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# Restoring Geomorphic Stability and Biodiversity in Streams of the Catskill Mountains, New York, USA

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*Abstract.*—Many stream and river channels in North America have been straightened, widened, and hardened to stabilize channel banks and beds, but these efforts have typically given little or no consideration to biological integrity of the affected ecosystems. Application of natural-channel design (NCD) techniques and Rosgen's river classification system to mimic stable "reference-reach" morphology has helped reestablish natural stream-habitat conditions in more recent restoration projects. Stable channel morphology was restored using NCD techniques in a degraded reach in each of three Catskill Mountain streams during 2000 or 2001, in an attempt to decrease bed and bank erosion rates, reduce sediment loading, and improve water quality. Channel-restoration designs were based primarily on bank-full characteristics of nearby stable (reference) reaches and models of local stream hydrology and geometry. The effects of NCD restoration on biological integrity were assessed through before-after-control-impact (BACI) and analysis of variance (ANOVA) analyses of the changes in fish-community characteristics at treatment reaches relative to changes at unaltered control reaches after reach restoration. In general, relative species richness, total biomass, and biomass equitability increased significantly after treatment reaches were restored. The observed responses indicate that fish communities were affected by the restorations and by normal year-to-year variations in uncontrolled factors such as temperature, precipitation, and stream discharge. These findings indicate that biodiversity of fish communities in degraded Catskill Mountain streams generally benefit from use of NCD techniques to restore geomorphic stability.

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## Introduction

The relations between geomorphic stability and condition of aquatic ecosystems have not been thoroughly documented, especially in regard to the effects of stream restoration. Stream channels that are geomorphically unstable typically have rapidly eroding or aggrading beds and banks; they also have fewer pools than more stable reaches, and lower pool area and pool to riffle ratios, higher width to depth ratios, more uniform water velocity, and higher rates of bank erosion, lateral-channel migration, and rates of sediment transport (Leopold et al. 1964; Leopold 1994; Rosgen 1996). Stream habitat within such channels can be relatively sterile and homogeneous with low species diversity and distorted ecosystem structure or function (Rosgen 1994b; Scott and Hall 1997; Pretty et al. 2003). Single-goal stream-stabilization efforts, often termed restorations, have generally entailed hardening of stream channels and banks to either minimize localized bed and bank erosion, improve water quality, or mitigate flooding. Whether termed stabilization or restoration, only a small number of studies have evaluated the short-term effects of channel restoration on wild fish populations and communities, normal stream processes, or the consequences in contiguous reaches (Pretty et al. 2003). Even fewer studies have monitored long-term success of stream restoration on channel morphology, fish habitat, bed and bank erosion rates, or biological integrity.

Since the early 1990s, private and nonprofit organizations, as well as public agencies in the Northeast, have attempted to base stream-restoration programs and projects on natural stream-channel morphology and fluvial processes to recreate appropriate (stable for a particular stream type) bank and channel geometry and near-natural habitat and ecosystem structure and function. The New York City Department of Environmental Protection (NYCDEP) and the Greene County Soil and Water Conservation District (GCSWCD) have implemented several demonstration stream restoration projects in the Catskill Mountains of southeastern New York as part of a larger NYCDEP program to implement multiobjective stream-management planning and design projects in the New York City West-of-Hudson Water Supply Watershed. These restoration projects are designed to address several stream-management issues, including flood hazards, aquatic-habitat condition, water quality, fisheries, and property protection. These channel restorations can produce self-sustaining reaches and satisfy more than one management issue because designs are based on the form (geomorphology) and function (hydraulics and sediment transport) of naturally stable streams. The projects conducted used the Rosgen stream-classification system (Rosgen 1994a, 1996) to (1) categorize streams according to bankfull-discharge hydraulic geometry, and (2) base natural-channel-design (NCD) restorations on bankfull, flood plain, and valley characteristics measured in nearby stable reference streams of the desired type in a similar valley setting (Rosgen 1994b). Specific changes in geomorphic stability of restored streams are not documented in the present paper.

In 1999, the U.S. Geological Survey (USGS), in cooperation with NYCDEP and GCSWCD, began a 7-year study to assess the effects that stream-restoration projects (utilizing natural-channel-design [NCD] techniques) had on the biodiversity and integrity of resident fish communities in three disturbed (unstable) stream reaches. Of the three types of biodiversity that may be measured—habitat diversity, genetic diversity, and species diversity—this paper focuses on species diversity, and its contribution to biological integrity. Biological integrity has been defined as "the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of the natural habitat of the region" (Karr 1981; Karr and Dudley 1981). By this definition, reaches subject to little or no anthropogenic stress would generally have high biological integrity. This study used indices of fish community density, biomass, richness, and equitability (evenness) observed at nearby undisturbed reference reaches as the basis to assess changes in biological integrity observed at restored reaches. Biological integrity in reference reaches, although not necessarily optimal, reflects the natural year-to-year fluctuations in fish community indices in untreated reaches. Community data from reference reaches provide a scale to standardize or separate the effects of restoration from differences that would normally occur in community indices at each treatment reach before and after restoration.

