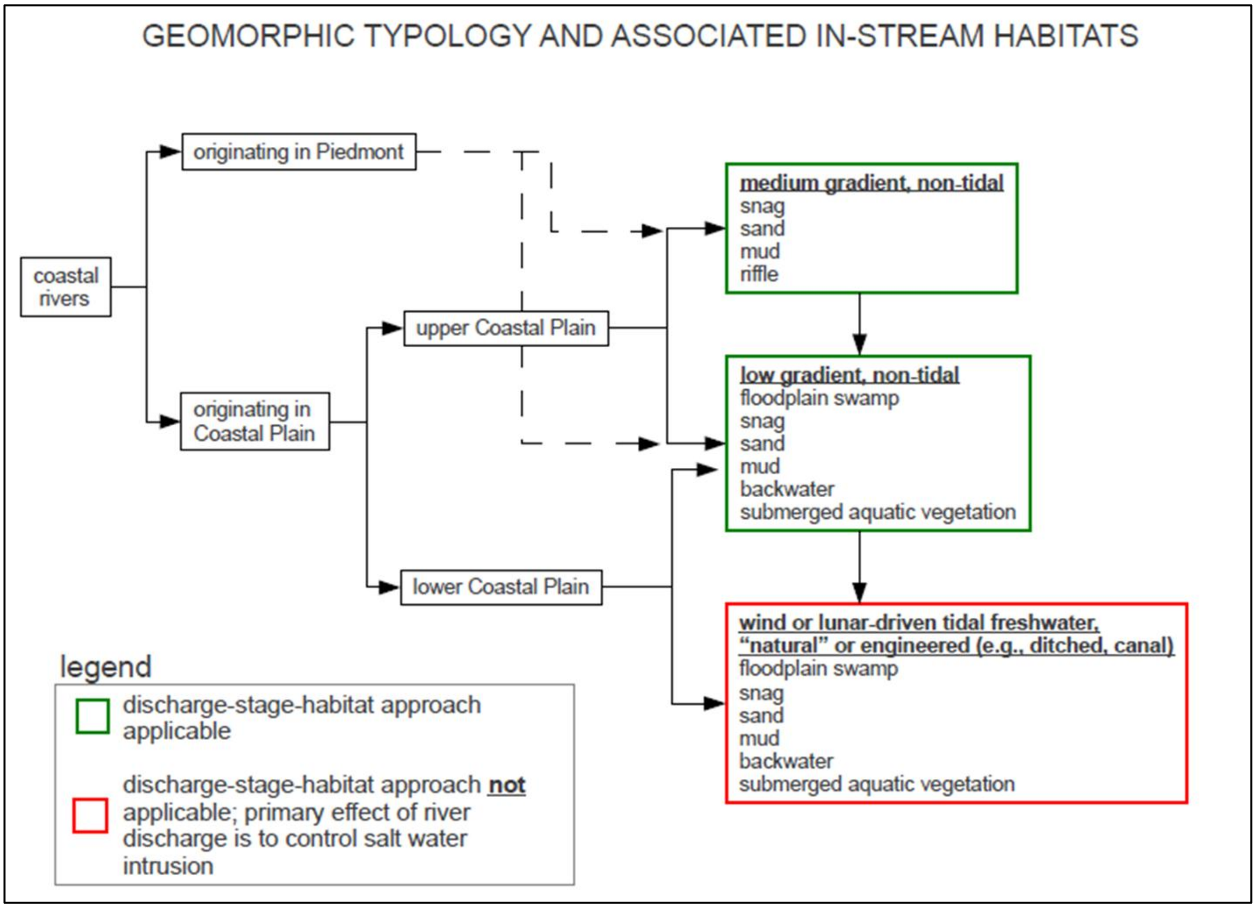

Figure 1. Typology of coastal streams proposed for Coastal Ecological Flows approach decision making.

Spatial modeling and mapping (led by Mike Griffin and Eban Bean)

An initial effort was made to map the typology and other characteristics of the coastal plain and its waterways. Existing data sources were researched and integrated to evaluate the accuracy, relevancy, and applicability for coastal waterway classifications. Key characteristics mapped were (1) the position of the upper and lower coastal plain, (2) origin of waterways, (3) slope categorization, (4) region of tidal influence, and (4) extent of the salt and freshwater interface. A summary map is provided (Figure 2), representing the combination of key features.

Key features were addressed based on the typology shown in Figure 1. The upper and lower coastal plain were initially divided by the Suffolk Scarp (Altor et al. 2005). However, this separation was considered to be of less importance to ecological flows than initially proposed. Mapping was done without this distinction. Waterway origins were manually digitized based on the western boundary of the Coastal plain (Fenneman and Johnson 1946). Stream slopes were determined using USGS 30m resolution digital elevation models (Gesch 2007, Gesch et al. 2002), a stream dataset provided by Kimberly Meitzen of the Nature Conservancy. The slopes varied over several orders of magnitude. A potential threshold between low and medium slope was set at 2.5 mm/m. This threshold places most medium slope streams in the Sand Hills, upper coastal plain, Cape Fear watershed and some tributary streams. The region of tidal influence was designated to be all streams below 1 m in elevation. This threshold appears to generally conform to observations on the Roanoke by Stanley Riggs and Dorothea Ames. The extent of the salt and freshwater interface was estimated by waters classified by the former NC Division of Water Quality (NCDWQ) to be "saltwater" (SA, SB, and SC). Note that the chosen thresholds are proposed to initiate further discussion and consideration.

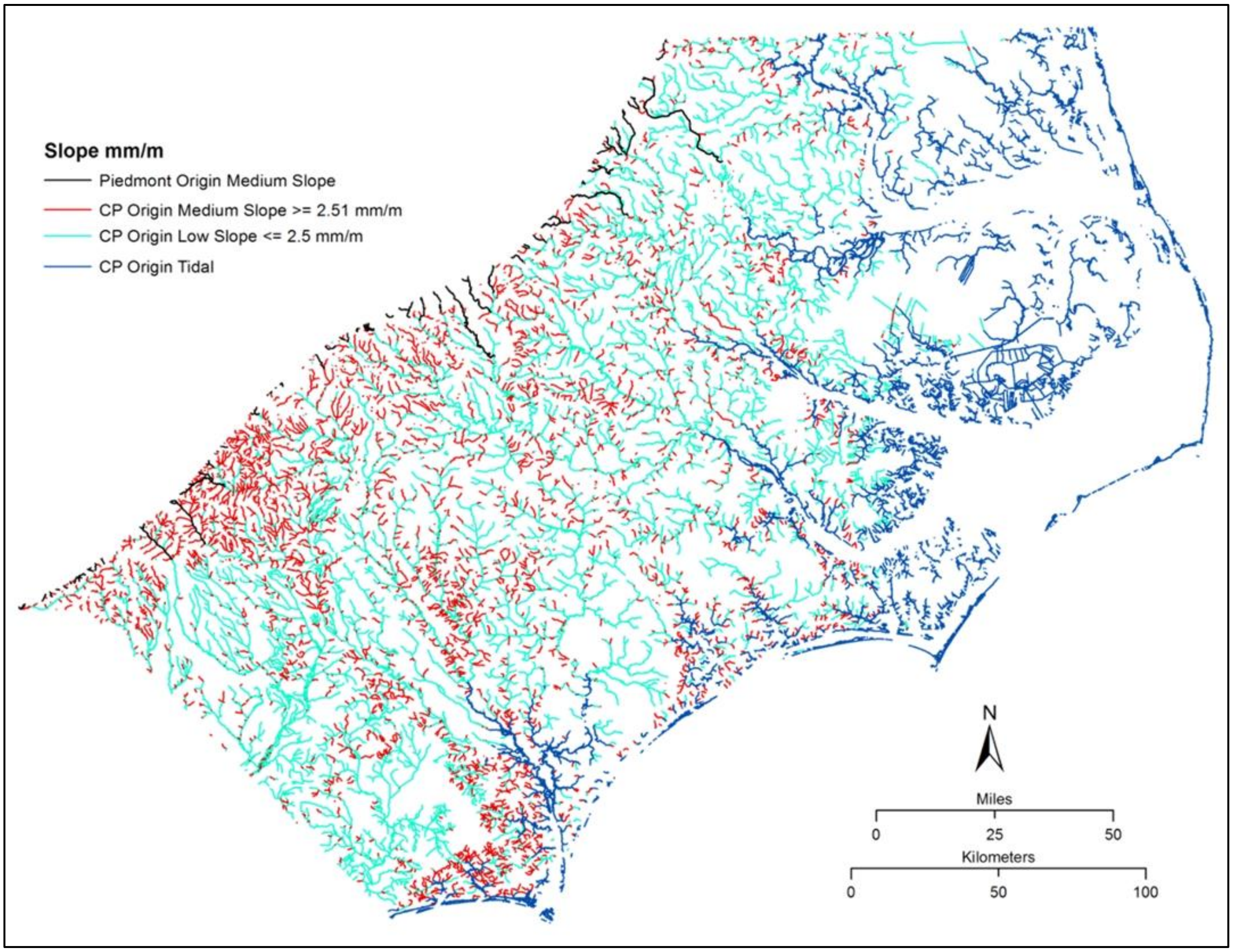

Figure 2. Summary map of key features for consideration of coastal ecological flows.

Relevant ecological and biological dependencies on flow

The CEFWG considered the aquatic communities and ecosystems of the coastal plain and focused attention on two major assemblages: nekton and plant, foundation species. Nekton were characterized as anadromous, catadromous, estuarine or resident species. The former two migrate and spawn in freshwater or the ocean, respectively. The final group tends to grow and develop in the same general area.

Of particular interest are the anadromous fish species. These are ecologically and economically important. Many of these species are important to the food web, acting as key links to primary production or as top predators. Both commercial and recreational fisheries are dependent on some of these species. A large database for them exists within the state as a result. Furthermore, habitat suitability models are available for most species. One critical aspect of habitat is flow. Flow is important to fish spawning and for the times of larval and juvenile growth and development. During these times, flow helps establish the position of the salt wedge and the extent of the freshwater habitat. Dissolved oxygen is another important aspect of habitat suitability related to flow. The Coastal Habitat Protection Plan (CHPP, Deaton et al. 2010) of the NC Division of Marine Fisheries (DMF) identifies some of these factors for specific anadromous fish species (Table 1 from Deaton et al. 2010). Other studies and environmental management actions concern flow requirements for these species. For example flow relations to habitat suitability for the Roanoke River have been established and incorporated into its environmental management.

Anadromous species range across a wide geographic area from conception to adulthood and spawning. Resident species have a narrower range of existence. Many species tend to reside in the lower coastal plain and specifically within the wind/tidal influenced waterways.

Table 1. Physical spawning (adult) and egg development requirements for resident freshwater and anadromous fishes inhabiting coastal North Carolina [Reproduced from Deaton et al. 2010]. [S] = Suitable and [O] = Optimum.

Species	Salinity (ppt)		Temperature (C)		Dissolved oxygen (mg/l)		Flow (cm/s)	Other parameters
	Adult	Spawn/ Egg	Adult	Spawn/ Egg	Adult	Spawn/ Egg	Spawning	Spawn/Egg
Alewife	[S] 0-5	[S] 0-5 [O] 0-2		[S] 11-28 [O] 17-21	[S] ≥3.6	[S] >4	[O] slow current	[S] suspended solids <1000 mg/l
American shad	[S] 0-18	[S] 0-18	[S] 10-30	[S] 13-26	[S] >5		[S] 30-90	
Blueback herring	[S] 0-5	[S] 0-22 [O] 0-2		[S] 14-26 [O] 20-24	[S] >5		[O] strong current	[S] suspended solids <1000 mg/l
Striped bass	[S] 0-5	[S] 0.5-10	[S] 20-22	[S] 12-24 [O] 18-22	[S] >5		[S] 30.5-500 [O] 100-200	
Yellow perch	[S] 0-13	[S] 0-2	[S] 6-30		[S] >5			[S] suspended solids <1000 mg/l
White perch	[S] 5-18	[S] 0-2	[S] 10-30	[S] 12-20	[S] >5			[S] suspended solids <100 mg/l
Sturgeon, Atlantic	[S] 0- >30	[S] 0-5	[S] 0- >30	[S] 12-20				
Sturgeon, Shortnose	[S] 0- >30	[S] 0-5	[S] 0- >30	[S] 5-15				

Riparian wetlands are an integral part of the aquatic ecosystems of the coastal plain. Overbank flow into these wetlands provides water and nutrients to the forests and marshes, but extended flooding in summer can deplete dissolved oxygen that stresses organisms in the wetlands. Swamps dominate the freshwater riparian wetlands and serve as nursery areas and habitat for a variety of aquatic invertebrates, finfish, and birds. Trees act as foundation species for these ecosystems by providing key habitat characteristics of shade, soil stability, and evapotranspiration.

Some coastal plain streams possess submerged aquatic vegetation that also act as foundation species. These species provide habitat for its community and stabilize sediment. The position and extent of these species is flow dependent, in part because of the flow controls the upstream extent of salinity intrusion, and thus alters the habitat requirements for submerged species.

The aforementioned assemblages of organisms provide links between flow and ecological integrity for ecological flow assessments. Individual categories of streams listed in Figure 1 can be expected to be associated with different assemblages (Table 2). Anadromous fish are an important component of the ecosystems of most categories. Plant foundation species are important in low gradient and wind/tidal influenced systems. Resident species of nekton may be another key to ecological flows of wind/tidal influenced systems. The assemblages at this scale are the same for low gradient streams within both the lower and upper coastal plain. Therefore these two categories were merged for later considerations.

Table 2. Link between waterway category and key assemblage that could be used for ecological flow assessment.

		Assemblage		
Origin	Slope	Anadromous Fish	Resident Fish	Vegetation (Foundation species)
Piedmont	Medium gradient	X		
Upper Coastal Plain	Medium gradient	X		
Upper Coastal Plain	Low gradient	X		X
Lower Coastal Plain	Low gradient	X		X
Lower Coastal Plain	Wind or tidal driven flow		X	X

Framework for potential coastal ecological flows criteria and protocols

It is quite evident that assessing ecological flows within the coastal plain is problematic and requires multiple approaches and approaches beyond those available for the piedmont and mountains. We do not have the knowledge at this time to identify quantitatively specific approaches. Rather we propose a framework that includes three potential directions for which quantitative approaches could be established. This framework is based on the relationship between flow, stage and salinity – all of which relate to habitat and ecosystem functions. Stage depends less on gradient related flow with lower elevation and proximity to the coast. Within stream habitat, volume depends on both stage and flow. Riparian, wetland habitat depends on stage and hence overbank flow. Position of salinity and extent of freshwater along a river depend on both flow and stage. These factors have been integrated into 4 ecological determinants from which assessment approaches can be established: (1) extension of whatever approaches endorsed by the EFSAB for piedmont streams, (2) direct discharge/habitat relationships based on CHPP and related guidelines, (3) position of a prescribed salinity or amount of salinity at a prescribed position, and (4) pattern of overbank flow. These are associated with the different waterway categories in Table 3.

Table 3. Categories of waterways within the coastal plain and relevant ecological flows determinants.

Origin	Slope	EF determinant			
		EFSAB extension	Discharge & Habitat	Downstream salinity	Overbank flow
Piedmont	Medium gradient	X	X	X	
Coastal Plain	Medium gradient	X	X	X	
Coastal Plain	Low gradient		X	X	X
Coastal Plain	Wind or tidal driven flow			X	X

Ecological flow relationships as proposed by the EFSAB, similar to those proposed for other regions, may be used where discharge and stage are still closely correlated. Water level stations exist within the coastal plain below modeled reaches of streams with piedmont reaches. These water levels could be correlated with the upstream or nearby flows from gage stations. When correlation meets some criteria of pattern similarity, regression can be used to extend known flows to ungaged reaches.

Flow requirements and recommendations for the viability of living aquatic resources have been developed for eastern North Carolina and for specific river basins. The NC DMF has developed the CHPP based on the concept of protecting habitat for protection of living marine resources, especially fish and shell fish. The fish and shell fish of concern include those discussed here. This approach has goals similar to the efforts of the EFSAB. The DMF should be directly engaged in establishing an approach based on CHPP and other environmental management plans. This action should also include plans to protect threatened and endangered species.

Salinity is a key water quality factor dependent on flow. Organisms have different physiological tolerances and dependencies for salinity that may vary with life stage. These in turn affect reproductive, developmental and other ecological success. Further, salinity distribution is linked to the potential for low dissolved oxygen conditions, especially in bottom waters. Affected organisms include both animals and plants. Foundation and keystone species can be affected. Either position of a prescribed salinity or the salinity at a prescribed position has been used by other states to index ecological flows. A recent study on the effects of future water withdrawals in Greenville, NC, used salinity within the Tar River as its indicator of effect. The study should provide insight into how this factor could be used for assessing ecological flow effects.

Overbank flow is dependent on stage with varying dependence on discharge associated with location and elevation of a reach. Riparian, freshwater wetlands are often inundated during colder months and dry or infrequently flooded during warner months. This pattern is needed to maintain community structure and ecosystem function of these wetlands. Blackwater streams from high dissolved organic matter concentrations and low DO flushed from wetlands, along with slow velocities, drive unique characteristics. Ecological flows within the coastal plain thus should address the ecological integrity of these wetlands more than what might be expected for the piedmont or mountains.

Process for moving forward

The framework presented here advances the assessment of ecological flows within the coastal plain but not to the extent of that in other regions. It represents a way forward, but requires further understanding of the relationships that control ecological flows and institution of assessment approaches. These can be provided by the resources of North Carolina. No one program within the state has the expertise or resources to fully advance and refine the framework. It will take coordination and cooperation of the agencies within DENR and the research community.

Several agencies within DENR can contribute expertise and effort to the cause. The Albemarle Pamlico National Estuary Program (APNEP) has ecological flows as a primary mission within its Comprehensive Conservation and Management Plan (2012). Its research director, Dean Carpenter, participated in the CEFWG and APNEP is prepared to further the work of the working group, at least for the watersheds of the Albemarle and Pamlico Sounds. The DMF and NC Wildlife Resources have expertise on the key species and habitats of coastal North Carolina. CHPP, fisheries management plans and habitat suitability models should be applied to the ecological flows. The expertise of what were the Division of Water Quality and Division of Water Resources is essential to extending both ecological condition of coastal ecosystems and the hydrological modeling. The Ecosystem Enhancement Program (EEP) also would have interest and relevant expertise. The Water Resources Research Institute (WRRI) and Sea Grant Program (SG) at NC State University provide a connection to the research community. All of these agencies have an interest and stake in ecological flows within the coastal plain that go beyond the immediate legislative needs directing the EFSAB.

Representatives of state agencies and others should meet to determine (1) general goals and objectives, (2) their needs within this topic, (3) expertise and resources available from each, and (4) a plan to move to achieve both general and individual goals. Once these agencies can establish their aggregated objectives and general approach, other organizations can be invited to participate. Other contributors should include various willing partners who participated in the EFSAB (e.g., industry and agricultural groups, federal and local government entities, environmental groups). This should include RTI, which did not have membership on the Board but contributed greatly. Initial leadership should come from someone associated with EFSAB activities, but once a path forward is determined, this requirement may not be necessary.

Coincidental to this activity should be the stimulation of research directed toward ecological flows within the coastal plain. WRRI and SG would be the likely sources of funds for this action, but other agencies may have more directed funding opportunities. Below is a list of research needs developed by the CEFWG and EFSAB.

Suggested research within coastal systems

Considerable information is needed before a quantitative approach can be established for the coastal plain. Below is a list of research or development that would benefit this effort.

