

## ABSTRACT

**ROBINSON, JASON LESLEY.** Discontinuities in fish assemblages and efficacy of thermal restoration in Toxaway River, NC (Under the direction of Peter S. Rand)

Biogeographical studies in the Toxaway and Horsepasture Rivers, (Transylvania County, NC) were initiated along with the creation of a state park in the area. This region is noted for extreme topographic relief, high annual rainfall totals and many rare and endemic plants and animals. The study area encompasses a portion of the Blue Ridge Escarpment and the associated Brevard Fault Zone. These geologic features are important factors in determining the distribution of stream habitats and organisms. I hypothesize that major waterfalls and cascade complexes have acted to discourage invasion and colonization by fishes from downstream. This hypothesis is supported by longitudinal fish assemblage patterns in study streams. Fish species richness in Toxaway River increased from 4 to 23 between Lake Toxaway and Lake Jocassee, a distance of 10 river kilometers. No species replacement was observed in the study area, but additions of up to 7 species were observed in assemblages below specific waterfalls.

A second component of the research examines the efficacy of a rapid bioassessment procedure in detecting thermal and biological changes associated with a reservoir mitigation project in an upstream site on Toxaway River. The mitigation project began in the winter of 2000 with the installation of a hypolimnetic siphon to augment the overflow release with cooler water during summer months. I record a greater summer temperature difference on Toxaway River below Lake Toxaway (comparison of pre- vs. post-manipulation), relative to control sites. The cooling effect of the mitigation decreases in magnitude with increasing distance from the dam. I offer a

critique of the mitigation effort based on a mismatch between the longitudinal extent of thermal restoration and the distribution of target organisms that were expected to benefit from the manipulation.. Secondly, I highlight some of the important limitations in drawing inferences from data collected using a rapid bioassessment approach. I conclude with suggestions on how to improve future research efforts in this area. I emphasize the importance of implementing process-oriented field work that could provide insights into mechanisms responsible for biological changes downstream from reservoir ecosystems.

**Discontinuities in fish assemblages and efficacy of thermal restoration in Toxaway River, NC.**

by  
**JASON LESLEY ROBINSON**

A thesis submitted to the Graduate Faculty of  
North Carolina State University  
in partial fulfillment of the  
requirements for the Degree of  
Master of Science

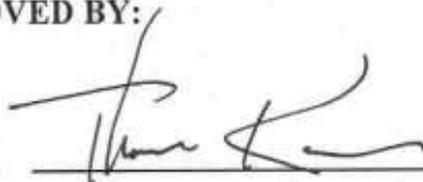
**ZOOLOGY**

Raleigh

2002

**APPROVED BY:**

  
\_\_\_\_\_

  
\_\_\_\_\_

  
\_\_\_\_\_

Chair of Advisory Committee

## **Autobiography**

I was born in the Southland, twenty- some odd years ago. To date, my biggest claim to fame is a five minute television spot on the Mr. Bill Cartoon Show when I was about seven years old. I was always more interested in playing in the creek than anything in school, and once I learned how to catch spring lizards I quickly became an avid bait fisherman. Trout frequently conspired to keep me out of attendance in high school, once I obtained a driver's license. I am more of a dry- fly fisherman since my sophisticated refinement in higher education, but I still like to play hooky and turn over rocks for a few hours. In fact, now it's my job.

In college and graduate school at NC State University, I have remained fascinated by questions about why objects (usually but not always animals, plants and geological formations) are in the places that we observe them. It's possible that this is nothing more than academic self-deceit; it may be that I am merely concerned with predicting the occurrence of speckled trout, ramp patches and good mushroom hunting. At any rate, these questions have 'matured' to involve the geologic history and watershed development in the Southern Appalachians.

A tantalizing sidetrack of this pursuit is the application of the question "Why is this object in this location?" to human activities and philosophy. I am related to people who have been dead for thousands of years, but for the past 250 years most of my ancestors have died in Madison and Yancey counties, NC, and in East Tennessee. As of yet I am unable to determine if my particular family are habitat specialists, or if they have

merely been able (thus far) to defend their territory and culture from invading Yankee and Preppie hordes. I am comfortable with both explanations.

My working philosophy about life, likely a direct result of graduate student starvation wages, is that it probably tastes good, fried in a little bacon grease. I enjoy hunting plants, tasty insects, fungus, fish and furry critters, but more than finding I enjoy eating such treasures. I daresay Abraham Lincoln would have stayed his dastardly cowardice had he known that an ultimate consequence of the destruction of agricultural society, (in the true sense of the word society), would be Mechanization, an effective disenfranchisement and separation of the people from the land. Thus, I forage as an Act of Resistance to Yankee Occupation; I find no more effective tool than procuring my own nourishment (whenever possible), rather than that provided by the state- sponsored machine.

In the future, I will continue playing backwards redneck inbred hillbilly music, using bad grammar and identifying obscure insects found in streams, seeps and other aquatic habitats. I will consider going down and registering to vote, if only Jimmy Martin will run for president. However, my chief desires are to understand plant and animal population and community distributions in the Southern Appalachians, with respect to historical (anthropic), evolutionary, geology and climatic processes. That, and to someday find a shred of self- respect and ambition amidst these ruined ashes of a man.

## **Acknowledgments**

This work would have been impossible to complete without major funding from the North Carolina Natural Heritage Program, including tuition and money for hiring an assistant. Additionally, I received financial assistance and support from Highlands Biological Station. Some support is better than money: A special thanks is in order to Doug Crisp, who keeps that place running, and isn't scared to spend a whole afternoon rigging up some god-awful contraption to shock fish and graduate students. The kitchen facilities provided at the station insured that we stayed out of trouble (preparing dinner becomes the evening entertainment in Highlands, in the absence of everything else). I can truly say that I have enjoyed some of the finer moments of my life there, watching the rain and thick fog swirl outside, around the lake, from my window in Illges Cottage.

This project required a good deal of backcountry sampling, and I was fortunate enough to have two tough and dedicated field assistants for both summers. Mike Trussell proved invaluable, and our first field assault could not have been completed without his dry sardonic wit and oxen-like work ethic. His valiant efforts were trumped only by Erica Sandberg, a Smith College undergraduate who worked for free, never ceasing to ask questions about everything we did and saw, contributing her cheery and optimistic outlook to each day. Numerous others contributed blood, sweat and tears, including Mr. Brad Lamphere, to whom I probably owe a couple of days work; David Rowland and Mathias Lee, who were ever willing to come and electroshock or hook and line sample for a few days; and many others who quickly learned that the work began AFTER the four mile hike and didn't show up too many more times.

Duke Power biologist Hugh Barwick provided valuable data and contacts. Jim Borawa of the North Carolina Wildlife Resources Commission was instrumental in providing feedback, data, equipment and morale boosting before, during and since the project. The NC Wildlife Federation graciously awarded me two scholarships that greatly enhanced my field efforts. Nat Greene Fly Fishers also assisted with scholarship funding. Dr Gary Grossman, University of Georgia, provided valuable temperature data for Coweeta Creek, NC. Dr Sam Mozley, NC State Zoology Department, was very helpful in getting me started on the long, tedious and frightfully enjoyable path of aquatic insect taxonomy. Dr John Morse of Clemson University helped me immensely with additional taxonomic references and occasional verifications along the way. Dr Pete Rand, my committee chairman, has been a model of patience and persistence as I have struggled with the ordeal of thesis preparation. Finally, Mom and Dad have been the best resource of all, and hopefully I can finally get all my waders, nets and bottles out of their house now.

## **Table of Contents**

<b>List of Figures</b>	<b>vii</b>
<b>List of Tables</b>	<b>viii</b>
<b>Chapter 1 DISCONTINUITIES IN FISH ASSEMBLAGES IN TOXAWAY RIVER, NC</b>	<b>1</b>
<b>Chapter 2 EFFICACY OF THERMAL RESTORATION IN TOXAWAY RIVER, NC</b>	<b>27</b>
<b>Literature Cited</b>	<b>45</b>

## **List of Figures**

<b>Chapter 1</b>	<b>Page</b>
Figure 1.1 Major drainage basins in North Carolina.	19
Figure 1.2 Fish sampling sites in 2000- 2001.	19
Figure 1.3 Proportions of habitat types (riffle, pool and cascade) in each section of Toxaway River Gorge	20
Figure 1.4 Fish species richness and corresponding elevation (m above sea level) for all sample sites	20
Figure 1.5 Fish species richness, sites grouped by stream order	24
Figure 1.6 Hierarchical cluster dendrogram depicting sampling sites.	24
Figure 1.7 Map of major waterfalls and fish assemblages in study area.	25
Figure 1.8 Hierarchical cluster dendrogram depicting 3 <sup>rd</sup> order sites, with introduced species excluded.	26
<b>Chapter 2</b>	
Figure 2.1 Study area, Transylvania County, NC.	40
Figure 2.2 Hourly stream temperatures 2/7/00 to 8/7/01.	40
Figure 2.3 Summer stream temperature differences (2001- 2000).	41
Figure 2.4 Annual stream temperature differences (2001- 2000).	41
Figure 2.5 Annual difference in mean macroinvertebrate family richness for site pairs (Toxaway – Horsepasture).	42
Figure 2.6 Annual difference in mean macroinvertebrate density for site pairs (Toxaway – Horsepasture).	42
Figure 2.7 2001 Annual proportional differences in six macroinvertebrate trophic guilds for site pairs (Toxaway- Horsepasture).	43

## **List of Tables**

### **Chapter 1**

**Page**

Table 1.1 Comprehensive list of all fish sampling sites. 21

Table 1.2 Fish species collected at each site. 22

Table 1.3 Total stream lengths measured in Toxaway River  
and Bearwallow Creek 23

### **Chapter 2**

Table 2.1 Mean 2000 and 2001 macroinvertebrate family richness values  
for Toxaway and Horsepasture sites. 43

Table 2.2 Mean 2000 and 2001 macroinvertebrate densities for Toxaway  
and Horsepasture sites. 43

Table 2.3 Regression estimates of bootstrap slopes. 44

# DISCONTINUITIES IN FISH ASSEMBLAGES IN TOXAWAY RIVER, NC

## Introduction

A main goal of ecology is to identify the factors that work to determine the species composition of ecological communities. Conceptual models, suggesting a hierarchical suite of ‘filters’ or ‘screens’, have been developed by several workers to describe this process in aquatic ecosystems (Smith and Powell, 1971; Tonn, 1990). Generally, these schemes involve a description of biotic and abiotic processes at broad geographic and temporal scales (e.g., continental drift, macroevolution), and proceed to more localized phenomena (e.g., community interactions, habitat preferences). In rivers and streams, many of these factors may work simultaneously at multiple spatial and temporal scales (Matthews, 1998).

The River Continuum Concept (hereafter referred to as RCC) was formulated to help explain community assemblage patterns in lotic systems, by drawing a connection between physical properties and biological resources, from headwaters to larger rivers (Vannote et al. 1980; Minshall et al. 1985). One would thus expect to see community composition change along this longitudinal gradient, reflecting changes in the physical and biological properties (represented as a function of stream order, *sensu* Horton, 1945; Strahler, 1957). Specifically, one would find limits to each species distribution along this gradient based on the relative success of a species given the physical and biological template to which they are exposed along the gradient. Based on what we know about how habitat changes from headwaters downstream, the RCC would predict that

assemblage changes should arise primarily by gradual species replacement along the elevation gradient.

Conversely, assemblage patterns observed along the gradient may be better explained by limitations to dispersal. Barriers to upstream movement are common in streams, particular those of low order that drain areas of high topographic relief. In this particular situation, we would expect to see low variation in species richness within segments of stream bounded by barriers, contrasted with high variation in richness between segments that are separated by obstructions (discontinuities). The dominant mechanism giving rise to community diversity in this case would be species addition, as one progresses downstream.

Here I confront these two concepts with fish community data collected from several high elevation streams in western North Carolina. I evaluate changes in fish species richness, both by replacement and addition over all elevations and stream orders. I then discuss the degree of support for an alternative hypothesis that explains changes in fish species richness as a function of obstacles to dispersal (waterfall barriers).

## **Study Area**

The study area is in a headwater portion of the Savannah River basin, in southwestern Transylvania County, North Carolina. The Savannah basin drains, from north to south, across the main shelf of the east-west oriented Blue Ridge Escarpment. This is the smallest major watershed in North Carolina, with a total area of 391 km<sup>2</sup> (Figure 1.1). The escarpment, an uplifted fault zone, is a remnant of geologic activity of

the Tertiary Period (White, 1950). This portion of the Blue Ridge front is characterized by high topographic relief and high annual precipitation, often greater than 200 cm (Highlands Biological Station, Highlands, NC, unpublished data). These features have created a landscape shaped by erosional processes, including stream capture and head-cutting (White, 1950). Above the escarpment, streams drain broad, level valleys. Along the escarpment, streams quickly descend in spectacular cascades and waterfalls. These portions of the stream valleys are deeply incised, narrow canyons, with exposed rock faces.

Several forest types are found in the study area, but forest vegetation in the area can be generally described as mixed mesophytic (Cooper, 1963). Stream valleys are dominated by *Tsuga canadensis*, *Liriodendron tulipifera*, *Pinus strobus*, *Acer rubrum*, and *Rhododendron* spp. Rocky, exposed ridges are associated with *Kalmia latifolia*, *Pinus rigida*, *Pinus strobus*, *Pinus virginiana*, and *Vaccinium* spp. Endemic plant and tree species include *Shortia galacifolia* and *Juglans cinerea*. Waterfalls and rock faces are refugia for tropical ferns and rare spray-cliff plant communities (Cooper, 1963).

Many areas in the region show obvious signs of significant natural (floods, landslide) and anthropogenic (logging, cultivation) disturbances. At one time there were several agricultural communities in the lower elevations of the study area, but these were gone before the impoundment of Lake Jocassee, which is the southern boundary of the study area. Sedimentation sources are mostly upstream of the study area, but also include the existing access roads within the game lands, the state park and National Forest.

Waterways in the study area range from small seeps and intermittent streams to 4<sup>th</sup> order riverine habitats. The section of Toxaway River studied extends from the

tailwater released from the impoundment at Lake Toxaway to Lake Jocassee, a distance of approximately 10 river kilometers. Below Lake Toxaway, Toxaway River remains 3<sup>rd</sup> order until joined by Toxaway Creek (4<sup>th</sup> order) at Lake Jocassee (Figure 1.2). Discharge above the confluence with Bearwallow Creek averaged 1.32 m<sup>3</sup>/sec during collection periods in April, May and June 2000 (Robinson and Rand, unpublished data). These measurements represent a summer minimum base flow. Horsepasture River is impounded several times upstream of the study area. We focused sampling along 6.5 km of stream, between NC 281 and Lake Jocassee. This section of the Horsepasture River was similar to our selected section of Toxaway River with respect to elevation and stream order classification. Base discharge was somewhat higher in the Toxaway, with a mean of 2.13 m<sup>3</sup>/sec during 2000, measured at the Upper Whitewater Road bridge (two km upstream of the study area).