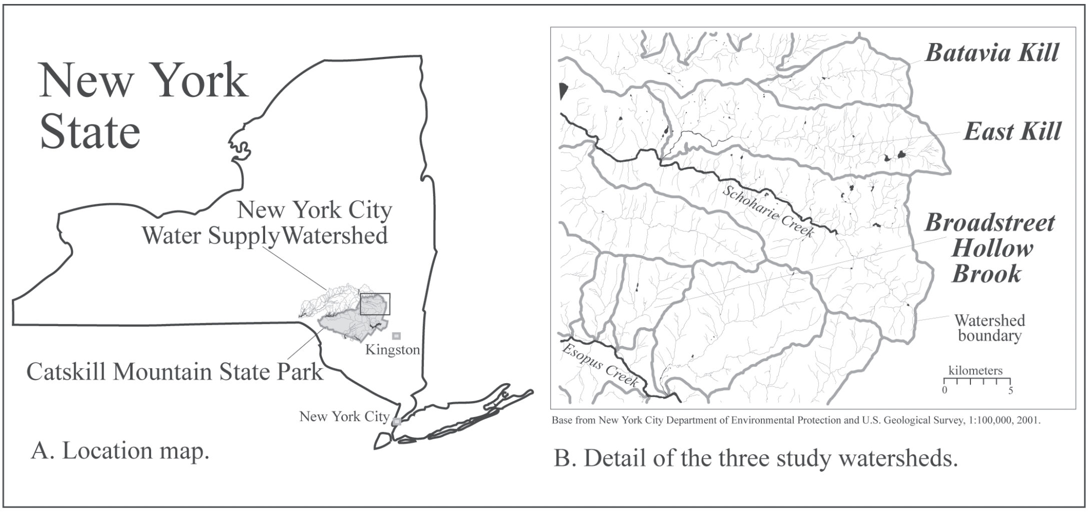
Though the number of studies that assess fish response to large scale stream modifications were rare, several efforts that increased habitat heterogeneity in streams also documented a shift in fish communities, away from an overabundance of a few species that were tolerant of high sediment loads, toward balanced assemblages with a greater number of species that were generally larger and less tolerant of high sediment loads (Riley and Fausch 1995; Flebbe 1999; Roni and Quinn 2000; Dethloff et al. 2001; Shields et al. 1995, 1998, 2000). The main hypothesis tested in the present study was that increased geomorphic stability in restored channels would decrease total fish density and increase the total fish biomass, number or species (richness), and species (or biomass) equitability of communities in the three previously unstable reaches. Absolute changes in each index at restored reaches, and annual changes in each index relative to that in corresponding reference reaches (differentials), were evaluated before and after restoration to quantify responses and to separate the effects of restoration from normal interannual fluctuations. The responses of fish communities in the three restored reaches are summarized and discussed herein.

## Methods

Stream-channel restorations were conducted independent from fish surveys in large (0.4–3.0 km) restoration project reaches on each of three streams; summaries of restoration approaches are provided below. Fish inventories were done annually at small (87–112 m) paired reference and treatment reaches one or more years before (1999, 2000, and 2001), and 2 years after treatment reaches were restored (2002 and 2003). References reaches were outside of restoration project reaches, but treatment reaches were entirely within restoration project reaches. Treatment reaches were, therefore, in a restored condition only after restoration project reaches were restored. The three study streams were Broadstreet Hollow Brook, the Batavia Kill, and the East Kill (Figure 1). The treatment reaches were assumed to be geomorphically unstable before restoration and more stable after restoration. Because reference reaches were not manipulated during the study, they provided information on the natural year-to-year changes in community indices (e.g., density, biomass richness, and equitability) that helped distinguish fish-community changes due to restoration from those due to natural variations in unmonitored factors, such as water temperature, precipitation volumes, or stream discharge.

### *Restoration Aproach*

The NYCDEP and GCSWDC selected stream-restoration project reaches that had low



Base from New York City Department of Environmental Protection and U.S. Geological Survey, 1:100,000, 2001.

A. Location map.

B. Detail of the three study watersheds.

**Figure 1.** Location of three demonstration stream-restoration projects in the eastern Catskill Mountain State Park and the New York City (west-of-Hudson) Water Supply Watershed.

geomorphic stability. The reaches typically had high rates of bed and bank erosion and copious sediment supplies that tended to produce overwide and shallow channels, rapid channel migration, homogeneous riffle habitat, and high concentrations of total suspended solids, especially where clay-rich deposits were exposed. The NYCDEP and GCSWCD implemented restoration projects in the three restoration project reaches to increase stability, alleviate negative impacts on water quality, minimize damage to public infrastructure and private property (lands and structures), maintain riparian structure and function, and improve stream habitat and fisheries. All restorations used the Rosgen (1994a, 1996) stream-classification system and based channel-geometry designs mainly on bank-full-channel characteristics of nearby stable reference reaches of the same type and on regional hydraulic-geometry relations (natural-channel-design principles). The reference reaches used for fish surveys appeared to be stable in general, but stability was not a requirement nor was it assessed in detail. Fish-reference reaches discussed in this study were sometimes, but not always, the same reference reaches used for geomorphic-design purposes.

