MACROHABITAT FACTORS AFFECTING DISTRIBUTION PATTERNS OF FRESHWATER MUSSELS IN THE CLINCH RIVER (VIRGINIA, TENNESSEE)

by

Gregory W. Church

Dissertation submitted to the Graduate Faculty of
the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

BIOLOGY

APPROVED:

Donald S. Cherry, Co-chairman

Richard J. Neves, Co-chairman

Ernest F. Benfield

John Cairns, Jr.

Jerry L. Farris

October, 1997

Blacksburg, Virginia

MACROHABITAT FACTORS AFFECTING
DISTRIBUTION PATTERNS OF FRESHWATER MUSSELS IN
THE CLINCH RIVER (VIRGINIA, TENNESSEE)

by

Gregory W. Church

(ABSTRACT)

Studies were conducted to determine the macrohabitat factors structuring high quality mussel habitat in the Clinch and Little rivers. In the first habitat study, 4 substratum variables, 7 channel morphology variables, and 3 stream and valley variables were compared between high and low mussel density aggregations from 6 study reaches. Wilcoxon rank-sum tests were conducted separately for all transects, unbraided (without islands) transects, and braided (anastomosing river channels with islands) transects. Stepwise discriminant analysis (SDA) was used in the first habitat study to identify variables which best differentiated high and low mussel density transect groups. Percent bedrock (PBR) ($p>F=0.002$), d50 particle size ($p>F=0.03$), and mean depth (MDEP) ($p>F=0.11$) were the most useful predictors (cumulative average squared canonical correlation (ASCC) = 0.30) when SDA was performed on all transects ($n = 66$). The ASCC values improved substantially when unbraided and braided transects were analyzed separately. PBR ($p>F=0.0001$), d84 particle size ($p>F=0.05$), MDEP ($p>F=0.03$), and direction of streamflow (DIR) ($p>F=0.05$) were selected by SDA (cumulative ASCC = 0.52) for unbraided transects ($n = 43$), and proximity to floodplain (PROX) ($p>F=0.0008$) and PBR ($p>F=0.005$) were selected by SDA (cumulative ASCC = 0.61) for braided transects ($n = 23$). In the second habitat study, 14 habitat variables were compared between high and low quality mussel sites documented in a TVA survey (1986). The variables PBR ($p>F=0.0001$), d84 ($p>F=0.0001$), DIR ($p>F=0.09$), and valley floor width (VFW) ($p>F=0.05$) were selected by SDA (cumulative ASCC = 0.69) when all sites were included in the analysis; and PBR ($p>F=0.0095$), d84 ($p>F=0.004$), d50 ($p>F=0.15$), and DIR ($p>F=0.07$) were selected (cumulative ASCC = 0.62) when only unbraided sites were included in the analysis. Mussels were associated with areas of smaller mean particle size with low exposed bedrock in the channel cross-section. Site location patterns for the entire TVA data set ($n = 141$ sites) were examined for patterns relative to streamflow direction. The greatest frequency of high quality unbraided sites occurred where the river flows in the direction of geologic dip. High quality braided sites occurred where the river flows along the line of geologic strike. The orientation of bedrock ledges relative to direction of streamflow seemingly determines the long-term stability of mussel habitat in unbraided reaches by retaining streambed alluvium during high discharge events.

Key words: Unionidae, freshwater mussels, sediment particle size, geology, habitat, distribution, discriminant analysis, Virginia, Tennessee.

ACKNOWLEDGEMENTS

First and foremost, I thank the members of my graduate advisory committee for their invaluable guidance throughout my research. I am especially indebted to the co-chairs of my committee, Donald S. Cherry and Richard J. Neves for their patience, expert guidance, and editorial help with each chapter. I am also greatly indebted to Panayiotis Diplas and Jon Fripp of the Civil Engineering Department at Virginia Tech for their guidance regarding streambed sampling techniques. Although Dr. Diplas was not a member of my committee, he spared me much of his time, and on one occasion accompanied me in the field. I am also grateful for the financial support provided for my research by American Electric Power Corporation, and for the cooperation and assistance provided me at the AEP power plant in Carbo, Virginia. Additional financial assistance was provided by The Nature Conservancy and the Virginia Natural Heritage Program during a critical period of fieldwork on the Clinch and Little rivers. The interest of these organizations in my research provided much of the impetus necessary to bring the project to completion.

I am also indebted to Tennessee Valley Authority. Without the extensive data base on the Clinch River mussel fauna established by Steve Ahlstedt and other TVA biologists, much of my research would not have been possible. I am also grateful to Raymond Mitchell and the TVA Mapping Division in Chattanooga for providing infrared aerial photographs of the Clinch River watershed. I also wish to thank the Department of Mines, Minerals, and Energy of the Virginia Division of Mineral Resources in Abingdon, Virginia for their assistance in providing geologic maps, and assisting me with interpretation of the maps. I am very grateful to the many property owners along the Clinch and Little rivers who allowed me access to study sites. Most of the property owners I talked with conveyed genuine concern regarding water quality in the Clinch River and its tributaries.

I am especially indebted to the many people who assisted me with fieldwork. These included my sister, Laura Church, and my good friends Gregory McConnell and Joanna Harris. I am also indebted to Mark Miller and Jennifer Fischer, as well as many other graduate students at Virginia Tech in this regard. I am most grateful to my parents, Grady and Nelda Church, who have always given me encouragement and emotional support in my endeavors, and have provided financial support during lean times. Finally, I am eternally grateful to God for looking after someone like me.

TABLE OF CONTENTS

LIST OF TABLES

Table Number

LIST OF FIGURES

Figure Number

CHAPTER 1. THE CLINCH RIVER MUSSEL FAUNA AND CHARACTERIZATION OF MUSSEL HABITAT

Description of the study area

The Clinch River, a well-aerated hardwater stream, originates in Tazewell County, Virginia and flows southwest approximately 575 stream kilometers to join the Tennessee River at Tennessee River Kilometer 913 near Harriman, Tennessee. The Clinch River is situated in a long, narrow basin (7,542 km^2) which lies along the boundary between the Valley and Ridge and Cumberland Plateau physiographic provinces (Figure 1.1). The Clinch River basin comprises about 10.8 percent of the total area of the Tennessee River basin (Ahlstedt 1984). Elevations in the watershed range from 1,429 m on Russell Beartown Mountain to approximately 260 m at the confluence with the Tennessee River. The Clinch becomes a 4th order stream with the confluence of the North Fork Clinch River near Tazewell, Virginia, 5th order with the confluence of Plum Creek at Clinch River Kilometer (CRK) 554, and 6th order with the confluence of Big Cedar Creek at CRK 454 (Paul Angermeier, Department of Fisheries and Wildlife Sciences, Virginia Tech, personal communication 1993).

Most of the major tributaries entering the Clinch River from the north (Powell River, Guest River) have their origin in the Cumberland Plateau and exhibit a dendritic drainage pattern. Tributaries which lie south of the Clinch River are entirely within the Valley and Ridge province and exhibit a trellis drainage pattern, imposed by the long parallel mountain ridges. Consequently, the larger of these tributaries (Little River,

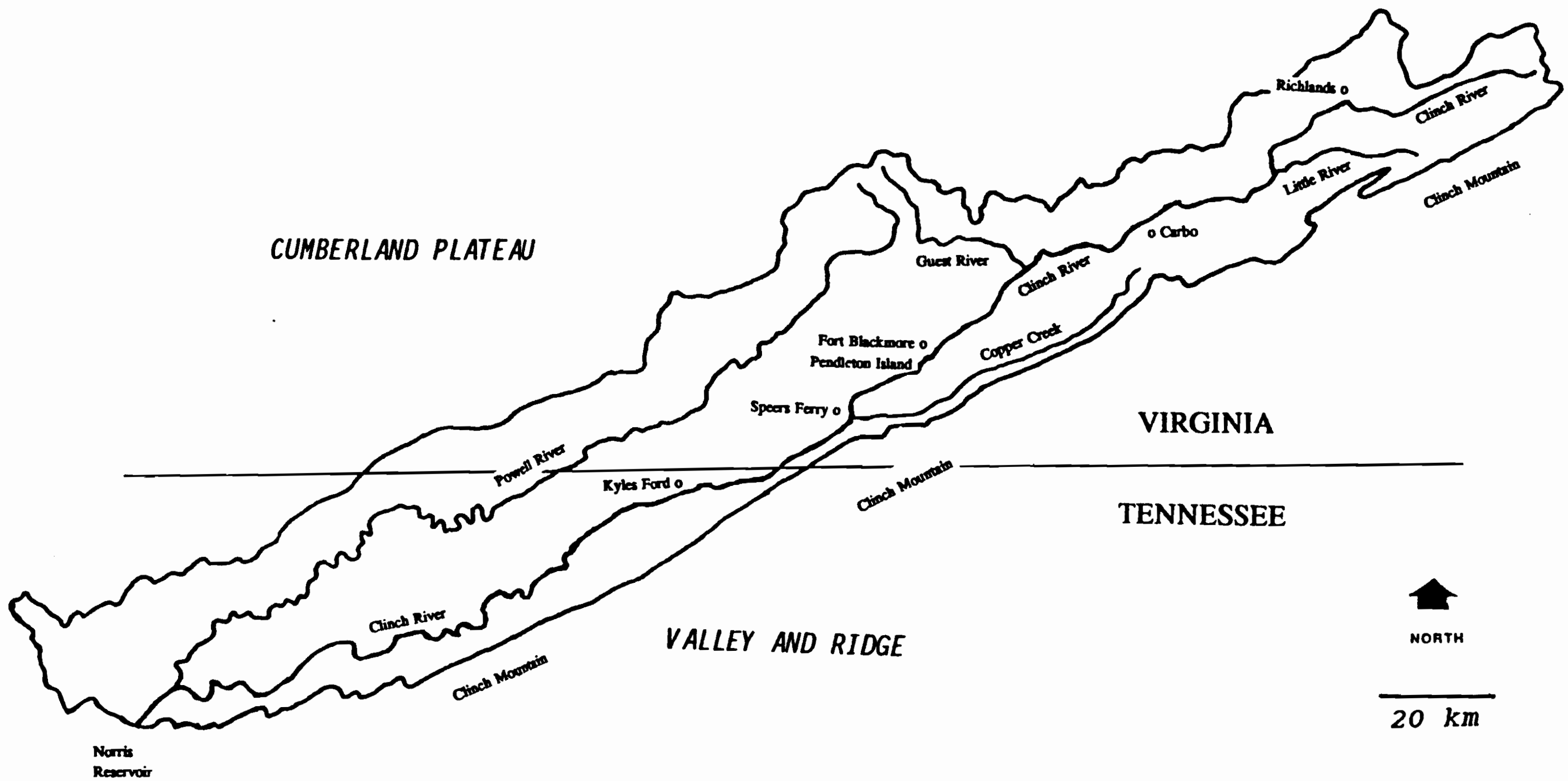

Figure 1.1. The Clinch River watershed upstream of Norris Reservoir.

Copper Creek) parallel the Clinch River for much of their lengths. Much of the streamflow within the carbonate formations of the Valley and Ridge portion of the basin is subterranean. The Little River, for example, drains from Fallen Rock Cave (one of the largest in Virginia) via Maiden Spring. The discharge of the Little River is much greater than its 52 km length and fourth order designation would suggest. The Clinch River was unimpounded prior to the completion of Norris Dam (CRK 128) in 1936 and Melton Hill Dam (CRK 37) in 1963 by the Tennessee Valley Authority. The confluence of the Powell River, the largest tributary of the Clinch, lies beneath the impounded waters of Norris Reservoir (Figure 1.1). Presently, only the 330 km of the Clinch River upstream of Norris reservoir remain free-flowing, and that is the area addressed in this dissertation.

The Clinch River basin is bounded to the southeast by the long ridge of Clinch Mountain, which is capped by the southeast-dipping Clinch sandstone of Silurian age. The heights of the Cumberland Plateau, which confine the watershed to the northwest, are capped by the nearly horizontal sandstone, shale, and coal strata of the Pennsylvanian-aged Lee and New River formations. The formations which lie between Clinch Mountain and the Cumberland Plateau range in age from Lower Cambrian to Mississippian, and are principally limestones, dolomites, shales and siltstones. The gradient, sinuosity, and valley morphology of the Clinch River are directly influenced by the geologic formations through which it flows. For example, reaches of the river which flow through the Rome Formation (a thick shale formation) are characterized by lower gradient and greater flood plain development than adjacent reaches that flow through limestone and dolomite.

Selected hydrologic data for the Clinch River are reported in Table 1.1 for Kyles Ford, Tennessee and Fort Blackmore, Virginia (TVA 1986). These data provide an indication of the temporal variability in discharge volume of the Clinch River upstream of Norris Reservoir. These unimpounded reaches of the Clinch are subject to periodic droughts and major floods spanning nearly three orders of magnitude of discharge volume. The greatest discharge volume recorded for the Clinch River to date was 89,000 cfs at Speers Ferry, Virginia on April 5, 1977 (USGS 1991). This flood, which crested at 16.7 feet above bankfull discharge, resulted in the abandonment of the town of Clinchport and permanent relocation of most of the town's residents.