Six instream temperature loggers (Hobo-Temp Stowaway, Onset Computer Corp.) were deployed in both river systems during February, 2000 to September, 2001. Annual minimum and maximum temperatures in Toxaway River were 0.1° C (Feb 2000, measured at several sites) and 31° C (July 2000, Toxaway Falls), respectively. Summer maximum temperatures decline with increasing distance downstream from Lake Toxaway, reflecting the effect of the impoundment on the thermal regime of the river and cool water input from tributaries (North Carolina Wildlife Resources Commission, unpublished data; Robinson and Rand, unpublished data). Horsepasture River annual minimum and maximum temperatures at Lake Jocassee (HP\_LK, see Table 1.1) were 0.1 C (Feb 2000) and 26.1 C (July 2000).

Bearwallow Creek is not impounded along its length, but has experienced heavy sediment inputs due to construction and development in the upper portion of the watershed (Duke Power, unpublished data). During April- June of 2000 and 2001, Bearwallow Creek, near the confluence with Toxaway River, averaged 0.50 m<sup>3</sup>/sec (site BW\_AH, Table 1.1). Bearwallow Creek was consistently several degrees cooler than reaches in the Toxaway River upstream of the confluence, throughout the spring, summer and fall (Robinson and Rand, unpublished data).

All three major streams flow southward, leaving the escarpment at about 900 m, creating a series of popular waterfalls on each stream at this elevation (Toxaway, Windy and Upper Bearwallow Falls). A second series of major waterfalls is found around 450 m on Bearwallow (Lower Bearwallow Falls) and Toxaway River (Chub Line Falls (not shown) and Eel- Line Falls).

## **Management History**

Numerous roads cross the watersheds, emphasizing the intensity of logging and recreational use occurring in the 20<sup>th</sup> century. At one time there were farming communities in the area, but most people had moved away by the 1940's, when Duke Power began purchasing large tracts of land for timber and hydropower (Barton, 1998). During the 1970s, Duke Power constructed several hydroelectric facilities in the region (Lakes Jocassee and Keowee in SC, and Bad Creek Pumped Storage Station in Jackson County, NC).

In the late 1990s, Duke Power began liquidating land holdings in the area, first offering the parcels to state and federal governments. In 1999, North Carolina purchased

approximately 40 km<sup>2</sup> for the construction of a state park (29 km<sup>2</sup>) and an adjoining game land (11 km<sup>2</sup>). This study is part of a larger effort by the NC Natural Heritage Program to survey and document rare species and habitats in the newly acquired public lands.

## **Site Selection**

Sites were chosen along the elevation gradient of the study area; major streams were sampled several times along the continuum. With three exceptions (sites TOX\_FALL, BW\_64, BW\_Mlark, see Table 1.1), all sites were located on Toxaway Game Land (NCWRC), Nantahala National Forest (US Forest Service) or Gorges State Park (NC Division of Parks and Recreation). Many private landowners provided access permission and information.

I utilized maps and local contacts to locate old logging roads and trails. Access points frequently determined the location of sampling sites in several streams. For instance, small tributaries were sampled within 100 meters of the confluence with the adjoining larger stream. Every attempt was made to sample fish assemblages above and below large waterfalls and cascade complexes.

Initial observations suggested that Toxaway River morphology changed considerably in the study area, along the descent down the Blue Ridge Escarpment. Using the 1:24000 7.5' USGS quadrangle (Reid, NC), I identified three distinct segments of Toxaway River where valley widths and/or stream slope markedly changed. In the field, these features were conveniently associated with popular waterfalls. Figure 1.2 identifies the location of the three identified segments.

## **Habitat Sampling**

During the summer of 2001, I censused habitat types within the three Toxaway River segments and Bearwallow Creek above and below Lower Bearwallow Falls, (from the confluence with Toxaway River to confluence with Indian Camp Branch (Figure 1.2). All habitat measurements were collected under base flow discharge conditions. The total length of stream sampled varied with weather and site accessibility. Habitat units were classified as pool, riffle or cascades. Cascades were units with falling water, while pools were units with low surface velocity and/or channel obstructions. Riffle habitats were units with unobstructed channels and visible surface velocities, but no falling water.

Habitat measurements included average width, depth and substrate measurements. Substrate percent coverage was estimated at 100 points along transects at sampling sites, according to a modified Wentworth scale (Gorman and Karr, 1978). I recognized 10 different types of benthic substrate (silt, sand, gravel, cobble, rock, clay, leaf litter, large woody debris, aquatic vegetation and overhanging rocks).

## **Fish Community Sampling**

Fish sampling methods varied with accessibility and available personnel. Although backpack electrofishing units were used most frequently, minnow traps, hook and line and snorkel observations also contributed additional important information regarding species distributions. Most sites were sampled at least twice during 2000 and 2001, and several more accessible sites (TOX\_AH, BW\_XXX) were sampled more than twice to better document temporal variability. Results from each survey method (snorkel

counts, hook and line and electrofishing) suggested markedly different species abundances.

The disparity among results produced by different sampling methods weakens quantitative comparisons of abundance between sites. Following this logic, I pooled all species presence/absence data at each site, over all sampling times and methods. This method may eliminate information about temporal variability at a site, which has been reported as significant in some systems (Horwitz, 1978; Grossman and Ratajczak, 1998). However, repeated sampling at my sites showed that species richness varied little between years (Robinson and Rand, unpublished data), suggesting that the combination of sampling methods fairly represents the fish assemblage. In several instances, no one sampling methodology reported all fish species known to occur at a site, reflecting the importance of the integrated sampling technique for describing assemblage composition.

## Data Analysis

Each site was scored for the presence/absence of all species collected at all study sites. This site-X-species matrix was constructed to calculate Euclidean distance (ED) between sample sites. Euclidean distance is a measure of the dissimilarity between two sites ( $j$  and  $k$ ), based on  $P$  species, expressed as

$$ED_{jk} = \sqrt{\sum_{i=1}^P (x_{ij} - x_{ik})^2},$$

where  $x_{ij}$  is the presence/absence of species  $i$  at site  $j$ , and  $x_{ik}$  denotes the presence/absence of species  $i$  at site  $k$ .

To illustrate the similarities between groups of sites, I employed Ward's minimum variance linkage, a general-purpose linkage procedure that minimizes distortions in the multivariate space (McCune and Medford 1999). Ward's method is a hierarchical procedure that agglomerates sites into clusters based on the variance between groups. Groups are formed such that the squared Euclidean Distance between sites (or clusters of sites), weighted by the number of sites in the cluster, is minimized (McGarigal et al 2000).

An initial clustering procedure used all sampling sites and the entire pool of all possible species encountered. To assess the validity of the clusters of sites in Toxaway and Horsepasture Rivers, I re-clustered those sites after removing introduced species (see Table 1.2). Menhinick et al (1991) and Lee et al (1980) detail the distributions of native and introduced fish species in major drainages in North Carolina and North America, respectively. This helped to determine whether observed patterns in fish assemblages are biased by introductions of species; hence, clusters without introduced species should be similar to clusters which include introduced species. Changes in the clustering of Toxaway and Horsepasture sites after removal of introduced species would suggest that the initial clusters are heavily influenced by the introduction and natural species richness is quite different.

## **Results**

Twenty-seven sites were sampled in the Bearwallow, Horsepasture and Toxaway watersheds in 2000 and 2001 (Figure 1.2). Sample sites ranged in elevation from 360-

940 m, and from 1<sup>st</sup>- 4<sup>th</sup> stream order (Table 1.1). Twenty-three species of fish were collected (Table 1.2).

A total of 180 habitat units (pool, riffle, cascade) in Toxaway River (total 4.5 km) and 149 units in Bearwallow Creek (total 2.0 km) were measured in habitat surveys (Table 1.3). The Lower Gorge section of Toxaway contained a larger proportion of riffle habitats than the Middle and Upper Gorge sections, but a similar average slope to the Middle Gorge. Alternatively, the Upper Gorge section had a steeper slope and larger proportion of cascades and pools than the lower 2 sections (Figure 1.4), but very few riffle areas. In some sections of the Upper Gorge, lengths of the river (<100 m) flowed through V-shaped fissures in huge bedrock slabs, often less than 0.5 m wide.

Species richness varied considerably among sites, from 0-17 species. Fish species richness increased with decreasing elevation (Figure 1.3) and increasing stream order (Figure 1.4). Six sites did not appear to contain fish populations, including 4 sites on Bear Creek. These sites were excluded from analysis, but the location of one site (BC, Site 1 in Table 1.1) is identified in Figure 1.4.

A general pattern of species addition is shown for each stream, and species in the upper portions of Horsepasture and Toxaway Rivers are present in lower reaches. I did not find evidence of species replacement, where species are present in upper reaches and not present in lower reaches, with one exception. A single *Salvelinus fontinalis* was collected at Bearwallow Creek at 927 m. I collected no other individuals of this species at any other site in the study area.

## **Cluster Analysis**

Hierarchical clustering techniques produced groups of sites sharing similar species assemblages. The initial cluster analysis was conducted using all species and all sampling sites, excluding sites with no fish present. Four major site groupings were identified (Figure 1.6). The first group, labeled the “Lower Gorge” assemblage, is named for the low elevation of all 6 sites in this cluster (Figure 1.7). The group of sites generally located upstream of the Lower Gorge sites are similarly designated as “Middle Gorge”. Additionally, the subsequent clusters, “Bearwallow” and “Tributary”, are named according to dominant group membership.

A second analysis excluded the effects of introduced species in Toxaway and Horsepasture Rivers (only third order sites, n=14). The results of this analysis group the Lower Gorge sites separately from the Middle Gorge sites (Figure 1.8), preserving the structure of the initial clustering shown in Figure 1.6. Within the Middle Gorge, Horsepasture and Toxaway sites are clustered into distinct groups. In this analysis, the Middle Gorge group includes the site below Toxaway Falls (TOX\_FALL), the only third-order site placed in the Tributary assemblage in the initial analysis (Figure 1.6).

## **Assemblage Properties**

Waterfalls delineate the boundaries of distinct fish assemblage ‘zones’ within the study area. Each zone has characteristic combinations of fish species that are unique to that zone, but many species are found in more than one zone. A general pattern of increasing species richness with decreasing elevation is evident. The strongest

discontinuity is at Lower Bearwallow Falls (Figure 1.7), where fish species richness decreased from 9 species below the waterfall to 2 species above.

The Bearwallow assemblage is located above Lower Bearwallow Falls (Figure 1.7). Lower Bearwallow Falls is a 15 m waterfall located 0.3 river km above the confluence with Toxaway River. This assemblage is represented by only two species, one of which is the introduced *Salmo trutta*. The other, *Rhinichthys atratulus*, may have been introduced by anglers (Steve Chapman, Sapphire Lakes Resorts, pers. comm.). The site at Meadowlark Lane provided one exception; one *Salvelinus fontinalis* and one *Salvelinus fontinalis* X *Salmo trutta*, (a natural hybrid) were collected at 980 m. All other fish collected above Lower Bearwallow Falls were either *S. trutta* or *Rhinichthys atratulus*. We did not collect *R. atratulus* at sites above the Escarpment (BW\_Mlark, BW\_PPF, BW\_64, BW\_UBWF; Table 1.1)

The Middle Gorge fauna is a subset of the Lower Gorge; there are no species occurring in the Middle Gorge which are not also present in the Lower Gorge. The abrupt transition to the Lower Gorge fauna is accomplished by the addition of several species (specifically *Percina nigrofasciata*, *Etheostoma inscriptum* and *Noturus insignis*). This transition occurs in both Horsepasture and Toxaway Rivers and is not associated with the deletion of any species from the assemblages. Table 1.2 details the species collected at each location.

Sites in the Tributary assemblage are low order tributaries, with the exception of Toxaway River below Lake Toxaway. These sites can be generally characterized by low species richness, but there are no species common to all sites. Milksick Branch, Frozen Creek and Auger Fork all contained *Oncorhynchus mykiss*, but this species was absent

from Toxaway River at Toxaway Falls and Cobb Creek. Incidentally, the only record of *Hybopsis rubifrons* is from Cobb Creek (Table 1.2, 1.4). Toxaway River at Toxaway Falls yielded two introduced species, *Micropterus salmoides* and *M. dolomieu*.

Figure 1.6 depicts the fish assemblages (grouped by symbols) in relation to major waterfall and cascade complexes. These features were identified from the 7.5' quadrangle and verified in the field. Site-specific GPS coordinates are given in Table 1.1. It is important to note that these features are by no means the only waterfalls on the streams; in fact most waterfalls were actually series of cascades. For example, the Wintergreen Falls complex of Toxaway is composed mostly of bare rock and plunge pools, dropping more than 80 meters in about one kilometer.

## **Discussion**

The addition of fish species from headwaters to rivers is a prevalent pattern in lotic systems (Matthews, 1986). Even so, zonation, (when assemblage changes are by replacement, and not addition, of species) has often been reported in the primary literature. Zonation has been attributed to temperature and other habitat requirements, dispersal boundaries or biotic interactions (Burton and Odum, 1945; Huet, 1959; Balon and Stewart, 1983; Rahel and Hubert, 1991; Paller, 1994; Gilliam et al, 1993; Marsh-Matthews and Matthews, 2000). In this system, the escarpment provides a clear mechanism (limitation of upstream dispersal and colonization) for explaining the observed patterns within the Toxaway, Bearwallow and Horsepasture systems.

Some workers have suggested that the increased diversity of downstream habitats is a likely explanation for longitudinal patterns in stream fish assemblages (Lotrich, 1973;

Gorman and Karr, 1978; Schlosser, 1982; Rahel and Hubert, 1991). Other studies have delivered contrasting results, reporting high species richness or diversity in headwaters (Paller, 1994), or decreased habitat diversity downstream (Reyes-Gavilan et al 1996). Some have reported that changes in the physical characteristics of stream habitats associated with the entrance of tributaries are determinants of fish assemblage diversity and structure (Sheldon, 1968; Lotrich, 1973; Gorman and Karr, 1978; Meffe and Sheldon, 1988).

