Sedimentation Impacts on Resident Rainbow Trout in a High-gradient Southern Appalachian Stream

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Abstract: Changes in substrate and rainbow trout *(Oncorhynchus mykiss)* catch rates in Howard Creek, a southern Blue Ridge escarpment stream were evaluated before and during sedimentation resulting from construction of a pumped-storage hydroelectric project. As substrate quality declined from road and dam construction, both y-o-y and adult rainbow trout catch rates declined. The decline in y-o-y catch rates preceded the decline of adult catch rates. The substrate component best correlated ($r = -0.96$ and -0.88) with declining y-o-y and adult rainbow trout catch rates was the very fine sand fraction. Accumulation of fine sediments in Howard Creek impacted spawning success of rainbow trout and lack of recruitment resulted in declining adult rainbow trout catch rates.

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Substrate is the underlying foundation of the stream ecosystem and is easily impacted by sedimentation (Bjornn et al. 1977, Herbert and Merkens 1961, Newcombe and MacDonald 1991). Excessive fine sediment in the substrate can be detrimental to salmonid reproduction, habitat, and survival (Cordone and Kelley 1961, Minshall 1984, Chapman 1988, Waters 1995). Most of the impact on stream substrate and biota is caused by fine sediments, but the definition of what fine sediment is and how much is harmful remains unsettled (Young et al. 1991).

We evaluated effects of increased fine sediment on wild rainbow trout populations in Howard Creek, a southern Blue Ridge escarpment stream, by monitoring prior to and during construction of the Bad Creek Reservoir (upper reservoir for the Bad Creek Pumped Storage Project). Objectives of our study were to: 1) relate chronological developments of construction activity to changing substrate conditions in Howard Creek, 2) correlate abundance of rainbow trout to increased sedimentation of riffle habitats, and 3) evaluate sand fraction analysis and composite substrate parameters as indicators of substrate changes associated with changes in rainbow trout catch rates.

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Methods

Howard Creek is a third-order, high-gradient, headwater mountain stream located in northwestern South Carolina, which flows from about 975 m above mean sea level to 335 m elevation at its confluence with Lake Jocassee. Typically <9 m wide and 0.5 m deep, Howard Creek consists mainly of a series of pools and riffles with steep sections of chutes and waterfalls. Average gradient over the total stream length is 8.6%. Two second-order streams, Limber Pole Creek and Corbin Creek, flow into Howard Creek within 1.6 km above Lake Jocassee. Howard Creek's baseflow discharge, monitored 20 m downstream of the Corbin Creek confluence, is approximately 0.6 m^3/sec.

The drainage basin of Howard Creek is characterized by mountainous terrain with moderate to steep slopes. Grades frequently in excess of 50% and up to 125% are common in some areas. Most of the soils in the watershed consist of a fine sandy loam derived from granite, granitic gneiss, and biotite mica.

Construction of Bad Creek Reservoir began in July 1981 and was completed in late 1990. An access road was constructed within the watershed in 1982, when significant earth-moving activities began. The peak period of clearing and construction occurred in 1985 and 1986. The main coffer dam was completed in 1986 and soil and drainage stabilization measures were put in place in 1987 to help control erosion. Additional land-clearing activities occurred sporadically in the West Bad Creek basin from 1987 into early 1990. By the end of 1990, >182 ha of forest had been cleared in the construction area.

Substrate Sampling

Monthly substrate sampling in Howard Creek began in January 1980 and continued through December 1990 at 3 locations. Station 3, the control station, was located upstream of any project-related activity. Station 2 was located immediately downstream of the project site, while station 1 was approximately 4.8 km further downstream.

Substrate samples were collected in riffles to a depth of about 5 cm along permanently located transects (1/site) by manually grabbing sediment at about 0.5-m intervals. Because the stream bottom was constantly changing in response to storm flows, repetitive sampling probably had no effect on sample composition. The total composite sample consisted of about 10–12 subsamples and typically contained 1–2 kg (dry weight) of fluvial sediment, substantially excluding all material larger than very coarse gravel (>32 mm) and provided a relative measure of the sand and silt fraction in the substrate.

Sediment samples were oven dried at 70 C for at least 24 hours and separated into respective standard size fractions by sieving. A full geometric sieve series that sampled gravels, sands, and silts and clays (i.e., 32-, 16-, 8-, 4-, 2-, 1-, 0.5-, 0.25-, 0.125-, and 0.062-mm sieve openings) was used. The dried fractions were weighed and converted to percentages. Substrate data from pre-construction conditions through construction and into the post-construction period for Howard Creek were analyzed (Dysart et al. 1981). Changes in relative distribution of different fractions provided an indication of changing substrate conditions, especially materials in the interstitial spaces among gravels and cobbles in the riffle areas being sampled.