1. Determine correspondence of known discharge patterns with nearby coastal plain stream flow patterns.

2. Determine the upper-most extent of tidal influence across coastal plain.

3. Evaluate juvenile abundance indices vs. flow and salinity/conductivity.

4. Map salinity distribution across coastal plain.

5. Quantify stream typology classes.

6. Evaluate Roanoke slabshell and other mussel distributions and abundance as informative of salinity and flow patterns.

7. Determine hydrologic metrics and characteristics of coastal streams.

8. Determine reference flow regimes for each river basin.

9. Assess the balance of withdrawals from and discharges to coastal streams.

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APPENDIX D – Flow Alteration – Biological Response Relationships to Support the Determination of Ecological Flows in North Carolina

FLOW ALTERATION – BIOLOGICAL RESPONSE RELATIONSHIPS TO SUPPORT THE DETERMINATION OF ECOLOGICAL FLOWS IN NORTH CAROLINA

A Final Report prepared for Environmental Defense Fund, North Carolina Department of Environment and Natural Resources, and North Carolina Wildlife Resources Commission

By RTI International and U.S. Geological Survey

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1. INTRODUCTION

The North Carolina General Assembly enacted House Bill 143 (§ 143-350) in 2010, which directs the North Carolina Department of Environment and Natural Resources (NCDENR) to develop hydrologic models for each of the 17 river basins in North Carolina (NC) (http://www.ncwater.org/data_and_modeling/eflows/H1743v7.pdf). This legislation tasks NCDENR to characterize the ecology in each river basin in order to identify the flows necessary to maintain ecological integrity. Ecological integrity refers to "the ability of an aquatic system to support and maintain a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to prevailing ecological conditions and, when subject to disruption, to recover and continue to provide the natural goods and services that normally accrue from the system [emphasis added]" (NC§ 143-350).

In order to achieve the goals of Bill 143, Session Law (SL) 2010-143 mandated NCDENR to create an Ecological Flows Science Advisory Board (EFSAB) to advise NCDENR in the characterization of the aquatic ecology of each river basin and the corresponding ecological flows needed to maintain ecological integrity. The EFSAB is composed of stakeholders, per specification by SL 2010-143, with expertise in aquatic ecology and who represent a range of interests regarding the identification and implementation of ecological flows in NC. The recommendations of the EFSAB will be presented to the NC Environmental Review Commission (NCERC) by November 1st, 2013.

Although increasingly being recognized by state and federal water managers as an important management goal, the task of identifying and implementing ecological flows is relatively new. In 2010, the five-step Ecological Limits of Hydrologic Alteration (ELOHA) was proposed as a framework for identifying and implementing ecological flows (Poff et al., 2010) (**Figure 1**). However, at the time of its release, the relationships between changes in streamflow and biological response presumed within the ELOHA framework had not been empirically correlated, nor had the full end-to-end process been demonstrated. Despite the lack of empirical evidence, the ELOHA framework has been widely embraced and used by at least 10 countries and 18 states in the U.S. (Conserve Online, 2012).

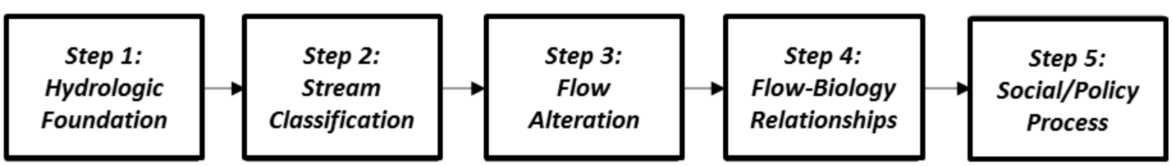

Figure 1. The five steps of the ELOHA framework (from Poff et al., 2010)

The first step of ELOHA is to develop a hydrologic foundation of unaltered and current streamflow conditions. An understanding of how flows have changed from baseline (e.g., unaltered) to current conditions is critical to understanding the relationship between changes in flow (Step 3) and ecological integrity (Apse et al., 2008; Poff et al., 1997). Flow alterations can occur in the five main components of the hydrologic regime: (1) magnitude of flows, (2) timing of flows, (3) duration of flow events, (4) frequency of events, and (5) the rate of change (Richter et al., 1996). One significant challenge in the development of the hydrologic foundation is that the characterization of flows is often limited to catchments with stream gages. Flow data are not available for most catchments, including many catchments containing aquatic biology monitoring stations. Flow alterations at biological stations are therefore often estimated with regression-based extrapolations that restrict flow measures to a single component of the flow regime, magnitude. In addition, the flow extrapolations are often not able to estimate flows under unaltered conditions nor can they be computed for current conditions on a daily time step (Kendy, 2012).

Stream classification is proposed as the second step of the ELOHA framework. The purpose of classifying streams is to allow the flow-biology relationships established with data from a limited number of streams to be extrapolated to all streams sharing similar flow characteristics (Poff et al., 2010). Streams are ideally classified by flow metrics that are biologically relevant and based on unaltered conditions. Numerous institutions have followed the steps of ELOHA in sequence and successfully developed a stream classification system (e.g., McManamay et al., 2012). However, in doing so, researchers have encountered the unforeseen need to conclusively link stream classes to the spatial distribution and assemblages of aquatic biology. If the stream classification does not have biologic fidelity, then grouping streams may weaken and not strengthen the statistical strength of flow-biology relationships, as was found for the middle Potomac River (Kendy, 2012; Middle Potomac Watershed Assessment, 2011).

Step four of the ELOHA framework is the determination of flow-biology relationships. These relationships form the main link between science and policy, as they are based on hypotheses developed from a combination of existing hydro-ecological literature, expert knowledge, and field studies (Poff et al., 2010). In many cases, this proposed approach has spawned elaborate, time intensive, expert-driven efforts to establish relationships that range from qualitative to quantitative. Potential limitations of such approaches are that the method is time and resource intensive and not easily transferable. In addition, the credibility of flow-biology relationships based on best professional judgment is subject to both scientific and political challenges.

A series of projects have been conducted in NC to support the determination of ecological flows for the State. Although not explicitly adopted from the start, the projects have addressed all five steps of the ELOHA framework (Figure 1), and the purpose of this report is to present the methods, results, and conclusions of these key projects and how the challenges of the ELOHA framework were addressed. The following sections specifically describe projects focused on stream classification, flow-biology relationships, and a proposed Ecological Flow Framework to support ecological flow determinations.

2. STREAM CLASSIFICATION

Stream classification is the process of grouping streams within a geographic region into a set number of classes. Stream classes are defined in such a way that all streams within a class exhibit similar attributes. These attributes can be based on the physical, chemical, biological, ecological, and/or hydrologic qualities of streams. In the ELOHA framework, stream classification is undertaken using ecologically meaningful streamflow characteristics to describe streams in terms of hydrological and ecological baselines (Poff et al., 2010).

Researchers have posited several benefits of incorporating stream classification into ecological flow determination. Stream classification may improve the significance of statistical analyses by maximizing attribute differences between different stream classes and minimizing differences within the same class. Classification also provides justification for extending ecological flow thresholds to streams that lack sampling data. Once flow-biology relationships and ecological flows have been established for a given stream class, these relationships and flows can be adopted for any stream within the same class, regardless of whether the site has been sampled for hydrology or biology. If the streamflow characteristics used to define the stream classification system are ecologically significant, in theory, streams in the same group should be similar in terms of biological assemblages and ecological response to alternations in baseline flow regime. This second characteristic is known as the 'flow-biology' relationship (Poff et al., 1997). The following sub-sections describe the stream classification projects that were conducted to support the determinations of ecological flows in NC, and the main conclusions from these projects.

2.1 EFS Stream Classification System

In 2011, a stream classification system was developed to support the determination of ecological flows in the streams and rivers of the State. This classification was developed by Environmental Flow Specialists, Inc. (EFS) based on 108 hydrologic flow metrics hypothesized to be ecologically relevant (Henricksen and Heasley, 2010). Data from a total of 231 gages were used in the analysis. Natural baselines and altered time periods were identified from the hydrologic flow metrics for each sample location; 185 gages were judged to have been minimally altered by human activities. A stream classification scheme was then derived via statistical analyses utilizing principal component analysis (PCA) and k-means clustering algorithms (Henricksen and Heasley, 2010). Six perennial stream classes and one seasonal stream class were identified for the State based on a wide range of hydrologic threshold values.

Following the development of the stream classification system, project reviewers began to question whether the classes adequately captured the variation in aquatic assemblages present in the State. The hydrologic metrics used in the classification process were judged *a priori* to be ecologically meaningful. However, no study had been undertaken to determine whether or how the flow metrics influenced aquatic biology and/or if the hydrology-based stream classes accurately mapped the geographic distribution of aquatic biology assemblages. In other words, does a given aquatic species have a greater probability of appearing in one versus other stream classes? To address this concern, a "biological fidelity" study (hereafter referred to as "biofidelity" study) was conducted to determine whether the hydrology-based stream classification developed by EFS also discriminated among biological assemblages across the seven stream classes.

Briefly, the biofidelity study involved a step-wise analysis approach to evaluate relationships between hydrologic stream classes and aquatic species and community assemblages. Fish community and benthic macroinvertebrate data from the State were mapped to the National Hydrology Dataset Plus (NHD+) catchments and EFS stream classes were determined for each catchment using hydrologic data from U.S. Geological Survey (USGS) stream gages and data modeled with RTI International Watershed Flow and Allocation (WaterFALL®) model (see page 16 of Section 3 for a description of the WaterFALL® model). Through this process and a comparison of stream classes determined by gaged and modeled data in 147 catchments, it was found that overall stream class correspondence between the two hydrologic data sources was less than 50% (**Table 1**).

Table 1. The percent similarity between EFS stream classes determined using USGS gage versus WaterFALL® hydrologic data

EFS Stream Classes[a]	Percent USGS – WaterFALL® Similarity
B – Small Stable	93% (54/58)
C – Large Stable	67% (10/15)
F – Medium Stable	25% (2/8)
D – Small Flashy	10% (4/42)
A – Coastal	10% (2/21)
G – Intermittent	0% (0/2)
E – Piedmont River	0% (0/1)
Total	**49% (72/147)**

[a] Classes B, C and F represent stable streams and classes D, A and G represent flashier streams.

An investigation into the discrepancy between stream class determinations led to a finding that many EFS stream classes were based on extremely sensitive flow metric thresholds. For several classes, a less than 10% change in one hydrologic metric resulted in a change in stream class. These “jumps” in stream class were found in comparisons of USGS gage and modeled hydrologic data and USGS gage data from different periods of record. These results called into question the stability of the EFS stream classification system; it would not be possible to confidently classify streams beyond the catchments with USGS gages. Therefore, the biofidelity analysis did not proceed any further, and it was concluded that an alternate stream classification system to support ecological flow determinations was required. A description of the methods and results of the biofidelity study are available at http://www.ncwater.org/files/eflows/sab/20121023/Biofidelity_Analysis_(RTI).pdf.

2.2 Biological-Environmental Classification (BEC) System

Based on the findings of the biofidelity analysis, the EFSAB determined the need for a stream classification system that

- represents the assemblages and distribution of aquatic biology across the State
- is not based on sensitive threshold values
- results in classes that are consistent and reproducible using USGS stream gage and modeled hydrologic data
- is easy to understand, implement, and map; and
- is applicable to all catchments throughout State.

These objectives served as the foundation of the Biological-Environmental Classification (BEC) System project. The specific goals of the BEC System were to use an iterative cluster-classification approach based on the geographic distributions of aquatic biota assemblages and associated environmental (physiographic and hydrologic) attributes to produce a stream classification that represented both biology and environmental attributes that influence hydrology. The below sub-sections describe the methods, results, and conclusions of the BEC System project.

2.2.1 Methods

Data

A variety of aquatic biology and environmental parameters were used in the development of the BEC System.

Aquatic Biology Data

Fish and benthic macroinvertebrates were selected as the aquatic taxa for the BEC System. Fish are viewed as the top of the food chain "integrators" of the biological condition of a river system (Kendy, 2012) and have a relatively fast recovery time to climate events that may cause local extirpation. The mobility, high trophic status, and preference for certain hydrologic conditions allow fish species to serve as sensitive indicators of ecological integrity with hydrologic alterations (Bragg et al., 2005). Additionally, fish are valued by wide segments of society and therefore often provide a relevant frame of reference for achieving public acceptance (Poff et al., 2010). Benthic macroinvertebrates are useful for monitoring change in flow because they are found in all waters, are sedentary, and are large enough to be easily collectible (NCDENR, 2012). The sedentary nature of benthos ensures that benthic invertebrate communities are responding to localized changes in hydrologic conditions. Benthic macroinvertebrate sample diversity is also considered to be a reliable indicator of local water quality conditions (NCDENR, 2012). The NCDENR Stream Fish Community Assessment Program[1] (http://portal.ncdenr.org/web/wq/ess/bau/ncibi-data) served as the source of fish data, and the NCDENR Benthic Macroinvertebrate Biological Assessment Unit served as the source of the benthic macroinvertebrate data (http://portal.ncdenr.org/web/wq/benthosdata). Both programs evaluate the community composition of fish and benthos, and are therefore suitable for the development of the BEC System.

Fish

Data on fish populations were extracted from the NCDENR Stream Fish Community Assessment Program. This program collects fish data from "wadeable" streams. Fish site selection is non-random, with the majority of sites being located at the most upstream, wadeable bridge crossing in a catchment. The wadeability of a stream varies by location, season, and the amount of precipitation present during the sampling year. Catchment samplings started in 1991 and river basins are on an alternating sampling schedule so that each basin is sampled every five years. At present, over 918 sites have been monitored by the Fish Community Assessment Program. The majority of sampling (73%) occurs in the spring (late March to early June) (Bryn Tracy, Personal Communication, May 6, 2013). All fish samples are collected following NC's standard biological monitoring operating procedures (NCDWQ, 2006). The constraints of the sampling methodology of the Stream Fish Community Assessment Program should be considered in the interpretation of the results from the BEC System and flow-biology relationships (described further in Section 3).

For the purposes of the BEC System, only a portion of the sites and data from the NCDENR Stream Fish Community Assessment Program were used in the analyses. The NCDENR database includes sites that were sampled multiple times over nearly two decades. Five hundred and seventy five sites were

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[1] Previous associated with NC Division of Water Quality (NCDWQ) within NCDENR.

sampled more than once between 1991 and 2011. Temporal and spatial filters were applied to the data to reduce pseudoreplication (i.e., samples that are not independent) and spatial autocorrelation of environmental variables (i.e., similarity among variables based on the proximity of samples sites) (Armstrong et al., 2011; Hurlbert, 1984). First, for those sites with multiple samples taken over time, only data from the most recent samples were maintained. This selection was based on the assumption that the most current samples are most reflective of current streamflow conditions. Second, a spatial filter flagging sites located within 0.5 km from each other was applied (Wenger et al., 2008). The locations of the monitoring sites were based on reported latitude and longitude coordinates assigned to National Hydrography Dataset Plus Catchment Identification (NHD+ COMID) and “snapped” to the nearest NHD+ stream segment using ArcGIS. Sites that changed COMID’s during the “snapping” process were assessed and placed on the correct stream, as indicated by the Stream Fish Community Assessment Program site name. If the sites were sampled at the same time and located along the same stream with no direct human alterations between sites (e.g., reservoir, withdrawal, or return), the most downstream site was kept and the upstream site deleted (Armstrong et al., 2011). If the sites were sampled at different time periods, were located in different streams, or had an instream alteration between them, then both sites were kept in the analysis. There were 57 sites located within 0.5 km of another site, of which 13 were deleted. In addition, all sites located downstream of a reservoir with greater than twice the drainage area of the fish sample site’s drainage area were removed. This step was taken to remove sites where flow conditions are dominated by artificial control structures. At the end of the filtering process for the BEC System, 858 fish sampling sites were available for classification.

A total of 156 fish species have been recorded by the NCDENR Stream Fish Community Assessment Program. Fish species differ in their habitat preferences (Persinger et al., 2011; Pyron & Lauer, 2004), which are largely formed by hydraulic conditions. Experts from NCDENR, NC Wildlife Resources Commission (NCWRC) and National Marine Fisheries Service adopted a system similar to Persinger et al. (2011) and classified the 156 NC species based on their primary habitat preferences during their spawning and adult life stages, considering combined sensitivity to streamflow velocity and depth (**Figure 2**). The riffle-run guild species assemblage was selected to represent fish for the development of the BEC System because it is known to be sensitive to both streamflow characteristics. Fish species that rely on riffles as their habitat during spawning or adult/juvenile stages of their life cycle may be significantly impacted by reduced flows. In addition, the riffle-run guild is well represented across the State, with members of the riffle-run guild present in 667 of the 858 stream fish community sampling sites (**Figure 3**). All of these sites were included in the BEC System analyses. However, only 649 sites were included in the flow-biology relationships because 18 sites were located in zones of tidal influence not modeled by WaterFALL® (described further in Section 3).

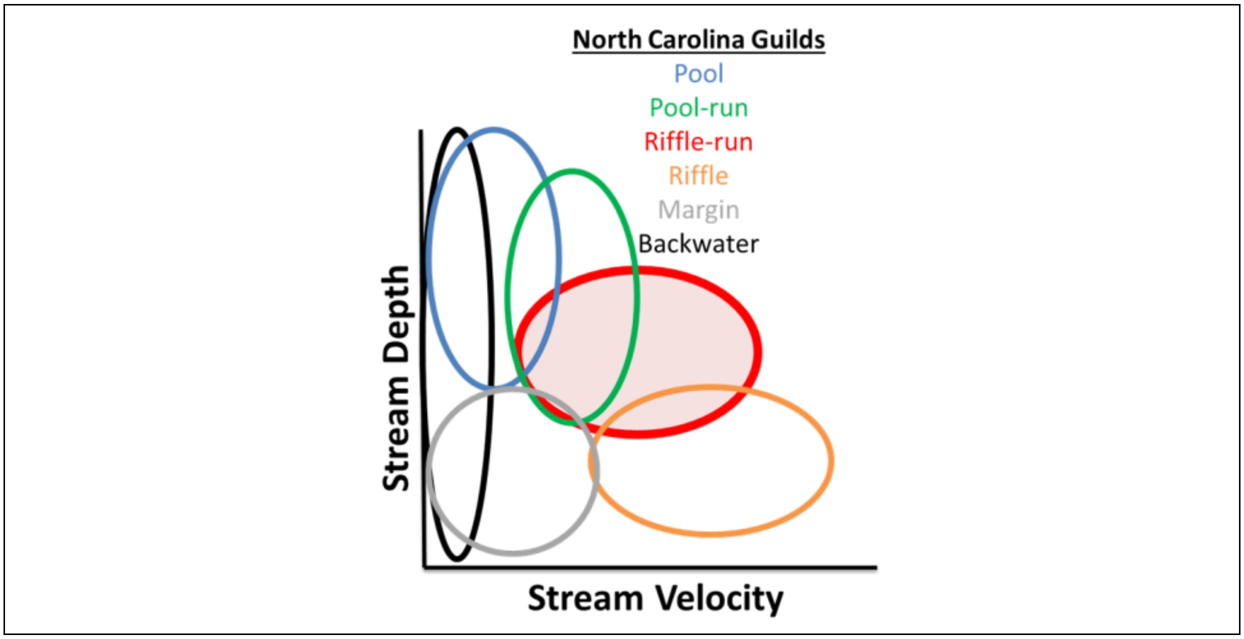


Figure 2. Flow-based habitat guilds used to classify NC fish species

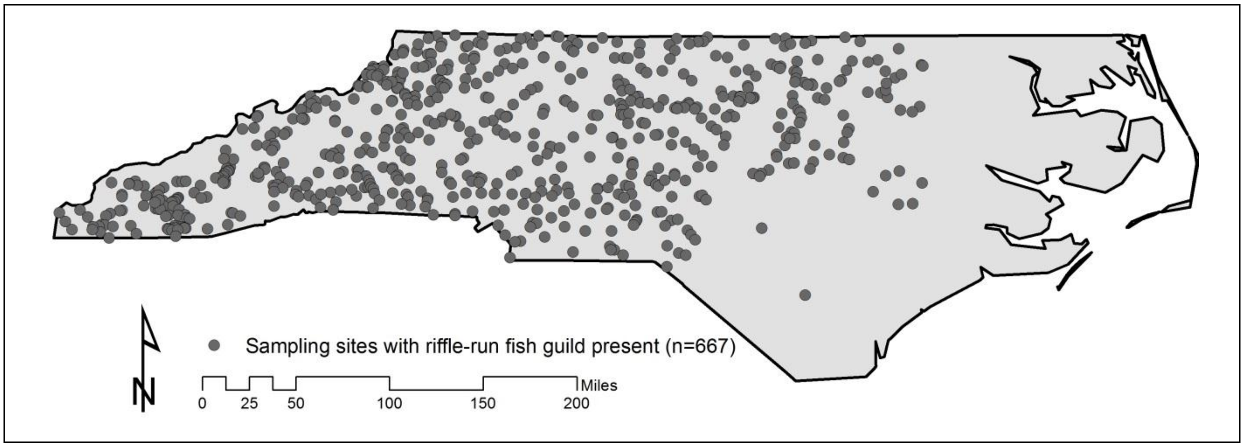


Figure 3. NCDENR Stream Fish Community Assessment Program sampling sites used in the development of BEC System

Data from the NCDENR Stream Fish Community Assessment Program included the number of fish collected for each species identified. From these data, three biologic metrics were derived: abundance, species richness, and the Shannon-Weaver Diversity Index (Mas-Riera et al., 1990; Gutierrez-Estrada et al., 2008; Arias-Gonzalez et al., 2012) (hereafter referred to as "diversity index" or "riffle-run fish guild diversity") (**Table 2**). The diversity index is calculated by (Eq. 1):

$$H = \sum_{i=1}^{R}(p_i)(ln(p_i)) \qquad \textbf{(Equation 1)}$$

where H is the diversity index, R is the number of species present, and p_i is the proportion of individuals (abundance) belonging to the *i*th species at the site. The value of the diversity index increases with the number of species present and as the "evenness" of the number of individuals belonging to each species increases. The diversity index approaches zero as the abundance becomes more concentrated in a single species.