Although I did not explicitly measure habitat diversity in this study, the physical template is changes (quite abruptly in some intervals), along the descent from the Escarpment (Figure 1.3). The Toxaway River flows through several different geological formations in the study area (M. Carter, C. Mersch, and R. Wooten, NCGS, unpublished data). In addition, R. Wooten (unpublished data) has detailed the distribution fluvial deposits along Toxaway River from a catastrophic flood event in 1916. Thus, there are trends in landscape and stream geomorphology that could potentially create gradients in habitat availability or diversity. Such a gradient could plausibly be responsible for the patterns I have observed in fish species assemblages. This scenario (i.e. habitat preferences as determinants of fish assemblage structure, rather than dispersal limitation by barriers) is only possible if stream habitats change abruptly at the geomorphological boundaries I selected to delimit the Upper, Middle and Lower sections of the Toxaway and Horsepasture Rivers. The multiple additions to fish assemblages, with no replacement (an instance where the loss of species is accompanied by the addition of others), is strong evidence that waterfalls and cascades are acting as barriers to prevent upstream dispersal.

Longitudinal patterns of increasing species richness and species replacement have long been noted along the length of streams and rivers (Shelford, 1911; Burton and Odum, 1945). Stream order has been correlated with fish species richness (Lotrich, 1973) and habitat diversity (Gorman and Karr, 1978). The general pattern of increasing fish species richness with stream order is not universal, as some reports describe overlapping ‘zones’ of fish assemblages (Hawkes, 1975; Balon and Stewart, 1983), or the lack of a strong correlation between order and fish species richness (Evans and Noble, 1979). Whatever the correlations between stream order and other biological variables are, it obviously does not stand alone as an explanation. To be a functional classification category, ‘stream order’ must be expanded to include information including climatic regime, disturbance history, forest cover and geologic history.

The River Continuum Concept (RCC, Vannote et al, 1980; Minshall et al, 1985) predicts general patterns of species richness along measurable physical and biological gradients (using stream order as a surrogate variable):

“... the physical structure coupled with the hydrologic cycle form a templet for biological responses, and result in consistent patterns of community structure and function and organic matter loading, transport, utilization, and storage along the length of a river.” (Vannote et al 1980, p. 131)

This conceptual linkage, between stream and landscape biological processes, has provided a framework for evaluating patterns in stream ecosystems, by assigning discrete mechanisms to the faunal ‘screens’ and ‘filters’ from the classic community ecology literature (Smith and Powell, 1971; Tonn, 1990). The RCC emphasizes the influence of physical and biological gradients in determining resource availability and variability

along a hypothetical 'river continuum', represented by a gradient of increasing stream order (Statzner and Higl, 1985).

Despite debate and modification, there has been overwhelming support for the RCC as a generic framework for pristine, temperate, lotic ecosystems (Statzner and Higl, 1985). The existence of gradient(s) is an intrinsic component of a lotic ecosystem, and many longitudinal studies along the gradient (headwaters to mouth) have reported similar patterns of increasing species richness in stream fish assemblages (Shelford, 1911; Burton and Odum, 1945; Sheldon, 1968; Lotrich, 1973; Hocutt and Stauffer, 1975; Gorman and Karr, 1978; Horwitz, 1978; Schlosser, 1982; Reyes-Gavilán *et al.* 1996). Clearly, many observations fit the predictions made by the RCC, but the mechanisms responsible for these patterns appear to be many and varied.

An assumption of the RCC distribution model is that species may choose habitats according to their survival requirements, a reasonable assumption for some aquatic species (e.g., insects with a winged adult stage). Fish assemblages, however, might be expected to exhibit the effects of dispersal and colonization limitations. This is especially important in regions with high topographic relief, such as my study area. Horwitz (1978) suggested that fish species richness within a river system could be related to the accessibility of the basin to colonizers, and that species richness in headwater streams may be limited by environmental variability. Long-term studies have shown considerable temporal variation in some fish assemblages, often correlated with variation in hydrological patterns (Seegrist and Gard, 1972; Freeman *et al.*, 1988; Strange *et al.*, 1992; Grossman and Ratajczak, 1998; Fausch *et al.*, 2001). An important feature of the Toxaway River (and other Blue Ridge Escarpment systems) is that the upstream

movement of some species appears to have been limited. Massive geological features, (the Brevard Fault zone and the Blue Ridge Front), and the resulting formations in the river (waterfalls, cascades and canyons) have provided formidable barriers to colonizers. Toxaway River and other Savannah basin streams are cutting headward into the Blue Ridge front and escarpment, a process involving active stream capture (White, 1950). This may help to explain the presence of fishes above the structures I have identified as barriers, especially since these fish species are commonly shared with the adjacent river basins (French Broad, Tuckasiegee; Menhinick, 1991).

Thus, there may be mechanisms operating to shape community assemblages that are not well described by the biological 'river continuum', and relatively unaffected by temporal variation in composition (unless we imply the geologic time scale, which uplifts mountains and erodes valleys, and creates features such as the Blue Ridge Escarpment). Balon and Stewart (1983) point out that, by definition, the notion of a continuum implies the existence of a discontinuum. In freshwater stream communities, fish assemblage discontinuities (also called 'faunal breaks') have been reported in a variety of situations. Faunal discontinuities have been reported in instances where changes in landscape features are associated with changes in habitat (Balon and Stewart, 1983; Carmona et al, 1999; Evans and Noble, 1979; Hocutt and Stauffer, 1975; Rahel and Hubert, 1991) and below reservoirs (Reyes-Gavilan et al, 1996). In any case, fish assemblages which exist behind dispersal barriers may have strikingly different compositions than assemblages where barriers are non-existent. In this instance, both factors, (changes in habitat characteristics and changes in landscape- scale features), both work to influence habitats and fish assemblages downstream.

In summary, I suggest that fish assemblages in the Bearwallow, Horsepasture and Toxaway drainages are strongly influenced by the topographic features of the Blue Ridge Escarpment. Waterfalls delineate the boundaries of these discontinuous assemblages by preventing upstream movements of fish. The location of these barriers defines fish assemblage composition within a stream order. This pattern may result from the relatively youthful intrusion of the Toxway River (and Savannah River Basin as a whole) into the Blue Ridge Front (White, 1950). The escarpment has proved a formidable barrier to fish species invasion from downstream, and prevents the construction of an environment where we might observe distributional patterns associated more with resource availability and/or habitat preferences.

Figure 1.1 Major drainage basins in North Carolina. The Upper Savannah includes Chattooga, Whitewater, Thompson, Horsepasture and Toxaway Rivers; draining from Transylvania, Jackson and Macon Counties.

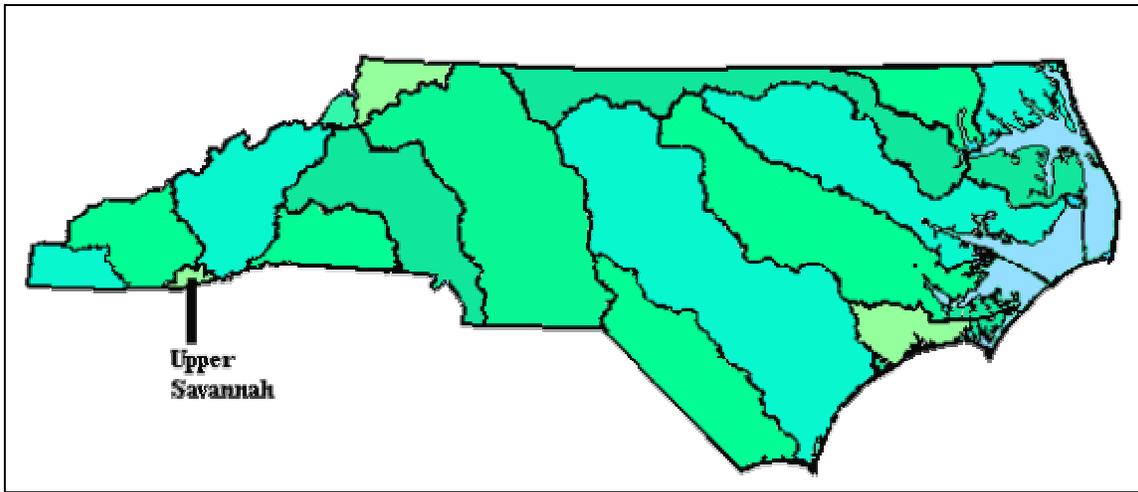


Figure 1.2 Fish sampling sites in 2000- 2001. Toxaway is divided into three sections as shown.

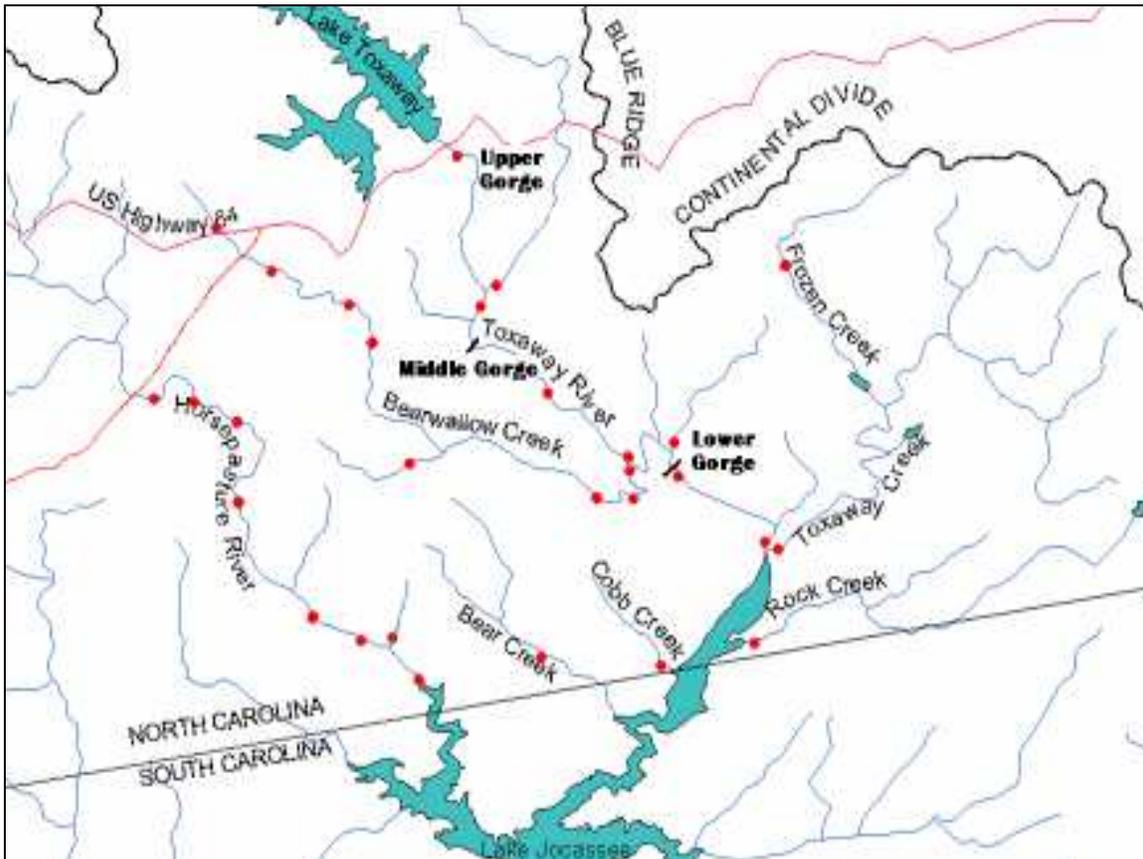


Figure 1.3 Proportions of habitat types (riffle, pool and cascade) in each section of Toxaway River Gorge.

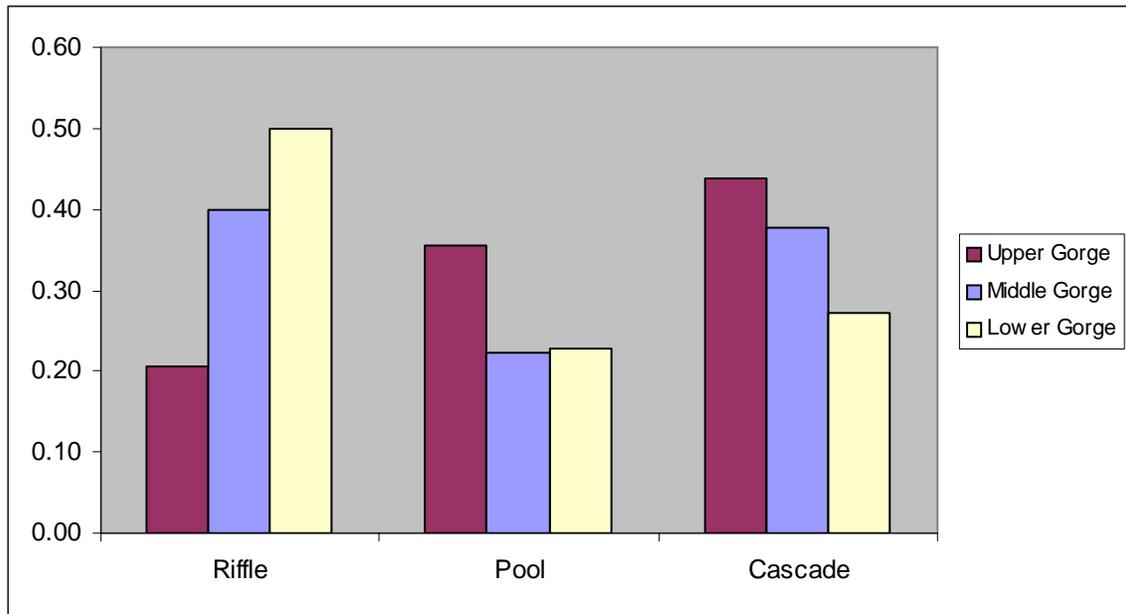


Figure 1.4 Fish species richness and corresponding elevation (meters above sea level) for all sample sites.

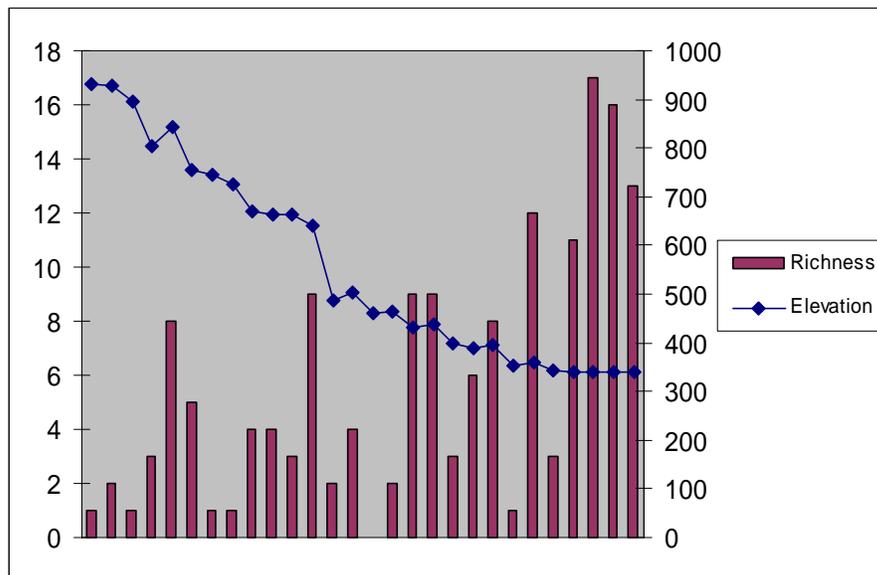


Table 1.1 Comprehensive list of all fish sampling sites. Includes, site code, descriptive name, latitude and longitude, fish species richness, elevation (meters above sea level) and stream order.