Two composite substrate parameters were calculated to characterize the entire sample, materials that passed through a sieve with 32-mm openings. Median particle size (D_{50}), the diameter at which 50% by weight of the material is finer, was calculated from a cumulative plot of "percent finer than" vs. "logarithm of particle diameter" (Garde and Ranga Raju 1977).

The relative proportion of fine and coarse particles in the entire sample was expressed as the Hatcher fine-to-coarse ratio (R, Dysart et al. 1973), which was calculated as the weight of material passing through a 0.5-mm sieve, divided by the weight of material retained on ≥0.5-mm sieves. R values ≥1 indicate a higher percentage of fine (by weight) than coarse material.

Fish Sampling

Fish sampling was conducted independently of substrate sampling at sampling stations that encompassed riffle areas used for substrate sampling or were in close proximity to substrate sampling areas. Stations 1, 2, and 3 were sampled annually for rainbow trout. Station lengths were 500, 450, and 350 m, respectively.

Rainbow trout in Howard Creek at station 1 had access to Corbin Creek and Lake Jocassee. Just below station 2, chutes of swift water over large, sloping rocks prevented upstream migration of any trout from Lake Jocassee, Corbin Creek, Limber Pole Creek, or lower Howard Creek. Station 3 was also isolated from any upstream migration of rainbow trout by a steep gorge.

Single pass electrofishing was conducted annually in October, 1980–1990, to determine relative abundance of rainbow trout at each station. Smith-Root Type VIII-A backpack electrofishers with direct current outputs of 50–150 milliamperes were used by 2 2-man teams at station 1 and 1 2-man team at stations 2 and 3. Two teams were used at the former station because of its greater stream width. During sampling, which began downstream of a major fall and progressed upstream to it, stunned fish were netted, measured for total length (mm), and returned alive to the creek at the station.

Graphical and Statistical Analyses

Since major earth-moving activities for Bad Creek Reservoir (129 ha) did not occur until 1982, Howard Creek pre-construction conditions at each station were established by averaging substrate and rainbow trout data collected from January 1980 through December 1981. These pre-construction data provided reference conditions against which impacts could be assessed.

Relations between trout catch rates and changing substrate composition were evaluated using graphical techniques. Ratios to pre-construction means were calculated by dividing measured post-construction values by their mean value during pre-construction at the same station. By plotting these ratios over time, trends were readily observable because the pre-construction average always equaled 1.0.

Correlation analysis was used to determine which substrate parameter(s) were most strongly related to fish catch rates. Correlation coefficients were calculated at each station for adult and y-o-y catch rates vs. 12-month averages for 5 substrate parameters from 1980 through 1986, the start of the study through the period of greatest impact. Correlation coefficients (r) were calculated using $\log(x + 1)$-transformed data of both the dependent (fish) and independent (substrate) variables.

Results and Discussion

Construction Effects on Sedimentation and Substrate Composition

Based on erosion models, cumulative sediment yield from the Bad Creek Project Area from January 1980 through July 1990 was 100,700 megagrams. From 1984 through 1988, sediment yield into Howard Creek averaged 18,300 megagrams/year, about 18 times higher than during the pre-construction period. During 1989 and 1990, sediment yield had decreased to <4,000 megagrams/year. Although erosion rates were high during the project, Ziegler (1990) estimated that approximately 90% of the potential erodible sediments was captured on site by in-place erosion management strategies. In spite of major efforts to control erosion, sedimentation still impacted Howard Creek.

Sand Fraction Analysis

Sand fraction analysis indicated a major shift in composition of the substrate toward finer sediments as Howard Creek was impacted by heavy sedimentation from construction activities. Changes in composition of the sand fraction of the substrate were first detected in 1982 (Fig. 1), when significant earth-moving activity began. Fine sediments (VFS and FS fractions) increased in the first quarter of 1982 at station 1 and in the second and third quarter of 1982 at station 2. During the third quarter of 1982, average percent VFS at station 2 was nearly 9 times greater than the pre-construction mean.

Percent VFS averaged about 12-fold greater than its pre-construction mean at station 2 during peak construction (1985–1986). A similar trend was observed at station 1, even though it was located 4.8 km downstream from the major impact site.