Table 1.1. Selected data for two Clinch River stations

Station	Drainage Area (miles^2)	Mean Flow (cfs)	7Q10 Flow (cfs)	20 Year Flood (cfs)
Kyles Ford (CRK 304.9)	1268	1806	110	52,000
Ft. Blackmore (CRK 365.9)	897	1267	70	38,000

Significance of the Clinch River mussel fauna

Van der Schalie and van der Schalie (1950) recognized six major freshwater mussel (family Unionidae) faunal regions having distinct species assemblages. These regions are: Atlantic, Pacific, Apalachicolan, Mississippian, Ozarkian, and Cumberlandian. The Ozarkian and Cumberlandian regions can be considered as major areas of unionid endemism within the Mississippian Region (Dennis 1984). The Cumberlandian region is comprised of the Tennessee River drainage from the headwaters to Muscle Shoals, Alabama, and the Cumberland River drainage from the headwaters to Clarksville, Tennessee. The Cumberlandian Region has long been recognized as a major center of freshwater mussel diversity and endemism (Ortmann 1924, 1925) and is perhaps the world's most prolific region for species of the Unionidae (Ahlstedt 1984).

The Clinch River, a Cumberlandian headwater tributary, has been recognized for its rich mussel fauna since the studies of Adams and Ortmann, which were reported by Ortmann (1918). These surveys, conducted at 26 sites, were the most complete pre-impoundment documentation of the Clinch River mussel fauna. Approximately 240 km of the Clinch River are now inundated beneath the impounded waters of Norris Lake and Melton Hill Lake. These impoundments cover some of the richest mussel-containing riffle and shoal habitats once found in the river (Ahlstedt 1984). While early investigations documented the mussel species richness of the river, they were not quantitative and therefore revealed very little about the relative abundance of mussel species. The only indication of relative abundance of mussel species in pre-history is from molluscan shells in aboriginal kitchen middens of American Indian villages. Parmalee and Bogan (1986) studied such a site along the Clinch River which was inhabited from about 800 B.C. to A.D. 1100. They concluded that molluscs were readily consumed as a food source, and that middens accurately reflected the composition and relative abundance of mussel species present at that time.

Several unionid surveys have been conducted on the Clinch River in recent years. These were probably precipitated in part by enactment of the Endangered Species Act in 1973 and subsequent inclusion of a number of unionids on the Federal List of Endangered and Threatened Wildlife. The results of major mussel surveys are summarized in Table 1.2. The most comprehensive survey of the Clinch River mussel fauna to date was conducted by Ahlstedt (1984) in which 47 species were identified from 204 collecting sites. Ahlstedt collected 43 species from 141 sites on the upper Clinch (upstream of Norris Reservoir), including 16 endemic Cumberlandian species. Ortmann (1918) reported 42 mussel species from 14 collecting sites on the upper Clinch, including 10 species not found by Ahlstedt. Ahlstedt concluded that these species "are now believed extirpated from the Clinch or are considered extinct".

Table 1.2. Mussel species richness reported from surveys of the Clinch River.

Investigator	Year	Sites	Species/subspp.
Ortmann & Adams	1918	26	60
		12 (LC)	53 (LC)
		14 (UC)	42 (UC)
Stansbery	1973	-	53
Bates & Dennis	1978	- (UC)	38
Neves	1980	6 (UC)	32
Ahlstedt (TVA)	1984	204	47
		63 (LC)	20 (LC)
		141 (UC)	43 (UC)
Ahlstedt (TVA)	1988	11 (UC)	35 (UC)

LC = Lower Clinch; UC = Upper Clinch above Norris Reservoir

Anthropogenic impacts to the mussel fauna

Most unionid species are particularly vulnerable to impoundment, siltation, and pollution (Sheehan et al. 1986). Impoundment is thought to be the single greatest factor responsible for the decline of Cumberlandian mussel species, and is also the most irreversible (USFWS 1983). Impoundment eliminates riffle-run habitats which are necessary for survival of riverine mussels (USFWS 1982). In addition, cold hypolimnetic discharges seriously impair growth and reproduction of mussels downstream from dams. Most unionids require specific fish hosts for the parasitic glochidial stage of their life cycles. Lotic host fishes may be eliminated by impoundment, which favors the establishment of lentic fish communities (Nielson et al. 1986). Dams, in addition to altering upstream and downstream flow and temperature regimes, are usually physical barriers to fish migration.

Siltation also has severely impacted freshwater mussels (USFWS 1983). Ellis (1936) demonstrated mortality in mussels, due to a 0.6 to 2.5 cm overlay of silt, which was attributed to suffocation and interference with feeding. Dennis (1984) observed that uptake of algae by mussels is reduced by 80 percent at silt levels over 1000 mg/l (total suspended solids), which supports the conclusion of Churchill and Lewis (1924) that mussels exhibit little ability to sort food particles qualitatively. Possible sources of siltation in the Clinch River basin include storm water runoff from mining, logging, road construction, agriculture, overgrazed pastures, urbanized areas, and streambank erosion following removal of riparian vegetation.

Decline of the mussel fauna

A number of investigators (Ahlstedt 1984, Sheehan et al. 1986, Stansbery et al. 1986) have identified a reach of the upper Clinch River between CRK 411 and CRK 431 as having a depauparate mussel fauna. The mussel fauna was presumably eliminated from this reach by two major toxic spills originating from the site of a steam-electric generating plant at Carbo, Virginia. This reach was impacted in June 1967 by 198 million m^3 of alkaline fly-ash slurry (pH 12) which washed into the Clinch River during a spate (Cairns et al. 1971). In June 1970, a sulfuric acid spill from the same facility impacted the same reach for 24 km downstream

(Cairns et al. 1971). Ahlstedt (1984) speculated that mussels may be unable to colonize this reach because of continued discharges from the steam plant and coal fines from Dump's Creek and Lick Creek. Discharge of metals is also a problem in some reaches of the river. Jacobson et al. (1993) documented the toxicity of copper to sensitive early life stages of freshwater mussels.

Church (1990-1993 surveys) observed a depauparate mussel fauna in the Clinch River in the vicinity of Richlands, Virginia, possibly extending as far downstream as the confluence of the Little River (CRK 482 to CRK 515). Probable sources of impact are coal mining and quarrying activity, municipal wastewater treatment plant outfalls, raw sewage, and septic tank discharges.

In addition to impacts to the mussel fauna from obvious point sources, several researchers have reported a decline in mussel abundance and species richness in reaches far removed from identified point source impacts (Jenkinson and Ahlstedt 1988, Dennis 1987, 1989). Dennis (1987) reported a drastic change in community structure at Speers Ferry, Virginia (CRK 339.7) and Kyles Ford, Tennessee (CRK 304.6) between 1975 and 1986. *Epioblasma capsaeformis*, a dominant species at both sites in 1975, had virtually disappeared from both sites by 1987. She also reported greater than 50 % reduction in total mussel density at Speers Ferry between 1975 and 1986. Jenkinson and Ahlstedt (1988) reported that the mean number of mussels in the Clinch River declined from 12.10/m^2 in 1979 to 6.01/m^2 in 1988, based on quantitative sampling at 10 sites from CRK 256.2 to CRK 517.6. Statistically significant declines were observed for seven mussel species over the 9 yr period, while no species increased in abundance. Dennis (1989) reported the mussel community age-class structure at Pendleton Island, Virginia (CRK 364.3) to be skewed toward older age-classes, indicating a general decline in recruitment of all mussel species at the site. Scott (1994) also observed a lack of juvenile recruitment for four mussel species at Slant, Virginia (CRK 359.3) since 1979 and speculated the decline may be due to high sedimentation from the Cove Creek watershed.

In studies with Clinch River sediments, Yeager (1994) demonstrated intermittent sediment toxicity to *Daphnia magna* and *Chironomus riparius*, and suggested that acute insults are related to the frequency, duration, and intensity of rainfall events. Yeager also observed fluctuations in the concentrations of metals in Clinch River sediments and observed mortality of juvenile mussels in in-situ assays at some sites. Jacobson (1990) demonstrated much greater sensitivity of isolated glochidia and juveniles to copper toxicity than to encysted glochidia or adult mussels. Toxicity of sediments to sensitive hypobenthic juveniles may be the cause of poor mussel recruitment at some Clinch River sites.

Mussel distribution and habitat characterization

Van der Schalie (1938) and Dawley (1947) classified mussel habitats into lotic and lentic waters, then subdivided lotic waters into size categories. The following review is confined to studies of mussel distribution and habitat in lotic systems. Many of the early North American mussel studies were zoogeographic, and documented distinct species assemblages associated with major river drainages (Simpson 1896, Walker 1918, Ortmann 1924, van der Schalie and van der Schalie 1950). More recently, researchers have attempted to explain patterns of mussel distribution among streams within zoogeographic regions. Sepkoski and Rex (1974) used cluster analysis to compare mussel species assemblages of 49 coastal rivers of eastern North America. They considered the rivers as biogeographic islands due to saltwater barriers to faunal exchange, and found that similarity of assemblages is strongly influenced by proximity to species source rivers. Sepkoski and Rex (1974) also reported that drainage basin area was the best predictor of mussel species richness. Dennis (1984), however, reported similar species richness from sites on the Tennessee, Clinch, and Powell Rivers, though drainage area and stream size were vastly different. She concluded that diversity of habitat, type of substratum, and shoal (glide) area are more significant in determining mussel abundance and species richness, than either stream length or drainage area. However, she acknowledged that there is a trend in small to medium sized streams toward increasing species richness with increasing stream size. The positive correlation between stream size and mussel species richness in smaller order streams has been well documented (Bogan and Starnes 1982, Ahlstedt 1984, Warren et al. 1984, Church 1991). Bogan and Starnes (1982) attributed the increase in mussel species in the downstream direction to a concomitant increase in fish species richness, since mussel glochidia are obligate parasites on fish and depend on them for distribution.

Bogan and Starnes (1982) hypothesized that the headwater limit of mussel distribution may be predicted by an examination of the stream's physiographic gradient. Warren et al. (1984) observed a trend toward decreased mussel diversity with higher stream gradient, although there was no significant correlation between gradient and average numbers of species per stream segment. In a study of six mussel macrohabitat descriptors by Strayer (1993), stream gradient had the least predictive power. Cicerello et al. (1991) reported that Cumberland Falls is a major barrier to mussel dispersal in the Cumberland River, with only 11 of the 87 mussel species reported from the Cumberland occurring above the falls. Jenkinson (1974) observed that the Fall Line (boundary between the Piedmont and Coastal Plain physiographic provinces) in Alabama appears to be a barrier for some mussel species and their fish hosts.

Neves and Widlak (1987) reported two periods of particularly high mortality during the unionid life cycle. Mussel glochidia that fail to achieve encystment on an appropriate fish host do not survive. Excysting juveniles which drop from fish hosts into unsuitable habitats are also unlikely to survive. Howard (1922) speculated that the location in which juvenile mussels drop from their host is determined by chance, with increased survival of individuals reaching favorable habitats. Juvenile mussels possess byssal holdfasts which enable them to attach to gravels and maintain their position in the current (Frierson 1905, Clarke 1986). Very little is known of the habitat requirements of juvenile mussels, particularly in lotic systems (Neves and Widlak 1987). Neves and Widlak reported the greatest density (39.6/m^2) of juvenile mussels (ages 0-3 years) from the upper stratum of finer sediments in eddies behind large boulders. The mean density of juveniles in riffle habitats was somewhat lower ($25.6/m^2$), followed by run habitats ($15.1/m^2$) and pools ($9.3/m^2$). Baker (1928) reported that juveniles often burrow deeply into streambed sediments. Clarke (1986) observed no individuals of *Potamilus capax* (Green) smaller than 70 mm during sampling surveys conducted during June and August in sandy substrata of the St. Francis River, Arkansas. During September, Clarke observed individuals from 30 to 60 mm in length, leading him to conclude that younger individuals of *P. capax* are hypobenthic during most of the year. Additional evidence for the hypobenthic existence of young individuals was the shiny, less abraded periostracum of individuals in the 30 to 60 mm length class.

Adult unionids, which lack byssal threads, are obligate burrowers in clastic sediments. Hynes (1970) contended that composition of bottom sediments is the major factor controlling the the occurrence of benthic organisms. However, it is unclear whether there is selectivity by mussels for habitat type, or merely passive dispersal by fish hosts and water current (Kat 1982). Strayer (1981) conducted a study of microhabitats of 22 mussel species in Michigan streams and concluded that most species coexisting at a site have similar mean microhabitats. Additionally Strayer concluded that mussel species have broad microdistributions within a site, resulting in a high degree of interspecific overlap. Other researchers have reported similar food, water quality, and substratum requirements for coexisting lotic mussel species (Bronmark and Malmqvist 1982, Miller et al. 1986). Tevesz and McCall (1979) concluded that substratum specificity is much less developed in freshwater bivalves than in marine bivalves. They attributed the apparent lack of specialization by freshwater bivalves to greater climatic variability, and ecological release from predation and competition pressure. However, Bronmark and Malmqvist (1982) were able to discern spatial separation of the two dominant mussel species in the Klingavalsan River, Sweden, and Salmon and Green (1982) detected a spatial pattern of microhabitat differentiation between some mussel species in the Middle Thames River, Ontario.