### *Study Reaches*

Fish communities at reference and treatment reaches were typically surveyed once, each July or August from 2000 through 2003, except for the East Kill and Broadstreet Hollow Brook, which were not sampled in 2001. Surveys were also done in 1999 at both reaches on Broadstreet Hollow Brook.

Surveys at Broadstreet Hollow Brook were completed in July or August of 1999, 2000, 2002, and 2003. This stream flows into Esopus Creek about 35 km northwest of Kingston (Figure 1). The treatment reach was 0.1 km long and about 3.2 km upstream from the confluence with the Esopus Creek. The treatment reach had a drainage area of about 23 km$^2$; discharge averaged 0.09 m$^3$/s, and wetted-width averaged 5.4 m during the four surveys. The corresponding reference reach, 0.7 km upstream from the treatment site, had an average discharge of 0.07 m$^3$/s and average wetted-width of 4.7 m. The restoration-project reach was 0.34 km long and was restored in September and October of 2000. Additional information on the restoration project and the watershed is available at http://www.gcswcd.com/stream/ (accessed December 2004) and in the provisional stream-management plan http://www.gcswcd.com/stream/broadstreet/smp/ (accessed December 2004).

Fish surveys were done in July of 2000–2003 at reference and treatment reaches in the Batavia Kill, about 42 km north-northwest of Kingston (Figure 1). The treatment reach was 1.4 km upstream from a small flood-control reservoir and 22 km upstream from the confluence with Schoharie Creek (Figure 1). The treatment reach had a drainage area of about 17 $km^2$; discharge averaged 0.06 $m^3/s$ and wetted-width averaged 4.7 m during the four surveys. The reference reach, 1.9 km upstream from the treatment reach, had an average discharge of 0.06 $m^3/s$, and average wetted-width of 4.8 m. The restoration project reach was 1.6 km long; the lower two-thirds of this reach was restored in the fall of 2001; and the upper third was restored in the fall of 2002. Additional information on the watershed and the restoration project is available at http://www.gcswcd.com/stream/(accessed Decemeber 2004).

Surveys were done at both reaches in the East Kill during July or August of 2000, 2002, and 2003, about 40 km north-northwest of Kingston (Figure 1). The treatment reach was 11 km upstream from the confluence with Schoharie Creek, had a drainage area of about 45 $km^2$, an average discharge of 0.29 $m^3/s$, and an average wetted-width of 8.4 m during the three surveys. The reference reach, 0.1 km upstream from the treatment reach, was contiguous with the upper end of the restoration project reach. Discharge at this reach averaged 0.34 $m^3/s$, and wetted-width averaged 12.4 m during the four surveys. The restoration project reach was 0.73 km long and was restored in the July and August of 2000. Additional information on the watershed and the restoration project is available at http://www.gcswcd.com/stream/(accessed December 2004).

### Fish Communities

Fish community surveys were done at the treatment reach and the reference (control) reach in each stream 1 or 2 years before restoration and 2 years after restoration. Fish in survey reaches were collected from seine-blocked, 87- to 120-m-long stream sections during three or four successive passes using a battery-powered backpack electrofisher and three fish netters. Fish from each pass were identified by species, and the lengths and weights of individual fish more than about 150 mm long were recorded. Lengths and weights of fish smaller than about 150 mm were obtained from 40 to 50 individuals of each species; thereafter, total weights and counts by species were recorded in batches of 10–50 individuals. Fish were returned to the stream after all processing was completed.

### Data Analyses

The number of fish captured during each pass was used to estimate annual mean population sizes and 95% confidence intervals (CI) for each fish species and for the entire fish community by the Moran-Zippin method of proportional reduction (Zippin 1958) and Microfish (v. 1) software (Van Deventer and Platts 1985). Species diversity (the number of fish species, or richness), and Shannon-Wiener diversity (species equitability) were calculated through standard methods (Whittaker 1975). Indices of community equitability were calculated using (1) the number of individuals of each fish species, and (2) the total weight of each species at each reach. Total community density (number of fish/$m^2$) and biomass (grams of fish/$m^2$) at each reach were estimated from the total number or biomass of all fish divided by the surface area of each survey reach. The overlap of 95% C.I.s was used to assess absolute differences ($P < 0.05$) in indices of community density and biomass between reaches or within reaches among sampling dates. These assessments are analogous to two-tailed Student's *t*-tests. Further evaluation of community responses to restoration at treatment reaches relied on ANOVA and BACI methods (Steward-Oaten et al. 1986; Underwood 1994).