At the upstream control station, percent VFS varied considerably from month to month. However, on only 2 occasions did percent VFS exceed 2.5 times the pre-construction mean for 2 consecutive months. These increases were attributed to the long drought which impacted the area from 1984 to 1988 and minimized the ability of the stream to flush sediments downstream.

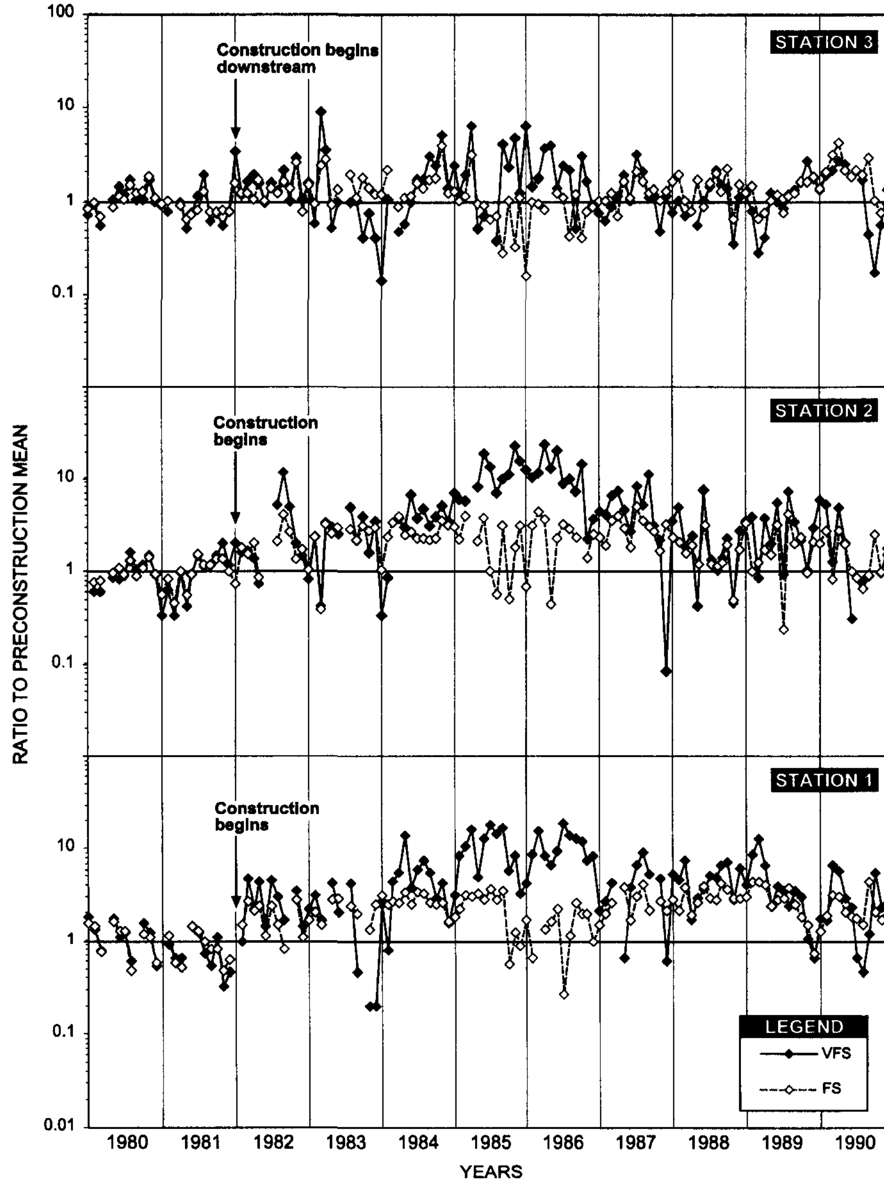

Figure 1. Changing composition of the sand fraction of the substrate at stations 1 and 2 in response to construction in the Howard Creek watershed, South Carolina. FS = fine sand and VFS = very fine sand. Station 3 was the upstream control.

VFS during the pre-construction period averaged 1.5, 2.4, and 2.9% at stations 1, 2, and 3, respectively. On 1 occasion, in April 1986, VFS comprised 56.1% of the sand fraction at station 2, a 23-fold increase over pre-construction conditions. High monthly values for VFS during construction, combined with the relatively long duration of elevated values, indicate a major change had occurred in the composition of the sand-size substrate relative to pre-construction conditions.