Table 2. Description of riffle-run fish guild metrics

Metric	Definition	Pros	Cons
Abundance	Total number of fish collected	Easy to understand	Sensitive variable and abundance may increase if exotic species are present
Species Richness	Total number of species present	Easy to understand More robust to change	Small range of variability when examining only Riffle-Run guild
Diversity Index	Index of the evenness of fish abundance distributed among the species present	Complex for management to understand and implement	Incorporates both abundance and species richness

Benthic Macroinvertebrates

The NCDENR Benthic Macroinvertebrate Biological Assessment Unit served as the source of the benthic macroinvertebrate data. Since 1978, the NC program has collected over 6,500 benthic macroinvertebrate samples at 1,737 sites in both wadeable and non-wadeable waters(http://portal.ncdenr.org/web/wq/benthosdata). Data on habitat, prevailing water quality parameters, and benthos are collected at each sampling site to assess site conditions (NCDENR, 2012). The macroinvertebrate data used in this report were collected using the NCDENR standard and swamp sample collection methods, as described in the Standard Operating Procedures manual (NCDENR, 2012). The NCDENR methods categorize invertebrate abundances as rare, common, and abundant. These categorical abundances were converted to numeric values (1, 3, and 10, respectively) in accordance with NCDENR procedures for calculating biological condition indices. The constraints of the sampling methodology of the Benthic Macroinvertebrate Biological Assessment Unit should be considered in the interpretation of the results from the BEC System and flow-biology relationships (described further in Section 3).

For the purposes of the BEC System, benthic data were linked to NHD+ catchments and filtered following the same procedures used for NC Stream Fish Community Assessment fish data. Through this filtering process, a total of 1,328 benthic sites were available for the BEC System analysis (**Figure 4**). Similar to fish, only 1,227 sampling sites were included in the flow-biology relationships because WaterFALL® does not model tidally influenced streams (described further in Section 3).

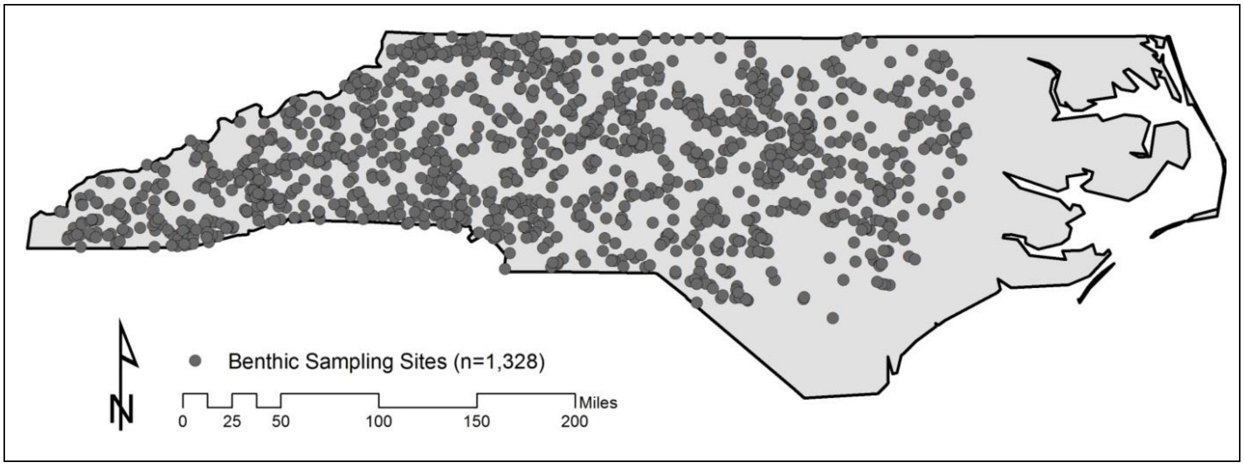


Figure 4. NCDENR Benthic Macroinvertebrate Biological Assessment Unit sampling sites used in the development of BEC System

Similar to fish, the individual benthic data were cleaned and grouped into assemblages and metrics reflective of flow. Ambiguous taxa were removed from each sample by distributing the abundance of ambiguous parents among their children in accordance with the relative abundance of the children using the Distribute Parents Among Children (DPACs) method (Cuffney and Brightbill, 2010). The resulting taxa-by-sample matrix was examined to assess the variability in identifications among samples (e.g., taxa identified to species in some samples and genus in others). Identifications were standardized across samples to provide a consistent dataset. Assemblage metrics were calculated using the attributes file associated with the USGS Invertebrate Data Analysis Software (IDAS) software (Cuffney and Brightbill, 2010). The attributes were optimized for the dataset using the southeastern tolerance and functional group information augmented with national information (NCDENR, 2012; Barbour et al., 1999). Information on streamflow velocity preferences were derived from Vieira et al. (2006). A total of 148 species groupings and metrics were considered. Spearman rank correlations between assemblage metrics and flow metrics (see Section 3 for a greater description of flow metrics) were used to identify benthic biological response metrics that warranted further investigation. These candidate metrics were evaluated in terms of ecological significance, interpretability, data quality (e.g., abundance metrics were derived from categorical data), response range, use in assessing water quality, and correlation with hydrologic variables.

Three biologic response metrics were selected for further analysis: 1) *Ephemeroptera, Plecoptera,* and *Trichoptera* richness (EPTr), 2) average tolerance (RichTOL), and 3) the number of taxa that prefer fast velocities (FastVelR) (**Table 3**). EPTr is the number of taxa in the insect orders Ephemeroptera, Plecoptera, and Trichoptera, which include some of the most alteration-intolerant species of benthos. EPTr is widely used to assess changes in water quality and is sensitive to changes in habitat conditions. RichTOL is the average tolerance of taxa in a sample. Tolerance values range from 0 (intolerant) to 10 (tolerant) and were derived from NCDENR (NCDENR, 2012) and the Environmental Protection Agency (EPA) (Barbour et al., 1999). The third metric was the number of taxa in a sample that prefer fast stream velocities (FastVelR) as defined by Vieira et al. (2006). These three metrics have the additional advantage of being derived from measures of taxa richness. Consequently, they do not rely on converting categorical abundances to numeric values as do metrics based on abundance. Of these three metrics, EPTr had the best combination of response range, correlation with indicators of hydrologic alterations, and relevance to water quality conditions. Therefore, EPTr was used to represent benthos in the development of the BEC System.

Table 3. Description of benthic macroinvertebrate metrics

Metric	Definition	Pros	Cons
EPTr	Number of EPT taxa collected at a site	Widely used by NCDENR for site condition assessments	Includes some tolerant forms
RichTol	Average tolerance of taxa in a sample	Ranks taxa by their tolerance to pollution and disturbance	Relatively narrow response range, tolerance values can vary by region and taxa level
Fast VelR	Number of taxa in a sample that prefer fast stream velocities	Closest benthic equivalent to the riffle-run guild in fish (see Section 3 for further description)	Not well established in the literature

Environmental Data

A large variety of mapable, statewide regional classification systems, and environmental and physiographic attributes were evaluated for the BEC System to develop stream classes. Pre-existing (hereafter referred to as "*a priori*") regional classifications systems that were evaluated in the analyses included Omernik Level III (Omernik, 1987) and IV (Griffith et al., 2002) ecoregions, Wolock hydrologic landscape regions (HLR) (Wolock et al., 2004), Bailey ecoregions (McNab et al., 2005), Fenneman (Fenneman, 1946) physiographic provinces, and The Nature Conservancy (TNC) Ecological Drainage Units (EDU) (TNC, 2005). The classification systems represent distinct physiographic, ecological or hydrologic regions at scales of 1,000 to 10,000 km^2 (Higgins et al., 2005). At this scale, the interactions among watershed boundaries, landscape features (e.g., elevation, geology), and climate (e.g., precipitation, temperature) influence broad patterns of aquatic ecosystems characteristics such as channel morphology and hydrologic, temperature, and nutrient regimes (Higgins et al., 2005). Finer scale differences across sample locations were also characterized using a range of environmental and physiographic variables, watershed and stream channel characteristics, and climatic data regional classification systems (**Table 4**). All data were assigned to the NHD+ catchments with benthic and/or fish biological monitoring data.

Table 4. Environmental variables considered in the development of the BEC System

Variable	Description	Source
Elevation	Elevation of sample site	Digital Elevation Model (DEM)
Channel Sinuosity	NHD+ channel sinuosity of sample reach	Calculated from NHD+ geometry
Slope	Average slope of NHD+ catchment	NHD+
Cumulative Upstream Drainage	Total upstream drainage from sample site	NHD+
Average Precipitation 1 Year Lag	Previous 1 year average precipitation of climate grid	NHD+
Average Precipitation	Average precipitation of climate grid	NHD+
Average Temperature	17 year average temperature	NHD+
Percent Sand	Percent soil sand in HLR unit	Wolock et al. (2004)
Minimum Elevation	Minimum elevation in HLR unit	Wolock et al. (2004)
Relief	Difference between min and max elevation in HLR unit	Wolock et al. (2004)
Percent Flat Total	Total percent of zero-slope area in unit	Wolock et al. (2004)
Percent Flat Upper Watershed	Total percent of zero-slope area in upper 50% of HLR unit	Wolock et al. (2004)
Percent Flat Lower Watershed	Total percent of zero-slope area in lower 50% of HLR unit	Wolock et al. (2004)

Analysis Approach

An iterative cluster-classification approach was applied to the biological and environmental data from the NHD+ catchments with fish and/or benthic monitoring data. Clustering techniques can be characterized as a form of 'unsupervised learning;' the user does not provide information regarding expected relationships between observations. Instead, the algorithm tries to find the number of groups within a data space such that differences among observations in the same group are minimized while differences between groups are maximized. Because clustering algorithms are randomized, multiple techniques and runs should be assessed so that the stability of results can be evaluated. The clustering approaches tested in the development of the BEC System included: partitioning around medoids (PAM), hierarchical agglomerative methods, and fuzzy clustering. In contrast, classification techniques are a form of 'supervised learning;' the user specifies group membership at the start of the analysis and the classification algorithm attempts to find combinations of predictor variables that best describe each group. The result of a classification analysis is a series of unique threshold values that differentiate the groups from one another. The classification techniques tested in the development of the BEC System included: classification and regression trees, conditional inference trees, random forest classification, and conditional inference forests.

The goal of the iterative analysis was to determine if the observed variability in the geographic distribution of aquatic biologic assemblages could be explained by differences in site-specific environmental and physiographic variables, or if the biological data itself could be partitioned in a way that explained variation across the State. Prioritizing biology in this way ensures that classes are characterized and/or tested by species data and that any significant relationships found between stream classes and environmental variables are directly relatable to stream biology. In addition, biological communities integrate physiochemical conditions across multiple temporal and spatial scales, which allow them to be sensitive indicators to changes in environmental conditions (Brenden et al., 2008). Two applications of the cluster-classification approach were attempted. In the first approach, several different clustering algorithms were applied to the environmental data (Table 4) in order to generate different numbers of classes. These classes were then tested against the associated biological data to determine if the clusters explained the variability observed in species assemblages. Indicator species analysis, classification, and non-parametric analysis of variance were used to assess the reasonableness of the environmental groupings. In the second approach, clustering algorithms were applied to the biological data itself, and the resulting classes were then grouped in terms of environmental variables and physiographic regions and tested for significance. The biology-based clusters were also tested for their ability to predict environmental and physiographic data.

2.2.2 Results

Fish

In general, the correspondence between independently derived environmental clusters and fish was weak. A range of clustering techniques, class numbers, and environmental variables were tested; in all cases, the ability of the resulting clusters to explain variability in the geographic distribution of aquatic biology was inconsequential. In contrast, several of the *a priori* regional classification systems demonstrated comparatively higher explanatory power, with the EDU and Omernik Level IV classes showing the most promise for fish. However, the overall amount of unexplained variability remained large (**Figure 5**).

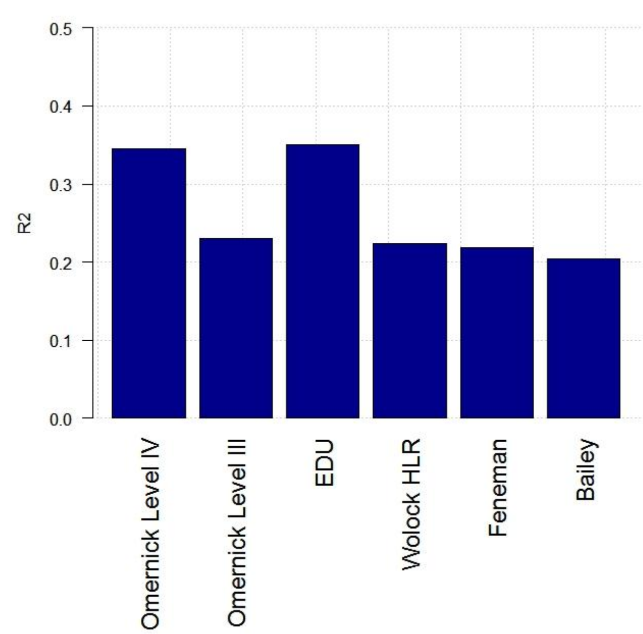


Figure 5. Amount of fish biological variability explained by *a priori* classification systems

The *a priori* regional classifications were also examined for indicator species relevance (Dufrêne and Legendre, 1997). Aquatic biology is known to be impacted by stream size. Therefore, the three classification schemes with the largest explanatory power (Omernick Level III, Omernick Level IV, and EDU) were partitioned by stream class to produce three additional classification systems for evaluation;

stream classes were determined by calculating the total upstream drainage area (**Table 5.**), based on the stream classification system developed by TNC for the northeastern United States (Olivero and Anderson, 2008). Indicator species analysis considers species frequency, abundance, and fidelity relative to a given classification scheme. An indicator species is one that occurs relatively frequently in only a small number of classes. In the context of an environmental-biological classification system, indicator species analysis provides another method of assessing how well a classification system describes unique biological assemblages. The results of the indicator species analyses demonstrated that the EDU classification and Omernik Level III ecoregions were best represented by unique species (

Table 6.); the larger number of classes in the Omernik Level IV classification made it more difficult to identify unique species in individual levels since multiple levels occurred in relatively similar environmental regions. For this reason, the inclusion of stream size, and the subsequent increase in classification levels, did not improve the analysis results.

Table 5. Stream class definitions based on upstream drainage area (adapted from Olivero and Anderson, 2008)

Stream Size Class	Drainage Size
Headwater & creek	< 100 km^2
Small rivers	$\geq$ 100 km^2 and <518 km^2
Medium rivers	$\geq$ 518 km^2 and < 2,590 km^2
Mainstem rivers	$\geq$ 2,590 km^2 and < 10,000 km^2
Large rivers	$\geq$ 10,000 km^2

Table 6. Results of riffle-run fish guild indicator species analysis for *a priori* classification systems

Classification System	No. of Significant Indicator Species	No. of Levels Represented	% of Levels Represented
EDU	92	11/11	100
EDU + Stream Size	24	8/43	19
Omernik Level III Ecoregions	114	4/4	100
Omernik Level III Ecoregions + Stream Size	13	7/18	39
Omernik Level IV Ecoregions	16	8/24	33
Omernik Level IV Ecoregions + Stream Size	28	6/74	8

Given these results, the EDU and Omernik Level III ecoregion classification systems were further evaluated in terms of fish biological data. More specifically, the ability of the biological data to correctly predict the membership of a sampling station was tested for each classification system. For this process, a conditional inference tree model was fit using species abundance as the predictor variable and the specific classes of a given regional classification as the response. In order to test the predictive power of these models, the inference trees were fit many times to a randomly selected 80% of the data. The resulting model was then used to predict the remaining 20% of the dataset that had not been utilized in the model fitting process. A measure of classification accuracy, called a kappa statistic, was calculated for each iteration. The results from these analyses further confirmed the EDU regional classification (without stream size as an additional classification factor) as the best predictor of the riffle-run fish guild abundance (**Figure 6**).

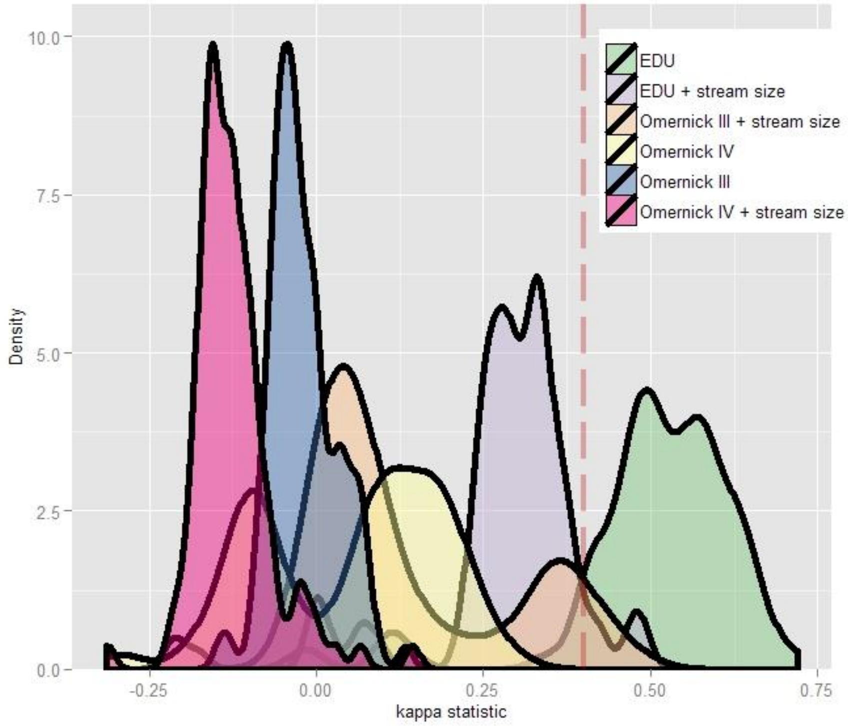


Figure 6. Kappa results for predicting *a priori* classifications with riffle-run fish guild data (a kappa value > 0.4 can be considered 'fair to good' agreement)

Macroinvertebrates

For benthic macroinvertebrates, the PAM cluster method was used to investigate efficacy of dividing the benthic macroinvertebrate data into 2 to 60 clusters. Similar to fish, the average silhouette widths obtained from the PAM cluster analyses were substantially less than 0.25; the PAM analyses indicate that the macroinvertebrate communities do not form discrete clusters. Instead, changes in community structure (composition) are continuous across the State.