Community indices of density, biomass, richness, and equitability at each treatment reach were scaled or standardized to the same index measured at corresponding reference reaches to calculate index differentials. A differential ($\Delta$) was calculated as the product of each index value at a given treatment reach minus the index value at its corresponding reference reach for a given survey period (year). The BACI method tests for changes in mean index differentials at treatment reaches before restoration (1999 and 2000) and after restoration (2001, 2002, and 2003) through a one-factor ANOVA within a single stream or though a two-factor ANOVA combining data from all three streams. Findings from the one-factor ANOVA are based on a sample size (*n*) of 4 at the Batavia Kill and Broadstreet Hollow Brook. Conclusions based on tests with such a low sample size may be disputed; nevertheless, the results quantify the differences in the magnitude and direction of community responses and illustrate that response mechanisms may differ among the three restored reaches. The two-factor ANOVA tests for (1) differences in each index differential before and after restoration, (2) differences in index differentials among the three streams, regardless of restoration, and (3) factor interaction (differing responses among the three streams). Almost all differentials used to test for effects of restoration were normally, or nearly normally, distributed (tested through a normal probability plot with 0.95 confidence intervals). Only the combined biomass equitability data were not distributed normally. Differences for all analyses were considered significant when *P*-values were less than 0.05, unless otherwise noted.

## Results and Discussion

Findings from the fish-community surveys and analyses of community-index responses to restoration are treated separately below. Due to the paucity of directly comparable studies, the related discussions are somewhat limited and are included, for the most part, with the findings.

### *Community Density*

Total community density (total number of fish/$m^2$) was greater each year after restoration (2002 and 2003) than during the 1 or 2 years before restoration at treatment reaches in Broadstreet Hollow Brook and the East Kill (Figures 2B, 2C), but not in the Batavia Kill (Figure 2A). Mean density differentials ($\Delta$ density) increased significantly at Broadstreet Hollow Brook by 0.91 fish/$m^2$ ($n = 4$, $P = 0.067$) after the restoration, but decreased in the other two streams (Table 1). Mean index differentials at the East Kill cannot be tested for significant change because only one survey was completed before restoration. Results of the two-factor ANOVA indicate that $\Delta$ density for the combined treatment reaches did not change significantly after restoration (Table 2). Although density of fish communities at the East Kill and the Batavia Kill treatment reaches increased after restoration, densities at their corresponding reference reaches changed such that the differentials were

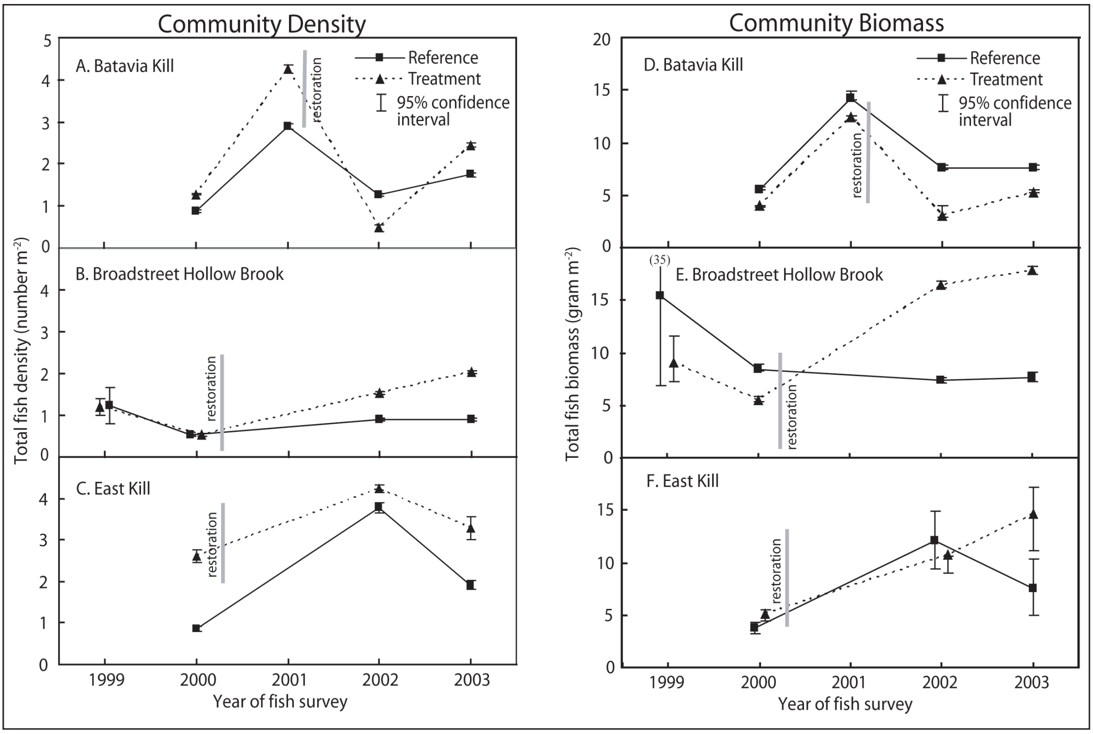


**Figure 2.** Total fish-community density and biomass, and 95% confidence intervals, at paired treatment and reference reaches in the three study streams before and after restoration, 1999–2003.

smaller (or negative) after restoration than before restoration in both streams (Figures 2A, 2C). The relative response of fish-community density at treatment reaches in both streams, therefore, was slightly negative (Table 2).