Label	Description of site location	Latitude	Longitude	Richness	Elevation	Order
BC	BEAR CREEK CAMP	35 3.607'	82 55.295'	0	475	2
AUGER_F	AUGER FORK AT TOX RIVER	35 5.054'	82 53.945'	3	396	2
BW_Camp	BEARWALLOW FIELDS, AT CAMP CROSSING	35 4.900'	82 59.401'	9	434	2
TOX_AH	TOXAWAY RIVER AT AUGER HOLE ROAD CROSSING	35 5.031'	82 54.39'	9	439	3
BW_XXX	BEARWALLOW CREEK AT AUGER HOLE ROAD	35 4.734'	82 54.685'	2	488	2
JAKE_B	JAKE'S BRANCH	35 4.89'	82 56.365'	1	725	1
MILK	MILKSICK BRANCH	35 3.581'	82 56.51'	1	354	1
FRZ_CK	FROZEN CREEK BELOW WOODEN BRIDGE	35 6.045'	82 52.797'	3	646	2
HP_WL	IRON BRIDGE ON HORSEPASTURE RIVER	35 3.706'	82 56.879'	12	354	3
BW_PPF	BEARWALLOW CREEK ABOVE PAWPAW FALLS	35 5.295'	82 56.478'	1	744	2
BW_LK	BEARWALLOW (LIME KILNS)	35 4.641'	82 54.432'	2	463	2
HP_FHT	HORSEPASTURE RIVER ABOVE FOOTHILLS TRAIL	35 3.424'	82 56.279'	16	341	3
TOX_CK	TOXAWAY CREEK ABOVE LAKE JOCASSEE	35 5.275'	82 53.119'	13	341	4
TOX_FHT	TOXAWAY RIVER ABOVE FOOTHILLS TRAIL	35 4.367'	82 53.191'	17	341	3
HP_OH	HORSEPASTURE RIVER, ABOVE OCEAN HOLE	35 3.906'	82 57.116'	8	372	3
TOX_PB	TOXAWAY RIVER BELOW PANTHER BRANCH	35 5.561'	82 55.017'	4	485	3
HP_WF	HORSEPASTURE RIVER ABOVE WINDY FALLS	35 4.601'	82 57.726'	9	640	3
HP_CS	HORSEPASTURE RIVER AT UNNAMED TRIBUTARY	35 5.251'	82 57.574'	5	756	3
TOX_IC	TOXAWAY RIVER BELOW INDIAN CREEK	35 6.264'	82 55.538'	4	655	3
IND_CK	INDIAN CREEK ABOVE TOXAWAY RIVER	35 6.343'	82 55.548'	4	671	3
TOX_FALL	TOXAWAY RIVER BELOW TOXAWAY FALLS	35 7.268'	82 55.542'	3	811	3
HP_RBF	HORSEPASTURE RIVER BELOW RAINBOW FALLS	35 5.914'	82 57.557'	8	792	3
BW_64	BEARWALLOW CREEK ABOVE US 64	35 6.750'	82 57.767'	1	933	1
BW_Mlark	BEARWALLOW CREEK AT MEADOWLARK LANE	35 6.533'	82 57.533'	2	927	1
BW_UBWF	BEARWALLOW CREEK AT UPPER BEARWALLOW FALLS	35 6.167'	82 56.600'	1	896	2
COBB_CK	COBB CREEK AT LAKE JOCASSEE	35 3.350'	82 54.017'	3	341	1
ROCK_CK	ROCK CREEK ABOVE FOOTHILLS TRAIL	35 3.567'	82 53.350'	11	341	3
TOX_EEL	TOXAWAY BELOW EEL LINE FALLS	35 4.900'	82 54.000'	6	390	3

Table 1.2 Fish species collected at each site. Site code abbreviations are explained in Table 1.3. Species codes are given below.

SITE																	
AUGER_F	BND	RBT	S														
BW_64	BT																
BW_Camp	BHC	BND	BT	NHS	RBT	S	TS	WPS									
BW_LK	BND	BT															
BW_Mlark	BT																
BW_PPF	BT																
BW_UBWF	BT																
BW_XXX	BND	BT															
COBB_CK	RBS	RFC	S														
FRZ_CK	BND	RBT	S														
JAKE_BR	BND																
TOX_CK	BBD	BHC	BT	CS	MMT	NHS	RBS	RBT	S	TQD	TS	WPS	YFS				
MILK	RBT																
ROCK_CK	BBD	BHC	LMB	MMT	RBS	RBT	REB	S	SBH	SMB	YFS						
TOX_AH	BHC	BT	NHS	S	SMB	TS	WPS										
TOX_EEL	BHC	NHS	RBS	SMB	TS	WPS											
TOX_FALL	LMB	RBS	SMB														
TOX_FHT	BBD	BHC	CS	LMB	MMT	NHS	RBS	RBT	REB	S	SBH	SMB	TQD	TS	WPS	YFS	YP
TOX_IC	BHC	NHS	RBS	SMB													
TOX_PB	BHC	NHS	SMB	TS													
HP_LK	ALE	BBD	BHC	BND	BT	CS	LMB	MMT	NHS	RBS	RBT	SBH	SMB	TQD	WPS	YFS	
HP_OH	BHC	CS	NHS	RBS	REB	SBH	TQD	WPS									
HP_RBF	BHC	BT	CS	MS	RBT	SMB	WPS										
HP_TRIB	BHC	CS	MS	SMB	WPS												
HP_WF	BHC	CS	LND	MS	RBT	REB	SMB	WPS	YFS								
HP_WL	BHC	CS	NHS	RBS	REB	SBH	SMB	TQD	TS	WPS	YFS						
IND_CK	BHC	NHS	RBT	SMB													

**Species List for Table 1.2**

*Alosa aestivalis* (Blueback Herring), **ALE**  
*Campostoma anomalum* (Central Stoneroller), **CS**  
*Cottus bairdi* (Mottled Sculpin), **S**  
*Etheostoma inscriptum* (Turquoise Darter), **TQD**  
*Hybopsis rubifrons* (Rosyface Chub), **RFC**  
*Hypentelium nigricans* (Northern Hogsucker), **NHS**  
*Ictalurus brunneus* (Snail Bullhead), **SBH**  
*Lepomis auritus* (Redbreast Sunfish), **RBS**  
*Micropterus coosae* (Redeye Bass), **REB**  
*Micropterus dolomieu* (Smallmouth Bass), **SMB**  
*Micropterus salmoides* (Largemouth Bass), **LMB**  
*Nocomis leptocephalus* (Bluehead Chub), **BHC**  
*Notropis coccogenesis* (Warpaint Shiner), **WPS**  
*Notropis leucodius* (Tennessee Shiner), **TS**  
*Notropis lutipinnis* (Yellowfin Shiner), **YFS**  
*Notropis spectrunculus* (Mirror Shiner), **MS**  
*Noturus insignis* (Margined Madtom), **MMT**  
*Oncorhynchus mykiss* (Rainbow Trout), **RBT**  
*Perca flavescens* (Yellow Perch), **YP**  
*Percina nigrofasciata* (Blackbanded Darter), **BBD**  
*Rhinichthys atrulatus* (Blacknose Dace), **BND**  
*Rhinichthys cataractae* (Longnose Dace), **LND**  
*Salmo trutta* (Brown Trout), **BT**  
*Salvelinus fontinalis* (Brook Trout), **BKT**  
*Salvelinus fontinalis* X *Salmo trutta* (Tiger Trout, hybrid), **TT**

Table 1.3 Total stream lengths measured in Toxaway River and Bearwallow Creek. # Units denotes the total number of units (riffle, pool and cascade) measured in each segment, % Segment denotes fraction of river segment measured. % Slope is average slope for each section, as determined from USGS 1:24000 (7.5' series) quadrangle.

Segment	Kilometers	# Units	% Segment	Ave Width	Slope (%)
Lower Gorge	0.69	22	31.5	12.0	2.2
Middle Gorge	2.23	85	50.4	10.5	3.6
Upper Gorge	1.61	73	49.9	7.6	9.5
Bearwallow	2.02	149	20.5	8.6	5.9

Figure 1.5 Fish species richness, sites grouped by stream order. Only one fourth order stream exists in study area (Toxaway Creek).

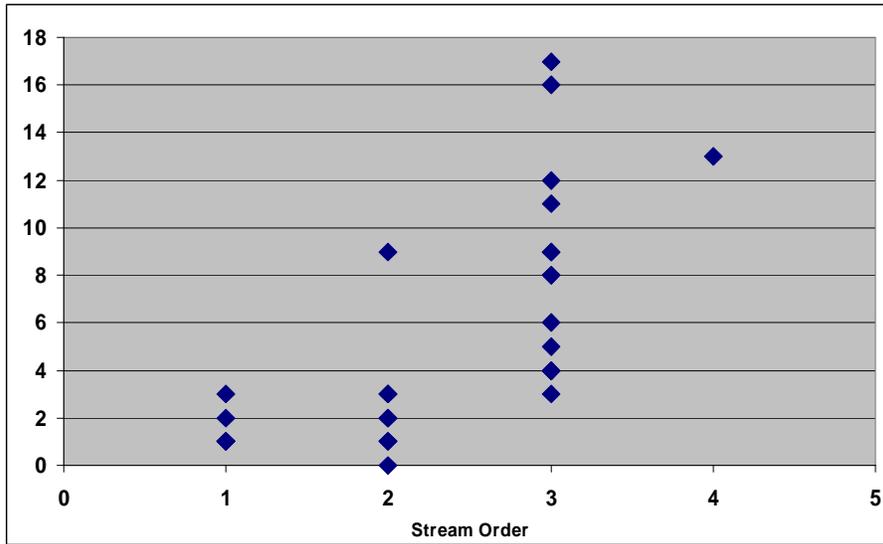


Figure 1.6 Hierarchical cluster dendrogram depicting sampling sites. Site codes correspond with those in Table 1.3 and Table 1.4.

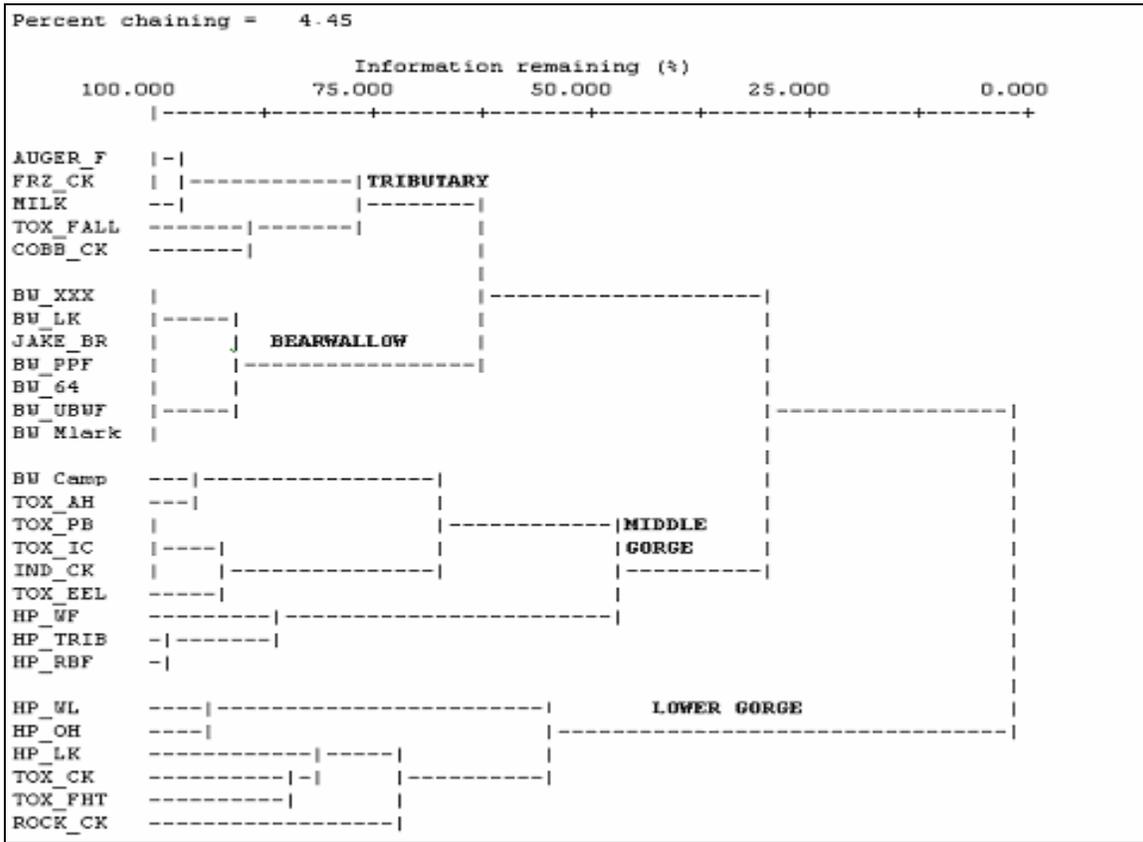


Figure 1.7 Map of major waterfalls in relation to fish assemblages. Assemblage clusters given from Fig 1.6 are given as symbols in legend.