Mussels have been reported from substrata ranging from liquid mud (Salmon and Green 1983) to boulders (Stern, 1983). Lewis and Riebel (1984) conducted burrowing studies of three mussel species in clay, mud, sand, and gravel. Although burrowing efficiency was greater in sand than in gravel substratum for all three species, they concluded that burrowing efficiency may not be strongly related to substratum selection and local distribution. Kat (1982) reported greater growth of *Elliptio complanata* in sand-gravel substratum than in mud in a Maryland stream, and attributed the differential rates of growth to differences in the energy required to maintain position, and to differences in nutriment delivered by currents. He concluded that high quality microhabitats are characterized by stable substrata, uncrowded conditions, and protection from bed scour. However, soft muds are not necessarily unstable for thin-shelled species, such as *Anodonta sp.*, which are well documented from the soft mud substrata of lakes, ponds, and low gradient streams.

A large number of researchers have reported sand, gravel, and cobble substrata to be the most productive mussel habitats in lotic systems (Sickel 1980, Strayer 1981, Stern 1983, Dennis 1984, Miller et al. 1986, Sheehan et al. 1986, Stansbery 1986). Sickel (1980) reported the greatest abundance of most mussel species from fine to medium sand substrata in the Altamaha River, a coastal plain stream in Georgia. However, the substrata he sampled ranged from clay to very coarse sand. Miller at al. (1986) reported extremely high mussel densities (up to $124/m^2$) from a gravel bar in the Ohio River. The gravel bar was characterized by particles ranging from 1.0 cm to more than 10.0 cm, with the greatest weight fraction in the 1.0 to 3.0 cm range. Stern (1983) observed the greatest species diversity and abundance of mussels in the Wisconsin River from transects characterized by a heterogeneous mixture of particles, ranging from sand to boulders.

Depth has been reported as a determinant of mussel distribution and abundance (Salmon and Green 1982, Stansbery et al. 1986). Stern (1983) concluded that depth is a factor affecting the distribution of mussels primarily because it is associated with gradations in current velocity and substratum particle size. Salmon and Green (1982) used measurements of five environmental variables (water velocity, depth, substrate type, percent vegetative cover, and distance to shore) to discriminate between samples with and without mussels in the Middle Thames River, Ontario. They reported increased mussel abundance in slow-moving, shallow water with relatively coarse substratum (substantial cobble fraction). Stansbery et al. (1986) observed that, "the riffle and run habitats of high-gradient streams harbor the greatest diversity and population densities of unionid mollusks. We have observed that the ponded parts of these streams, having deeper, slack water over finer sediments, typically have no unionids, or have only a few individuals of a restricted number of species." Current speed and spatial variation in current speed were the most useful predictors of mussel presence or absence in a study by Strayer and Ralley (1993). In their study, the presence of mussels in quadrats was more likely in areas of intermediate and spatially uniform current speed.

Vannote and Minshall (1982) suggested that local lithology and fluvial processes interact to regulate density and population size-class structure of the two dominant mussels in the Salmon River, Idaho. They hypothesized that large block-boulders (30-250 cm) lend stability to small mussel beds by preventing significant bed scour during major floods. This hypothesis is supported by higher mussel density, and greater frequency of old-aged individuals in boulder-sheltered areas. Strayer (1993) observed that some mussel species are more likely to occur in hydrologically stable streams than in hydrologically flashy streams. In addition to bed scour, Strayer (1993) suggested that hydrology may also affect mussels via the mechanisms of siltation, desiccation, thermal stress, and increased predation pressure during extremely low flows.

Subjective methods have frequently been used to characterize mussel habitat in lotic systems. Many studies have entailed the use of substratum designations such as muddy sand, sandy gravel, pebbles and cobbles, rather than quantifiable weight or volume measurements based on sieve fractionation. Among the studies which have utilized sieve fractionation, volumes and methods of sediment collection have varied. The pavement layer, or surface layer of particles lining the channel boundary, exhibits characteristics which reflect hydraulic conditions in the channel (Diplas 1989). This pavement layer is typically coarser in composition than the sediments which lie beneath it, and is relatively easy to sample in shallow streams (Diplas and Sutherland 1988). Descriptive terms such as riffle, glide, and pool, though somewhat ambiguous, have often been used in studies. Identification of these habitat types is certainly subjective, and may vary with the observer and level of discharge. Measurements of channel cross-sectional form and flow velocity (at a standardized level of discharge) are certainly more quantitative and facilitate statistical comparison.

Strayer and Ralley (1993) were disappointed by the low power of the microhabitat variables they chose to predict occurrence and density of mussels in the Neversink River of New York. Other investigators (Tevesz and McCall 1979, Holland-Bartels 1990) also have questioned the usefulness of microhabitat measurements to predict the occurrence and species composition of mussels in streams. Strayer and Ralley (1993) suggested an extension of the microhabitat approach by "including geomorphological descriptors of the streambed or working at spatial scales of hundreds of meters" in order to circumvent the "considerable small-scale variation in unionacean communities.

Channel morphology, valley morphology, and characteristics of geologic formations underlying river reaches have rarely been considered in relation to stream benthos, but may be important determinants of mussel habitat distribution and quality. Dolan et al. (1978) observed that most rapids (ranging from riffles to extremely turbulent rapids) in the Grand

Canyon of the Colorado River are within fracture zones which run perpendicular to the river. Most of the deep canyon pools occur immediately below large rapids. The frequency and distribution of rapids and deep pools can therefore, in large part, be explained in terms of bedrock characteristics. Dolan et al. (1978) concluded that hydraulic (autogenic) processes, which produce regularly spaced riffles in many streams, are less important than bedrock (exogenic) control in determining the distribution of rapids and pools in the Grand Canyon. Vannote and Minshall (1982) observed that mussels attain greatest density and age in areas of substratum that are sheltered from bed scour by large boulders. Therefore, it seems likely that bedrock composition and morphology (e.g. dip and strike of strata) may be major structural determinants of aquatic habitat distribution in many streams.

Statement of research objectives

The main purpose of this study was to determine the salient physical characteristics of high quality mussel habitat in a river renowned for high mussel diversity and endemism. Two distinct mussel data bases were used. I gathered the first between 1988 and 1991, by conducting in-stream quadrat sampling of seven river reaches. The second data base was collected during an earlier survey of 141 sites on the upper Clinch by TVA biologists between 1979 and 1983 (TVA 1986). Without the TVA data base, detection of large scale patterns of habitat distribution would have been unlikely. Even if such patterns had been hypothesized, statistical testing would not have been possible without mussel data from a large number of sites, and inferred patterns would remain speculative.

I selected mussel density as the dependent variable in analyses with the first data set because species richness and relative abundance change longitudinally along the river. Mussel site quality (based on numbers of mussels reported) was the dependent variable in analyses of the TVA qualitative data set. Physical habitat parameters (the independent variables) were selected to minimize subjectivity on the part of the measurer. Parameters selected for measurement may be considered as descriptors of physical habitat at three levels of scale. Substratum descriptors comprise the smallest level of scale. Quantitative descriptors of channel cross-section morphology comprise the next level of scale. Valley and stream reach morphology constitute the coarsest level of scale. The three major objectives of the study, followed by brief explanatory text, are listed below.

Objective 1. Compare mussel density, species richness, and length-class structure among seven river reaches in the Clinch and Little rivers (Chapter 2). Quadrat sampling of mussels was conducted in seven widely-spaced reaches of the Clinch and Little rivers to determine mussel densities and species richness. Mussel lengths were measured to permit comparisons of mussel length-class structure among reaches. These data were used to determine if density and recruitment were comparable among reaches. Hypotheses to be tested are that mussel density, species richness, and length-class structure differ among the seven river reaches.

Objective 2. Compare substratum, channel cross-section, and streamflow values associated with high and low mussel density transects from the seven reaches sampled in Objective 1 (Chapter 3). Substratum values associated with high and low mussel density transects were compared. In addition to substratum variables, metrics of channel cross-sectional morphology (width, mean depth, maximum depth, cross-sectional area, etc.) also were compared. Mean flow velocities associated with high and low density transects were compared as well. Due to observed distribution patterns of high mussel density habitats, direction of streamflow was added as a variable and compared between high and low mussel density transects. Hypotheses to be tested are that substratum, channel cross-section, and streamflow values associated with high mussel density transects, will be significantly different from values associated with low mussel density transects.

Objective 3. Compare substratum, channel cross-section, and macro-scale habitat values associated with high and low quality mussel sites from the TVA survey (TVA 1986) of 141 upper Clinch River sites (Chapter 4). In Chapter 4: Section 1, substratum, channel cross-section morphology, and valley and stream reach morphology values associated with 20 high quality and 23 low quality sites from the TVA data set were compared. In Chapter 4: Section 2, distribution patterns of mussel sites (n=141 sites) from the TVA survey, relative to the direction of stream flow were determined. I speculate that the observed distribution patterns of mussel sites may be explained in terms of geologic factors (dip, strike, and rock type). Hypotheses to be tested are that substratum, channel cross-section, and valley and stream values associated with high quality sites will be significantly different from values associated with low quality sites.

CHAPTER 2. CHARACTERISTICS OF MUSSEL ASSEMBLAGES IN REACHES OF THE CLINCH RIVER

Introduction

Methods of substratum characterization were initially tested in a pilot study on the Little River (Appendix A). Habitat studies were conducted to test these methods in the larger Clinch River in reaches with differing characteristics. In addition to the study reach on the Little River, six reaches on the main stem Clinch River were sampled for freshwater mussels. Substratum , channel, and valley characteristics were also measured in these reaches (Chapter 3). In this chapter, density, diversity, and length-class structure of mussels collected were compared among study reaches.

Selection of Study Reaches

Results of the Ahlstedt (1984) and Church (1991) mussel surveys were pooled to produce histograms of mussel species richness in the Clinch and Little rivers (Figures 2.1 and 2.2). Mussel species richness generally declines from downstream to upstream; however, two low points in species richness were particularly apparent in the Clinch River (segments 12 and 17 in Figure 2.1). These are reaches of documented anthropogenic disturbance downstream of Richlands (CRK 482.0-515.0), and between Carbo and St. Paul (CRK 407.0-431.0). These areas were excluded from consideration as habitat study reaches since the primary objective of the study was to determine important natural factors affecting riverine mussel

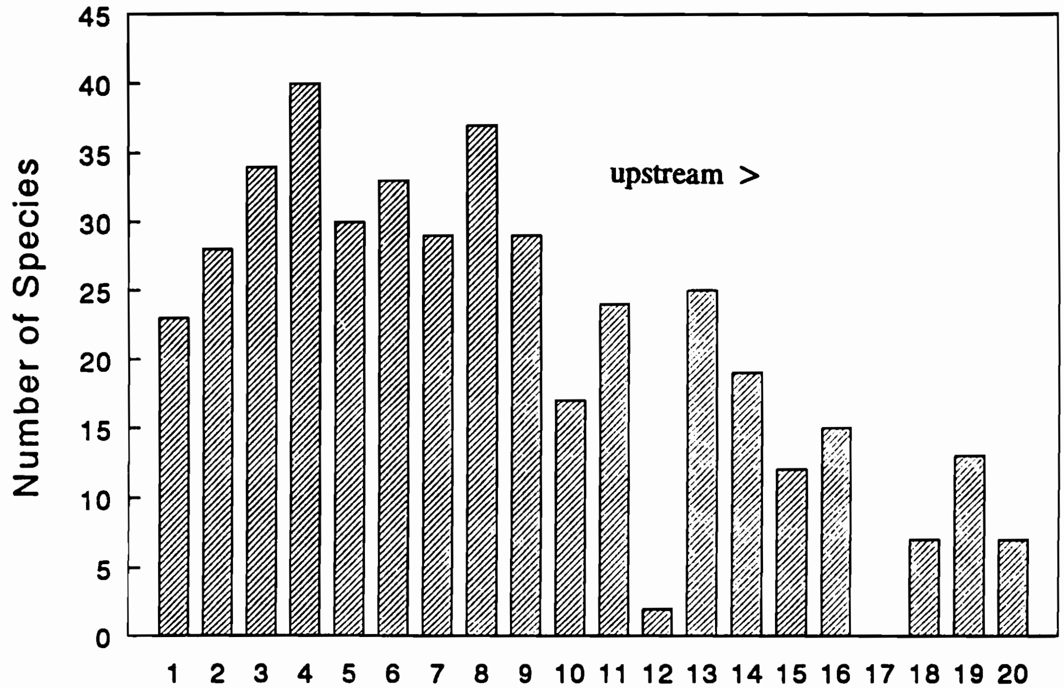

Figure 2.1. Mussel species richness in the Clinch River by 15 km river segments (CRK 260 - 560), compiled from Ahlstedt (1984) and Church (1991).