The inconsistent response of fish-community density to restoration is reasonable given the high level of interannual variability, initial fish-community condition, and the various geomorphic stability issues at each restored stream reach. Interannual variations in density of fish communities at the Batavia Kill ranged from about 2 to 4 g/m$^2$ (Figure 2A), and greatly exceeded the mean change (-0.93 g/m$^2$) possibly caused by restoration (Table 1). The unusually high fish density and biomass (per unit area) at the Batavia Kill in 2001 were expected because that summer was exceptionally dry, and stream discharge and sample area at the time of the survey were smaller than during the other 3 years. Only at Broadstreet Hollow Brook were the numbers of fish/m$^2$ significantly greater at the treatment reach after restoration than before. The density of fish in the East Kill treatment reach also increased significantly after restoration (Figure 2C); Δ density declined (Table 1), however, because larger relative increases in density at its corresponding reference reach reduced differences in density estimates between the treatment and reference reaches during both years following the restoration (Figure 2C).

The natural-channel design (NCD) restorations did not significantly affect fish-community density across the three restored reaches; therefore, restored stability did not lower total fish densities and the null hypothesis that

**Table 1.** Mean increase (+) or decrease (-) in index differentials, and the results (*P*-values - in parentheses) of 1-factor ANOVAs assessing differences in each index, before and after restoration at the three treatment reaches. All data are normally distributed. Boldface values indicate *P*-values < 0.15**.**

| Mean change in index differentials | | | |
|---|---|---|---|
| Community index | Batavia Kill (n=4) | Broadstreet Hollow Brook (n=4) | East Kill (n=3) |
| Total density | -0.93<br>(0.402) | **0.91**<br>(0.067) | -0.84<br>(na) |
| Total biomass | -1.68<br>(0.273) | **14.34**<br>(0.015) | 1.48<br>(na) |
| Richness | **5.00**<br>(0.019) | 0.00<br>(1.000) | 3.00<br>(na) |
| Equitability (species density) | 0.068<br>(0.488) | 0.053<br>(0.535) | 0.275<br>(na) |
| Equitability (species biomass) | **0.363**<br>(0.099) | **0.031**<br>(0.137) | 0.343<br>(na) |

no differences in density exist before and after restoration, was not rejected. The original hypothesis assumed that large numbers of small species, such as slimy sculpin *Cottus cognatus*, blacknose dace *Rhinichthys atratulus*, and longnose dace *Rhinichthys cataractae* in unstable treatment reaches would be replaced by fewer individuals and larger species (e.g., trout) after restoration. This could have occurred at the Batavia Kill, but unusually high total densities during the drought of 2001 may have disrupted any discernible trend at this stream. In general, densities of fish at all restored reaches decreased on average by 0.112 fish/m$^2$ ($P$ = 0.509) relative to fish densities at the corresponding reference reaches. The NCD restorations at Broadstreet Hollow Brook may have increased community density; however, normal interannual variations in other factors that were not evaluated in this study (e.g., precipitation, discharge, and temperature, or differences in recruitment, survival, and predation) could be the reason for the lack of significant trends in the three restored reaches.

### *Community Biomass*

Like total density, community biomass in the treatment reaches at Broadstreet Hollow Brook and the East Kill were significantly greater both years after restoration than during the 1 or 2 years before restoration (Figure 2D, 2E), but not in the Batavia Kill (Figure 2F). The Δ biomass averaged 14.34 g/m$^2$ greater ($P$ = 0.015) after restoration than before restoration only at the Broadstreet Hollow Brook treatment reach (Table 1). Results of a two-factor ANOVA that combines biomass differentials from all three streams indicate that (1) biomass differentials increased significantly on average by 5.32 g/m$^2$ after restoration ($P$ = 0.054), (2) mean biomass differentials differed slightly ($P$ = 0.123) among the streams, and (3) the response of biomass to restoration differed ($P$ = 0.03) across the three streams (Table 2).

The NCD restorations significantly increased community biomass at treatment reaches;

thus, the hypothesis—that increased stability produced greater total community biomass in restored reaches—was accepted. The null hypothesis—that no differences in biomass existed before and after restoration—was rejected. Results indicate that total community biomass at treatment reaches tended to increase after restoration in absolute terms, but may decrease or increase relative to interannual changes in community biomass that normally take place in all streams. Significant increases or decreases in biomass in the three treatment reaches indicate that physical and biological conditions unique to each stream may dictate the magnitude and direction of change in community biomass in response to restoration. Further evaluations of species-specific responses might better elucidate the basis for the observed variability. Large interannual fluctuations in total biomass at all reference reaches annegall and, at treatment reaches before restoration, suggest that normal year-to-year changes in other environmental factors must also affect biomass of fish communities.