Similar to fish, the next step was to investigate the correspondence between *a priori* regional classification systems (with and without stream size classes) and macroinvertebrate communities. This correspondence was assessed using indicator species analysis (Dufrêne and Legendre, 1997) and analysis of similarities (ANOSIM; Clarke and Gorley, 2006). ANOSIM is a nonparametric ANOVA procedure that assesses the significance of *a priori* classes on the basis ofthe similarity in communities among sites.

Indicator species analysis established that all Omernik Level III ecoregions (40 to 151 indicator taxa) and EDU classes (3 to 72 indicator taxa) could be distinguised by the presence or absence of indicator taxa. However, incorporating stream size (**Table 7**) into these classification systems dramatically reduced the number of classes that had statistically significant indicator taxa. These results suggest that Omernik Level III ecoregions and EDU may serve as the most suitablle classification systems for benthos and that adding stream size classes does not improve the resolution of the regional classication systems.

ANOSIM (Clarke and Gorley 2006) tests the hypothesis that there are no assemblage differences between groups of samples specified by the predefined classes as well as testing for differences between pairs of classes. ANOSIM was used to analyzed the four classification systems (Omernik Level III and EDU with and without stream size classes). The ANOSIM results showed that some classes were significantly different (p = 0.001) within all four classification systems (Table 7). However, examination of pair-wise comparisons indicated that only Omernik Level III ecoregions had classes that were all significantly distinguishable. The number of distinquishable classes dropped with the inclusion of stream size. Based on these analyses, Omernik Level III ecoregions (without stream sizes) provide the best regional classification system for benthos in NC.

Table 7. ANOSIM showing the correspondence between invertebrate community structure and regional classification systems with and without consideration of stream size (*p-value = 0.001)

Classification Approach	Omernik Level III Ecoregion		EDU	
	Overall Correlation	% Significant Pairs	Overall Correlation	% significant Pairs
Not Considering Stream Size	0.475*	100	0.359*	95
Considering Stream Size	0.440*	84	0.399*	75

A prior classification systems were also examined on the basis of benthic macroinvertebrate metrics. Metrics aggregate individual taxa into ecologically meaningful groups based on ecological traits or taxonomic characteristics. One hundred and forty-eight metrics were examined as part of the evaluation of predefined classifications systems and for the examination of flow–biology relations. Classification and Regression Tree (CART) analyses were used to determine the number of clusters that best represented the macroinvertebrate assemblage metrics. The number of significant divisions generated by the CART analyses was compared with the number of divisions (classes) in the four classification systems to determine if the CART analyses supported the classification systems. Results from the CART analyses showed that only the Omernik Level III classification system was consistent with the CART analyses. The other systems defined more classes than could be supported using CART analysis.

2.3 Conclusions

Two stream classification approaches were explored to support the determination of ecological flows in NC. The EFS Classification System, consistent with the ELOHA framework and based on ecologically relevant flow metrics, was found to be too sensitive to changes in flow and not easily transferred beyond catchments with USGS gage data. Similarly, a BEC System based solely on physiographic, environmental, or biological data could not be easily developed. In all cases, the ability of the developed classifications to explain the variability observed in the geographic distribution of fish and benthic aquatic assemblages was weak. Statistically significant clusters could be derived, but the large number of classes produced by the classification systems greatly lowered the management utility of these approaches. The best approach for classifications appeared to be the use of *a priori* regional classification systems without stream size classes. The EDU classification produced the best results for the stream fish community dataset, while Omernik Level III ecoregions provided the best regionalization of benthic macroinvertebrate assemblages. Section 3 discusses the utility of the EDU and Omernik Level III ecoregion classes in the development of flow–biology relationships for the streams and rivers of NC.

3. FLOW–BIOLOGY RELATIONSHIPS

The purpose of flow–biology relationships is to quantify the change in ecological integrity associated with flow alterations. Specific ecological flows or thresholds can then be determined from these curves to maintain a level of desired ecological integrity. A project was conducted to empirically derive flow–biology relationships using statewide spatially explicit aquatic biology databases paired with estimates of flow alteration based on modeled flows under unaltered and current conditions. Using these data, a cross-sectional analysis approach that replaces space for time was applied. In theory, with a large enough dataset, the full range of flow alterations and corresponding biologic metrics will be well represented and able to characterize aquatic communities and associated flow alterations (Poff and Zimmerman, 2010; Carlisle et al., 2011). The following sections describe the methods, results, and conclusions of the project work devoted to the development of flow–biology relationships to support the determinations of ecological flows in NC.

3.1 Methods

The following sub-sections describe the methods adopted for each of the components of the flow–biology relationships: biological metrics, hydrologic foundation, flow metrics, and statistical analysis approach.

3.1.1 Biological Metrics

Biological metrics were used to characterize the biological condition of a stream and the response of biology to changes in flow. As with the BEC System, fish and benthic macroinvertebrates were selected to represent the biological condition of streams and rivers and to develop of flow–biology relationships for NC. The diversity index of the riffle-run guild was chosen to represent the biological metric for fish (Table 2), and EPTr was selected to represent the biological metric for benthic macroinvertebrates (Table 3). As discussed in the previous section, the riffle-run fish diversity is hypothesized to be sensitive to flow alterations and is well represented at monitoring stations across the State. Similarly, benthic EPTr was found to have the best combination of response range, correlation with indicators of hydrologic alterations, and relevance to water quality conditions. As outlined in Section 2, a total of 649 sites were used to develop the fish metrics and 1,227 sites were used to develop the benthic metrics.

3.1.2 Hydrologic Foundation

The hydrologic foundation consisting of baseline (i.e., unaltered) and current condition flows was developed using the WaterFALL® model. This model enables interactive, quantitative investigation of water availability at multiple geographic scales. It employs an enhanced version of a well-established hydrologic model, the Generalized Water Loading Function (GWLF; Haith et al., 1992; Haith and Shoemaker, 1987), which has been modified to run on EPA's NHD+ stream network. WaterFALL® functions as an intermediate-level, distributed hydrologic model that accounts for spatial variability of the land surface as well as climatic forcing functions. The watershed model encompasses all major components of the hydrologic cycle using the curve number method for computing runoff (SCS, 1986) and a first-order depiction of infiltration loss to deep aquifer storage. Enhancements include the representation of human interactions with the natural hydrologic system, thereby allowing for the simulation of altered conditions and routing routines to transport water from upstream to downstream through the catchment network.

WaterFALL® relies on national data sources, where available, for the climate, land use, and soils parameters necessary to drive the rainfall-runoff simulation mechanisms. To produce the hydrologic foundation for NC, daily climate data were developed by the Parameter-elevation Regressions on Independent Slope Model (PRISM) Climate Group at Oregon State University for 46 years (1960–2006) and provided by the U.S. Department of Agriculture (USDA). The data were formatted into 4 km grids of daily precipitation totals and average temperatures (DiLuzio et al., 2008). Soils data were obtained from the Soil Survey Geographic database (SSURGO) and the U.S. General Soil Map where SSURGO data were unavailable. Landcover data were obtained for two different time periods in order to model unaltered and current conditions. Unaltered landcover were obtained from the Potential Natural Vegetation (PNV) landcover developed by the Conservation Biology Institute as a proxy for landcover prior to human presence (Kuchler, 1964). The unaltered landcover for NC consisted predominantly of different forest types, wetlands, and barren cover. Current landcover were obtained from the National Land Cover Dataset (NLCD) provided by the USGS for the year 2006. Landcover types include forest, wetlands, agriculture, grasslands, and different levels of development. Water system discharges and withdrawals were obtained from NC databases on public and non-public systems. These data account for permitted human alterations to natural flow regime from industry, public water supply, wastewater treatment, and agriculture. In order to account for temporal variation in each dataset, data were aggregated by month and averaged across recent years (2000–2011) to represent current conditions. Human alterations from major regulated control structures were also included in the model. There were eleven major control structures in NC that were located directly upstream from USGS gages with time series flow data. WaterFALL® was available for use in non-tidal streams in NC (**Figure 7**).

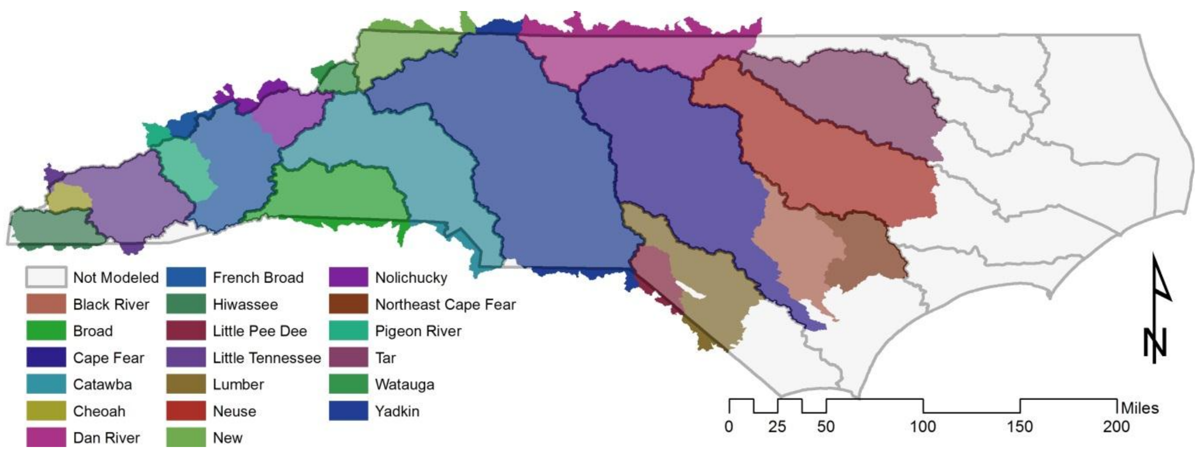


Figure 7. Availability of WaterFALL® hydrologic data in NC by River Basin

WaterFALL® was calibrated at 61 locations where long-term USGS stream gages were present. WaterFALL® parameters were optimized with the goal of minimizing the differences in log-transformed daily flows. This objective function gives equal weight to differences in streamflows at the low and high end of the hydrograph, which often results in better representations of low flows at the expense of potentially underestimating peak streamflows. Model performance was evaluated at the location of USGS gages by an overall volume error (OVE) measure or percent bias and by the Nash-Sutcliff Efficiency (N-S). Using watersheds ranging in size from 39 km^2 to 3,181 km^2 across both reference and non-reference conditions, the majority of the calibrated sites had N-S > 0.35 and OVE within 10% on a daily time step.

To validate the performance of WaterFALL®, a suite of hydrologic metrics generated by WaterFALL® were compared to metrics calculated using hydrologic data from 55 USGS gages. These gages were chosen to characterize both reference and altered streams, over a range of stream sizes (drainage area ranged from 9 to 6,223 km^2), and across the State. For each month, five metrics were compared: the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles of flows to cover the spectrum of extreme low to very high flows. A high degree of correlation (within 30% bounds) between WaterFALL® model predictions and USGS observations for these five metrics were found across the majority of sites. Out of the 55 streams represented, there was only one stream that consistently fell outside of the 30% range and two additional sites that fell outside of the range during some months. These results demonstrated that using WaterFALL® to model flow conditions and flow metrics in ungaged catchments is suitable for the purpose of determining flow–biology relationships.

In summary, a hydrologic foundation consisting of flows under unaltered and current conditions was produced. Unaltered hydrologic flows were modeled with the WaterFALL® model using the climate data from 1966–2006, PNV landcover, and no instream flow alterations (i.e., no withdrawals, discharges, or impoundments). Current hydrologic flows were modeled using the same 40-year climate period (1966–2006) with 2006 NLCD landcover and instream human water uses (i.e., water withdrawals, discharges, and impoundments). The 40-year climate record was selected and held constant between model simulations to mute natural climate variability and characterize the changes in streamflow attributable to human influences.

3.1.3 Flow Metrics

The objectives of flow metrics within the flow–biology relationships are to represent components of the flow regime that directly or indirectly influence aquatic biology. The hydrologic regime has been widely recognized as an important factor governing ecological integrity in streams (Poff and Ward, 1989). Physical habitat structure is of paramount importance in determining both the abundance and species composition of fish (Peeters, and Gardeniers, 1998), and the most important physical habitat variables include components of flow (Geist et al., 2002; Ahmadi-Nedushan et al., 2006). For this reason, flow is considered to be a “master variable”, and ecologists have translated flows into five main ecologically relevant components of flow: magnitude, timing, frequency, duration, and rate of change of events (Poff et al., 2010).

For the purposes of developing flow–biology relationships for streams and rivers in NC, flow metrics were determined at each NHD+ catchment with a fish or benthic monitoring station. The Indicators of Hydrologic Alteration (IHA) framework developed by TNC and the ecosurplus/ecodeficit framework developed by Vogel et al. (2007) served as the sources of the initial metrics considered in the flow–biology analyses (**Table 8**).

Table 8. Flow metrics initially considered for the development of fish and benthic flow–biology relationships (n = 94)

Time Step	Type	Flow Metric	Flow Criterion	No. of Metrics
Monthly Flow (Magnitude)	IHA	Extreme Low Flow	10^{th} percentile	12
		Low Flow	25^{th} percentile	12
		Median Flow	50^{th} percentile	12
		High Flow	75^{th} percentile	12
Seasonal Flow Winter (Dec–Mar) Spring (Apr–Jun) Summer (Jul–Sep) Fall (Oct–Nov) (Magnitude)	IHA	Extreme Low Flow	10^{th} percentile	4
		Low Flow	25^{th} percentile	4
		Median Flow	50^{th} percentile	4
		High Flow	75^{th} percentile	4
Annual Flow (Magnitude & Duration)	IHA	Minimum Flow	3, 7, 30, and 90 days	4
Seasonal Flow Winter (Dec–Mar) Spring (Apr–Jun) Summer (Jul–Sep) Fall (Oct–Nov)	IHA	Minimum Flows	3, 7, 30, and 90 days	12
Annual Flow Winter (Oct–Jun) Summer (Jul–Sep) (Events)	IHA	Extreme Low Flow Magnitude	10^{th} percentile	3
		Extreme Low Flow Events	Number of Events	3
		Extreme Low Flow Duration	Maximum Duration	3
Annual Flow Seasonal Flow Winter (Dec–Mar) Spring (Apr–Jun) Summer (Jul–Sep) Fall (Oct–Nov)	EcoDeficit	EcoDeficit	Magnitude and Timing	5

The IHA metrics are composed of 67 ecologically relevant statistics (Richter et al., 1996) and are widely accepted for assessing hydrologic alterations and ecological flows (Gao et al., 2009). From these, a total of 89 IHA-based flow metrics were developed and evaluated in the development of flow–biology curves (Table 8). These consisted of a sub-set of the IHA metrics outlined by Richter et al. (1996) and IHA metrics split by month and season. The date ranges of the seasons were selected for consistency with flow patterns and the Physical Habitat Simulation (PHABSIM) analyses conducted for NC and consisted of winter (December to March), spring (April to June), summer (July to September), and fall (October and November). Changes in streamflow were calculated as the percent alteration from unaltered to current flow conditions (Eq. 2).

$$\textit{Percent Hydrologic Alteration} = \left(\frac{A}{U} - 1\right) \times 100, \qquad \textbf{(Equation 2)}$$

where A is the altered hydrologic indicator averaged from 1960 to 2006, and U is the unaltered hydrologic indicator averaged from 1960 to 2006.

Vogel et al. (2007) addressed the high degree of autocorrelation among IHA metrics by developing generalized indices to capture the magnitude and timing of hydrologic alterations. These indices were coined “ecosurplus” and “ecodeficit”, and are calculated by taking the difference between the median flow duration curve (FDC) of unaltered (or baseline) and altered conditions, and normalizing that difference by the area beneath the unaltered FDC (**Figure 8**). The median annual FDC reduces the noise presented by high levels of inter-annual variation in flow due to variable climatic conditions. Thus, the median annual FDC better reflects the variability of daily streamflow within a typical year (Vogel et al., 2007). Ecosurplus is the total area located above the unaltered FDC and below the altered FDC, divided by the total area beneath the unaltered FDC. Ecodeficit is the ratio of the area below the unaltered FDC and above the altered FDC. The timing component of changes in hydrologic flow can be taken by segmenting the FDC into seasons. Five ecodeficit-based metrics were considered in the development of the flow–biology curves for NC (Table 8).

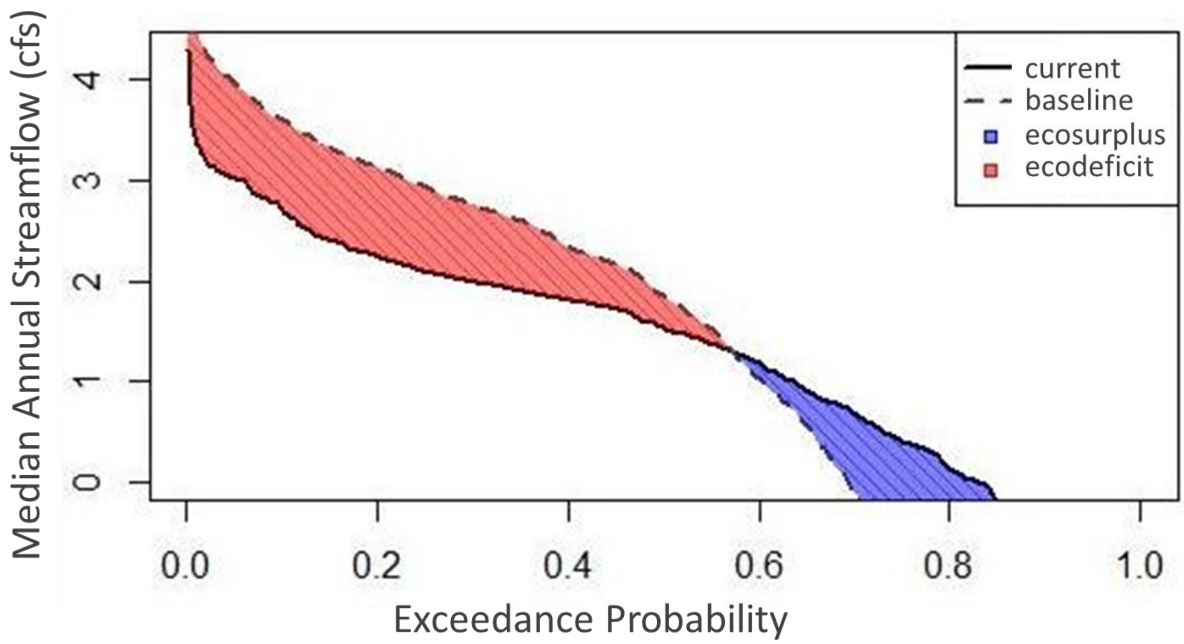


Figure 8. Schematic illustrating annual ecodeficit and ecosurplus for a site in the Roanoke River Basin

The final selection of flow metrics used in the flow–biology relationships was determined through an iterative process that considered the following objectives. The flow metrics, to the degree possible, had to be (1) ecologically relevant and represent as many of the five components of the flow regime as possible, (2) focused on low flows to be consistent with NCDENR management objectives, (3) recognize the seasonality of flows and management objectives, (4) accurately modeled by WaterFALL®, and (5) have a low degree of inter-correlation.

Analyses of the 94 original metrics found that little to no change occurred in the IHA annual and seasonal extreme low flow events metrics. These metrics were therefore dropped from the remaining analyses. The monthly and seasonal IHA metrics were also found to be highly correlated with one another (Spearman Rank: average = 0.76 ± 0.15 for monthly and Spearman Rank: average = 0.75 ± 0.12 for seasonal), a trend which has been reported in other studies (Gao et al., 2009; Arthington et al., 2006; Olden and Poff, 2003). In contrast, IHA minimum flow durations (i.e., 3-, 7-, 30-, and 90-day annual average minimum flows) had a lower average correlation of 0.58 ± 0.18 with the seasonal magnitude metrics. Similar to the IHA metrics, high degrees of correlation among annual and seasonal ecodeficit variables (0.84–0.96; Spearman Rank Correlation) were found. However, these metrics have been reported to explain the majority of hydrologic variation captured by IHA metrics and offer a comprehensive, integrated alternative. Therefore, ecodeficit metrics were selected over IHA metrics for comparable measures of flow.