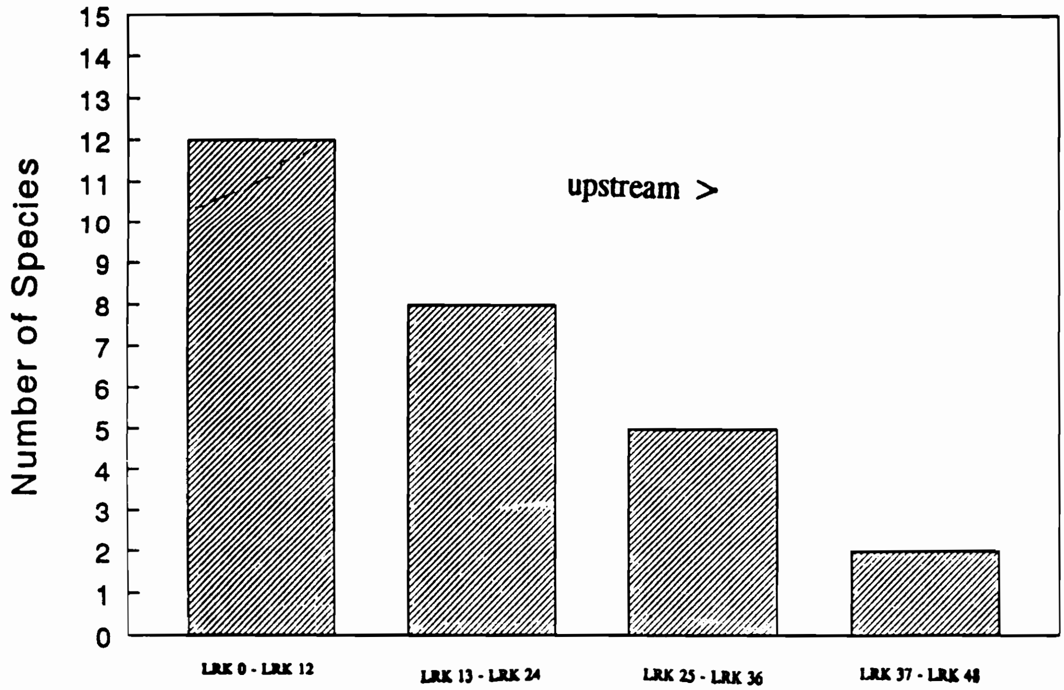

Figure 2.2. Mussel species richness in the Little River by 12 km river segment (LRK 0 - LRK 48), compiled from Church (1991).

density. The major impacts to these reaches were summarized in Chapter 1.

Six reaches of the Clinch River were selected for study between CRK 359 and CRK 543 (Figure 2.3). The Little River reach (Appendix A) was included as a seventh study reach. The reaches varied in stream size (4th to 6th order) and channel morphology (unbraided to highly braided). Four of the reaches selected (CR2, CR4, CR5, and CR6) were sampled by TVA biologists between 1979 and 1983 (TVA 1986). Two reaches (LR1 and CR1) were selected because of particularly high abundances of fresh-dead mussel shells in muskrat foraging middens (Church 1991). One reach (CR3) was subjectively judged by the investigator to possess exemplary riffle-run, or shoal habitat. Study reaches ranged from 0.4 to 0.7 km in length, with all reaches containing some areas of low-quality mussel habitat, as well as high quality habitat.

Even though efforts were made to exclude impacted reaches, quadrat sampling of mussels revealed differences in mussel density and recruitment (as evidenced by length-class structure) among the study reaches. Although differences in mussel density among reaches of differing morphology were not particularly surprising, differences in the length-class structure of mussel populations indicated impaired recruitment of mussels in some reaches. Study reach mussel assemblages appeared to be in unequal states of biotic integrity.

Mussel sampling methods

All mussel sampling was conducted during the summers of 1990 and 1991. A stratified random sampling design was used in which 3-m wide transect

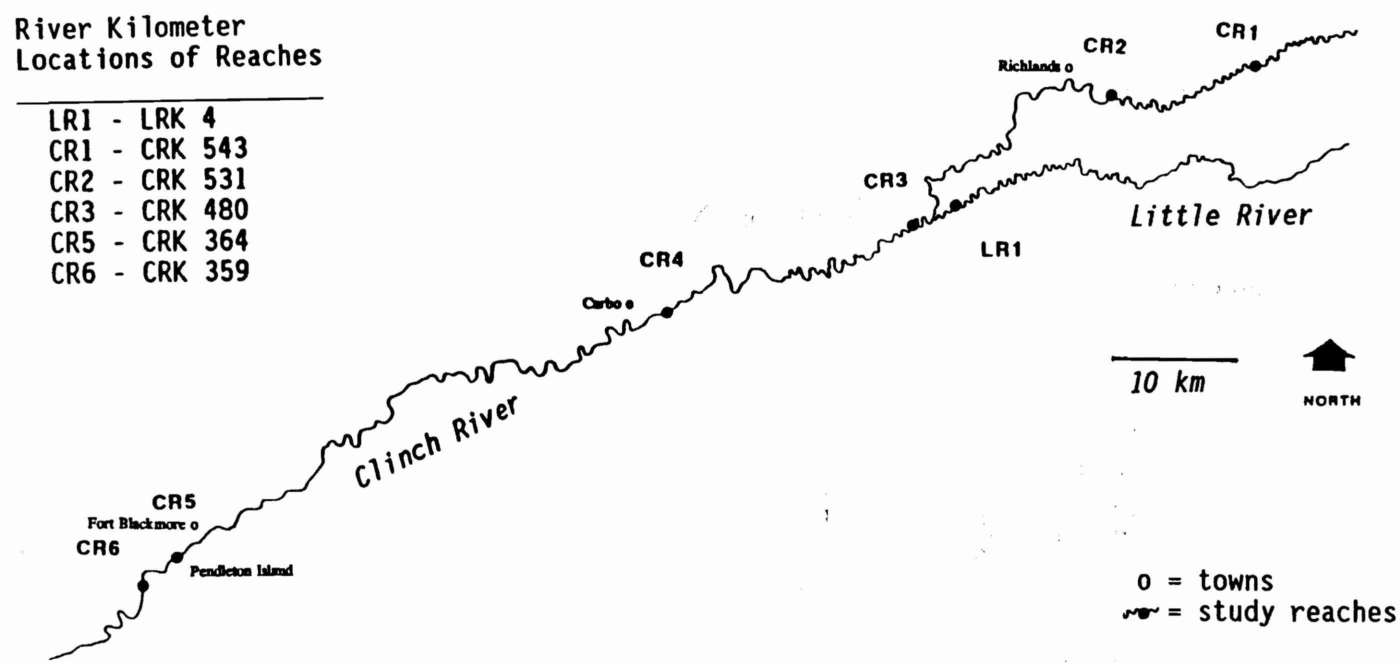

Figure 2.3. Locations of reaches selected for study of mussel assemblages on the Clinch and Little rivers in Virginia.

zones, exhibiting a diverse array of substratum conditions, were selected. Each transect zone was subdivided into three equal sectors. A 1.0 m^2 quadrat frame was randomly tossed into each sector. Numbers of quadrats sampled per reach are included at the bottom of Table 3.1. The number of transects per reach varied depending on my subjective assessment of reach complexity (variations in depth, percent bedrock, number of bends, number of channels, etc.). In addition, 24 of the 60 quadrat samples in the Little River (LR1) were located in point bars, in order to compare mussel density in point bars to main channel habitats (Appendix).

The substratum within each quadrat was searched for mussels for 15 minutes to a depth of 12-15 cm. In some bedrock-dominated transect zones, clastic sediments lay in linear recesses of bedrock strata. In these cases, an area equal to 1 m^2 was excavated for 15 min without using the quadrat frame. All mussels collected were enumerated, identified to species, and measured (mm) along their greatest longitudinal axes. Mussels were then returned to locations where they were collected, following replacement of excavated sediments.

Duncan's Multiple Range test (SAS 1985) was used to compare quadrat mussel densities among study reaches. Point bars were documented as unsuitable mussel habitat in the Little River study (Appendix). Therefore, point bar quadrat samples (n=36) were excluded from the analyses.

Results of quadrat sampling

Nineteen unionid species were identified during this sampling effort (Table 2.1). The Tennessee clubshell, *Pleurobema oviforme*, was probably

Table 2.1. Freshwater mussels collected in quadrat samples from study reaches.

Mussel Species	LR1	CR1	CR2	CR3	CR4	CR5	CR6	TOTAL
Actinonaias ligamentina	-	-	-	4	13	28	18	63
Actinonaias pectorosa	10	-	-	30	107	33	9	189
Alasmidonta marginata	-	-	-	-	2	-	-	2
Amblema plicata	-	-	-	-	-	10	11	21
Cyclonaias tuberculata	-	-	-	-	1	6	6	13
Elliptio dilatata	-	-	-	1	50	12	4	67
*Fusconaia barnesiana**	96	72	5	23	27	13	10	246
Fusconaia cuneolus	-	-	-	-	14	5	2	21
Fusconaia cor	-	-	-	-	7	-	-	7
Lampsilis fasciola	7	12	1	2	19	2	2	28
Lampsilis ovata	-	-	-	-	10	1	1	12
Lasmigona costata	3	-	-	2	19	2	2	28
Medionidus conradicus	64	41	1	1	20	-	-	127
Potamilus alatus	-	-	-	-	1	-	-	1
Ptychobranchus fasciolaris	4	-	1	15	10	3	5	38
Ptychobranchus subtentum	6	-	1	3	7	2	-	19
Quadrula cylindrica	-	-	-	-	6	1	-	7
Villosa iris	205	214	31	28	8	1	1	488
Villosa vanuxemensis	-	-	-	-	-	1	-	1
Species Richness	8	4	6	10	17	15	12	20
Number of Mussels	395	339	40	109	321	120	70	1394
Number of Quadrats	60	30	30	33	36	33	27	249
Mussel Density/m^2	6.58	11.3	1.3	3.3	9	3.6	2.7	5.6

* *Pleurobema oviforme* was lumped together with *Fusconaia barnesiana* because they are difficult to differentiate based only on external shell characteristics.

collected as well but is difficult to distinguish from the Tennessee pigtoe, *Fusconaia barnesiana*, when only external shell characteristics are used. These two species were therefore lumped together in Table 2.1 under the name *Fusconaia barnesiana*, as this species was more frequently encountered in the TVA (1986) survey.

Mean mussel density per m^2 ranged from 11.3 at CR1 to 1.3 at CR2. Species richness ranged from 4 species at CR1 to 17 species at CR4. Four species, *Villosa iris* (rainbow), *Fusconaia barnesiana*, *Actinonaias pectorosa* (pheasantshell), and *Medionidus conradicus* (Cumberland moccasinshell), accounted for 75.3 percent of all mussels collected. The relative abundances of these species varied greatly among study reaches (Figure 2.4). *Villosa iris* was the most frequently encountered species (35 %), followed by *Fusconaia barnesiana* (17.6 %), *Actinonaias pectorosa* (13.6 %), and *Medionidus conradicus* (9.1 %). *Alasmidonta marginata* (elktoe), *Potamilus alatus* (pink heelsplitter), and *Villosa vanuxemensis* (mountain creekshell) were the most rarely encountered species. Twenty-eight individuals of two federal endangered mussel species were identified; the fine-rayed pigtoe, *Fusconaia cuneolus* (21 individuals), and the shiny pigtoe, *Fusconaia cor* (7 individuals).