The ability of BACI analyses to detect and more accurately quantify the effects of reach restoration can be illustrated through examination of the small decrease in relative biomass at the Batavia Kill (Figure 2D) and the large increase in relative biomass at Broadstreet Hollow Brook (Figure 2E) following restorations. Estimates of biomass at the Batavia Kill treatment reach before and after restoration varied highly from year to year, and mean biomass decreased by about 4.0 g/m$^2$ after restoration. The biomass differential at the Batavia Kill treatment reach averaged -1.7 g/m$^2$ before restoration and -3.4 g/m$^2$ after restoration. Consistent differences during both periods (before and after restoration) lessen the effects of interannual variability and provide evidence (though not significant) for a negative effect of restoration on community biomass (net loss of 1.68 g/m$^2$) at the restored Batavia Kill reach. Estimates of biomass at the Broadstreet Hollow Brook treatment reach indicate that biomass increased on average by about 9 g/m$^2$ after restoration (Figure 2e). Biomass differentials in Broadstreet Hollow Brook averaged -4.7 g/m$^2$ before restoration and -9.7 g/m$^2$ after restoration (Figure 2E). Consistent biomass differentials at both reaches for 2 years before and 2 years after restoration produce low variance. Combined with a large increase mainly at the treatment reach, these data provide strong evidence of a significant increase in fish biomass (14.34 g/m$^2$) due to restoration. Thus, the BACI analyses, which standardize observed responses in treatment reaches against the normal year-to-year variations in community indices in corresponding reference reaches, help define the effects of restoration on fish communities.

The main concerns with BACI analyses are that different communities or local and regional factors at the paired reference and treatment reaches might produce dissimilar year-to-year changes in indices, which would invalidate the assumed parallel community trends. A qualitative assessment of indices at reference and treatment reaches in Broadstreet Hollow Brook and in the Batavia Kill prior to each restoration suggests that reach pairs exhibited similar seasonal fluctuations before treatments. Reference reaches for all three streams were selected for their close proximity to corresponding treatment reaches; therefore, the reference reach at the East Kill can also be considered appropriate for the BACI analyses, despite the lack of survey replication (two sample years) before reach restoration.

### *Communitry Richness*

Annual statistics (means and confidence intervals) could not be generated for community richness (or for density and biomass

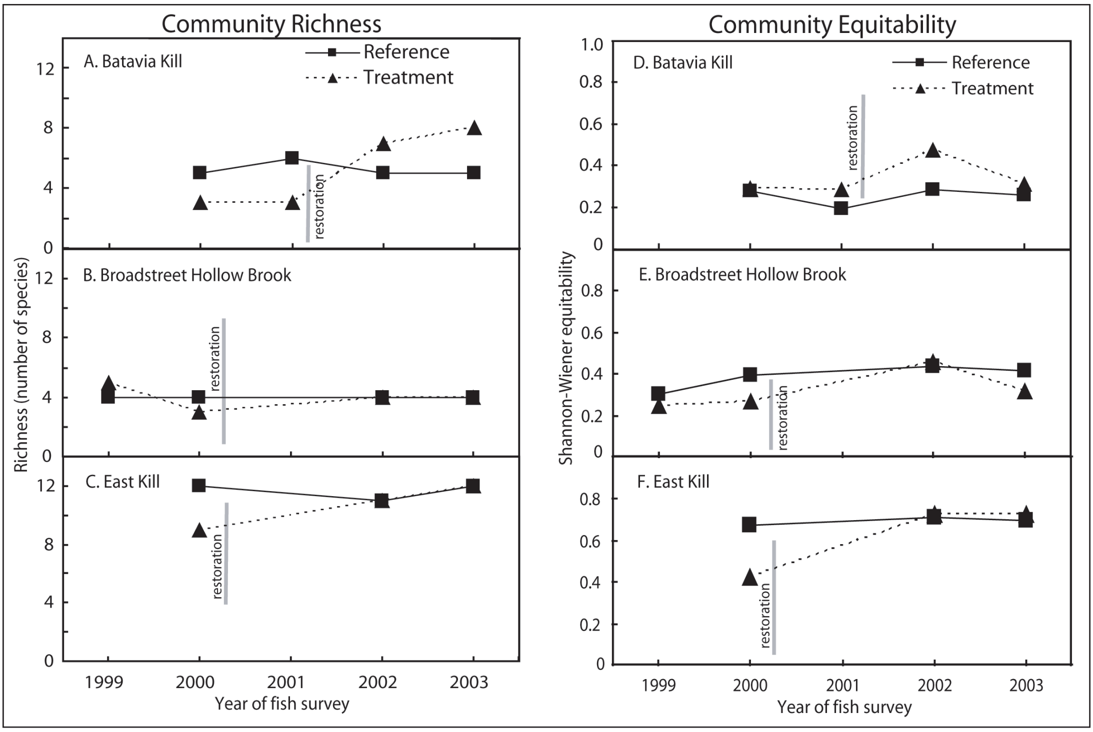


**Figure 3.** Total fish-community richness (number of species) and species equitability (Shannon-Wiener diversity) at paired treatment and reference reaches in the three study streams before and after restoration, 1999–2003.