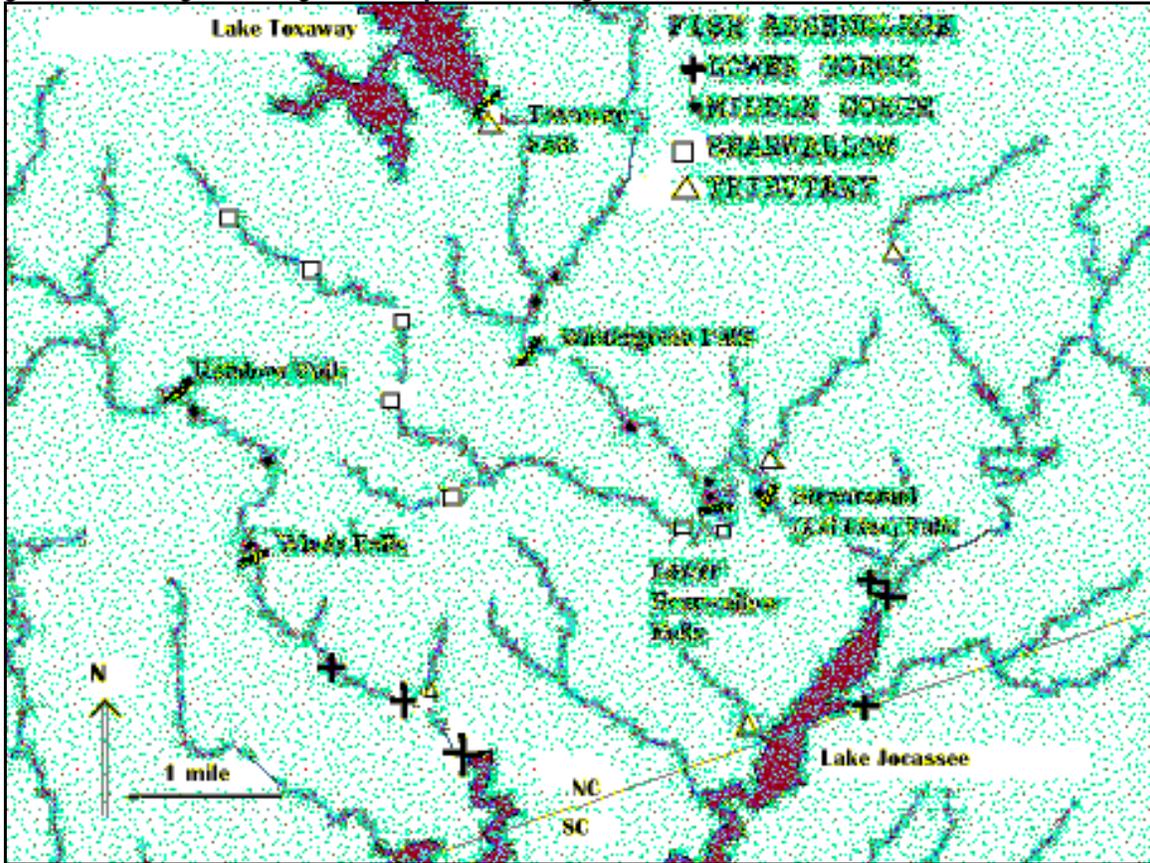
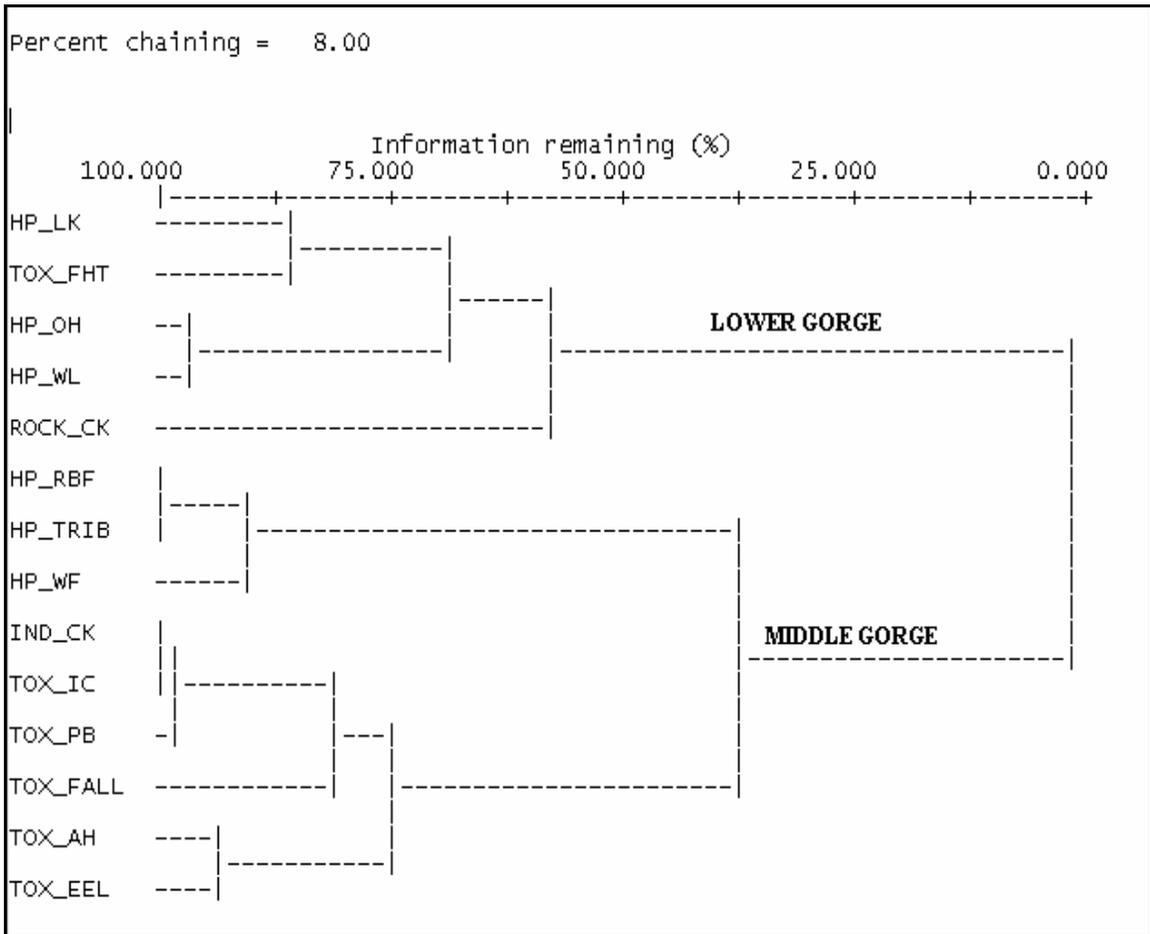


Figure 1.8 Hierarchical cluster dendrogram depicting 3<sup>rd</sup> order sites, with introduced species excluded.



# **EFFICACY OF THERMAL RESTORATION IN TOXAWAY RIVER, NC**

## **Introduction**

The proliferation of reservoirs has called attention to the ecological and hydrological effects of these structures. Analyses of these effects are often constrained by practical limitations (typically involving budget or time constraints) and technical limitations (e.g. inadequacy of experimental design, unknown variables). Additionally, most studies of this sort lack good baseline information about the stream before the construction of the reservoir.

Downstream of impoundment, streams exiting reservoirs often exhibit altered stream temperature and discharge regimes; these and other changes alter energy and nutrient transport in the stream (especially by withholding seasonal energy input and discharge fluxes, Wotton, 1995; Baxter, 1997). Temperature and discharge, among other factors, are known to influence benthic macroinvertebrate assemblage composition and distribution (Ward and Stanford, 1979; Vannote et al, 1980; Ward and Stanford, 1982). Thus, lotic systems downstream of dams are sensitive to the nature of the water discharged from the reservoir. Changes in the depth of the release, (from surface water to mostly hypolimnetic, or vice-versa), may produce measurable effects in fish and macroinvertebrate assemblages.

This chapter documents a change in thermal regimes associated with changes in the discharge system of a small Southern Appalachian reservoir. The remote and rugged nature of my study streams forced me to consider a rapid bioassessment procedure. My

objective in this research is to determine if such a rapid quantitative bioassessment could be used to evaluate the effectiveness of a thermal mitigation project at Lake Toxaway. I suggest general physical and biological properties which might more reasonably serve as potential response variables in a future study. I summarize by detailing specific aspects of this study which limit the interpretation of the results. These findings underlie the importance of background data and the formulation of mechanistic hypotheses in impact assessment type applications.

## **Background**

Lake Toxaway is a large private lake in Transylvania County, NC. US Highway 64 served as a northern border for the study area, and also overlooks a waterfall directly downstream of the Lake Toxaway dam. Lake Jocassee is the southern, downstream boundary of the study area, fed by both Toxaway and Horsepasture Rivers (Figure 2.1). The Blue Ridge here is the continental divide, separating the French Broad (Tennessee River System) from the Toxaway (Savannah River System), and the Horsepasture (Savannah) from the headwaters of the Tuckasegee River (Tennessee River System). Both the Toxaway and Horsepasture watersheds are moderately developed, with golf courses and summer homes above the 900 m contour, and both are largely forested in public land below the contour of the Blue Ridge Escarpment. Horsepasture River contains multiple small reservoirs along its length above the study area, contrasted with one large reservoir (Lake Toxaway, the site of the thermal mitigation project) on the Toxaway River. Both streams are used for irrigation and recreational purposes above the escarpment (900 m contour).

The original Lake Toxaway was destroyed in a catastrophic flood in 1916, an event which scoured the river bed, removed riparian vegetation and created enormous fluvial deposits for several miles downstream (Rick Wooten, NCGS, unpublished data). The dam was rebuilt, in approximately the same dimensions, in the 1960s (Barton, 1988). Fluvial sediment deposits and scour marks from the flood remain visible along the entire reach of the Toxaway River, to Lake Jocassee (Robinson, unpublished data).

In the 1980s and 1990s, the North Carolina Wildlife Resources Commission (NCWRC), determined that summer temperatures in the Toxaway River, approximately one mile below Lake Toxaway, were warmer than desired. The NCWRC suggested that the owners of the dam be required to mitigate (Jim Borawa, NCWRC, pers. comm.). The mitigation project, which began in the winter of 2000, required the installation of a hypolimnetic siphon at a depth of 10 meters. The siphon would supplement the surface release mechanism during the months of May- September, the period of warm surface water release (NCWRC, unpublished data).

## **Temperature Measurements and Analysis**

Before collecting any biological information, I placed temperature loggers (Hobo-Temp Tidbit Stowaway, Onset Computer Corp.) at locations in Horsepasture and Toxaway Rivers (Figure 2.1). These devices recorded hourly stream temperatures for the duration of the study. Temperature data from Horsepasture River served as a control for annual comparisons (before-after). I obtained hourly temperature measurements of another stream from Dr. Gary Grossman at the University of Georgia (Coweeta Creek, Macon County, NC, approximately 35 air-miles from the study area). These data

corresponded with the duration of my study (Grossman and Ratajczak, unpublished data). Coweeta Creek measurements were taken with identical devices and deployed similarly (i.e. inside weighted anchors or blocks). Coweeta Creek stream temperatures served as an additional control to Toxaway River, my experimental system.

I determined that the most effective comparisons of annual stream temperature would compare hourly and daily measurements for the two summers. I paired hourly and daily stream measurements for all sites where the data series included spring and summer for 2000 and 2001 (including Coweeta Creek). This required eliminating sites where recorders had been lost or destroyed; these sites are not shown in Figure 2.1. I then subtracted measurements in 2000 from measurements in 2001 (year 2 – year 1). Pairing measurements by year, day and hour in this manner enabled me to test several hypotheses about the effect of the summer hypolimnetic release schedule.

After the hypolimnetic release was installed, year 2 (2001) hourly stream temperature differences in Toxaway River should tend to be more negative than control streams (Horsepasture and Coweeta). This relationship should hold between streams (Toxaway and controls), no matter what annual differences in temperature regime might be observed within streams. Secondly, the effect of the hypolimnetic release on stream temperature would lessen with increasing distance from Lake Toxaway, implying that annual differences would be less negative at more downstream sites on Toxaway River.

## **Benthic Macroinvertebrate Collection and Analysis**

I selected three sites on Toxaway and Horsepasture Rivers, roughly paired by elevation (Figure 2.1). At each site, I collected seven replicate benthic macroinvertebrate samples with a Surber Sampler (363  $\mu\text{m}$  mesh, .09  $\text{m}^2$ , Wildco Distributors). The location of each replicate sample was randomly assigned from a plot of the study site, generally about ten meters of stream length. In the laboratory, benthic macroinvertebrates were identified to the highest possible level of taxonomic resolution using Merritt and Cummins (1996a). An exception was taken with the dipteran families Chironomidae and Tipulidae, all other dipteran larvae were only identified to order. From these data, I first calculated mean benthic macroinvertebrate density and mean family richness. I then tabulated the proportion of organisms in each of six trophic groups: predators, shredder-detritivores, filter-feeders, collector-gatherers, shredder-herbivores and scrapers. I used Merritt and Cummins (1996a) to determine trophic group membership from family data.

A resampling (bootstrapping) procedure was utilized to determine if our sample sizes were adequate for describing family richness and macroinvertebrate density at a site (Efron and Tibshirani, 1993). From each initial site-year sample I randomly selected, with replacement, two observations from the population of subsamples (surber samples) from which I had calculated the original site means. This was repeated 50 times, providing 50 means (resample size  $n=2$ ). I then repeated the resampling procedure, increasing the resample size each time by one until we exhausted the available replicate samples (usually 7 replicates, but a few samples were destroyed, reducing the resample replication by one or two samples). In this way, I resampled means and standard

deviations for both family richness and benthic density, for all sample sizes (2-7) at all sites in each year.

I then calculated the slope of a fitted linear regression of bootstrap estimates onto sample size. Line slopes falling outside of a 95% confidence interval are significantly different than zero ( $\alpha = .05$ ), and imply that the replicate sample size was inadequate for describing the variable of interest. Line slopes which are not significantly different than zero suggest that sample size has no effect on the estimate of the mean and that my sample size is sufficient (Efron and Tibshirani, 1993).

I analyzed the mitigation impact by comparing the difference between sites, between years (see Stewart-Oaten et al 1986 and Stewart-Oaten et al 1992 for a discussion of site-differences). I cannot use the Before-After-Control-Impact models to analyze these data because I only have one series (the site- differences between Toxaway and Horsepasture for 2000 and 2001). Replicating the entire sampling scheme on another stream would provide a complete set of differences (Toxaway measure– Control stream measure) necessary for true replication (Hurlbert, 1984).

The rapid bioassessment is designed to measure both thermal and biological variables and identify patterns between sites that might respond to the change in temperature in Toxaway River. A necessary component of that task is then to describe the patterns in the differences between Toxaway sites (before comparing that to a set of differences of another stream, which may have fundamentally different annual and/or serial patterns of density and richness). Many series of control streams would be needed to compare the before-after difference of those streams from Toxaway to statistically detect any annual changes that might occur during the mitigation project.

## Results

Hourly stream temperatures for Toxaway River, Horsepasture River and Coweeta Creek are shown in Figure 2.2. The general seasonal patterns are similar between years, but a decrease in the summer maximum is evident for the Toxaway Falls site in July 2001 (Figure 2.3). Other sites do not exhibit such a marked difference in hourly stream temperatures between years, although a slight negative (cooler) trend is evident for 2001 (Figure 2.4). The negative trend in Toxaway River temperature differences is strongest at Toxaway Falls, intermediate at Indian Creek and least at Bearwallow Creek. Coweeta stream temperatures are consistently lower than study site temperatures, but all sites reached a winter minimum near 0 C (Figure 2.2).