Point bars were documented as inferior mussel habitat in the Little River (Appendix). LR1, CR1, and CR3 were the only reaches in which point bars were sampled. Therefore, in order to make valid comparisons of mussel density among study reaches, the 39 point bar samples were excluded from the Duncan's Multiple Range comparison. Mussel densities per 1 m^2 in quadrats from reaches LR1 (mean=9.6) and CR1 (mean=12.1) were not

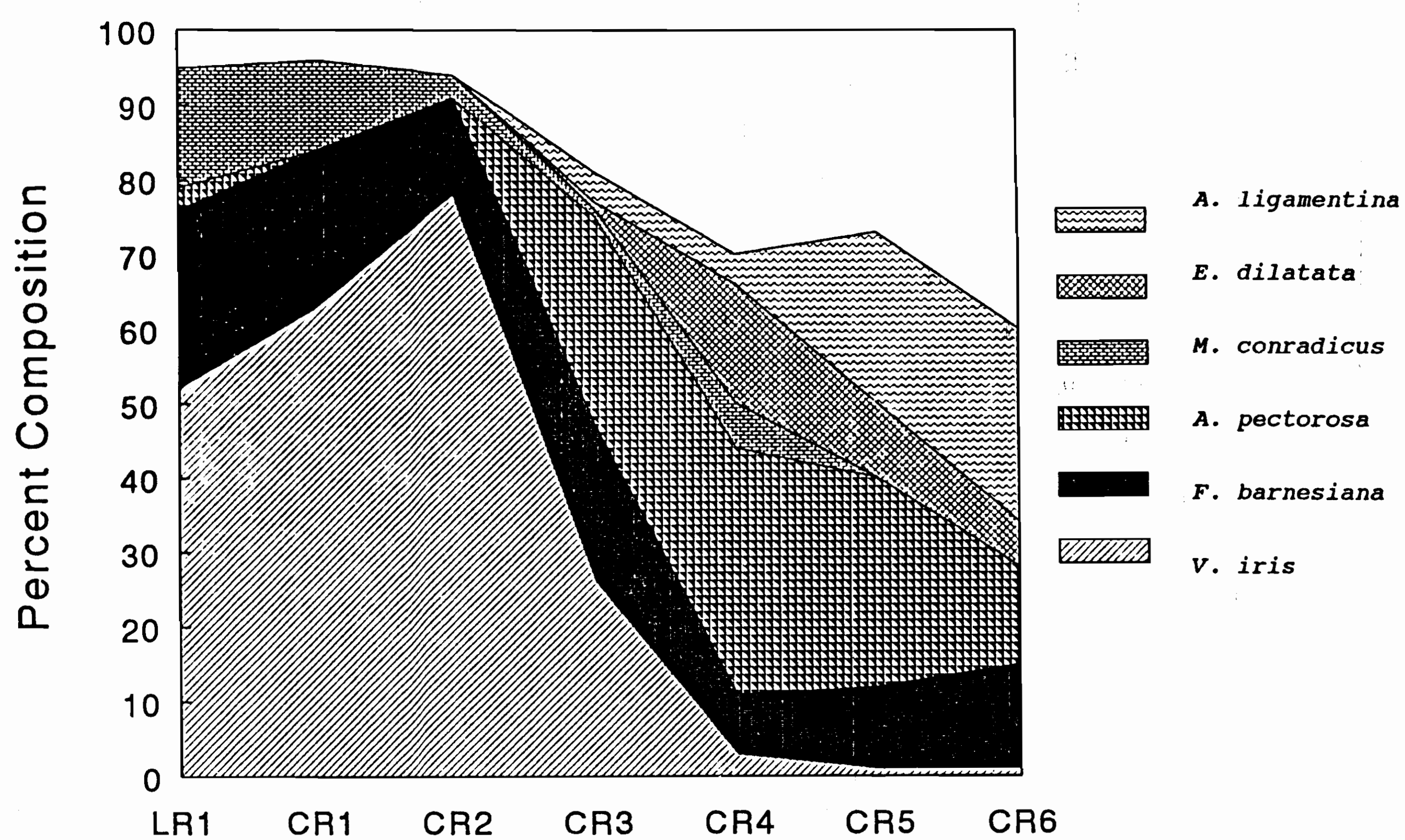

Figure 2.4. Relative abundance (percent composition) of common mussel species in study reaches.

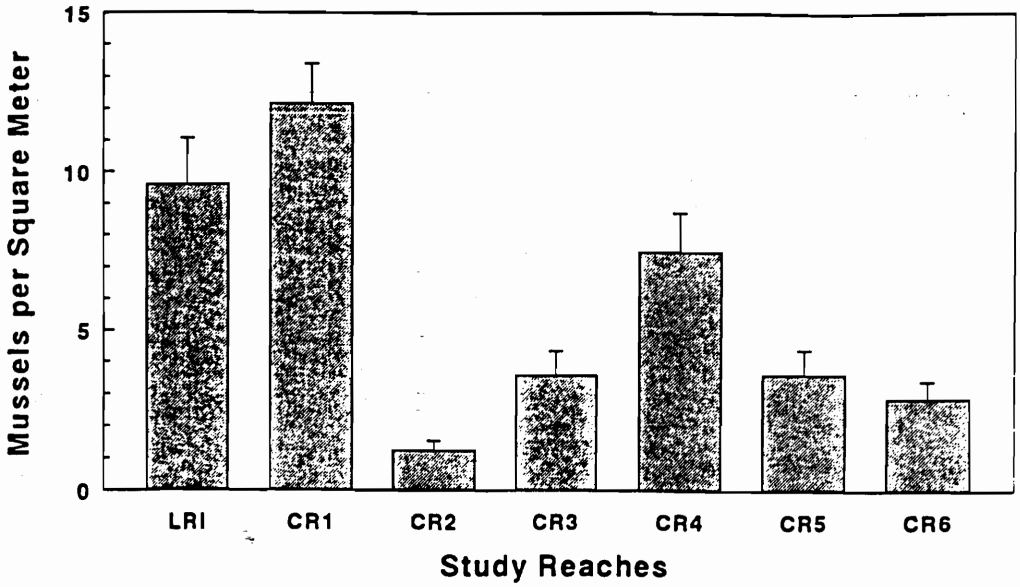

Figure 2.5. Mussel densities (mean + 1 SE) in study reaches with point bar samples removed (n=210 1 m^2 quadrat samples).

significantly different at an alpha level of 0.05. Mussel densities in reaches LR1 and CR1 were significantly greater than in CR2 (mean=1.3), CR3 (mean=3.6), CR5 (mean=3.6), and CR6 (mean=2.9). Mussel densities at CR4 (mean=6.9) were not significantly lower than at LR1, but were significantly less than at CR1 (Figure 2.5).

Discussion

Based on population density and land use within its basin, LR1 was expected to have the best water quality and least impacted mussel fauna of the study reaches. Therefore, the lower mussel density observed at LR1 (relative to CR1) may be due to differences in physical habitat quality. The relatively low mean density of 3.6 observed from the eleven transects at CR5 (Pendleton Island) was particularly surprising in light of the reputation of this reach as one of the best remaining mussel sites. However it should be noted that other channels, besides the channel containing the best mussel habitat, were sampled at Pendleton Island. The mean density of 2.9 observed at CR6 (Slant), located 4.8 km downstream of CR5, was also surprisingly low.

The extremely low mussel density at CR2 (1.2 mussels per m^2) was the most unexpected of the sampling results. This reach was selected due to an abundance of fresh-dead mussel shells in muskrat middens, which were collected by Dr. R. J. Neves and me in 1989. Abundant midden shell material usually indicates the presence of areas with numerous mussels. This reach also included sites which appeared to possess the physical attributes of exemplary mussel habitat (i.e., large, contiguous, shallow areas with gravel-cobble substratum). Additionally, the two samples having the greatest mussel density (n=6 in both cases) occurred in the two transects farthest upstream. One of these samples was excavated in a point bar, and the other in coarse cobble-boulder substratum, both of which are typically areas of inferior mussel habitat. Mean mussel density at CR1, which is 12 km upstream of CR2, was an order of magnitude greater than at CR2. In response to these enigmatic findings, additional sampling (three 1 m^2 quadrat samples) was conducted at a site 3.0 km upstream of CR2. The mean mussel density at the added reference site was also an order of magnitude greater (mean density=12.7 mussels per m^2) than at CR2. Additionally, dense mats of water stargrass, *Heteranthera dubia*, were present in the other six study reaches and the added reference site, but were absent from the entire CR2 study reach. It was noted during subsequent observations that this macrophyte, ubiquitous throughout most of the Clinch and Little rivers, was entirely absent in the Clinch River from CR2 to the Little River confluence (approximately 45 km). For these reasons, CR2 was considered to be the site of recent anthropogenic disturbance and therefore was excluded from further analyses.

Differences in mussel density among reaches could certainly be due to differences in physical habitat quality, rather than differences in the relative biological integrity of study reaches. It was therefore desirable to use another metric as an indicator of mussel population integrity. Length-class structure of common mussel species was selected to compare the relative biological integrity of mussel assemblages in the study reaches.

Comparisons of mussel length-class frequencies among study reaches

Mussels continue to grow throughout their lifespans, secreting calcareous shell material with subsequent increases in shell length, width, and thickness. Annual periods of growth rate reduction or cessation are recorded in the shell as dark annuli, visible internally in sectioned shells, and externally in the periostracum. Relationships between age (manifested as internal shell annuli) and length of Clinch River mussel species were studied by Scott (1994). Scott's regression plot of *Actinonaias pectorosa* in the vicinity of CR4 is displayed in Figure 2.6. During quadrat sampling in the study reaches, all live mussels were measured to the nearest 1 mm along their greatest

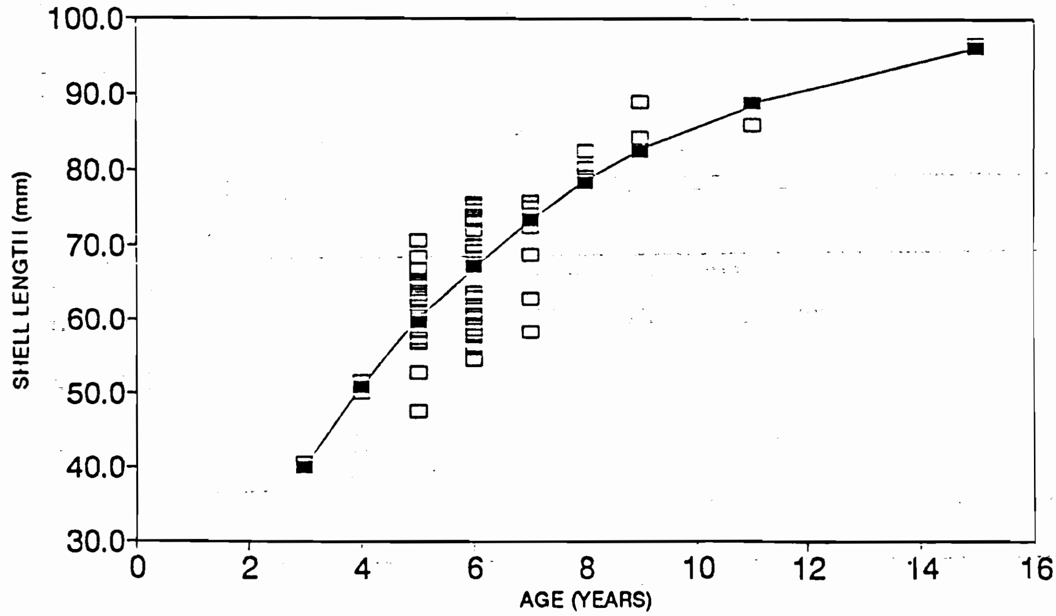

Figure 2.6. Age-length regression plot for specimens of the Pheasantshell (*Actinonaias pectorosa*) collected near CR4 (Scott 1994).

longitudinal axis. Therefore, in the following comparisons length-class structure is used in lieu of age-class structure.

Given the possibility that significant differences in the growth rates of species may occur among study reaches, comparisons of the relative proportions comprised of smaller (i.e., younger) individuals are examined, rather than comparisons of means of entire length-class distributions. A hypothetical example will demonstrate the rationale for this approach. If 100 individuals of Species A have been collected from each of two river sites, and 50 percent of the mussels from Site 1 are from 1-40 mm in length, but only 5 percent of the mussels from Site 2 are from 1-40 mm, one can infer with some certainty that recruitment at Site 2 is lower relative to Site 1. Individuals, regardless of growth rate, spend some minimal period growing from 1 to 40 mm in length, and therefore must be present if the population is a recruiting, sustainable one. Additionally, stable populations (ruling out the possibility of immigration and emigration) are characterized by a larger proportion of individuals younger than the median age to compensate for annual mortality.

The four most abundant species encountered during quadrat sampling (*Villosa iris*, *Fusconaia barnesiana*, *Actinonaias pectorosa*, and *Medionidus conradicus*) were used to compare length-class frequencies among study reaches. Unfortunately, these species were not evenly distributed among the reaches (Figure 2.4), thereby precluding the possibility of making comparisons among all reaches for each species. A sample size of at least 20 individuals per species per reach was considered the minimum necessary to make valid inferences on length-class structure of populations. The reach at LR1 was considered to have the best water quality and is treated here as a reference site. The depauparate reach (CR2), which was apparently impacted by recent disturbance, was excluded from length-class structure analyses (only one short-lived species, *Villosa iris*, occurred here in adequate numbers to permit comparison). Due to proximity (5 km apart), relatively low mussel densities, and strikingly similar population length-class distributions, CR5 and CR6 data were pooled to obtain the number of individuals needed for comparison with other reaches. These two reaches are collectively referred to as CR5/CR6 in the following comparisons.

The millimeter values labelled on the X axes of Figures 2.7 through 2.11 (10, 20, 30, etc.) are the upper limits of each length-class interval.

For example, the column labelled 10 contains individuals from 1 mm to 10 mm in length. In reaches exhibiting the best mussel recruitment (LR1 and CR1), the relatively low proportion of individuals reported in the 10 and 20 mm length-classes are likely due to the inherent difficulty of detecting very small individuals, and should be interpreted as under-estimations of the relative proportions actually present. Individuals smaller than 15 mm are easily overlooked amidst like-sized, similarly colored gravel.

Villosa iris is a relatively small Cumberlandian endemic species. Despite being the most abundant species encountered in the study, *V. iris* was only present in sufficient numbers for comparison (n>20) at LR1, CR1, and CR3 (Figure 2.7). Twenty-three percent of the individuals at LR1 (the site presumed to have the best water quality) were 30 mm or less in length. Twenty percent of the individuals at CR1 were 30 mm or less. However, at CR3 there were no individuals 30 mm or less in length, which indicates poor recruitment relative to LR1 and CR1. This is corroborated by the low mean density of 3.6 mussels per m^2 at CR3, compared to densities of 9.6 and 12.2 at LR1 and CR1, respectively.