equitability) at each reach, but the mean number of fish species for 2 years after restoration in the Batavia Kill and East Kill treatment reaches (Figure 3A, 3C) was greater than the mean during the 2 years before restoration. Richness also appeared to be relatively stable at all reference reaches during the study (Figure 3A, 3B, 3C). Richness differentials increased significantly ($P = 0.019$) by 5.0 species after restoration only at the Batavia Kill treatment reach, although it also increased on average by 3.0 species ($P$ not available) at the restored East Kill reach (Table 1). Results of the two-factor ANOVA, using combined richness differentials, indicate that 1) restoration increased community richness by an average of 2.43 species ($P = 0.003$), 2) richness differed ($P = 0.101$) among the three streams, and 3) the response of community richness to restoration differed ($P = 0.016$) among the 3 streams (Table 2). These results indicate that community richness at the three treatment reaches responded differently in magnitude or direction of change to respective stream restorations (Figure 3A, 3B, 3C).

The NCD restorations significantly increased community richness at treatment reaches; thus, the hypothesis—that increased stability increases the number of fish species in restored reaches—was accepted. The null hypothesis—that no differences in richness exist before and after restoration – was rejected. The 60% increase in the number of fish species on average after restorations has several important implications. First, the NCD restorations had a strong effect on species richness. Second, biodiversity (a critical component of biological integrity) can recover relatively quickly

**Table 2.** Results of before-after-control-impact analyses summarizing mean changes in index differentials after restoration of the three treatment reaches, and results (*P*-values) of two-factor ANOVAs assessing differences in combined index differentials (1) before and after restoration, (2) among the three streams (regardless of restoration), and (3) factor interaction (differing responses among the three streams). [*n*=11; boldface values indicate *P*-values < 0.15.]

| | | *P*-values for differences in index differentials | | |
|---|---|---|---|---|
| Community index | Mean change | Before-after restoration | Stream-to-stream | Interaction |
| Total density | -0.112 | 0.509 | 0.238 | 0.185 |
| Total biomass | **5.32** | **0.054** | **0.123** | **0.030** |
| Richness | **2.43** | **0.003** | **0.101** | **0.016** |
| Equitability (species density) | 0.101 | 0.260 | 0.270 | 0.176 |
| Equitability (species biomass) | **0.207** | **0.004** | **0.016** | **0.063** |

in disturbed streams after restoration, provided that other stream sections contain source populations. Third, if the increased number of species is coupled with an increased range in tolerance to environmental conditions in restored reaches, then these fish communities can be expected to be more resilient or adaptable to ecosystem perturbations than communities in disturbed stream reaches. Thus, the NCD techniques used in this study should be given serious consideration if restoration goals include increasing fish biodiversity in disturbed stream systems.

### *Community Equitability*

Neither variations in density (numeric) equitability within each treatment reach (Figures 3D, 3E, 3F), nor shifts in density-equitability differentials within individual streams (Table 1) or in all three treatment reaches combined (Table 2) identified significant changes that could be attributed to restoration. These findings indicate that the restorations did not cause any significant change in the evenness or balance of fish populations within the treated reaches. In other words, the few general or opportunistic species that are tolerant of harsh or extreme environmental conditions and low habitat diversity, and that typically dominate fish communities in unstable reaches before restoration, did not appear to be substantially replaced by a more balanced fish-species assemblage, which might be better suited to greater habitat diversity and less extreme environmental conditions. Numeric domination of fish communities by a small number of species appears to continue at restored treatment reaches; thus, the species with the largest population (largest proportion of the community) may or may not change after restoration.

Though NCD restorations did not drastically alter the numeric balance of fish species, they strongly influenced the distribution of species biomass within communities at restored treatment reaches; biomass equitability was higher both years after restoration than before restoration at treatment reaches in all three streams (Figure 4A, 4B, 4C). Biomass-equitability differentials were 0.031 greater ($P$ = 0.137) after restoration than before restoration at Broadstreet Hollow Brook, 0.363 greater ($P$ = 0.099) at the Batavia Kill, and 0.343 higher ($P$ not available) at the East Kill (Table 1). Results of ANOVA using biomass-equitability differentials from all three streams indicate that (1) restoration increased biomass-equitability differentials significantly by 0.207 ($P$ = 0.004), (2) biomass-equitability differentials differed ($P$ = 0.016) among the three streams, and (3) the response of biomass equitability to restoration also differed ($P$ = 0.063) among streams (Table 2).