Macroinvertebrate family richness measures are shown for 2000 and 2001 for three site pairs in Toxaway and Horsepasture Rivers (Table 2.1). Mean family richness decreased at both middle sites in 2001. Upper and lower pairs showed increases in mean family richness in 2001. The mean family richness site-difference changed from negative to positive in 2001 at the middle and upper pairs of Toxaway and Horsepasture sites (Figure 2.5).

Macroinvertebrate density at both upper and lower pairs was higher in 2001, while mean density decreased at both middle sites (Table 2.2). In 2001, the mean density site-difference changed from negative to positive, at the lower and upper pairs of Toxaway and Horsepasture rivers (Figure 2.6).

More than half (13 of 24, including both family richness and density measures) of all estimates of bootstrap regression slopes are significantly different than zero ( $p < .05$ , Table 2.3). In 2001, 4 of 12 family richness bootstrap slope estimates were significantly

different than zero (no 2000 slopes for this measure were significantly different from zero ( $p > .05$ , Table 2.3). I found 9 of 12 total mean density bootstrap slope estimates (both years combined) were significantly different from zero ( $p < .05$ ). The only measure sufficiently described for all sample sites was mean family richness, but this only occurred in 2000.

There were many changes in the proportions of various macroinvertebrate trophic groups between years (Figure 2.7). The site- difference of the upper pair of sites (including Toxaway Falls) shows a small increase in predators in Toxaway and a decrease in shredder- herbivores in Horsepasture River. The middle and lower site differences are more complex, with many of the differences changing sign between years (Figure 2.7).

## **Discussion**

Determining the effect of environmental ‘impacts’ on natural systems has been an active area of research, aided by a growing interest (public and private) in mitigation and restoration projects (Beyers, 1998). Statistical analyses used in these types of problems often have assumptions which are violated (e.g. independence of samples). The fundamental problem is that there is usually no replication for large-scale disturbances such as toxic spills or catastrophic fires (Bernstein and Zalinski, 1983; Hurlbert, 1984; Stewart- Oaten et al, 1992; Smith et al, 1993; Wiens and Parker, 1995; Michener, 1997). The implications of these very real limitations to this type of problem solving have been extended into other areas of research, reaching spatial statistics and classical experimental designs (Eberhardt, 1976; Walters et al, 1988; Dutilleul, 1993;

Legendre, 1993). A broad conclusion of this research is that system knowledge (in this instance stream ecology) is invaluable when determining the proper ‘currency’ for measurement (Mellina and Hinch, 1995).

I selected easily measured physical and biological attributes (currencies) that might reasonably be expected to show a response to the thermal mitigation project, but I could not absolutely assume that any response I observed in my comparisons was an effect of the mitigation project. The most apparent, and best-documented, responses were the changes in stream temperatures in the Toxaway River, not only in comparison with other streams but also within the longitudinal reach of Toxaway River itself. Temperature data are theoretically not as vulnerable to sampling error, so I have more confidence that I sampled with minimal error. Further, thermal properties are more uniform and less variable than biological properties (Hynes, 1970). Thus, it follows that the patterns of stream temperatures I have described support the hypothesis that the Toxaway River was cooler in the second summer and warmed downstream of Lake Toxaway, which is consistent with the intended effect of mitigation.

Benthic macroinvertebrate data, however, do not show clear patterns that can be directly explained by the hypolimnetic manipulation. There are two issues here that need clarification. First, the bootstrapping results suggest that I did not sample a large enough benthic area at most sites to accurately characterize and compare macroinvertebrate density or family richness (Table 2.3). Secondly, even if the sampling effort at each site was sufficient (e.g., if no bootstrap slope estimates were significantly different from zero) before-after comparisons of site-differences would likely remain difficult to interpret because benthic macroinvertebrates respond to many factors, many of which are poorly

known (Merritt and Cummins, 1996b). Increasing replication by sampling additional control streams would have allowed me to draw stronger inferences from any “before-after” biological differences I documented in my experimental river system.

Ultimately, however, there is no means of determining causal relationships with this information. My intention here was to conduct an assessment of a descriptive nature. To account for processes that contribute to the patterns I measured (macroinvertebrate density and taxa richness), a study might examine primary production, rates of material/nutrient transport and processing, longitudinal trends in habitat availability and macroinvertebrate distributions in the Toxaway River. Clearly, these objectives were beyond the scope of my project.

A proper environmental impact assessment of this type would no doubt utilize prior work to formulate testable hypotheses about the post-mitigation effects downstream. Reservoirs have been known to dramatically alter downstream aquatic systems, but the type of discharge mechanism is an important determinant in downstream impacts. Even so, both hypolimnetic and surface releases are quite different than a ‘normal’ situation with no reservoir (Wotton, 1995; Baxter, 1997). Hauer and Stanford (1982) found that a hypolimnetic release in the Upper Flathead River (Montana) ‘reset’ relevant ecological features (i.e. resource availability, thermal regime) of a 6<sup>th</sup> order stream to a state more similar to that of a 4<sup>th</sup> order stream. Thermal changes can potentially change population dynamics and life-histories, and thus distributions, of some species (Ward and Stanford, 1979; Vannote and Sweeney, 1980; Vannote et al, 1980; Ward and Stanford, 1982).

The imprecision in my estimates of family richness, macroinvertebrate density and functional morphology representation underscores the high degree of natural spatial and temporal variability reported in macroinvertebrate assemblages (Rabeni and Minshall, 1977; Larsen and Herlihy, 1998). Although conceptual models exist for making inferences from the functional feeding group data (Cummins, 1973; Merritt and Cummins, 1996a, Merritt and Cummins, 1996b; Merritt et al, 2002), these inferences are limited (in this application) by the large amount of benthic variability within and among sites, rivers and years. We can not be sure whether any changes we have observed are due to the hypolimnetic release, or to other unmeasured factors. For instance, if benthic macroinvertebrates in the Horsepasture River were affected by a chemical spill in the winter of 2000, I would be unable to detect such a change. This would render such an effect indistinguishable from a mitigation effect, and there may be many of these types of factors working on a benthic community (Merritt and Cummins, 1996a).

Although this mitigation action was intended to reduce summertime water temperatures to benefit rare species and game fish in the river downstream, there are several reasons why using these metrics (or ‘currencies’) would have failed to provide a fair description of mitigation impacts. I have documented (Robinson, Chapter 1) that the rare species of fishes (*Etheostoma inscriptum*, *Micropterus coosae*, *Percina nigrofasciata*, *Hybopsis rubifrons*) only occur below the last shelf of the Blue Ridge Escarpment (the barrier, Eel-Line Falls, is about one stream mile below Bearwallow Creek, Figure 2.1). Stream temperatures below the confluence with Bearwallow Creek were not strongly affected by changes at Toxaway Lake (Figure 2.3), so it is unlikely that these rare species (below Eel-Line Falls) would be measurably affected by the mitigation.

Trout species (*Salmo trutta* and *Oncorhynchus mykiss*) were rarely collected or observed in Toxaway River, although the stream is managed by the North Carolina Wildlife Resources Commission as a Wild trout stream. The use of trout species as bioassessment indicators was therefore severely limited, although the mitigation was suggested as a possible way to help trout populations in the area, suspected to be numerically small (NCWRC, unpublished data). If the mitigation improved trout habitat, a likely source of recolonizing trout would be Indian Creek (Figure 2.1), where I did collect trout species. The discontinuous nature of Toxaway River, however, would seriously discourage recolonization in an upstream direction (Robinson, Chapter 1).

Thus, this study questions the likelihood of achieving the bioremediation goal of reducing temperatures in the mainstem of Toxaway to help restore trout and non-game species of concern. The thermal mitigation process seems to have worked, as there is a measurable temperature decrease in the Toxaway River after the mitigation. The cooled stretch of Toxaway River appears to have extended at least as far downstream as Indian Creek during 2001 (Figures 2.1, 2.3). The 'system knowledge' (the distribution of rare and game fishes) unavailable at the beginning of my study is likely the most important piece of information I report. This information would have greatly aided decision-making by resource managers, had it been available before the implementation of the mitigation project.

Drawing inferences from my interannual site differences is problematic for many reasons, thus I cannot confidently conclude that the observed trends in benthic macroinvertebrates are a response to the altered thermal regime. I conclude that a rapid bioassessment approach to investigate effects of thermal changes in rivers be avoided, in

favor a more rigorous field experimental design that includes sufficient control replication to allow more meaningful inferences to be drawn. Furthermore, given sufficient resources, I would recommend a more process-oriented field study that is capable of focused analysis on key physical and biological phenomena that could be mechanistically linked to changes in the physical, chemical and biological properties of water released downstream of a reservoir.

Figure 2.1 Study area, Transylvania County, NC. Location of temperature loggers and paired sites (Up, Mid, Low) shown by dots.

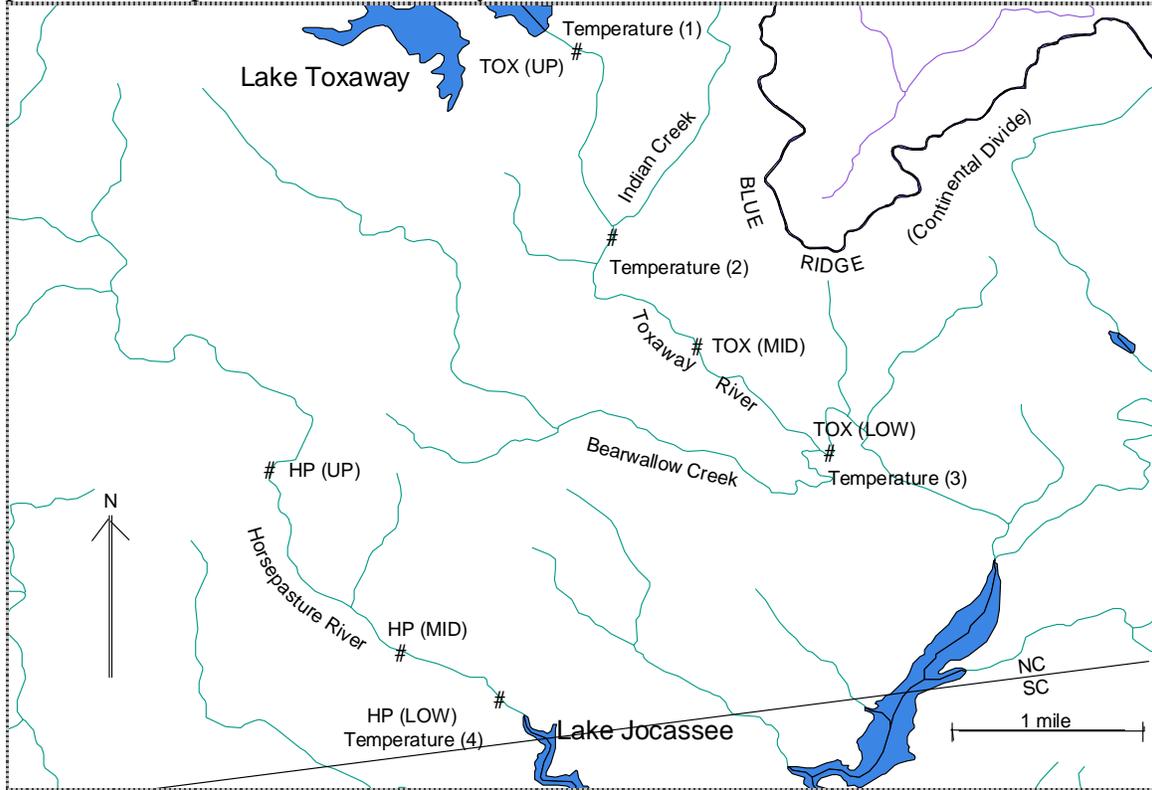


Figure 2.2 Hourly stream temperatures 2/7/00 to 8/7/01. Horsepasture (HP at Lake Jocassee) and Coweeta do not receive the hypolimnetic treatment imposed upon Toxaway sites.

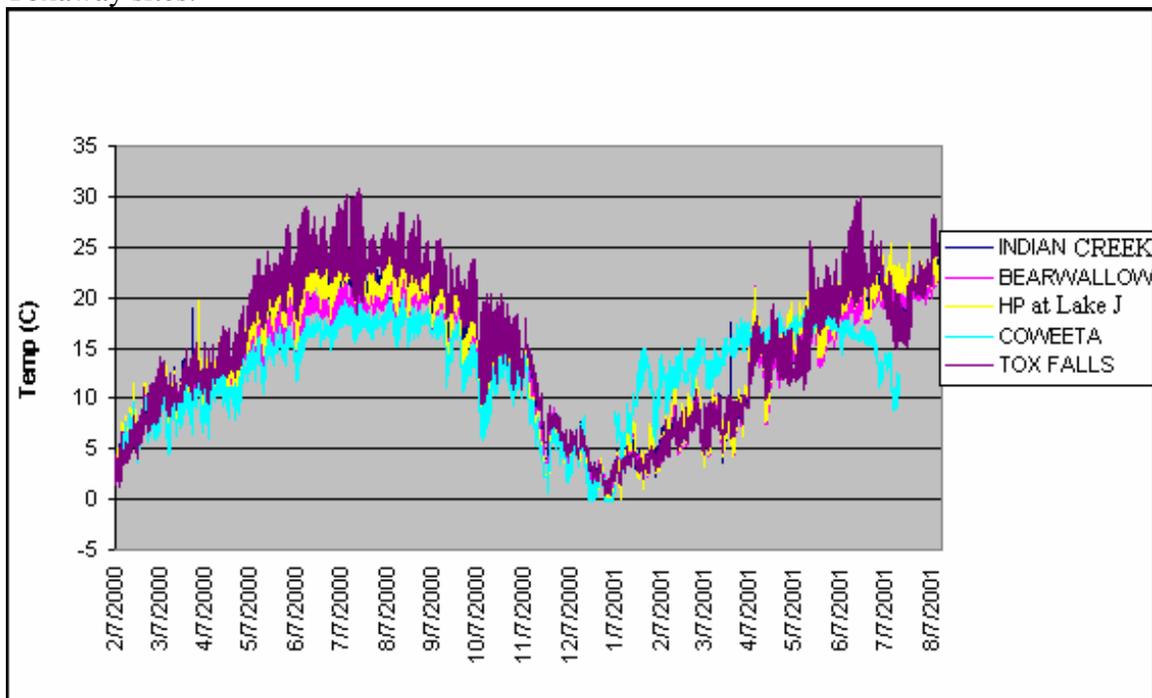


Figure 2.3 Summer stream temperature differences (2001- 2000). Toxaway Falls, Indian Creek and Bearwallow Creek sites are Temperature sites 1, 2 and 3 in Figure 2.1.