Medionidus conradicus, another small Cumberlandian species, occurred in adequate numbers for comparison only at LR1, CR1, and CR4, the three reaches with the greatest mussel densities. Thirty-nine percent of the individuals were 30 mm or less in length at LR1, compared to 17 percent at CR1, and 20 percent at CR4 (Figure 2.8).

Fusconaia barnesiana, a mid-size Cumberlandian species, had the greatest utility for comparison across all reaches, since it occurred in adequate

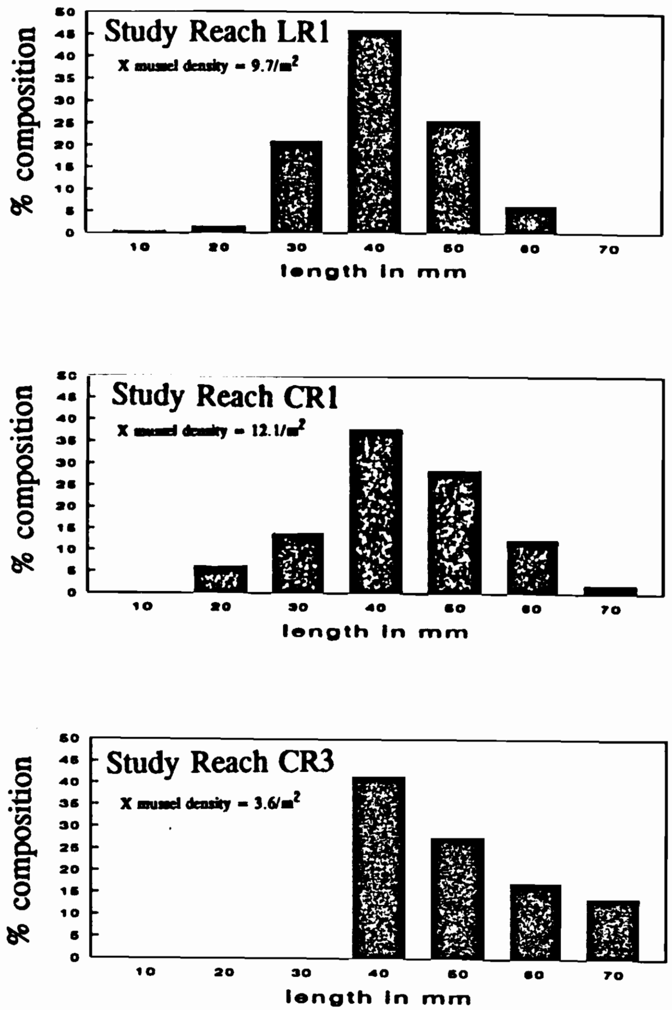

Figure 2.7. Length-class structure (mm) of *Villosa iris* in three study reaches sampled by Church (1991).

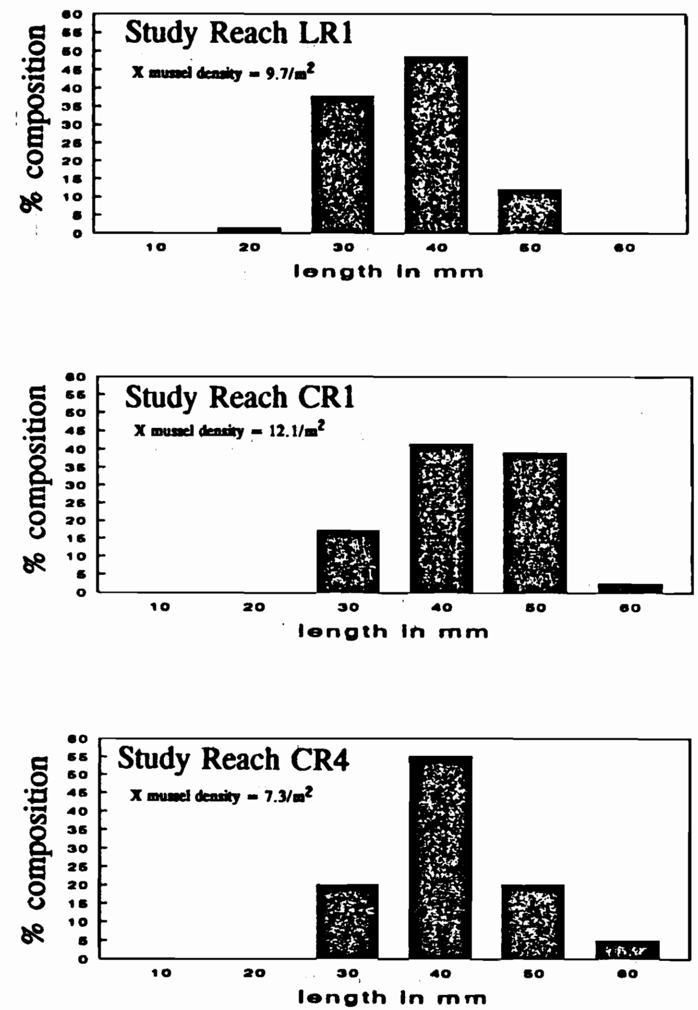

Figure 2.8. Length-class structure (mm) of *Medionidus conradicus* in three study reaches sampled by Church (1991).

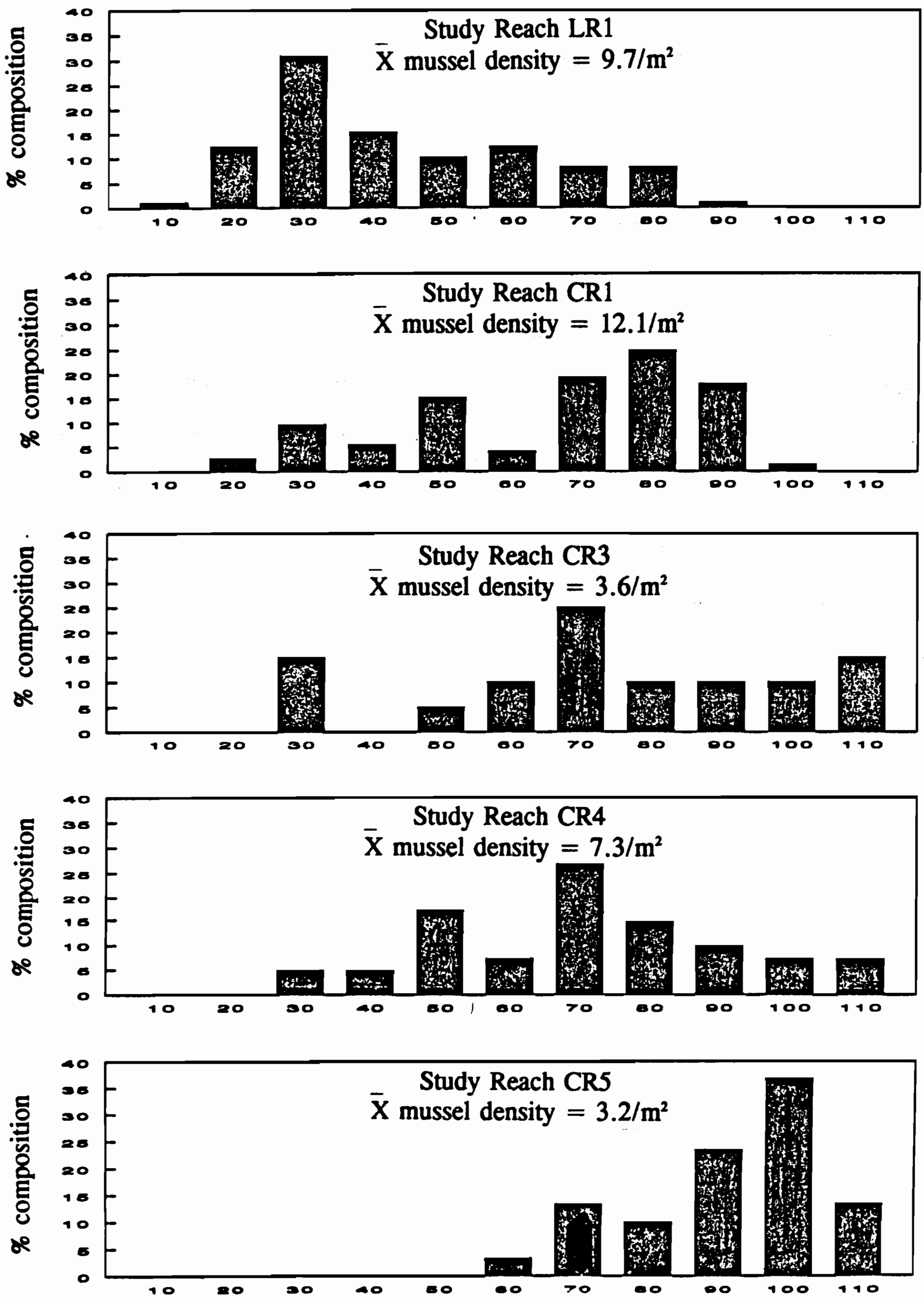

Figure 2.9. Length-class structure (mm) of *Fusconaia barnesiana* in five study reaches sampled by Church (1991).

numbers in all reaches (excepting CR2). Seventy percent of the individuals collected at LR1 were 50 mm or less, compared to 33 percent at CR1, 20 percent at CR3, and 27 percent at CR4 (Figure 2.9). No individuals less than 50 mm were collected at CR5/CR6. If reaches are ranked from best to worst based on the percentage of *F. barnesiana* individuals less than or equal to 50 mm, the order is LR1, CR1, CR4, CR3, and CR5/CR6. If reaches are ranked by mean mussel density, the order is CR1, LR1, CR4, CR3, and CR5/CR6. Except for mean density at CR1 being greater than at LR1, recruitment data corroborate mussel density data.

Actinonaias pectorosa, a comparatively large, fast-growing Cumberlandian species, occurred in sufficient numbers for comparison only at CR3, CR4, and CR5/CR6. Forty-three percent of the individuals at CR4 were 90 mm or less, compared to 3 percent at CR3, and 4 percent at CR5/CR6 (Figure 2.10). While recruitment at CR4 is not particularly high, it is much worse at CR3 and CR5/CR6. Mean mussel density (all species) was also much greater at CR4 ($7.3/m^2$), than at CR3 ($3.6/m^2$) or CR5/CR6 (combined mean of $3.2/m^2$).

Other species at CR5/CR6

Pooling data from CR5 and CR6 provided samples large enough to permit length-class distribution inferences for three additional species at these reaches (Figure 2.11). These were the mucket, *Actinonaias ligamentina* (n=46), threeridge, *Amblema p. plicata* (n=21), and spike, *Elliptio dilatata* (n=16). Only 3 percent of individuals of *A. ligamentina*, a relatively large species, were 80 mm or less. No individuals of *A. p.*

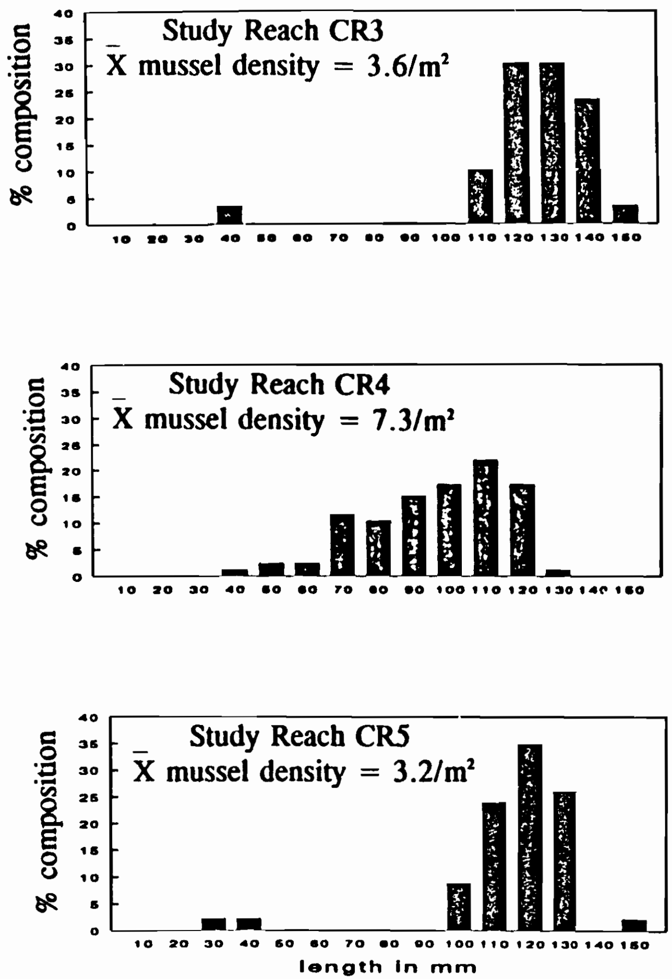

Figure 2.10. Length-class structure (mm) of *Actinonaias pectorosa* in three study reaches sampled by Church (1991).