These findings support the hypothesis that increased channel stability increases the equitability of species biomass in restored reaches. The null hypothesis—that no differences in biomass equitability exist before and after restoration—was rejected. Increased biomass equitability in restored reaches indicates that the restorations significantly improve biological integrity in previously degraded streams. For example, total biomass of fish communities at the East Kill and the Batavia Kill treatment reaches before restoration consisted almost entirely of one or two small prey species (as high as 99% slimy sculpin, blacknose dace, and/or longnose dace), with few or no top predator species. After restoration, biomass and the proportion of brown trout *Salmo trutta*, brook trout *Salvelinus fontinalis*, and rainbow trout *Oncorhynchus mykiss* increased, whereas biomass (and proportion) of minnow species decreased. The fish communities that were established in restored reaches generally resembled the natural, evenly balanced fish communities in corresponding reference reaches. The NCD restorations, therefore, helped to reconstitute more diverse, balanced, and complete fish communities and enhanced the biological integrity of these aquatic ecosystems.

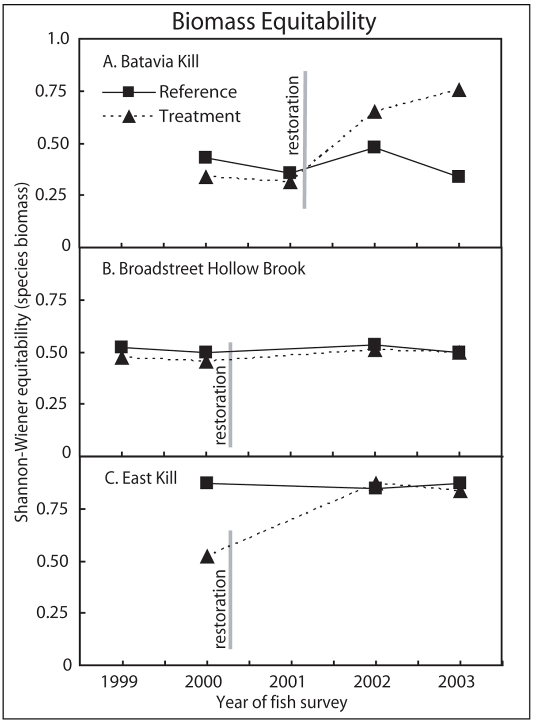


**Figure 4.** Biomass equitability (Shannon-Wiener) for fish communities at paired treatment and reference reaches in the three study streams before and after restoration, 1999–2003.

### *Related studies*

The authors are unaware of any studies that describe the response of fish communities to restoration of stable-stream geomorphology through natural-channel-design principles. A few diverse studies, however, show that other types of restorations benefited fish populations and communities in a manner similar to that observed in the restored Catskill Region streams. Manipulation of coarse or large woody debris in streams has been investigated far more than any other stream-improvement technique. For example, addition of large woody debris in 15 streams in the Northwest was correlated with lower water velocities, increased total pool area and numbers of pools, as well as increased density of juvenile coho, cutthroat, and steelhead trout in relation to those in reference streams during summer or winter periods (Roni and Quinn 2000). Placement of drop-log structures in six small Colorado streams also decreased water velocity and increased pool volume, depth, and cover, and typically increased the abundance and biomass of age-2 brook, brown, and rainbow trout (Riley and Fausch 1995). Addition of stone spurs, which are somewhat analogous to the rock veins used in our NCD restorations, to stabilize banks of several incised or rapidly eroding warmwater streams in Mississippi usually (but not always) increased species richness and significantly shifted community composition away from colonist cyprinids and small centrachid species and toward higher densities and biomass of large catostomid, ictalurid, and centrarchid species (Shields et al. 1997, 1998, 2000). Though not a manipulative study, fish communities in geomorphically degraded streams of the coastal plain of Maryland had low diversity and were dominated by a few tolerant taxa; however, less impacted streams had more balanced species assemblages and higher indigenous species richness and abundance (Scott and Hall 1997). Although none of the above efforts used NCD techniques, the observed effects on resident fish communities demonstrate that findings of the present investigation are not unique and that a variety of restoration techniques can have beneficial effects on stream ecosystems. The effectiveness of various techniques probably differ; however, potential differences cannot be assessed at present from the available information.

In conclusion, significant increases in species richness and biomass equitability in treated reaches clearly demonstrate that biodiversity of fish communities in small streams in the Catskill Mountains is positively affected by NCD restorations. Increases in fish biomass and equitability following restoration indicate that the normal structure and function, and thus biological integrity of resident fish communities are also improved in previously degraded reaches. These data, however, describe the response of fish communities to restoration over a relatively short period of time. Continued monitoring of fish communities in these reaches and in additional restored reaches, therefore, is necessary to verify that the changes observed during the first two years following restoration are sustained over the long term. The improvements in fish communities were likely related to increased habitat quality, quantity, and diversity and increased geomorphic stability generated by the NCD restorations. Additional analyses and interpretation of habitat and stability data are underway to confirm that NCD techniques increase geomorphic stability, and that habitat condition and stream stability are correlated with the integrity of fish communities.

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