In summary, annual and seasonal ecodeficits and average annual 30-day minimum flows were the flow metrics that met the five main objectives and were selected for the development of the flow–biology relationships for the riffle-run fish guild and benthic EPTr in NC (**Table 9**).

Table 9. Flow metrics selected to develop fish and benthic flow–biology relationships (n = 6)

Time Step	Flow Metric	Flow Regime Component	No. of Metrics
Annual Winter (Dec–Mar) Spring (Apr–Jun) Summer (Jul–Sep) Fall (Oct–Nov)	EcoDeficit	Magnitude and Timing	5
Annual	Reduction in annual average 30 day minimum flow	Magnitude and Duration	1

3.1.4 Statistical Analysis Approach

A comprehensive, iterative statistical analysis approach was adopted in the development of flow–biology relationships for the streams and rivers of NC. The main objective of the approach was to determine the “best” model to describe the relationships between the rigorously selected riffle-run fish diversity and benthic EPTr metrics and flow metrics, with “best” being defined by a combination of statistical strength and ease of implementation by water resource managers. The following sub-sections describe the individual steps in the analysis approach.

Step 1: Quantile or Upper-Limit Regressions

The first step was to select the statistical analysis approach to best describe the relationship between flow alteration and biological response. Two modeling approaches were considered: quantile and upper-limit regressions. Both of these approaches develop the flow–biology relationship with a focus on the upper 80th or 90th percent of the data and are based on the assumption that these data represent the upper limit of the response attributable to flow alteration (Armstrong et al., 2011; Cade and Noon, 2003). In other words, the 80th or 90th percentile can be viewed as the upper limit of influence that a change in flow can have on the biology, with the remainder of the variation in biological response being a function of other stresses such as water quality, habitat structure, sampling season, etc.

Quantile Regression

Quantile regression is a univariate method for estimating the relationships between variables at any portion of the probability distribution, such as the 80th or 90th percent of the data (Cade and Noon, 2003; Koenker and Basset, 1978). This allows for the modeling of rates of change in all parts of the distribution, whereas traditional regressions are fitted only to the mean of the data. Quantile regressions are solved using the simplex method in linear programming that optimizes the partitioning of the data into groups by breaking up the x-axis in such a way that the points fall within similarly sized groups. The quantile of interest is calculated within each partition and a line function is fitted to all points such that the line runs between the points within the quantile of interest and points outside the quantile (**Figure 9**). The quantile method is more robust against outliers than traditional regression and has been well established for assessing ecological and flow–biology relationships (Armstrong et al., 2011; Cade and Noon, 2003). A main disadvantage of the method is that it is heavily influenced by the distribution of the data, particularly in data scarce partitions.

For the purposes of the development of flow–biology relationships, an 80th quantile analysis approach was tested. The 80th percentile was selected to maintain the upper limit of the response while incorporating a larger range of flow alteration in the upper 20% than was included in a 90th quantile regression.

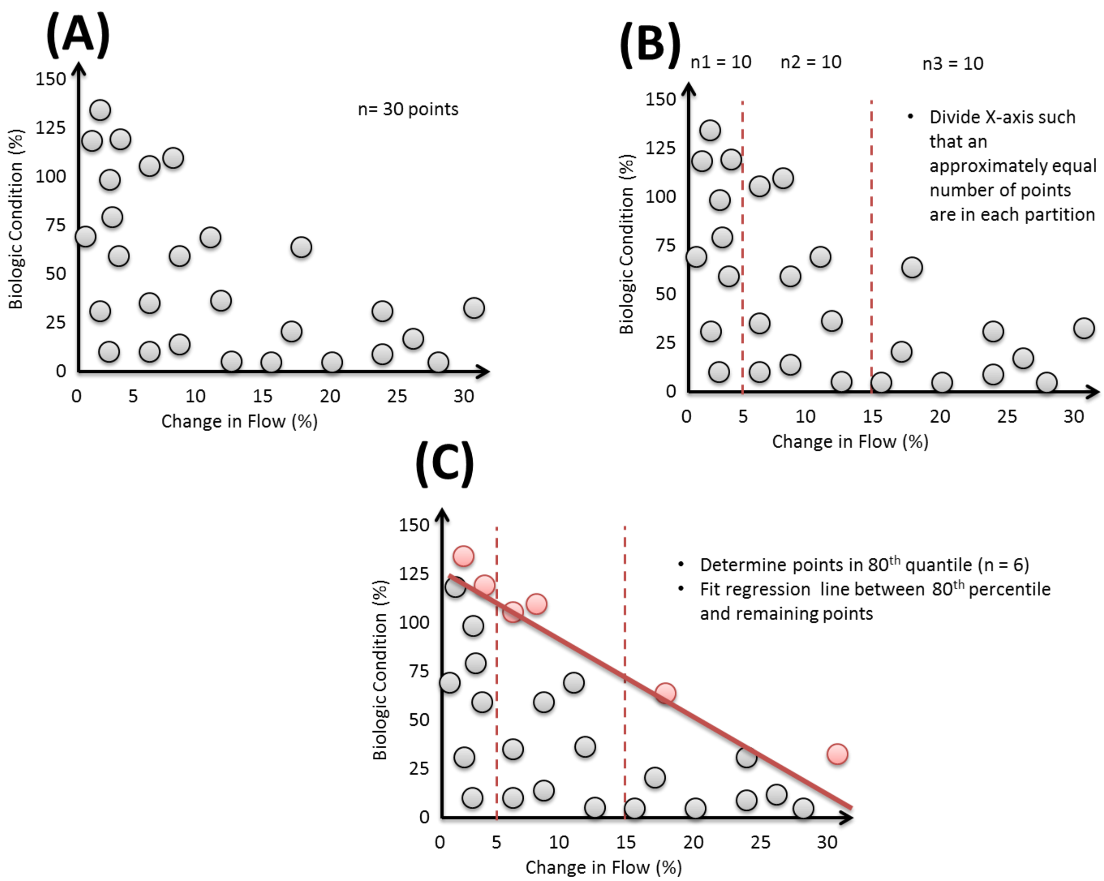


Figure 9. Process of calculating quantile regressions for flow–biology relationships: (A) Flow–biology data, (B) Algorithm partitioning data for quantile regression, (C) Straight line fit to quantile

Upper-Limit Regression

Upper-limit regression, as termed in this report, refers to sub-setting the data to contain the upper percentile of the X–Y relationship and running a regression on that subset of data. It involves partitioning the x-axis in fixed increments to allow for equal representation of the range of values along the axis. For example, the upper 80^{th} percentage of data within each x-axis increment is selected and a regression line is fit to these data (**Figure 10**). The advantage of this method is that it models the top 20^{th} percentile of the distribution of points within each partition and will therefore closely fit the data distribution across the x-axis. A disadvantage of the upper-limit method is that the number of data points included in the model varies between flow metrics, making it difficult to compare models. Similar to the quantile method, this method is also sensitive to the distribution of points along the x-axis, placing greater emphasis on more data sparse areas (e.g., the number of data points included in the regression may not represent the upper 80^{th} percent if less than 10 points are present in an x-axis increment). Upper-limit regression is also more sensitive to outliers since the model fitting process minimizes the distance between data points and the averaging value of the response variable.

For the purposes of the development of flow–biology relationships, an 80^{th} upper-limit regression was tested. The x-axis was partitioned into 0.5% increments and the 80^{th} percentile of data within each increment was included in the regression analysis.

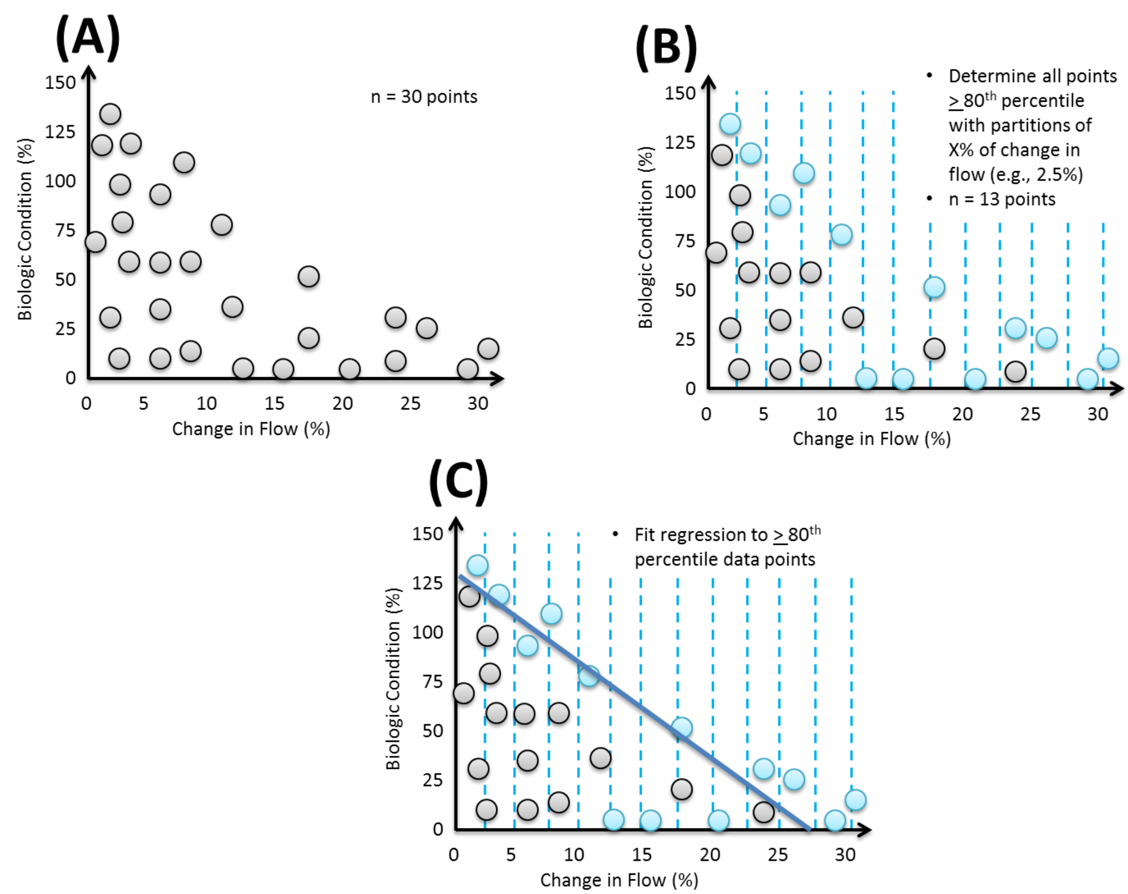


Figure 10. Process of calculating the upper-limit regression for flow–biology relationships: (A) Flow–biology data, (B) Partition x-axis into evenly spaced increments and select 80^{th} percentile of data points, (C) Linear regression of selected data

It was not possible to statistically compare the goodness of fit of the quantile and upper-limit regressions. Both methods consistently resulted in statistically significant flow–biology relationships for fish and benthos and both exhibited similar flow-biology response. Based on the prior application of quantile regressions in flow–biology analyses, the 80th quantile regression analysis approach was adopted to characterize the response for riffle-run fish guild diversity and benthic EPTr to flow alterations in NC.

Step 2: Linear or Non-Linear Regressions

Once the 80th quantile regression was selected, the flow–biology relationships were fitted with linear (Eq. 3) and non-linear (Eq. 4) exponential decay regressions to see which regression best fit the data. It was hypothesized that the non-linear exponential decay model would be the best fit because the conditions of fish and benthos decreased rapidly in response to flow alterations less than 5% prior to leveling out at higher degrees of flow alterations.

$$\textbf{Linear: } Y = A + BX \qquad \textbf{(Equation 3)}$$
$$\textbf{Non-Linear: } \log(Y+1) = A + BX \qquad \textbf{(Equation 4)}$$

where, Y is the biologic metric, X is the hydrologic metric, A is the Y-intercept, and B is the slope.

The linear and non-linear models were found to produce similar flow–biology relationship for fish and benthos that were comparable in statistical strength. Linear regressions were selected for the flow–biology relationships for riffle-run fish guild diversity and benthic EPTr because a linear response across the full range of flow alteration is easier to understand and implement.

Step 3: Relationships by Regional Classification or State

The next step in the analysis approach was to assess the robustness of flow–biology relationships developed for each *a priori* regional class determined in the BEC System project versus flow–biology relationships determined for the whole State. The EDU classification system was found to best describe the assemblages of fish species across NC, and the Omernik Level III ecoregions best described benthos. According to the ELOHA framework and flow–biology theory, developing flow–biology relationships for each class should reduce the variability in the relationships; flow–ecology relationships may vary by stream type with respect to flows and the biological community. The main objectives of this step in the analysis approach were therefore to (1) confirm the availability of sufficient fish and benthic data within each class to determine class-specific flow–biology relationships, (2) determine if the biological communities in each stream class differ in their responses to changes in flow, and (3) determine how regional flow–biology relationships compare with statewide flow–biology relationships.

The responses of fish and benthos to summer ecodeficits were compared at the regional class and statewide levels. **Table 10** and **Table 11** present a summary of the number of sites located in each regional class, the linear flow–biology relationship by regional class, and the statistical significance of each relationship for riffle-run fish guild diversity and benthic EPTr, respectively. For fish, the number of sites in each region varied from 2 to 170 (**Figure 11**), with only two of the flow–biology relationships being statistically significant. However, the two significant flow–biology relationships in the Upper Pee Dee and Upper Santee rivers shared very similar slopes, suggesting similar response functions in the two basins. For benthos, the number of sampling sites in each region was higher (13 to 655) (**Figure 12**). Similar to fish, however, not all regional flow–biology relationships were significant. In contrast, for both fish and benthos the statewide flow–biology relationships were significant. There were sufficient biological data, and the statistical strength of the statewide fish and benthos response models was high. Therefore, flow–biology relationships determined at the statewide level were adopted to characterize the responses of riffle-run fish guild diversity and benthic EPTr to flow alterations. The benefits of statewide analyses are they incorporate the maximum amount of available data available and simplify implementation of the flow–biology relationships by water resource managers.

Table 10. Summary of the number of sites, flow–biology relationships and statistical significance of the flow–biology relationships at the EDU and statewide levels for riffle-run fish guild diversity in response to summer ecodeficits (significant flow–biology relationships at the p≤0.05 are in bold)

EDU	No. of Sites	Flow-biology Equation	*p*-value
Upper Savannah River	2	NA	NA
New River	31	Y=100+3.2X	0.46
Albemarle/Pamlico-Piedmont	90	Y=100-0.86X	0.25
Upper Roanoke River	18	Y=100-1.68X	0.67
Cape Fear River-Coastal Plain	9	Y=100-3.84X	0.32
Cape Fear River-Piedmont	63	Y=100+1.54X	0.62
Pee Dee River-Coastal Plain	17	Y=100-3.35X	0.21
Upper Pee Dee River	**131**	**Y=100-2.57X**	**0.05**
Upper Santee River	**109**	**Y=100-2.04X**	**0.02**
Albemarle/Pamlico-Coastal Plain	9	Y=100-4.08X	0.54
Tennessee River-Blue Ridge	170	Y=100-0.24X	0.92
Statewide	**649**	**Y = 100-2.76X**	**0.00**

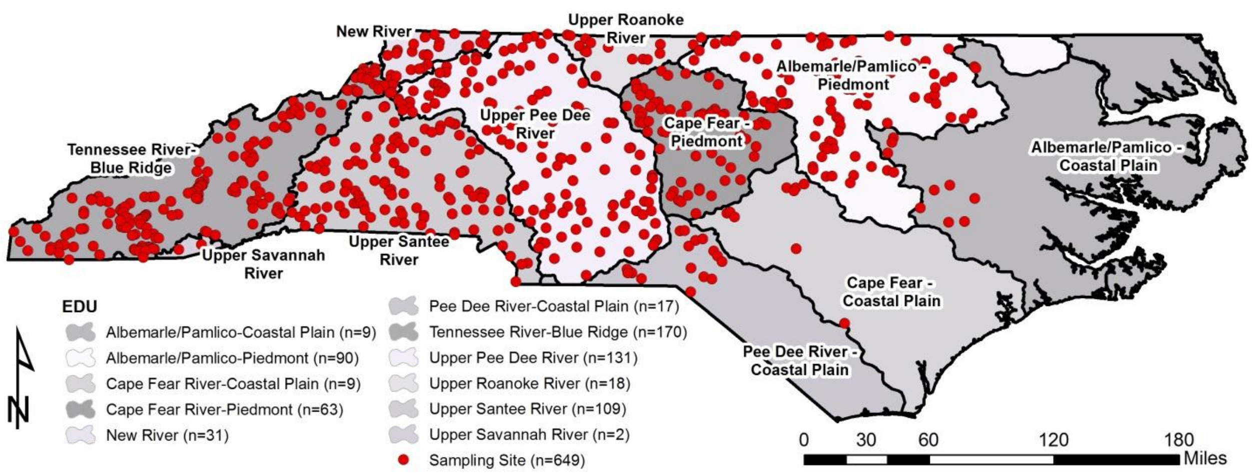


Figure 11. NCDDWR Stream Fish Community Assessment Program sample sites with riffle-run fish guild species by EDU

Table 11. Summary of the number of sites, flow–biology relationships and statistical significance of the flow–biology relationships at the Omernik Level III ecoregion and statewide levels for benthic EPTr in response to summer ecodeficits (significant flow–biology relationships at the p≤0.05 are in bold)

Omernik Level III Ecoregion	No. of Sites	Flow-biology Equation	*p*-value
Blue Ridge	363	Y = 100 - 0.47X	0.26
Piedmont	**655**	**Y = 100 - 1.83X**	**0.00**
Southeast Plains	196	Y = 100 - 0.64X	0.30
Mid Atlantic Coastal	13	Y = 100 - 2.82X	0.14
Statewide	**1,227**	**Y = 100 - 2.43X**	**0.00**

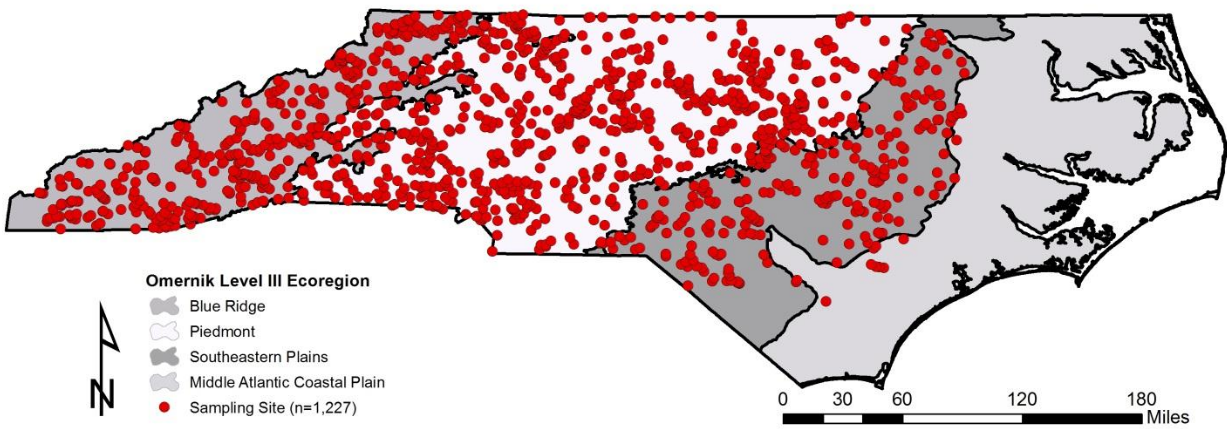


Figure 12. Benthic Macroinvertebrate Biological Assessment Unit sampling sites by Omernik Level III ecoregion

Step 4: Normalized or Raw Biological Data

Following the decision to determine flow–biology relationships at the statewide level, an evaluation of the magnitudes and ranges of fish and benthic metrics across NC became important. If riffle-run fish guild species richness, counts, and diversity and benthic EPTr were similar in all regions of the State, the raw biological metrics could be used in the flow–biology relationships. However, if the metrics differed by physiographic region, it may be necessary to normalize the biological data by region prior to conducting the flow–biology analyses. Summaries of riffle-run fish guild are presented in **Table 12**, and summaries of benthic EPTr are presented in **Table 13.** For the analyses of benthic EPTr, the Mid Atlantic Coastal Plain ecoregion was combined with the Southeastern Plain Ecoregion and analyzed as the Coastal Plains due to a low number of sampling sites in the Mid Atlantic Coastal Plain Ecoregion (Table 11). The species richness of the riffle-run guild was found to be higher in the mountain regions than in the coastal plain (**Figure 13**). Benthic EPTr follows a similar trend with higher EPTr in mountain regions than in the coastal plain (**Figure 14**). Similarly, there was considerable variation in the species richness, counts, and diversity of the riffle-run guild and benthic EPTr by drainage basin or Omernik Level III ecoregion. These results suggest either inherent differences in aquatic biology by basin or region, which would warrant data normalization, or differences in aquatic biology due to location-specific stresses. For example, differences in flow alteration may account for the differences in the riffle-run fish diversity by drainage basin and benthic EPTr by Omernik Level III ecoregion, as suggested by **Figure 15**.