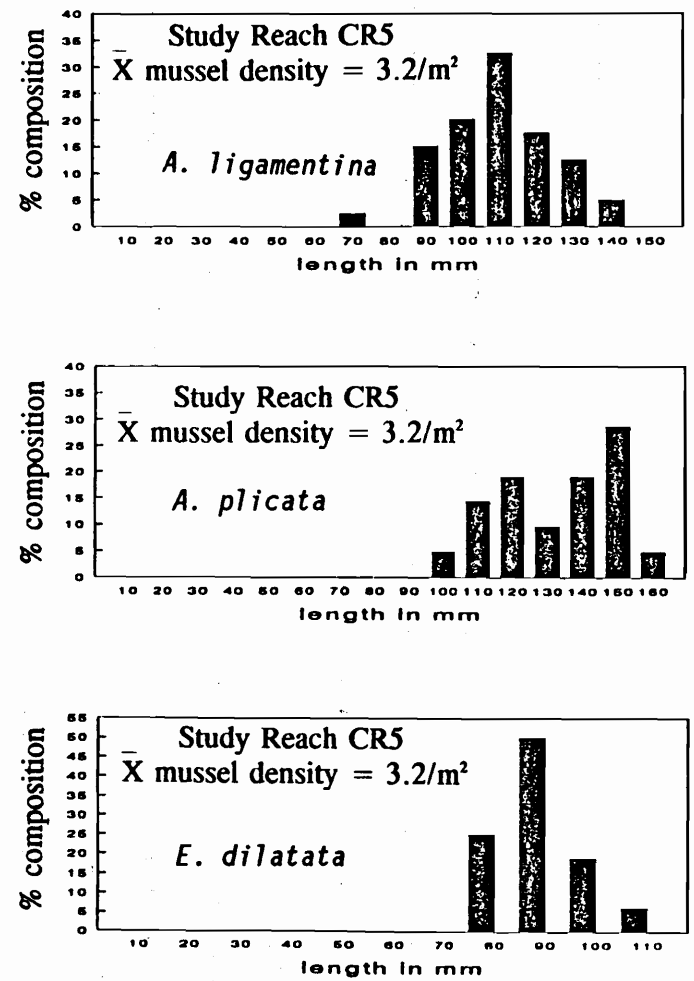

Figure 2.11. Length-class structure (mm) of other common mussel species sampled by Church (1991) at CR5/CR6.

plicata, a large species, were less than 90 mm in length. Likewise, no individuals of *E. dilatata*, a mid-sized species, were less than 70 mm. Each of these distributions corroborate the low mean mussel densities observed at CR5 and CR6.

Discussion

The presence of abundant fresh-dead mussel shells at CR2 the previous year, absence of the aquatic macrophyte *Heteranthera dubia*, and in-stream mussel densities an order of magnitude greater at CR1 and immediately upstream of CR2, all suggest that CR2 has been subjected to severe anthropogenic disturbance. For these reasons, CR2 was excluded from ensuing habitat analyses.

The only reaches with mussel length-class distributions skewed toward young to middle-aged individuals were LR1 and CR1, which indicates comparatively high levels of recruitment. Intermediate levels of recruitment were indicated at CR4. Length-class distributions skewed toward large (old) individuals were observed for most species at CR3, CR5, and CR6, indicating low recruitment during recent years. For example, there were few individuals of *Actinonaias pectorosa* less than 100 mm in length at CR3, CR5, and CR6. Regression plots of age versus length for *A. pectorosa* at CR4 indicate that 100 mm individuals are greater than fifteen years of age (Figure 2.6). These data indicate that recruitment in these three reaches has been seriously reduced for at least fifteen years. Dennis (1989) observed very few mussels in young age-classes from quadrat sampling at Pendleton Island (CR5). Scott (1994) observed a lack of juvenile recruitment for four mussel species at Slant, Virginia (CR6) since 1979 and speculated the decline may be due to high sedimentation from the Cove Creek watershed. A significant decline in mussel species diversity and density since 1979 was observed by TVA (1988) during a reassessment of Clinch River sites. In studies with Clinch River sediments, Yeager (1994) demonstrated intermittent sediment toxicity to *Daphnia magna* and *Chironomus riparius*, and suggested that acute insults are related to the frequency, duration, and intensity of rainfall events. She also observed fluctuations in the concentrations of metals in Clinch River sediments and observed mortaility of juvenile mussels in in-situ assays at some sites. Jacobson (1990) demonstrated much greater sensitivity of isolated glochidia and juveniles to copper toxicity than to encysted glochidia or adult mussels. Toxicity of sediments to sensitive hypobenthic juveniles may be the cause of poor mussel recruitment at some Clinch River sites.

It is interesting to note that *M. conradicus* only occurred (except for 1 individual at CR2 and 1 at CR3) in reaches with the greatest mean mussel densities and best recruitment characteristics (LR1, CR1, and CR4). *M. conradicus* reappears, however, much further downstream near the Tennessee border, becoming relatively common again at Tennessee sites upstream of Norris Reservoir. This species has been documented historically from sites all along the Clinch River, including extensive reaches in which it now is quite rare. It may be that this species is particularly susceptible to certain pollutants (e.g., metals, chlorine) and is among the first species to disappear in the presence of these stressors. In a study of 17 aquatic species occurring in the Clinch River, only *Lampsilis fasciola* was more sensitive than *M. conradicus* in acute toxicity to copper (Cherry et al. 1991).

Reaches CR1 and LR1 had significantly greater numbers of mussels/m^2 than the other reaches. These reaches also exhibited the best recruitment characteristics, with greater percentages of mussels in smaller (younger) length-classes. Mussel densities at CR4 were significantly less than at CR1, but were significantly greater than at CR2, CR3, CR5, and CR6. Recruitment of mussels, as manifested by length-class structure, was also generally better at CR4 than at CR3, CR5, and CR6.

Based on low mussel densities and poor recruitment characteristics at CR2 and CR3, the degraded reach around Richlands is apparently more extensive than previously documented. Similar observations were made at CR5 and CR6. It is anticipated that these differences in the biotic integrity of study reaches may interfere with the outcome of ensuing habitat analyses.

CHAPTER 3. HABITAT ANALYSES AT SIX STUDY REACHES IN THE CLINCH RIVER

Introduction

Characteristics of mussel assemblages in seven study reaches were described in Chapter 2. In this chapter, habitat parameters associated with high and low mussel density transects of study reaches are compared. In Chapter 2, mussel quadrat sampling data were summarized (Table 2.1) and density, diversity, and length-class structure of mussel assemblages were compared among study reaches. Differences in mussel density and recruitment, as evidenced by length-class structure, were observed. Due to extremely low mussel densities relative to upstream reaches, CR2 (Cedar Bluff, CRK 531) was excluded from the following habitat analyses. All habitat analyses were conducted using transects as the unit of comparison. Transects were lumped into approximately equal low and high mussel density groups based on the number of mussels collected from the three 1 m^2 quadrat samples (1 per sector) comprising each transect.

Study reaches

Criteria for the selection of study reaches are elaborated in the "study reach selection" section of Chapter 2. Locations of these reaches are indicated on the map in Figure 2.3 of Chapter 2. Reaches were selected that exhibited an array of habitat conditions ranging from shallow pools to turbulent, erosional reaches, and varied in stream size (4th to 6th order) and channel morphology (unbraided to highly braided). The planimetric morphology and stream flow direction for study reaches are illustrated in Figure 3.1. Each short line segment perpendicular to the stream channel indicates the location of a sampling transect zone, which was subdivided into three sectors for substratum characterization. Although 76 transects were sampled, the ten transects of Reach CR2 were excluded from habitat analyses for reasons elaborated in Chapter 2.

Methods

Mussel Sampling

A stratified random sampling design was used in which 76 3-m wide transect zones exhibiting a diverse array of substratum conditions, were selected for sampling. Each transect zone was subdivided into three equal sectors (Figure 3.2, page 46). A 1 m^2 quadrat frame was randomly tossed into each sector. The substratum within the quadrat frame was searched for mussels during a 15 min excavation period. This search period resulted in sediment removal to a depth of 12-15 cm. In some bedrock-dominated transect zones, clastic sediments lay in linear recesses of bedrock strata. In these cases, an area equal to 1 m^2 was excavated for 15 min without using the qaudrat frame. All mussels collected were enumerated and identified to species (Table 2.1, page 26). Mussels were then returned to locations from which they were collected, following replacement of excavated sediments.

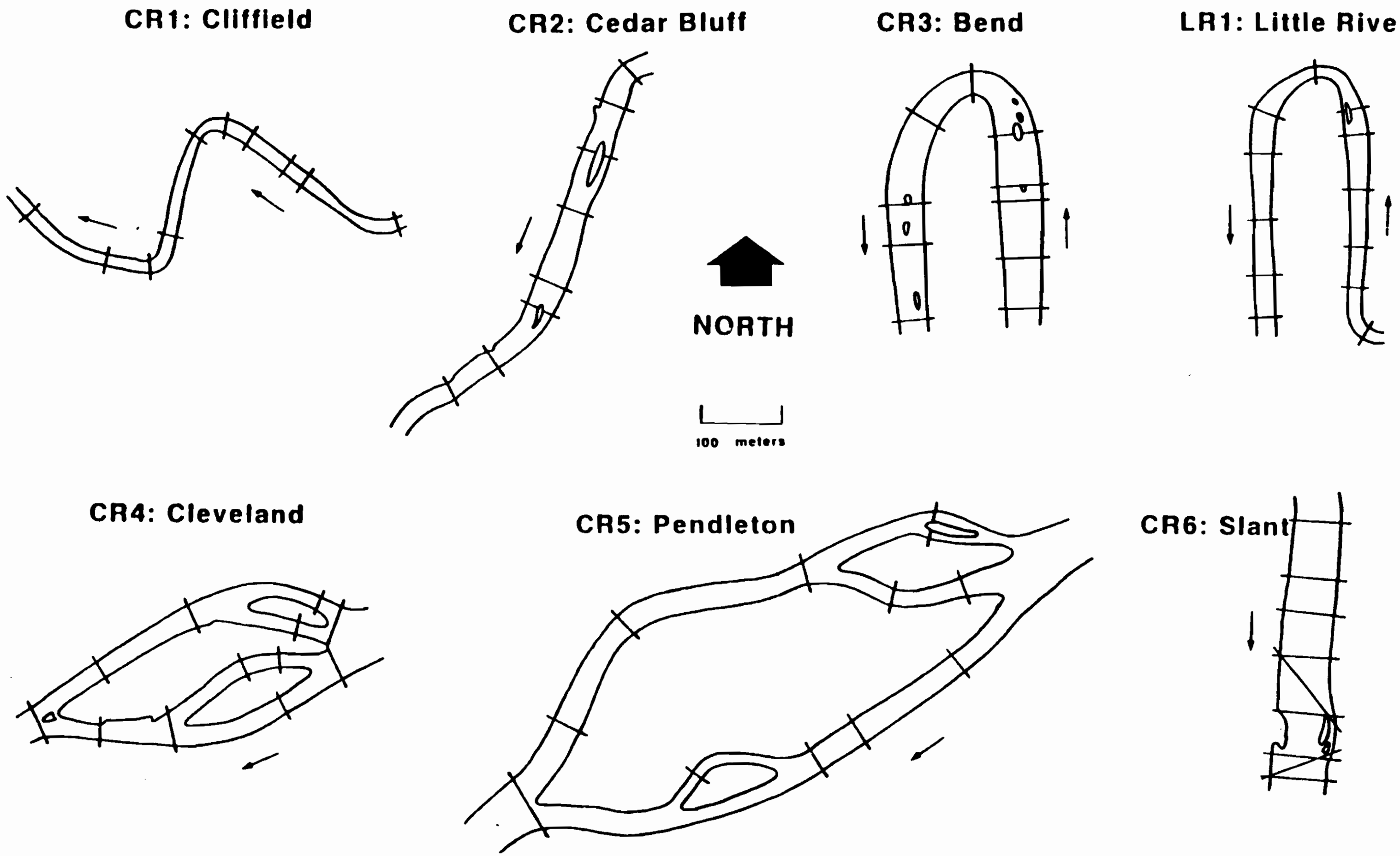

Figure 3.1. Individual maps of study reaches. Short line segments perpendicular to channels indicate locations of sampling transects. Small arrows indicate direction of stream flow.

Substratum variables

Four substratum variables, percent bedrock (PBR), d50 particle size, d84 particle size, and geometric standard deviation (GSD) of particle size distributions, were determined for each 3 m wide transect zone. Geologic dip and strike were measured with a protractor where bedrock ledges lay exposed in the streambed, but were not treated as variables. Geologic dip is the maximum declination of sedimentary rock strata from the horizontal, measured as an acute angle. Strike is the compass direction of a line perpendicular to the direction of dip, referenced from true North. Substratum variables and methods of measurement are described below.