The influence of major erosion-control measures and the coffer dam were best reflected by the 1987–1990 overall downward trend of percent VFS from peak impact conditions. This trend was more evident at station 2 than at station 1, and may indicate that fine sediments had flushed out of the upper station but were not yet removed from the lower station.

Changes in Composite Substrate Parameters

The vast majority of eroded particles reaching Howard Creek were sand-size or finer and visibly changed the nature of the entire substrate. Composite substrate samples, which included all particle fractions smaller than very coarse gravels, reflected this change.

At impacted stations, D_{50} decreased 90%–94% from pre-construction conditions to 1986 (Table 1). The R value increased markedly from 1980 through 1986 at impacted stations, while remaining relatively constant at the control station. At station 2, R in 1986 was about 15 times that of the pre-construction mean.

Sedimentation Effects on Fish

The relatively constant catch rates of fish at the control station contrasted sharply with generally declining catch rates for adult rainbow trout at station 1 and y-o-y and adult rainbow trout at station 2 (Fig. 2). Although substrate conditions in 1988 had improved (Fig. 1), catch rates at impacted stations remained low.

Y-o-y and adult rainbow trout catch rates remained low at station 2 through 1990, but y-o-y catch rates at station 1 increased during 1987–1990. While substrate composition improved, it remained doubtful that these fish were spawned in Howard Creek. They were not recruiting to the adult population and were apparently entering lower Howard Creek from tributary streams (Limber Pole Creek and Corbin Creek). Lack of spawning habitat would be expected to slow trout recovery in sediment-

Table 1. Changes in composite substrate parameters[a] at impacted stations in Howard Creek from preconstruction conditions to the period of peak impact in 1986.

	Pre-construction		1986	
Station	D_{50} (mm)	R	D_{50} (mm)	R
1	8.4	0.15	0.5	1.14
2	3.0	0.40	0.3	5.87

a. D_{50} = median particle size at which 50% by weight of the sample is finer; R = Hatcher fine-to-coarse ratio (Dysart et al. 1973).

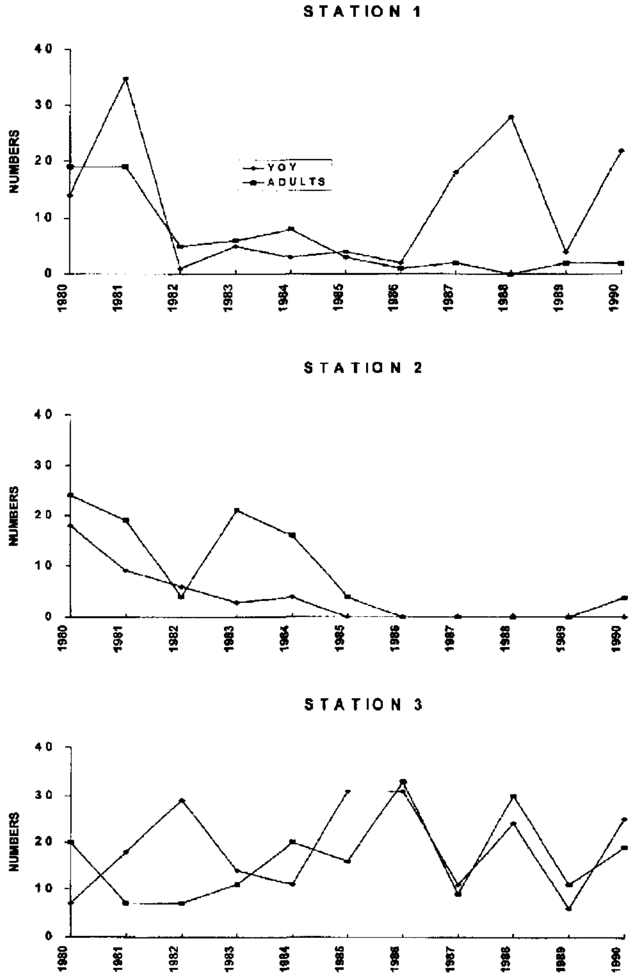

Figure 2. Catch rate trends for adult and y-o-y rainbow trout at control (station 3) and impacted reaches (stations 1 and 2) on Howard Creek, South Carolina.

impacted streams (Cordone and Kelly 1961, Bjornn et al. 1977, Lotspeich and Everest 1981, Young et al. 1991).