Step 4 in the analysis approach evaluated the need to normalize the biological data and whether the flow-biology relationships developed using raw biological data were better fits than those developed using normalized data. For this comparison, the fish and benthic metrics were normalized by dividing each value by the 80th percentile of the respective metric within each respective physiographic region. For fish, the metrics were normalized by river basin and for benthos the metrics were normalized by Omernik Level III ecoregion. Although EDU was found to be the most significant physiographic predictor of fish assemblages (see Section 2), the fish metrics were normalized by river basin because EDU and basin boundaries are similar, fish cannot cross river basin boundaries and are hydrologically isolated from each other, and river basins have more management relevance. Benthic EPTr was normalized by Omernik Level III ecoregions (Blue Ridge Mountains, Piedmont, and Coastal Plains [Southeastern Plain and Mid Atlantic Coastal Plain]) because this classification system was the most significant physiographic predictor of benthic EPTr species assemblage. The 80th percentile was selected as the value to normalize the metrics because it was seen to represent the highest standard of biological potential in the physiographic region. For fish, the 80th percentile value within each river basin was applied directly (Table 12). For benthos, NCDENR classifies the condition of each monitoring sites as excellent, good, good-fair, fair, and poor based on the biological community composition. Monitoring sites with an excellent rating were deemed to be the highest-quality sites, i.e., those sites that have experienced minimum disturbance and should have the greatest EPTr. Therefore, benthic EPTr was normalized by the 80th percentile of EPTr with excellent site conditions (Table 13).

Table 12. Maximum and 80th percentile of riffle-run fish guild metrics by river basin

River Basin	No. of Sites	Maximum Value			80th Percentile		
		Abundance	Species Richness	Diversity Index	Abundance	Species Richness	Diversity Index
French Broad	72	1,554	13	2.15	527	9	1.56
Hiwassee	19	1,016	10	1.68	605	8	1.50
Little Tennessee	60	1,373	10	1.73	401	8	1.45
New	31	1,870	13	1.91	1,243	11	1.56
Savannah	2	120	3	0.43	110	3	0.41
Watauga	19	776	9	1.43	430	4	0.85
Broad	43	448	6	1.52	93	4	1.14
Cape Fear	72	163	6	1.30	73	3	0.73
Catawba	66	724	7	1.56	211	5	1.33
Lumber	12	21	2	0.39	10	1	0.00
Neuse	47	597	4	1.25	140	4	0.90
Roanoke	36	578	14	2.20	363	11	1.69
Tar	34	218	6	1.52	100	5	1.13
Yadkin	136	1,645	9	1.81	227	6	1.29
TOTAL	**649**						

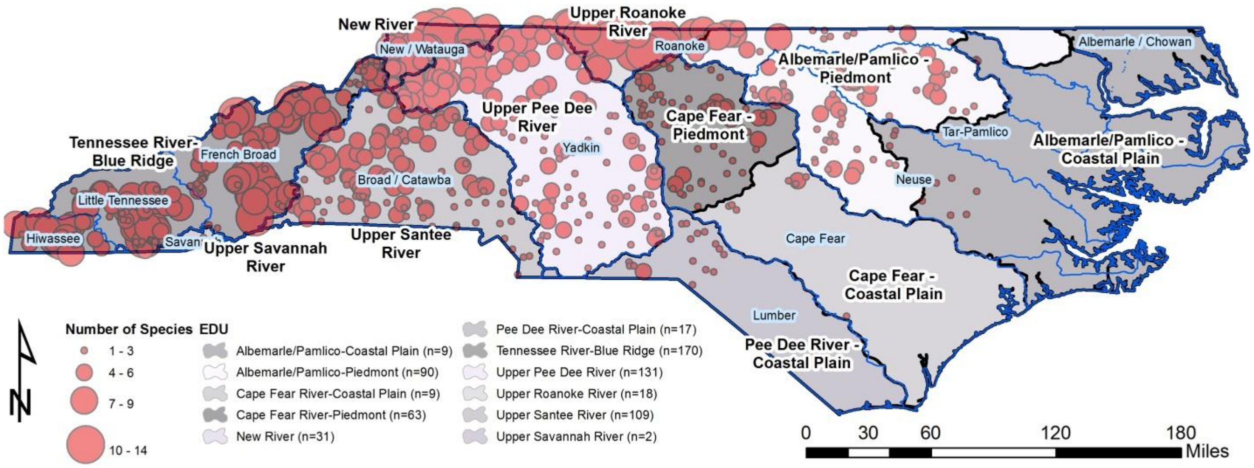


Figure 13. Riffle-run fish guild species richness within each river basin and EDU

Table 13. Maximum and 80th percentile of benthic EPTr by Omernik Level III ecoregion

Omernik Level III Ecoregion	No. of Sites	No. of Excellent Condition Sites	Maximum Value	80th Percentile of Excellent Condition Sites
			EPTr	EPTr
Blue Ridge	363	159	61	48
Piedmont	655	49	54	45
Southeast Plains & Mid Atlantic Coastal	209	28	40	33
Total	**1,227**	**236**		

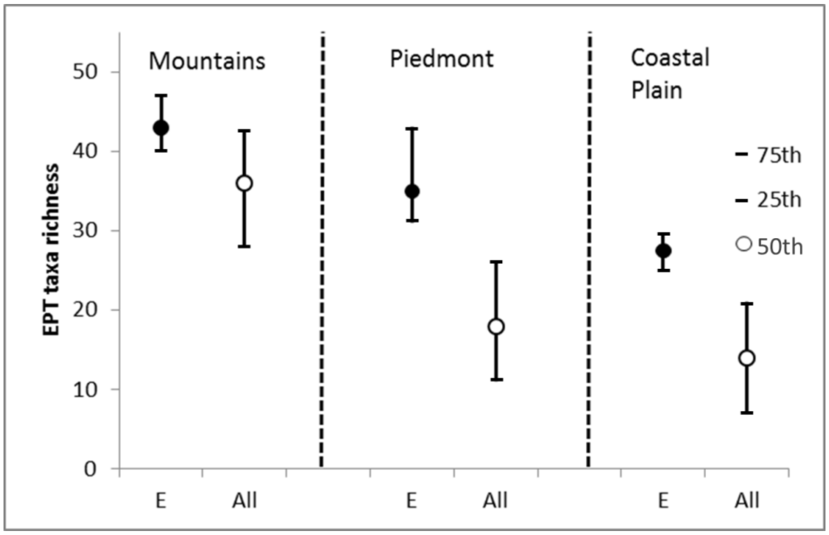


Figure 14. Average benthic EPTr (25th, 50th, and 75th percentiles) within each Omernik Level III ecoregion (open circles indicate all sites, closed circles indicate sites with excellent (E) site condition).

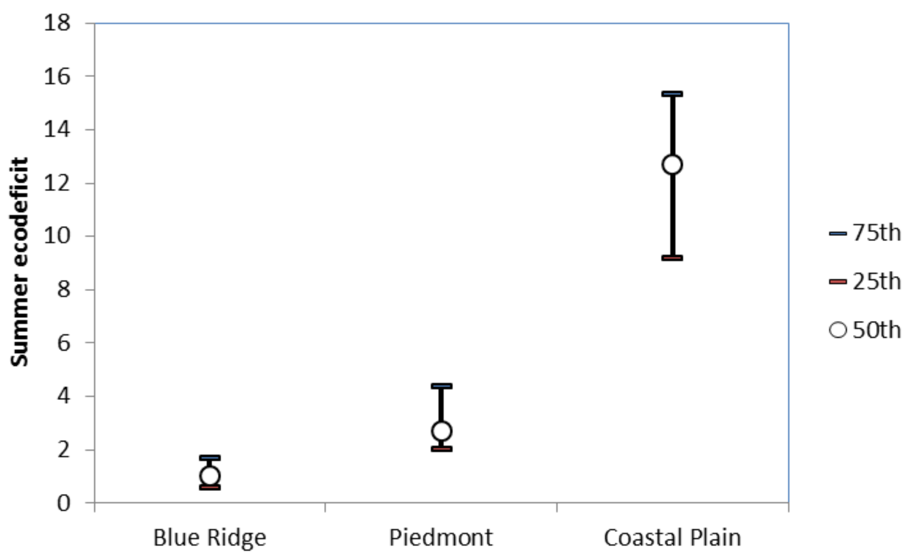


Figure 15. Summer ecodeficit (25th, 50th, and 75th percentiles) at benthic monitoring sites with excellent condition within each Omernik Level III ecoregion

To evaluate the performance of flow–biology relationships developed using normalized versus non-normalized data, responses of the riffle-run fish diversity and benthic EPTr to the annual and four seasonal ecodeficits and reductions in 30-day average annual minimum flows were compared. Models were evaluated on the basis of the degree to which differences in fish and benthic biology between basins/ecoregions could be accounted for by differences in flow alteration between the same basins/ecoregions. In other words, to what degree can the differences in flows at the benthic excellent condition sites by ecoregion (Figure 15) account for the differences in benthic EPTr by ecoregion (Figure 14)?

This procedure involved determining the "reference" condition in each ecoregion or river basin. The 80th percentile of benthic EPTr at the excellent condition monitoring sites was used to represent the "reference" condition for benthos in each Omernik Level III ecoregion. To be comparable with benthos, the reference condition for fish was determined by taking the 80th percentile of the 80–100th percentile riffle-run fish guild diversity within each river basin. To be comparable to benthos, river basins were grouped into Omernik Level III ecoregions (Piedmont Ecoregion = Broad, Catawba, Roanoke, and Yadkin/Coastal Plains Ecoregion = Neuse, Tar, and Cape Fear). The fish and benthic "reference" sites within ecoregions with higher amounts of flow alteration, as reflected by ecodeficits (i.e., Piedmont and Coastal Plains ecoregions) (Figure 15) were then predicted using the normalized versus non-normalized regression equations. These predicted values were subsequently compared to the observed values within the ecoregions to determine the degree of biological variation not explained by the normalized versus non-normalized models.

For both fish and benthos, the model comparisons indicated that the statewide flow–biology relationships developed using raw biological data were able to describe a larger proportion of the biological response to flow alteration; the deviations between observed and predicted benthic EPTr and riffle-run fish guild diversity were, in general, less for the non-normalized than normalized flow–biology models (**Table 14 and 15**). More specifically, for benthos, normalization by ecoregion increased errors in estimates of EPTr in the Piedmont and Coastal Plains ecoregions by 0.4–22%. Errors were particularly large in the Coastal Plain (17–22%) which had much larger ecodeficits at excellent condition sites than did the Piedmont ecoregion. Although less distinct and consistent for fish, normalization increased errors in the riffle-run fish diversity by as much as 10%. Based on these results, normalization of the biological data appears to reduce the sensitivity of the analyses because differences in biological condition by ecoregion are largely accounted for in the fish and benthic models. Therefore, for both fish and benthos, non-normalized data were used to develop the statewide linear 80th quantile flow–biology relationships for NC. To facilitate a comparison of the responses of benthos and fish to the different metrics, the biological responses (i.e., y-axis) were scaled to 100%.

Table 14. Deviation between the observed and predicted benthic EPTr in the Piedmont and Coastal Plains ecoregions using flow–biology relationships developed with normalized and non-normalized benthic data (Deviation = (predicted-observed)/observed*100%)

Flow Metric	Non-normalized Data		Data Normalized by Ecoregion	
	Piedmont	Coastal Plains	Piedmont	Coastal Plains
Annual Ecodeficit	5.6	13.7	6.0	27.7
Winter Ecodeficit	5.2	11.2	5.9	27.9
Spring Ecodeficit	2.4	5.8	4.1	21.9
Summer Ecodeficit	2.2	3.0	3.8	18.0
Fall Ecodeficit	1.4	3.0	3.6	20.4
Reduction in average annual 30-day minimum flow	3.2	21.2	4.2	28.0

Table 15. Deviation between the observed and predicted riffle-run fish guild in the Piedmont and Coastal Plains ecoregions using flow–biology relationships developed with normalized and non-normalized fish data (Deviation = (predicted-observed)/observed*100%)

Flow Metric	Non-normalized Data		Data Normalized by River Basin	
	Piedmont	Coastal Plains	Piedmont	Coastal Plains
Annual Ecodeficit	17.6	36.7	17.4	35.0
Winter Ecodeficit	14.7	28.7	17.7	35.0
Spring Ecodeficit	14.2	27.9	17.2	34.3
Summer Ecodeficit	13.3	21.8	12.4	22.2
Fall Ecodeficit	12.7	23.1	17.1	32.8
Reduction in average annual 30-day minimum flow	12.1	23.1	17.3	33.0

3.2 Results

The twelve statewide flow–biology relationships characterizing the responses of riffle-run fish diversity and benthic EPTr to flow alteration were statistically significant (**Table 16 (A and B) and Table 17 (A and B)**), supporting previously documented findings that any human-induced flow alterations can negatively impact aquatic biology (McManamay et al., 2013). In addition, the responses of fish and benthos to all six flow metrics were found to be similar in magnitude and direction. **For each 10% decrease in flow, there is an average decrease of 18.2 ± 5.3% in the riffle-run fish guild diversity and 22.8 ± 4.1% in Benthic EPTr** (**Figure 16, 17, 18, 19, 20, and 21)**. Benthos, in general, appears to be more consistently sensitive to changes in flow than fish; benthic EPTr responses to four of the six flow metrics were greater than the responses of riffle-run fish diversity. However, the largest reductions in biological condition were seen in the fish response to summer ecodeficits. With each 10% increase in summer ecodeficit, riffle-run fish diversity is predicted to decrease by 27.6%. Benthic EPTr was found to be most responsive to spring ecodeficits. With each 10% increase in spring ecodeficit, Benthic EPTr is predicted to decrease by 26.6%.

Table 16. Statewide quantile regression models (Y = A + BX) relating ecodeficit (X) to biological responses (Y) for riffle-run fish guild diversity (the smaller number of sites for the Reduction in Average Annual 30-Day Minimum Flow flow-biology relationships is due to only including sites with reductions in flow)

(A) Non-scaled relationship (i.e., raw data)

Flow Metric	No. of Sites	Intercept (A)			Slope (B)		
		Value	Standard Error	*p*-value	Value	Standard Error	*p*-value
Annual Ecodeficit	649	1.41	0.035	<0.001	-0.020	0.006	<0.001
Winter Ecodeficit	649	1.40	0.035	<0.001	-0.019	0.006	<0.001
Spring Ecodeficit	649	1.42	0.034	<0.001	-0.024	0.006	<0.001
Summer Ecodeficit	649	1.48	0.028	<0.001	-0.041	0.007	<0.001
Fall Ecodeficit	649	1.47	0.032	<0.001	-0.031	0.007	<0.001
Reduction in Average Annual 30-Day Minimum Flow	361	1.30	0.057	<0.001	-0.021	0.006	<0.001

(B) Relationship scaled to 100% y-axis intercept

Flow Metric	No. of Sites	Intercept (A)			Slope (B)		
		Value	Standard Error	*p*-value	Value	Standard Error	*p*-value
Annual Ecodeficit	649	100	2.580	<0.001	-1.429	0.429	<0.001
Winter Ecodeficit	649	100	2.383	<0.001	-1.353	0.530	0.011
Spring Ecodeficit	649	100	2.365	<0.001	-1.653	0.332	<0.001
Summer Ecodeficit	649	100	1.797	<0.001	-2.761	0.469	<0.001
Fall Ecodeficit	649	100	2.326	<0.001	-2.093	0.444	<0.001
Reduction in Average Annual 30-Day Minimum Flow	361	100	4.434	<0.001	-1.606	0.459	<0.001

Table 17. Statewide quantile regression models (Y = A + BX) relating ecodeficit (X) to biological responses (Y) for benthic EPTr (the smaller number of sites for the Reduction in Average Annual 30-Day Minimum Flow flow-biology relationships is due to only including sites with reductions in flow)

(A) Non-scaled relationship (i.e., raw data)

Flow Metric	No. of Sites	Intercept (A)			Slope (B)		
		Value	Standard Error	*p*-value	Value	Standard Error	*p*-value
Annual Ecodeficit	1227	38.47	0.850	<0.001	-0.902	0.149	<0.001
Winter Ecodeficit	1227	38.55	0.790	<0.001	-0.935	0.129	<0.001
Spring Ecodeficit	1227	38.59	0.775	<0.001	-1.025	0.118	<0.001
Summer Ecodeficit	1227	38.47	0.772	<0.001	-0.936	0.099	<0.001
Fall Ecodeficit	1227	39.83	0.689	<0.001	-0.932	0.066	<0.001
Reduction in Average Annual 30-Day Minimum Flow	764	32.26	0.811	<0.001	-0.474	0.049	<0.001

(B) Relationship scaled to 100% y-axis intercept

Flow Metric	No. of Sites	Intercept (A)			Slope (B)		
		Value	Standard Error	*p*-value	Value	Standard Error	*p*-value
Annual Ecodeficit	1227	100	2.210	<0.001	-2.344	0.387	<0.001
Winter Ecodeficit	1227	100	2.050	<0.001	-2.427	0.334	<0.001
Spring Ecodeficit	1227	100	2.009	<0.001	-2.657	0.307	<0.001
Summer Ecodeficit	1227	100	2.005	<0.001	-2.433	0.257	<0.001
Fall Ecodeficit	1227	100	1.730	<0.001	-2.341	0.166	<0.001
Reduction in Average Annual 30-Day Minimum Flow	764	100	2.713	<0.001	-1.469	0.153	<0.001

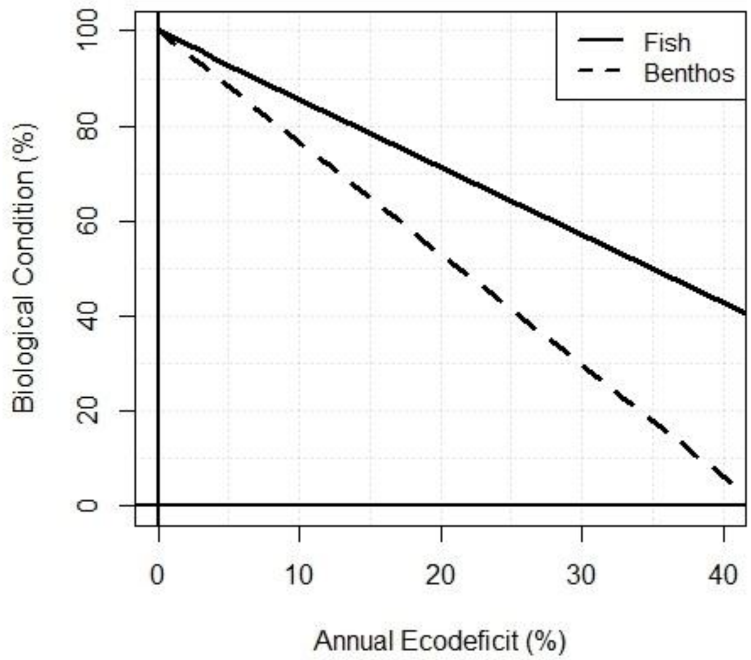


Figure 16. Responses of riffle-run fish guild diversity and benthic EPTr to annual ecodeficit (fish and benthic biological condition on y-axis are scaled to 100%)