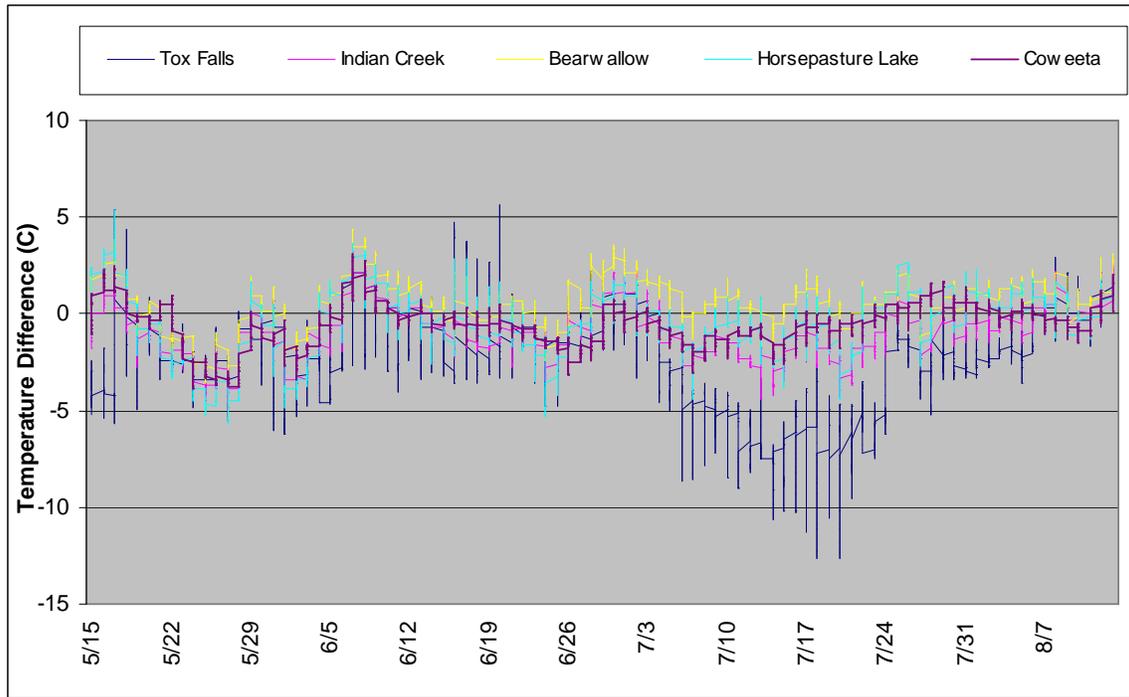


Figure 2.4 Annual stream temperature differences (2001- 2000). Hypolimnetic release began in the beginning of May and ended in early September.

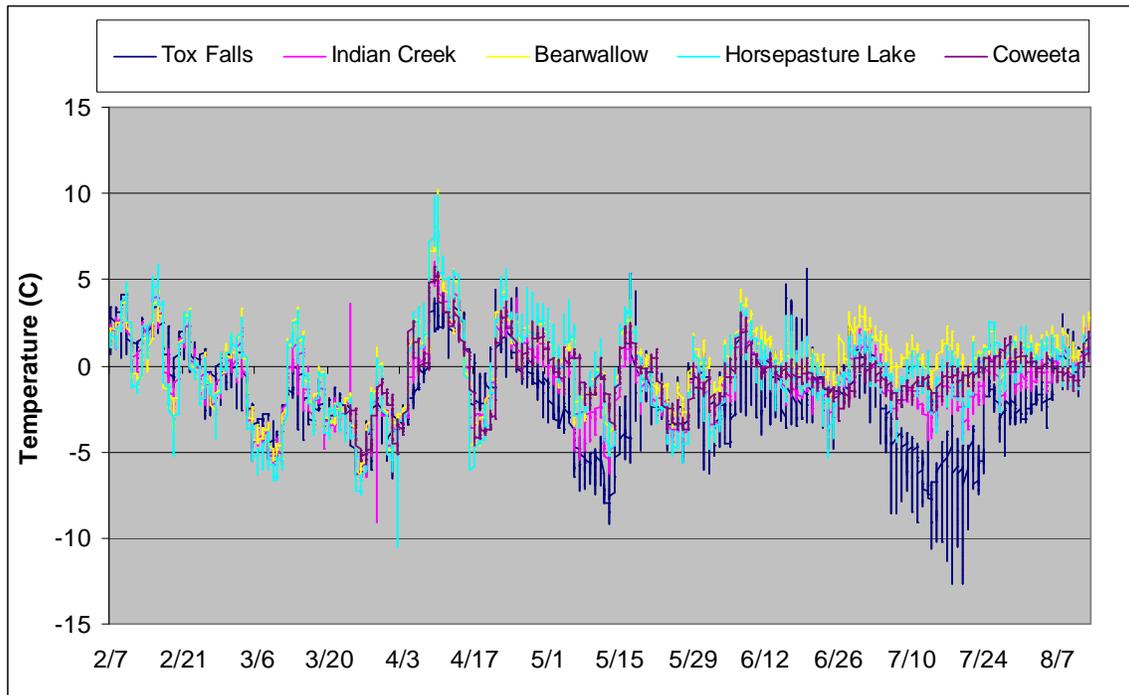


Figure 2.5 Annual difference in mean macroinvertebrate family richness for site pairs (Toxaway – Horsepasture).

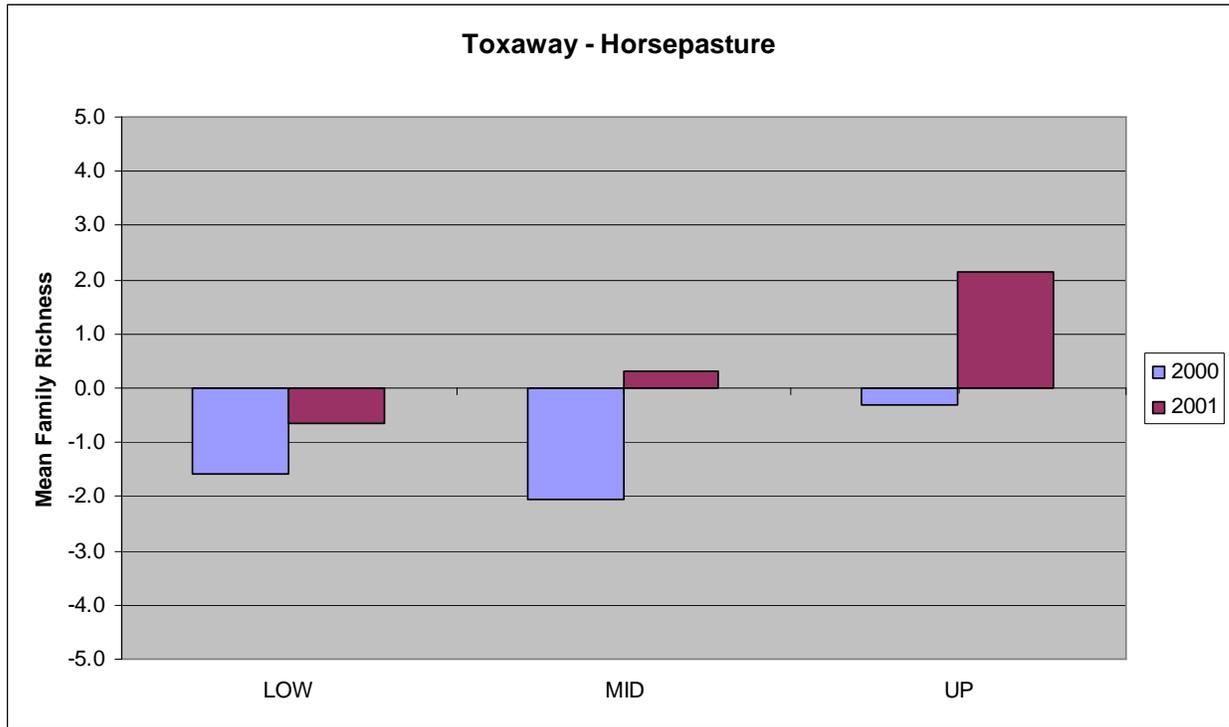


Figure 2.6 Annual difference in mean macroinvertebrate density for site pairs (Toxaway – Horsepasture).

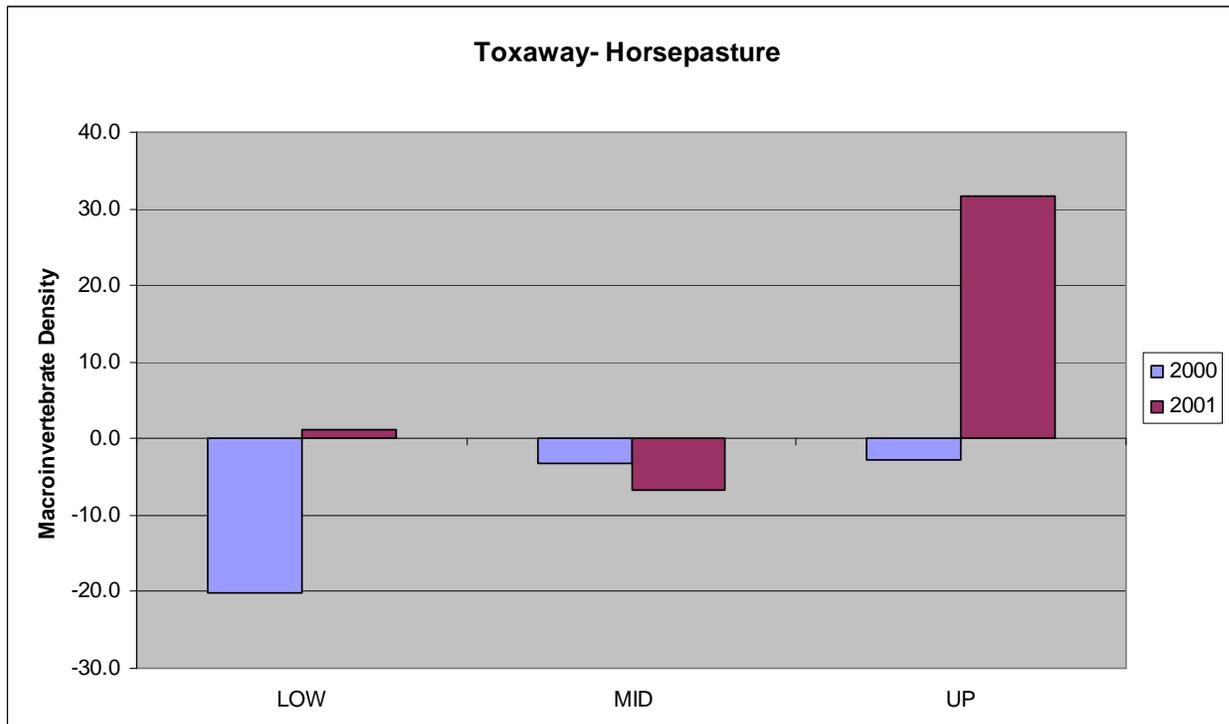


Table 2.1 Mean 2000 and 2001 macroinvertebrate family richness values for Toxaway and Horsepasture sites.

Fam R	2000	2001	2000	2001		% Change	
	TOX	TOX	HP	HP		TOX	HP
UP	0.9	5.4	1.2	3.3		500%	175%
MID	4.9	4.5	6.9	4.2		-8%	-39%
LOW	3.7	8	5.3	8.7		116%	64%

Table 2.2 Mean 2000 and 2001 macroinvertebrate densities for Toxaway and Horsepasture sites.

Density	2000	2001	2000	2001		% Change	
	TOX	TOX	HP	HP		TOX	HP
UP	2.9	43.0	5.7	11.3		1383%	98%
MID	15.3	11.5	18.6	18.2		-25%	-2%
LOW	8.3	38.4	28.4	37.3		363%	31%

Figure 2.7 2001 Annual proportional differences in six macroinvertebrate trophic guilds for site pairs (Toxaway- Horsepasture).

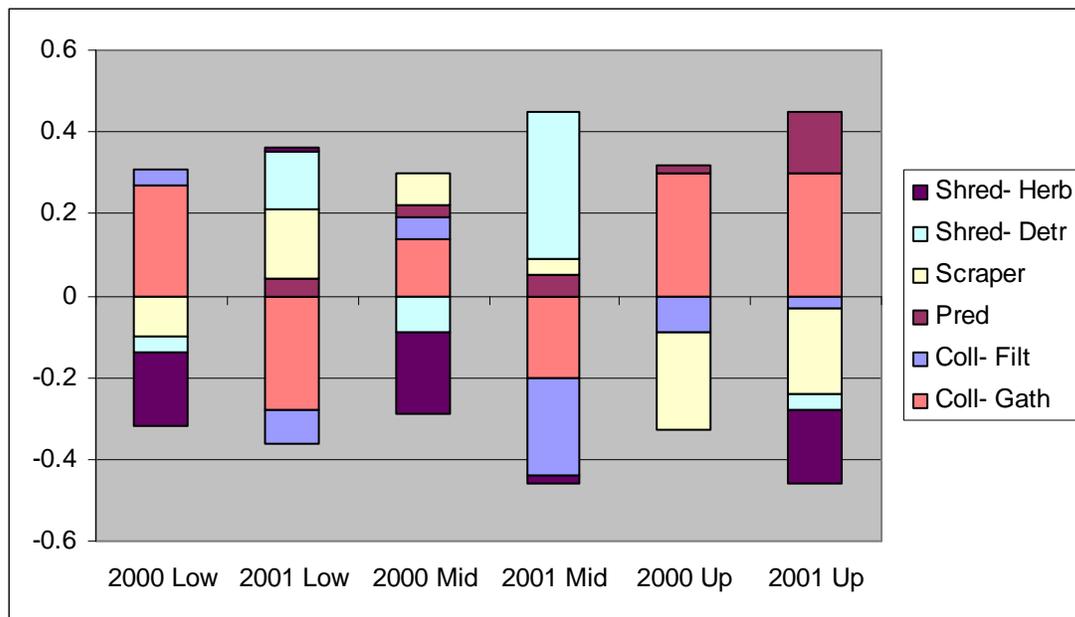


Table 2.3 Regression estimates of bootstrap slopes. Bold text denotes slopes significantly different from zero ( $\alpha = .05$ ).