Graphical analysis illustrates that both life stages of rainbow trout were adversely affected by heavy sedimentation from Bad Creek Reservoir construction. The increase in the VFS after construction started corresponded to gradually declining adult and y-o-y catch rates. In 1983 and 1984, elevated VFS levels at station 2, averaging about 3 times higher than the pre-construction mean at this station, corresponded to relatively constant, yet lower, catch rates. As VFS continued to increase, catch rates for fish continued to decrease until, in 1985, no y-o-y were captured. In 1986 (the first year that neither adult nor y-o-y trout were collected), VFS averaged 33.2% of the sand fraction at station 2 compared to an average of 2.4% prior to construction.

Statistical evaluation of the data supported the graphical interpretation. Because there were no significant inflows, the most realistic comparison of effects of changing substrate conditions in riffles with trout catch rates was at station 2. Here, VFS yielded the highest negative correlation coefficients of any substrate parameter with y-o-y (−0.96) and adults (−0.88) trout catch rates (Table 2). Correlation coefficients were generally not as strong at station 1, probably because this station was accessible to trout movement into and from tributaries.

Other substrate parameters were also correlated, either in a negative (FS, Silt/Clay, R) or positive (D_{50}) manner, with trout catch rates. As expected, correlation coefficients derived from data only through 1986 (peak impact) resulted in higher *r* values than using data from the entire study period. All substrate parameters at station 2 were strongly correlated with y-o-y catch rates, which was not always the case for adult trout catch rates. Spawning success was apparently critically affected by increased sedimentation.

Establishment of a threshold value where VFS or some other substrate parameter becomes detrimental to trout is still elusive. Fish catch rates varied widely (0–35 trout) when VFS was <10% and no threshold value above which trout populations collapsed was evident. Rather than a threshold value, this study suggests that chronic sedimentation gradually reduced the quality of the habitat until spawning was unsuccessful.

Heavy sedimentation can cause failure in spawning and eliminate rearing habitat (Cordone and Kelley 1961, Bjornn et al. 1977, Alexander and Hansen 1986, Waters 1995). Life spans of wild rainbow trout in Howard Creek are short, with relatively few trout reaching 3 years of age (Duke Energy Corp., unpubl. data). Without adequate recruitment, adult rainbow trout populations quickly declined at the downstream stations.

Factors other than reduced spawning success were probably secondary contributors to the decline in trout catch rates at impacted stations in Howard Creek.

Table 2. Correlation coefficients for y-o-y and adult trout catch rates vs. substrate parameters in Howard Creek, based on 12-month averages, during the period of increasing sedimentation (1980–1986).

	Station 2		Station 1	
Parameter[a]	y-o-y	Adult	y-o-y	Adult
VFS	−0.96	−0.88	−0.64	−0.89
FS	−0.81	−0.49	−0.47	−0.29
Silt/Clay	−0.88	−0.81	−0.72	−0.91
D_{50}	+0.79	+0.49	+0.79	+0.87
R	−0.79	−0.39	−0.07	−0.29

a. VFS = very fine sand; FS = fine sand; D_{50} = median particle size at which 50% by weight of the sample is finer; R = Hatcher fine-to-coarse ratio (Dysart et al. 1973).

Macroinvertebrate food resources in Howard Creek were reduced during the construction period (Dillard 1992). Direct effects of sediment on other components of trout habitat, such as roughness elements on the streambed, foraging territories, and water depth, are not addressed in this paper, but may have also contributed to the decline in trout catch rates. Reductions in fish populations are often related to loss of cover by sand deposits (Saunders and Smith 1965, Elwood and Waters 1969, Barton 1977, Tripp and Poulin 1986).

Conclusions

The following conclusions are drawn from this 11-year investigation of the effects of sedimentation on the resident rainbow trout population of Howard Creek:

1. Changes in the composition of the substrate of Howard Creek were closely associated through time with heavy sedimentation caused by construction activities.
2. Of the substrate fractions investigated, strongest association with fish catch rates was exhibited by the VFS. Increasing VFS through 1986, the peak period of impact, correlated well with declining trout catch rates through that time. Other measures of the substrate, including composite substrate parameters, indicated increasing fines on the stream bottom and were related to declining trout catch rates.
3. We attribute the immediate decline in y-o-y and adult trout catch rates to reduced spawning success and loss of recruitment. Spawning success gradually declined as fine sediments accumulated in the substrate, until finally a point was reached where trout reproduction ceased.
4. Despite trapping 90% of erodible sediments on site, Howard Creek was severely impacted by sedimentation. More effective erosion control measures need to be implemented in early phases of construction projects when most sedimentation occurs.

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