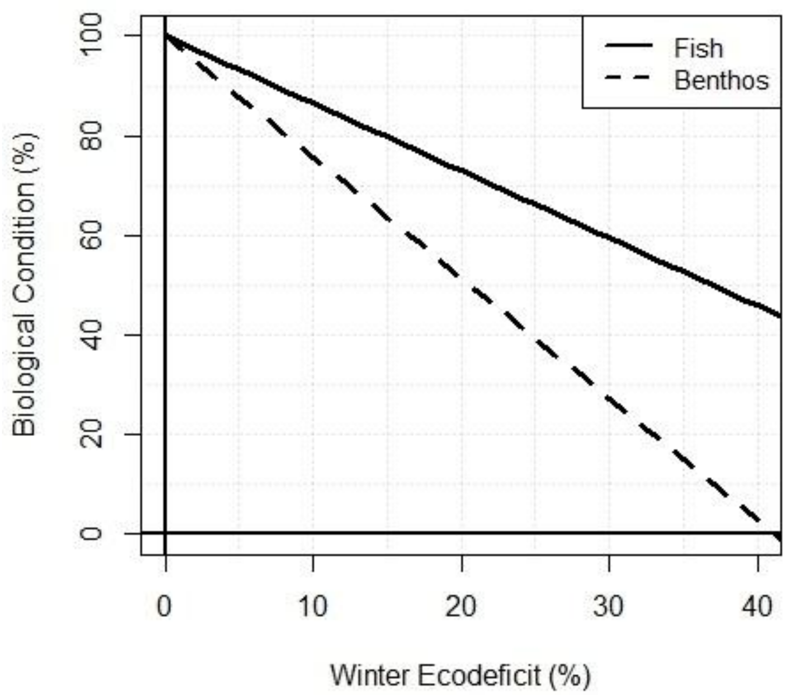


Figure 17. Responses of riffle-run fish guild diversity and benthic EPTr to winter ecodeficit (fish and benthic biological condition on y-axis are scaled to 100%)

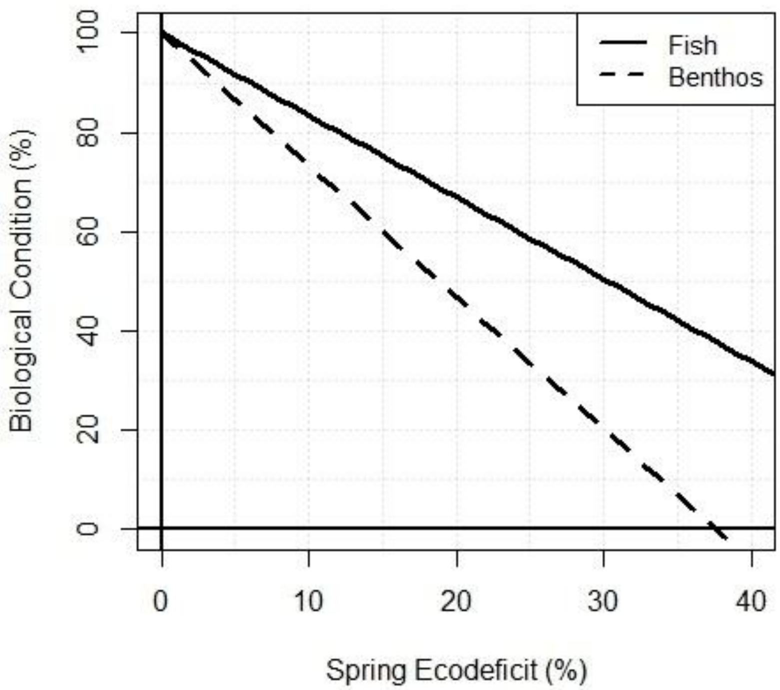


Figure 18. Responses of riffle-run fish guild diversity and benthic EPTr to spring ecodeficit (fish and benthic biological condition on y-axis are scaled to 100%)

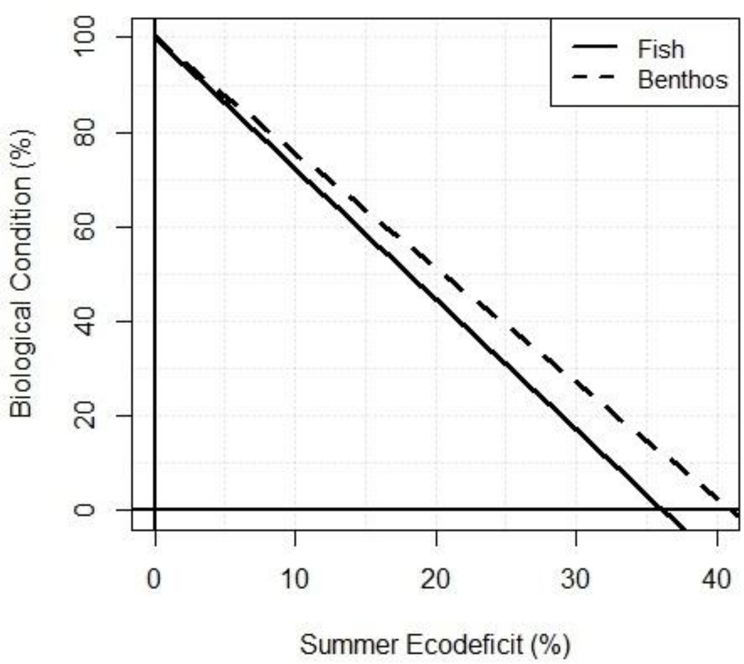


Figure 19. Responses of riffle-run fish guild diversity and benthic EPTr to summer ecodeficit (fish and benthic responses on y-axis are scaled to 100%)

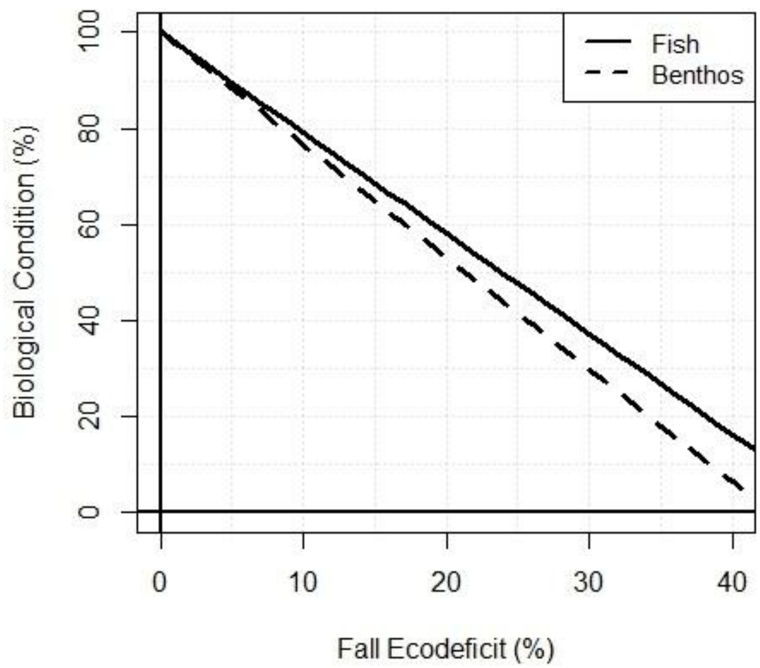


Figure 20. Responses of riffle-run fish guild diversity and benthic EPTr to fall ecodeficit (fish and benthic biological condition on y-axis are scaled to 100%)

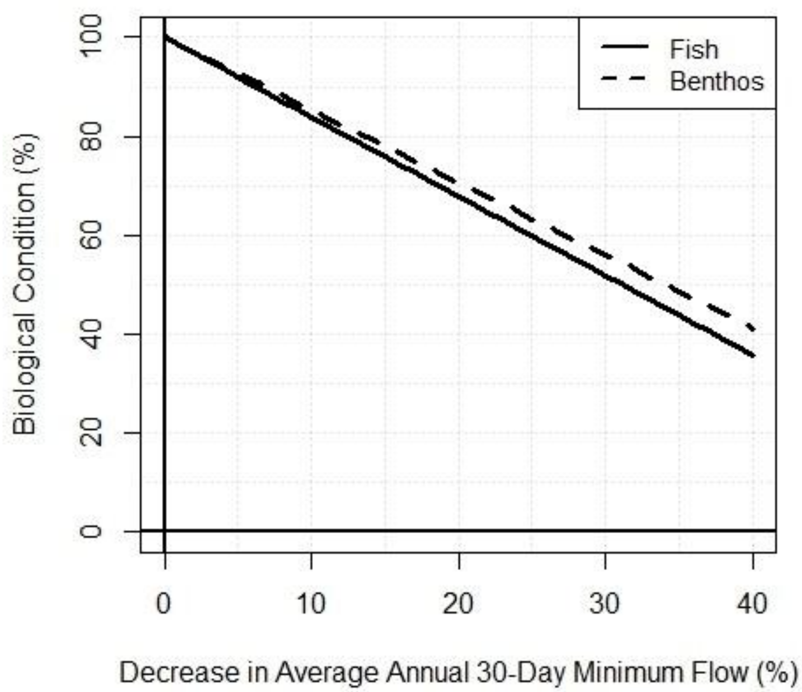


Figure 21. Responses of riffle-run fish guild diversity and benthic EPTr to decreases in annual average 30-day minimum flow (fish and benthic biological condition on y-axis are scaled to 100%)

3.3 Conclusions

In summary, through a comprehensive, iterative, step-wise evaluation approach a scientifically defendable method was developed to characterize the responses of riffle-run fish diversity and benthic EPTr to flow alteration. This method includes the use of (1) six flow metrics which are amenable to management and address magnitude, timing, and duration components of flow (annual and seasonal ecodeficits, reductions in average annual 30-day minimum flows), and (2) linear 80th percentile flow–biology relationships developed at the statewide level using non-normalized biological data. Application of this approach produced 12 statistically significant flow–biology relationships that could support the determination of ecological flows in NC; both benthos and fish showed negative responses to flow alteration. The responses of benthic EPTr to reductions in flow were consistent and generally greater than that of riffle-run fish diversity. However, the riffle-run guild showed the greatest reductions in biological condition in response to summer ecodeficits. The relative consistency of sedentary benthic macroinvertebrates to flow alterations and the higher sensitivity of fish that rely on riffle-run habitats to summer ecodeficits highlights the need for water managers to consider ecological flows in a seasonal context.

4. ECOLOGICAL FLOW FRAMEWORK

4.1 Proposed Ecological Flow Framework

Having selected ecodeficits and reductions in the annual average 30-day minimum flow as the most indicative and management-relevant flow parameters and the diversity of the riffle-run fish guild and benthic EPTr as the best indicators of biological condition, it was necessary to design a strategy for relating these parameters and indicators to determine when ecosystem integrity would be threatened by flow alterations. Within the bounds of our data and for all 12 flow–biology relationships, any measurable ecodeficit or decrease in flow produces some measurable decline in biological condition. The responses are linear with no obvious precipitous change in biology associated with a certain amount of flow alteration. In addition, it is not possible to identify a flow alteration threshold beyond which the biological condition noticeably degrades. Therefore, it was not possible to identify upper or lower biology-based thresholds of flow alteration from the relationships.

As humans increasingly use more water, flows will continue to be altered to support their enterprises. Therefore, a strategy is needed for determining which rivers and streams can tolerate more alteration. Two strategies were considered. First, a distributed impacts strategy encourages society to get its water from the rivers and streams in the best ecological condition, so that all rivers and streams move toward a medium level of biological alteration which will deteriorate over time. Second, a working rivers strategy encourages society to meet its water needs mainly from rivers and streams that are already showing more biological alteration (Connecticut DEP, 2009). The working rivers strategy was selected because it is the only one that can maintain some rivers and streams in good enough condition for the most sensitive species and to serve as biological benchmarks for understanding aquatic ecosystems.

A number of studies in the literature indicate that species losses in relatively small percentages produce significant reductions in ecosystem resilience (e.g., Rockström et al., 2009). Acknowledging that all flow alterations appear to cause a decline in fish and benthic biological condition, human society needs and will continue to need water for its enterprises, relatively small biological condition reductions can be problematic for ecosystem resilience, and a working rivers strategy is preferable, the following Ecological Flow Framework is proposed for translating the fish and benthic flow–biology relationships into ecologically based flow management.

The proposed Ecological Flow Framework consists of Ecological Flow Categories and Biological Response Thresholds. The Ecological Flow Category for a given river, stream, gage or modeled node is **the amount of biological alteration associated with the current level of flow alteration**. Characterization of the current degree of flow alteration is based on a comparison of flows under potential natural vegetation cover (PNV) and current conditions, as described in Section 3. This flow alteration is then converted to a measure of biological alteration based on the respective flow–biology relationships. The Biological Response Threshold associated with each Ecological Flow Threshold refers to the change in biological condition that indicates a future flow condition that may be beyond an acceptable level of change and warrants further investigation. **Table 18** provides the proposed values for the Ecological Flow Categories and the corresponding Biological Response Thresholds. Note that the more pristine the flow condition is at the place in question, the smaller the amount of biological alteration required to flag the alteration for further evaluation, which is in keeping with the working rivers strategy.

Table 18. Ecological Flow Categories and Biological Response Thresholds for the proposed Ecological Flow Category Framework to support the determination of ecological flows in NC

Ecological Flow Category– (%)	Biological Response Threshold
100–80 (Excellent)	5%
80–60 (Good)	10%
60–35 (Fair)	15%
<35 (Poor)	Alternative flow standard

The Biological Response Thresholds are based on the average range of biological condition represented by each NCDENR benthic site condition class (**Table 19**). Through an evaluation of EPTr by site condition class at each of 1,227 benthic monitoring stations, it was found that each site condition class averaged a 19% change in biological condition. Using this 19% change in biology as the foundation of the Biological Response Thresholds, a half-class change in site condition (i.e., 10%) was deemed a tolerable level of change in the fish or benthic biological condition for a river in good Ecological Flow condition. In keeping with the working rivers approach, a more stringent or protective Biological Response Threshold (i.e., one-quarter class change – 5%) was seen as an acceptable level of change in the biological condition of fish or benthos for a river in an excellent Ecological Flow condition. For rivers with a fair Ecological Flow condition, a three-quarter change in site condition class– 15%) was assigned as an acceptable level of change in the fish or benthic biological condition. For rivers with a poor Ecological Flow condition, an alternative flow standard is recommended (e.g., 7Q10 or September monthly median flow).

Table 19. NCDENR Benthic Site Condition Classes and range of benthic EPTr biological condition within each class

Benthic Site Condition Classes	Benthic Condition (EPTr normalized by 80th percentile value in each Omernik Level III Ecoregion)	Change in Benthic EPTr Condition within Site Condition Class
Excellent	> 77%	23%
Good	56–76%	20%
Good-Fair	34–55%	21%
Fair	16–33%	17%
Poor	< 16%	16%
MEAN		**19%**

4.2 Example Application of the Ecological Flow Framework

This section provides two examples of the application of the Ecological Flow Framework to benthic and fish flow–biology relationships, using the responses of benthic EPTr and riffle-run fish diversity to summer ecodeficit as the example scenarios. **Figure 22** and **Figure 23** display the application of the Ecological Flow Categories and associated Biological Response thresholds to the benthic and fish relationships, respectively.

To determine the amount of flow alteration that can occur within a stream without triggering a caution flag with respect to change in benthic biological condition (i.e., exceedance of the Biological Response Threshold), the current Ecological Flow Category of the stream has to be determined. For example, a stream under evaluation may currently have a summer ecodeficit of 6% compared to the unaltered baseline. Using the summer ecodeficit–benthic EPTr flow–biology equation ((Y=100-2.4X), this 6% ecodeficit is calculated to be associated with a benthic biological condition of 85.4% (Figure 22) and puts the stream in the excellent Ecological Flow Category (Table 18). The Biological Response Threshold for streams in this Category is 5%. Therefore, an acceptable amount of change in the stream benthic condition would be from 85.4% to 80.4%. Based on the same the summer ecodeficit–benthic EPTr flow–biology equation, this 80.4% biological condition is associated with a summer ecodeficit of 8%. Therefore, a future condition that increases summer ecodeficit by more than 2% (8– 6%) would trigger a caution flag.

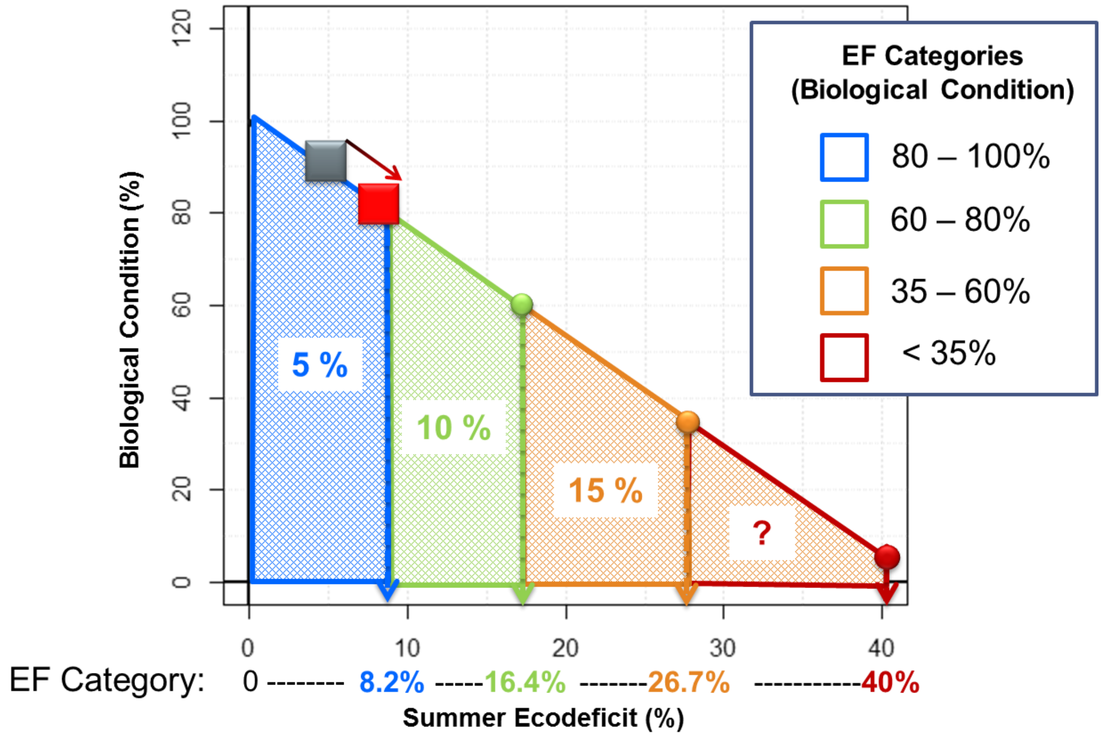


Figure 22. Ecological Flow Framework applied to summer ecodeficit–benthic EPTr flow-biology relationship

As a second example, the same procedure is applied to a riffle-run fish guild flow–biology relationship. In the stream in this example, an 8% summer ecodeficit is estimated relative to the unaltered condition (Figure 23). Using the summer ecodeficit - riffle-run fish guild flow–biology equation, a current biological condition of 78.2% is determined and the stream is in the Good Ecological Flow Category (Table 18). A stream within this Category has a Biological Response Threshold of 10%, thereby allowing the condition of riffle-run fish to be reduced from 78.2% to 68.2%. This 68.2% biological condition corresponds to a summer ecodeficit of 11.7%. Therefore, flow alterations from a proposed future scenario resulting in an additional summer ecodeficit of 3.7% (11.7–8%) would not raise a caution flag.