Fam R	HP(LOW)	TOX(LOW)	HP(MID)	TOX(MID)	HP(UP)	TOX(UP)
2000	0.01	0.03	0.33	0.03	0.04	0.02
2001	<b>0.05</b>	0.08	0.09	<b>0.04</b>	<b>0.01</b>	<b>0.02</b>
Density						
2000	<b>0.23</b>	<b>0.06</b>	<b>0.08</b>	0.20	<b>0.13</b>	<b>0.05</b>
2001	0.35	<b>0.32</b>	<b>0.26</b>	<b>0.06</b>	0.09	<b>0.49</b>

## Literature Cited

- Balon, E.K. and D.J. Stewart. 1983. Fish assemblages in a river with unusual gradient (Luongo, Africa-Zaire system), reflections on river zonation, and description of another new species. *Environmental Biology of Fishes* 9: 225-252.
- Barton, T. 1998. A history of the Auger Hole, encompassing a 9600 acre tract of land (offered for public sale to a state or federal agency by Duke Power Company), drained by the Toxaway River, in the southwest corner of Transylvania County, North Carolina: A report prepared for the Sierra Club Pisgah Group.
- Baxter, R.M. 1977. Environmental effects of dams and impoundments. *Annual Review of Ecology and Systematics* 8: 255-283.
- Bender, E.A., T.J. Case and M.E. Gilpin. 1984. Perturbation experiments in community ecology: Theory and practice. *Ecology* 65: 1- 13.
- Bernstein, B.B. and J. Zalinski. 1983. An optimum sampling design and power tests for environmental biologists. *Journal of Environmental Management* 16: 35- 43.
- Beyers, D.W. 1998. Causal inference in environmental impact studies. *Journal of the North American Benthological Society* 17: 367- 373.
- Brittain, J.E. and S.J. Saltveit. 1989. A review of the effect of river regulation on mayflies (Ephemeroptera). *Regulated Rivers: Research and Management* 3: 191- 204.
- Burton, G.W. and E.P. Odum. 1945. The distribution of stream fish in the vicinity of Mountain Lake, Virginia. *Ecology* 26: 182- 194.
- Carmona, J.A., I. Doadrio, A.L. Marquez, R. Real, B. Hugueny and J.M. Vargas. 1999. Distribution patterns of indigenous freshwater fishes in the Tagus River, Spain. *Environmental Biology of Fishes* 54: 371- 387.
- Cooper, A.W. 1963. A survey of the vegetation of the Toxaway River Gorge with some remarks about the early botanical explorations and an annotated list of the vascular plants of the gorge area. *Journal of the Elisha Mitchell Society* 79: 1- 21.
- Cummins, K.W. 1973. Trophic relations of aquatic insects. *Annual Review of Entomology* 18: 183- 206.
- Dutilleul, P. 1993. Spatial heterogeneity and the design of ecological field experiments. *Ecology* 74: 1646- 1658.
- Eberhardt, L.L. 1976. Quantitative ecology and impact assessment. *Journal of Environmental Management* 4: 27- 70.
- Efron, B. and R.J. Tibshirani. 1993. An introduction to the bootstrap. Chapman and Hall: New York, NY.
- Elliot, J.M. 1994. Quantitative ecology and the rown trout. Oxford University Press, Oxford, UK.

- Evans, J.W and R.L. Noble. 1979. The longitudinal distribution of fishes in an East Texas stream. *The American Midland Naturalist* 101: 333- 343.
- Fausch K.D., Y. Taniguchi, S. Nakano, G.D. Grossman and C. Townsend. 2001. Flood disturbance regimes influence rainbow trout invasion success among five holarctic regions. *Ecological Applications* 11: 1438-1455.
- Freeman, M.C., Crawford, M.K., Barret, J.C., Facey, D.E., Flood, M.G., Hill, J., Stouder, D.J., and Grossman, G.D. 1988. Fish assemblage stability in a Southern Appalachian stream. *Canadian Journal of Fisheries and Aquatic Sciences* 45: 1949- 1958.
- Gilliam, J.F., Fraser, D.F., and M. Alkins-Koo. 1993. Structure of a tropical stream fish community: A role for biotic interactions. *Ecology* 74: 1856- 1870.
- Gorman, O.T. and J.R. Karr. 1978. Habitat structure and stream fish communities. *Ecology* 68: 1856- 1862.
- Green, R.H. 1979. Sampling design and statistical methods for environmental biologists. John Wiley and Sons: New York, NY.
- Grossman, G.D. and R.E. Ratajczak, Jr. 1998. Long-term patterns of microhabitat use by fish in a Southern Appalachian stream from 1983- 1992: Effects of hydrologic period, season and fish length. *Ecology of Freshwater Fish* 7: 109- 131.
- Hauer, F.R. and J.A. Stanford. 1982. Ecological responses of hydropsychid caddisflies to stream regulation. *Canadian Journal of Fisheries and Aquatic Sciences* 39: 1235- 1242.
- Hawkes H.A. 1975. River zonation and classification. *pp.* 312 – 374. *In:* B.A. Whitton (ed.). *River Ecology*. University of California Press: Berkeley, CA.
- Hinch, S.G., K.M. Somers and N.C. Collins. 1994. Spatial autocorrelation and assessment of habitat-abundance relationships in littoral zone fish. *Canadian Journal of Fisheries and Aquatic Science* 51: 701- 712.
- Hocutt, C.H. and J.R. Stauffer. 1975. Influence of gradient on the distribution of fishes in Conowingo Creek, Maryland and Pennsylvania. *Chesapeake Science* 16: 143- 147.
- Horne, A.J. and C.R. Goldman. 1994. *Limnology*. McGraw- Hill, Inc: New York, NY.
- Horton, R.E. 1945. Erosional development of streams and their drainage basins. *Bulletin of the Geological Society of America* 56: 275- 370.
- Horwitz, R.J. 1978. Temporal variability patterns and the distributional patterns of stream fishes. *Ecological Monographs* 48: 307- 321.
- Huet, M. 1959. Profiles and biology of Western European streams as related to fish management. *Transactions of the American Fisheries Society* 88: 153-163.
- Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological field experiments. *Ecological Monographs* 54: 187- 211.

- Hynes, H.B.N. 1972. The ecology of running waters. University of Toronto Press, Toronto.
- Klugh, A.B. 1923. A common system of classification in plant and animal ecology. *Ecology* 4: 366-377.
- Kuehne, R.A. 1962. A classification of streams, illustrated by fish distribution in an Eastern Kentucky creek. *Ecology* 43: 608- 614.
- Larsen, D.P. and A. T. Herlihy. 1998. The dilemma of sampling streams for macroinvertebrate richness. *Journal of the North American Benthological Society* 17: 359-366.
- Lee, D.S., Gilbert, C.R., Hocutt, C.H., Jenkins, R.E., McAllister, D.E., and Stauffer, J.R., (eds.). 1980. Atlas of North American freshwater fishes. North Carolina State Museum of Natural History: Raleigh, NC.
- Legendre, P. 1993. Spatial autocorrelation: Trouble or new paradigm? *Ecology* 74: 1659- 1673.
- LeGrand, H.E. and S.P. Hall. 1999. Natural Heritage Program list of the rare species of North Carolina. NC Department of Environment and Natural Resources (DENR): Raleigh, NC.
- Lemkuhl, D.M. 1972. Changes in thermal regime as a cause of reduction of benthic fauna downstream of a reservoir. *Journal of the Fisheries Research Board of Canada* 29: 1329- 1332.
- Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman: San Francisco, California.
- Lotrich, V.A. 1973. Growth, production, and community composition of fishes inhabiting a first-, second- and third- order stream of Eastern Kentucky. *Ecological Monographs* 43: 377- 396.
- Margalef, R. 1960. Ideas for a synthetic approach to the ecology of running waters. *International Revue ges. Hydrobiologia* 45: 133- 153.
- Marsh- Matthews, E., and Matthews, W.J. 2000. Geographic, terrestrial, and aquatic factors: Which most influence the structure of stream fish assemblages in the Midwestern United States? *Ecology of Freshwater Fish* 9: 9- 21.
- Matthews, W.J. 1986. Fish faunal 'breaks' and stream order in the Eastern and Central United States. *Environmental Biology of Fishes* 17: 81- 92.
- Matthews, W.J. 1998. Patterns in freshwater fish ecology. Chapman and Hall: New York, New York.
- McCune, B. and Mefford, M.J. 1999. PC- ORD for Windows. Multivariate analysis of ecological data, Version 4.0. MJM Software: Gleneden Beach, Oregon.
- McGarigal, K, S. Cushman and S.G. Stafford. 2000. Multivariate statistics for wildlife and ecology research. Springer: New York, NY.
- Meffe, G.K. and Sheldon, A.L. 1968. The influence of habitat structure on fish assemblage composition in Southeastern blackwater streams. *The American Midland Naturalist* 120: 225- 240.

- Mellina, E. and S.G. Hinch. 1995. Overview of large- scale ecological experimental designs and recommendations for the British Columbia Watershed Restoration Program. Watershed Restoration Program Project Report, No. 1.
- Menhinick E.F. 1991. The freshwater fishes of North Carolina. North Carolina Wildlife Resources Commission: Raleigh, NC.
- Merona, B. and P. Albert. 1999. Ecological monitoring of fish assemblages downstream of a hydroelectric dam in French Guinea (South America). *Regulated Rivers: Research and Management* 15: 339- 351.
- Merritt, R.W. and K.W. Cummins (eds.). 1996a. An Introduction to the aquatic insects of North America. Kendall/Hunt Publishing Company: Dubuque, IA.
- Merritt, R.W., and K.W. Cummins. 1996b. Trophic relations of macroinvertebrates. *In* F.R. Hauer and G.A. Lamberti (eds.). *Methods in Stream Ecology*. Academic Press: Orlando, FL.
- Merritt, R.W., K.W. Cummins, M.B. Berg, J.A. Novak, M.J. Higgins, K.J. Wessell and J.L. Lessard. 2002. Development and application of a macroinvertebrate functional- group approach in the bioassessment of remnant river oxbows in southwest Florida. *Journal of the North American Benthological Society* 21: 290- 310.
- Michener, W.K. 1997. Quantitatively evaluating restoration experiments: Research design, statistical analysis, and data management considerations. *Restoration Ecology* 5: 324-337.
- Minshall, G.W., Cummins, K.W., Petersen, R.C., Cushing, C.E., Bruns, D.A., Sedell, J.R., and Vannote, R.L. 1985. Developments in stream ecosystem theory. *Canadian Journal of Fisheries and Aquatic Sciences* 42: 1045- 1055.
- Paller, M.H. 1994. Relationships between fish assemblage structure and stream order in South Carolina coastal plain streams. *Transactions of the American Fisheries Society* 1123: 150- 161.
- Rabeni, C.F., and G.W. Minshall. 1977. Factors affecting microdistribution of stream benthic insects. *Oikos* 29: 33-43.
- Rader R.B., and J.V. Ward. 1988. Influence of regulation on environmental conditions and the macroinvertebrate community in the upper Colorado River. *Regulated Rivers: Research and Management* 2: 597- 618.
- Rahel, F.J. and Hubert, W.A. 1991. Fish assemblages and habitat gradients in a Rocky Mountain- Great Plains stream: biotic zonation and additive patterns of community change. *Transactions of the American Fisheries Society* 120: 319- 332.
- Reyes- Gavilan, F.G., R. Garrido, A.G. Nicieza, M.M. Toledo and F. Brana. 1996. Fish community variation along physical gradients in short streams of Northern Spain and the disruptive effect of dams. *Hydrobiologia* 321: 155- 163.
- Schlosser, I.J. 1982. Fish community structure and function along two habitat gradients in a headwater stream. *Ecological Monographs* 52: 395- 414.

- Seegrist, D.W., and Gard, R. 1972. Effects of floods on trout in Sagehen Creek, California. *Transactions of the American Fisheries Society* 101: 478- 482.
- Sheldon, A.L. 1968. Species diversity and longitudinal succession in stream fishes. *Ecology* 49: 193-198.
- Shelford, V.E. 1911. Ecological succession. I. Stream fishes and the method of physiographic analysis. *Biological Bulletin* 21: 9- 35.
- Smith and Powell, 1971. The summer fish communities of Briar Creek, Marshall County, Oklahoma. *American Museum Novitates* 2458: 1-30.
- Smith, E.P., D.R. Ordos and J. Cairns, Jr. 1993. Impact assessment using the Before- After- Control- Impact model: Concerns and comments. *Canadian Journal of Fisheries and Aquatic Sciences* 50: 627- 637.
- Statzner, B., and Higler, B. 1985. Questions and comments on the River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences* 42: 1038- 1044.
- Stewart-Oaten, A.J, W.W. Murdoch and K.R. Parker. 1986. Environmental impact assessment: "Pseudoreplication " in time? *Ecology* 67: 929- 940.
- Stewart- Oaten, A., J.R. Bence and C.W. Osenberg. 1992. Assessing effects of unreplicated perturbations: No simple solutions. *Ecology* 73: 1296-1404.
- Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. *Transactions of the American Geophysical Union* 38: 913- 920.
- Strange, E.M., P.B. Moyle and T.G. Foin 1992. Interactions between stochastic and deterministic processes in stream fish community assembly. *Environmental Biology of Fishes* 36: 1- 15.
- Tonn, W.M. 1990. Climate change and fish communities: A conceptual framework. *Transactions of the American Fisheries Society* 119: 337-352.
- Underwood, A.J. 1991. Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* 42: 569- 587.
- Underwood, A.J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. *Ecological Applications* 4: 3- 15.
- Vannote, R.L. and B.W. Sweeney. 1980. Geographic analysis of thermal equilibria: A conceptual model for evaluating the effect of natural and modified thermal regimes on aquatic insect communities. *The American Naturalist* 115: 667-695.
- Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell and C.E. Cushing. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 130- 137.
- Walters, C.J., J.S. Collie and T. Webb. 1988. Experimental designs for estimating transient responses to management disturbances. *Canadian Journal of Fisheries and Aquatic Sciences* 45: 530-538.

- Ward, J.V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes and aquatic conservation. *Biological Conservation* 83: 269- 278.
- Ward, J.V. and J.A. Stanford. 1979. Ecological factors controlling stream zoobenthos with emphasis on thermal modification of regulated streams, pp. 35- 55. *In* J. V. Ward and J.A. Stanford [eds]. *The Ecology of Regulated Streams*. Plenum Press: New York, NY.
- Ward, J.V. and J.A. Stanford. 1982. The serial discontinuity concept of lotic ecosystems. *In* T.D. Fontaine and S.M. Bartell [eds]. *Dynamics of Lotic Ecosystems*. Ann Arbor Science Publishing: Ann Arbor, MI.
- Webb, B.W. and D.E. Walling. 1997. Complex summer water temperature behaviour below a UK regulating reservoir. *Regulated Rivers: Research and Management* 13: 463- 477.
- White, W.A. 1950. The Blue Ridge, a fault scarp. *Bulletin of the Geological Society of America* 61: 1309- 1346.
- Wiens, J.A. and K.R. Parker. 1995. Analyzing the effects of accidental environmental impacts: Approaches and assumptions. *Ecological Applications* 5: 1069- 1083.
- Wotton, R.S. 1995. Temperature and lake- outlet communities. *Journal of Thermal Biology* 20: 121- 125.