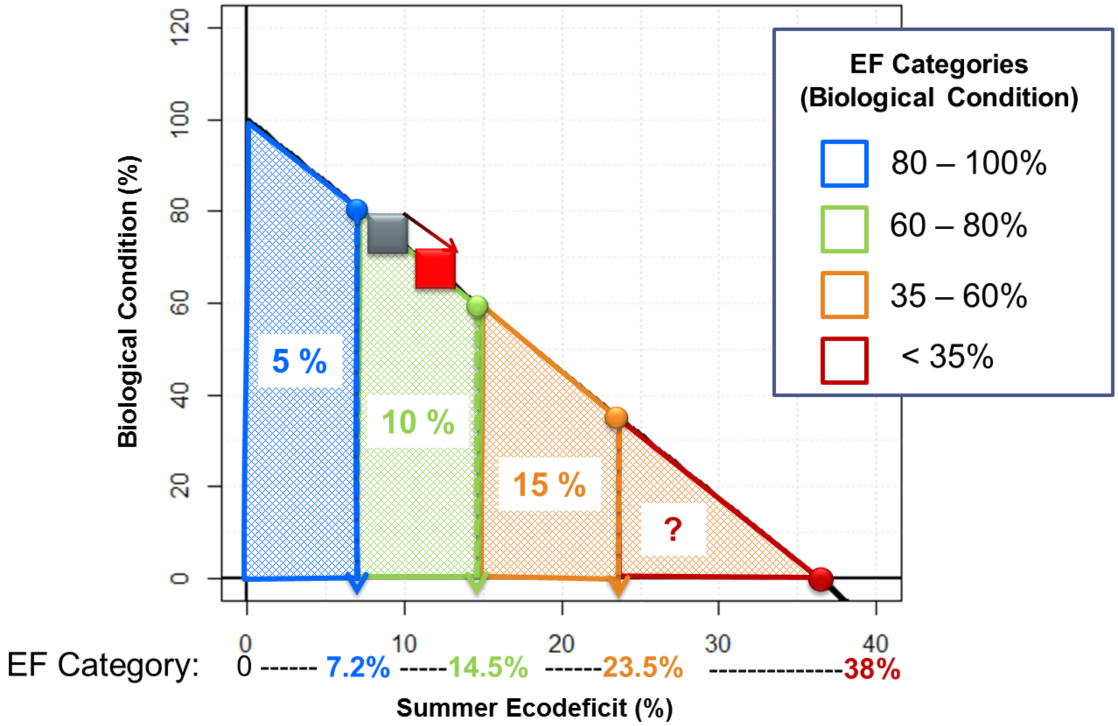


Figure 23. Ecological Flow Framework applied to summer ecodeficit–riffle-run fish guild diversity flow–biology relationship

4.3 Implementing the Ecological Flow Framework in the Upper Neuse River

This next section provides an example of the application of the Ecological Flow Framework in two NC stream/river segments and translation of flow metrics into volumes of flow. Two sites in the Neuse River Basin–Eno River State Park and the Neuse River at Goldsboro–were selected to serve as case studies. The two sites differ in drainage area, and both have hydrologic data based on flow records from the nearest adjacent node modeled by HydroLogics Inc. Operational Analysis and Simulation of Integrated Systems (OASIS™) reservoir modeling tool. The Eno River State Park watershed is approximately 270 km^2 and the Neuse River at Goldsboro is approximately 2,000 km^2 (**Figure 24**). In this example, WaterFALL® was used to model the current and acceptable levels (i.e., hydrologic alteration associated with Biological Response Threshold) of hydrologic alteration, and OASIS™ was used to project future levels of hydrologic alteration. The process of combining these two models for water management purposes is described below.

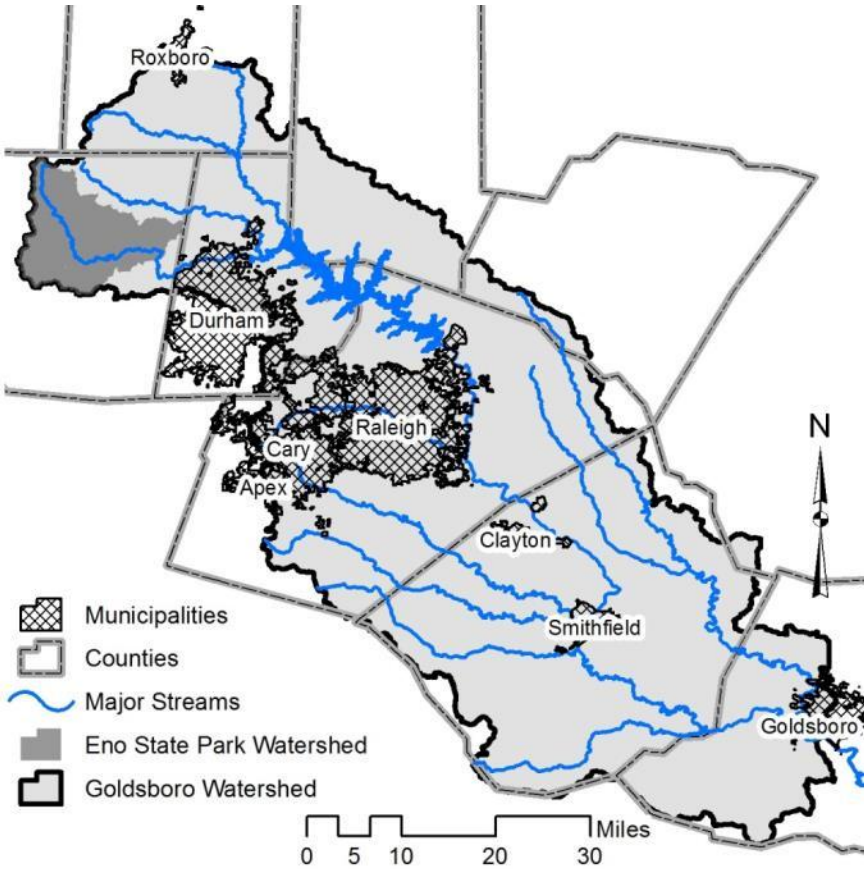


Figure 24. The Eno River State Park and the Neuse at Goldsboro catchments used in the example applications of the Ecological Flow Framework

First, the unaltered and current flow conditions modeled by WaterFALL® are used to calculate the current summer ecodeficits. The Eno River State Park stream segment has a summer ecodeficit of 5.3% and the Neuse River at Goldsboro has a current summer ecodeficit of 17.1%. (**Tables 20, 21, 22, and 23**).

Next, the summer ecodeficit flow–biology relationships (Figure 19) are used to estimate the respective biologic condition for fish and benthos at each location. Based on the summer ecodeficit relationships, Eno River State Park stream segment has a current biologic condition of 87.1% for benthos and 85.4% for fish (Tables 20 and 21). The Neuse River at Goldsboro has a biologic condition of 58.4% for benthos and 52.8% for fish (Tables 22 and 23). With respected to Ecological Flow Category, Eno River State Park stream segment is in the Excellent Ecological Flow Category for both benthos and fish and given a Biologic Response Threshold of 5% (Table 18). Using the respective flow–biology equations, this 5% change in biological condition corresponds to summer ecodeficits of 7.8% and 7.1% for benthos and fish, respectively. Therefore, an additional summer ecodeficit of 2.5% in the Eno River State Park stream segment would be tolerable for benthos and 1.8% would be acceptable for fish. In contrast, the current summer ecodeficits of the Neuse River at Goldsboro classify the river segment in the Fair Ecological Flow Category for both fish and benthos. This Ecological Flow Category corresponds to a Biologic Response Threshold of 15% (Table 18), and additional summer ecodeficits of 6.2% (23 – 17.1%) and 5.9% (22.5 – 17.1%) for benthos and fish, respectively.

The OASIS™ model simulates current and future hydrologic conditions out to 2050. The OASIS™ 2050 projections therefore provide an opportunity to evaluate whether future water uses may threaten ecological integrity and flows (i.e., exceed the Biological Response Thresholds for individual rivers). Based on the 2050 projections, the OASIS™ model estimates additional summer ecodeficits of 5.4% for the Eno River State Park stream segment and 3.1% for the Neuse River at Goldsboro (Table 20, 21, 22, and 23). Applying the flow–biology equations for benthos and fish, the biologic condition associated the projected 2050 summer ecodeficits in the Eno River State Park stream segment is 70.6% for fish and 74.1% for benthos. For the Neuse River at Goldsboro, the projected biologic conditions are 44.1% and 50.8%, respectively. In an evaluation of the projected changes in biological condition, the Eno River State Park stream segment is projected to exceed the Biologic Response Thresholds for both fish and benthos (**Figure 25 (A and B) and Figure 26**). In contrast, the already highly altered Neuse River at Goldsboro is not projected to exceed the Biologic Response Thresholds established for the Fair Ecological Flow Category. This example highlights the working river approach of the proposed Ecological Flow Framework; rivers that are in excellent hydrologic condition are awarded a higher level of protection to ensure these high quality waters are preserved, whereas rivers that are already hydrologically altered are allowed to undergo further alteration.

Table 20. Current (WaterFALL®) and OASIS™ 2050 projected hydrologic condition and associated benthic EPTr biological condition at the Eno River State Park stream segment (MGD = Million Gallons per Day)

Flow Metric	No. of Days	Current EcoDeficit (WaterFALL®)		OASIS™ Projected 2050 EcoDeficit		Benthic EPTr Biologic Condition (%)		
		%	MGD	%	MGD	Current	2050	Difference
Annual Ecodeficit	365	2.5%	1.32	3.8%	2.00	94.1	85.2	9.0
Winter Ecodeficit	121	2.5%	2.04	4.2%	3.35	93.9	83.8	10.1
Spring Ecodeficit	91	3.7%	1.62	2.8%	1.36	90.2	82.6	7.5
Summer Ecodeficit	92	5.3%	0.88	5.4%	1.09	87.1	74.1	13.0
Fall Ecodeficit	61	3.5%	1.13	3.0%	0.51	91.8	84.7	7.0
Reduction in Annual Average 30-Day Minimum Flow	30	1.7%	0.04	13.1%	0.95	97.5	78.3	19.2

Table 21. Current (WaterFALL®) and OASIS™ 2050 projected hydrologic condition and associated benthic EPTr in the Neuse River at Goldsboro (MGD = Million Gallons per Day, "NA" indicates an increase in the annual average 30-day minimum flow)

Flow Metric	No. of Days	Current EcoDeficit (WaterFALL®)		OASIS™ Projected 2050 EcoDeficit		Benthic EPTr Biologic Condition (%)		
		%	MGD	%	MGD	Current	2050	Difference
Annual Ecodeficit	365	12.8%	203.75	1.7%	25.45	69.9	65.8	4.1
Winter Ecodeficit	121	12.8%	277.82	2.5%	57.35	69.0	62.9	6.2
Spring Ecodeficit	91	12.5%	141.74	2.5%	32.14	66.8	60.2	6.6
Summer Ecodeficit	92	17.1%	174.54	3.1%	27.35	58.4	50.8	7.6
Fall Ecodeficit	61	21.1%	219.76	4.1%	22.87	50.5	40.9	9.6
Reduction in Annual Average 30-Day Minimum Flow	30	NA	NA	NA	NA	NA	NA	NA

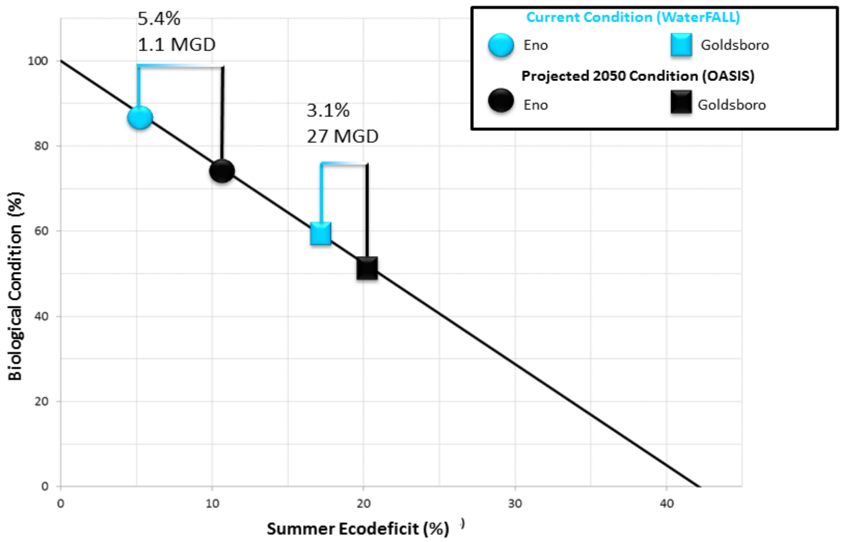
Table 22. Current (WaterFALL®) and OASIS™ 2050 projected hydrologic condition and associated riffle-run fish guild diversity in the Eno River State Park stream segment (MGD = Million Gallons per Day)

Flow Metric	No. of Days	Current EcoDeficit (WaterFALL®)		OASIS™ Projected 2050 EcoDeficit		Riffle-run Fish Guild Diversity Biological Condition (%)		
		%	MGD	%	MGD	Current	2050	Difference
Annual Ecodeficit	365	2.5%	1.32	3.8%	2.00	96.4	91.0	5.5
Winter Ecodeficit	121	2.5%	2.04	4.2%	3.35	96.6	91.0	5.7
Spring Ecodeficit	91	3.7%	1.62	2.8%	1.36	93.9	89.2	4.7
Summer Ecodeficit	92	5.3%	0.88	5.4%	1.09	85.4	70.6	14.8
Fall Ecodeficit	61	3.5%	1.13	3.0%	0.51	92.7	86.4	6.3
Reduction in Annual Average 30-Day Minimum Flow	30	1.7%	0.04	13.1%	0.95	97.3	76.3	21.0

Table 23. Current (WaterFALL®) and OASIS™ 2050 projected hydrologic condition and associated riffle-run fish guild diversity in the Neuse River at Goldsboro (MGD = Million Gallons per Day, "NA" indicates an increase in the annual average 30-day minimum flow)

Flow Metric	No. of Days	Current EcoDeficit (WaterFALL®)		OASIS™ Projected 2050 EcoDeficit		Riffle-run Fish Guild Diversity Biological Condition (%)		
		%	MGD	%	MGD	Current	2050	Difference
Annual Ecodeficit	365	12.8%	203.75	1.7%	25.45	81.7	79.2	2.5
Winter Ecodeficit	121	12.8%	277.82	2.5%	57.35	82.7	79.3	3.4
Spring Ecodeficit	91	12.5%	141.74	2.5%	32.14	79.3	75.3	4.1
Summer Ecodeficit	92	17.1%	174.54	3.1%	27.35	52.8	44.1	8.7
Fall Ecodeficit	61	21.1%	219.76	4.1%	22.87	55.9	47.4	8.6
Reduction in Annual Average 30-Day Minimum Flow	30	NA	NA	NA	NA	NA	NA	NA

(A)



(B)

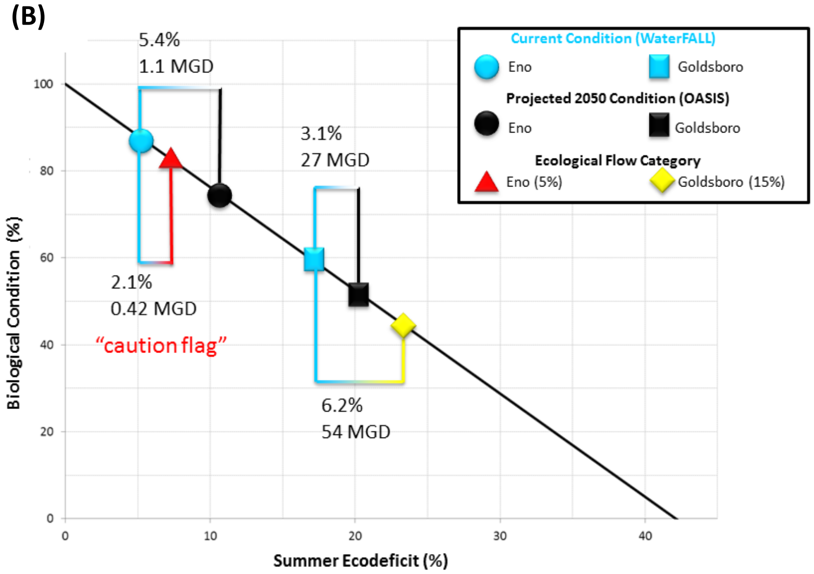


Figure 25 (A and B). Step-by-step application of Ecological Flow Framework (using the summer ecodeficit – benthic EPTr flow-biology relationship) applied to stream segment at Eno River State Park and the Neuse River at Goldsboro.

(A) Step 1 - Plot current and projected summer ecodeficits and associated biological condition, using the regression equation (see Table 17 for equation slope and intercept values) and WaterFALL and OASIS flow records, respectively. These % ecodeficits can be translated into MGD by relating the areas under the curves during the defined time period (i.e., July–September) at the Eno River State Park and Neuse River at Goldsboro locations (see Gao et al. (2009) for additional information). (B) Step 2 - Based on the Ecological Flow Category of each stream or river segment, determine the corresponding Biological Response Threshold and calculate the associated summer ecodeficit using the regression equation. In this example, the stream segment at the Eno River State Park and the Neuse River at Goldsboro are in the Excellent and Fair Ecological Flow categories which correspond to 5% and 15% change in biological condition Biological Response Thresholds, respectively. A "caution flag" is triggered for the stream segment at the Eno River State Park because the 2050 projected summer ecodeficit may cause a change in biological condition that is greater than 5%.

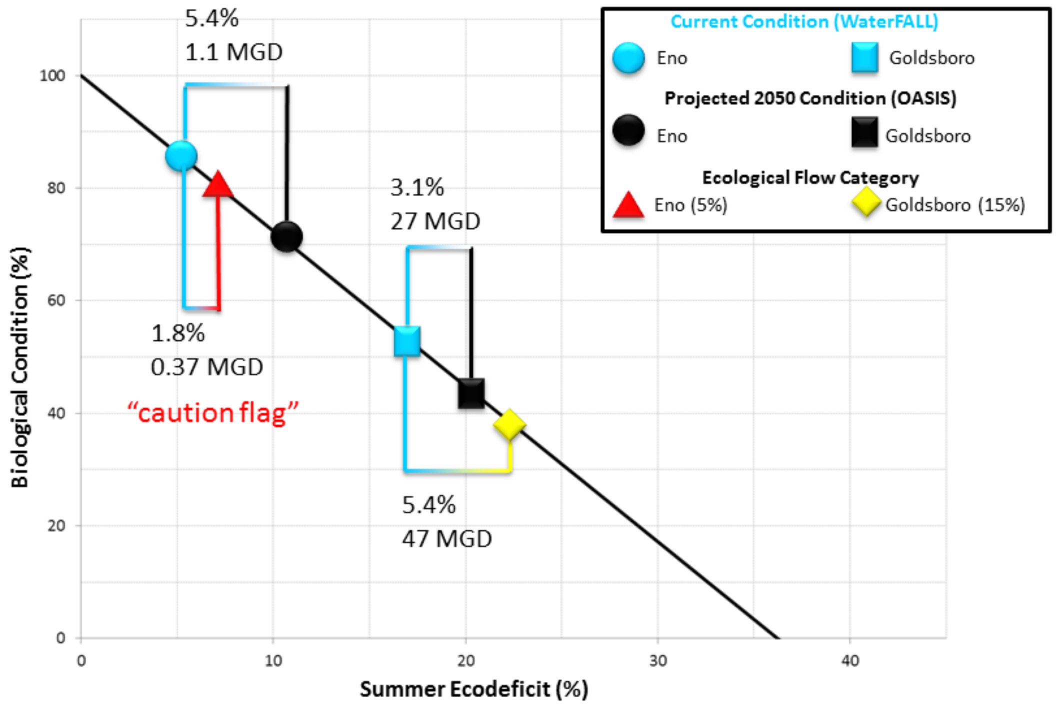


Figure 26. Ecological Flow Framework (using the summer ecodeficit – riffle-run fish guild diversity flow-biology relationship) applied to stream segment at the Eno River State Park and the Neuse River at Goldsboro (MGD = Millions of Gallons per Day). The values in this figure are determined using the same step-by-step approach described in Figure 25 (A and B).

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