Percent bedrock (PBR): The percent surface area within each 3 m wide transect zone comprised of bedrock (not covered by clastic sediments). PBR was visually estimated by the investigator for the three sectors comprising each transect zone. These three estimates were averaged to obtain a PBR value for each transect (Figure 3.2).

d50 particle size: The d50 or median particle size (by number) is the particle diameter at which 50 percent of the particles in the sample are of smaller diameter. Median particle size values were determined by a modification of the grid sampling technique used in gravel bed streams by Kellerhals and Bray (1971) and Wolman (1954), in which only the surface or pavement layer is sampled. Within each sector, 35 steps were taken in random directions. With each step, the particle beneath the toe of the investigator's shoe was collected and sized on a plexiglass template (gravelometer) with square openings corresponding to a progression of sieve sizes (Hey and Thorne 1983). Particle diameter data from the three

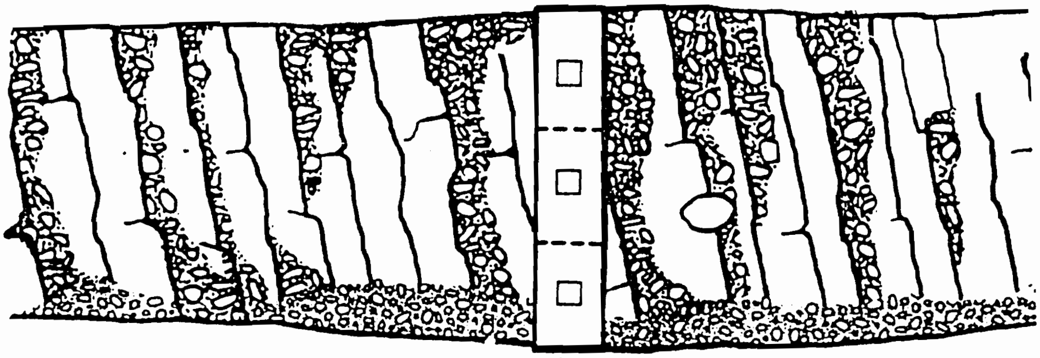

Figure 3.2. Mussel density and percent bedrock (PBR) sampling methods. Three 1 m^2 quadrats (small squares) were excavated in each 3 m wide transect zone. A visual estimate was made of the percent bedrock in each transect zone.

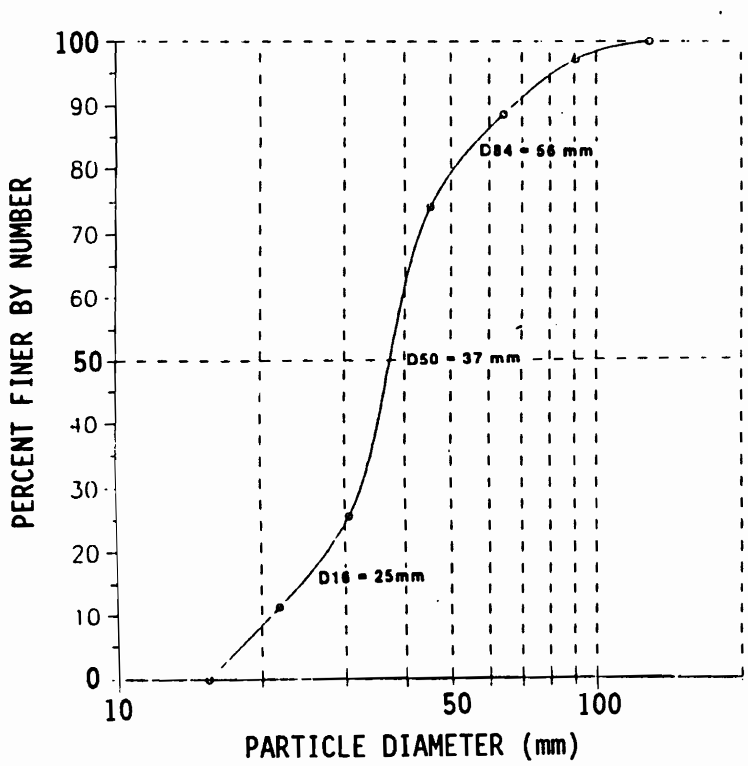

Figure 3.3. Particle-size distribution curve for a streambed sample from the Little River. The d50 particle size is also referred to as the median particle size.

sectors comprising each transect were then pooled, permitting a particle-size distribution curve to be plotted (Figure 3.3) for each transect. Estimates of d50 particle size (mm) for each transect were then determined from these curves.

d84 particle size: The d84 particle size is the diameter at which 84 percent of the particles in the sample are of smaller diameter. The d84 values were determined from the same curves used to determine d50 values (Figure 3.3). The d84 particle size value is sometimes used as a measurement of streambed roughness in hydraulics equations.

Geometric standard deviation of particle size distribution (GSD): Geometric standard deviation is the value obtained by dividing the square root of the d84 value by the d16 value (ASCE, 1975).

Channel morphology variables

Except for bank height (BHT), channel morphology parameters are descriptors of channel cross-sectional shape (perpendicular to the direction of flow). Depth measurements for reaches were taken during late summer of 1990, and were adjusted to a standardized level of discharge by means of reference depth markers installed on relatively permanent streamside objects (i.e., bridge supports, tree trunks) at each study reach. The standardized level of discharge corresponded to a gauge height of 1.82 feet (216 cfs discharge) at United States Geological Survey gauging station #03524000 at Cleveland, Virginia. Channel morphology variables and methods of measurement are listed below.

Mean depth (MDEP): The mean of all cross-section (transect) depth measurements (m). Depth measurements were taken every two paces across the width of the stream.

Streambed width (BWID): The distance (m) across the water surface of the cross-section at standardized level of discharge.

Cross-sectional area (XSEC): The streambed width (BWID) multiplied by the mean depth (MDEP) of the cross-section (m^2).

Maximum depth (DMAX): The deepest point of the stream cross-section in meters.

Width to depth ratio (WDR): The streambed width (BWID) divided by the mean depth (MDEP).

Depth heterogeneity (DH): The standard deviation of cross-section depth measurements. Low values indicate comparatively even depth across the channel. High values indicate high variability of depth across the channel.

Bank height (BHT): Height (m) of the lowest streambank above the water surface level, at standardized discharge. Discharge levels exceeding bankfull discharge would overflow this bank first.

Stream and valley variables

Direction of streamflow 1 (DIR1): The compass direction in which the stream was flowing for each transect, measured as azimuth degrees (North=0°, East=90°, South=180°, West=270°).

Direction of streamflow 2 (DIR2): Due to the great numeric difference between closely juxtaposed North flowing channel vectors measured in azimuth degrees, a second method of indicating directional orientation was used in the second density group breakdown. Two North flowing vectors measured as 359 and 1 azimuth degrees are only two azimuth degrees apart, and when averaged yield an azimuth orientation of 180 degrees or due South. This created problems in analysis and interpretation of directional data. To circumvent this problem, the compass azimuth was divided into eight 45-degree arc segments numbered counter clockwise. Arc segment 1 corresponds to Northeast (23 to 68 azimuth degrees), segment 2 to North, segment 3 to Northwest, segment 4 to West, segment 5 to Southwest, segment 6 to South, segment 7 to Southeast, and segment 8 corresponds to East.

Mean flow velocity (MFLO): The mean flow velocity (velocity at 60 percent of depth) recorded at a discharge level of 206 cfs (gauge height of 1.78 feet) at USGS gauging station #03524000 at Cleveland, Virginia. A flow velocity reading was taken in the approximate location of each excavated quadrat with a Marsh McBirney flowmeter and the three flow rates were averaged to yield a mean flow rate for the channel cross-section (transect). These measurements were taken on November 20 and 21, 1990 following an 8 day period without rain, so that no standardization of depth data among study reaches was necessary.

Proximity to floodplain (PROX): A designation used only in braided reaches characterized by multiple anastomosing channels. Channels were assigned discrete numeric values based on their proximity to the floodplain. The channel farthest removed from the floodplain (or nearest the steep slope) was designated as 1, with additional channels numbered consecutively in the direction of the floodplain (Figure 3.4).

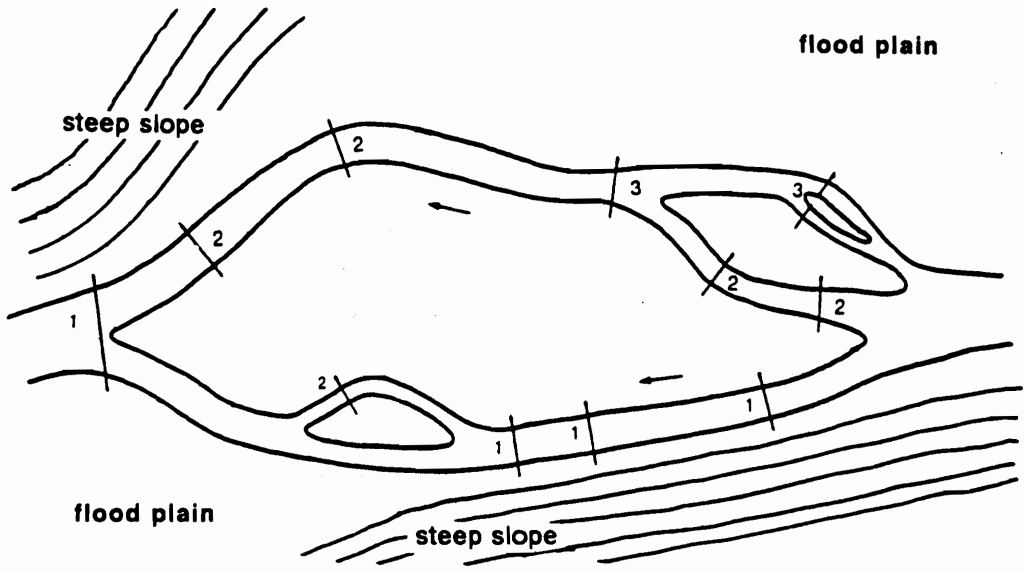

Figure 3.4. Channel numbering system used to indicate proximity to floodplain (PROX) at CR5 (Pendleton Island). Channels closest to steep slopes are designated as 1. Channels farthest from steep slopes (lying entirely within flood plain) are designated as 3. Arrows indicate direction of stream flow.

Wilcoxon rank-sum tests

Wilcoxon rank-sum tests (PROC NPAR1WAY, SAS 1985) were used to test for significant differences between habitat measurements associated with transect groups of high and low mussel density.

Differences in mussel density among reaches are more likely due to differential recruitment, than to differences in habitat quality (Chapter 2). For example, CR5 (Pendleton Island) has been documented as an exemplary mussel site in past surveys (Ahlstedt, 1984). However, only 27 of the CR5 transects fell into the high density group when the first anlaysis method was used. Conversely, 90 percent of the transects at CR1 fell into the high density group (Figure 3.5). In consideration of differences in mussel density and length-class structure among reaches, a second analysis method was used in which transects were divided into equal high and low mussel density groups by study reach prior to analysis (Figure 3.5).

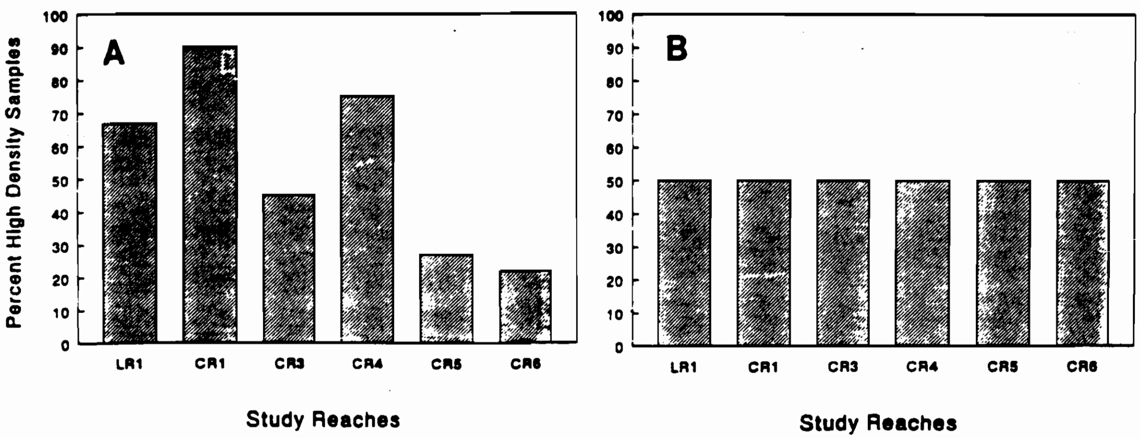

Figure 3.5. Percentage of transects classified as high density among study reaches using two different analysis methods. A. First analysis method. B. Second analysis method.

Stepwise discriminant analysis

In order to identify the most important variables affecting mussel density (habitat quality), all significant habitat variables were subjected to stepwise discriminant analysis (SDA). These analyses were conducted using PROC STEPDISC (SAS 1985). This program uses forward and backward selection to pick variables, using the value of Wilk's Lambda (p=0.15) as the selection criterion for variable entry or removal.

Results

Wilcoxon test results of habitat parameter comparisons using the first analytical method for all transects, unbraided transects, and braided transects are presented in Tables 3.1 through 3.3. Results of habitat parameter comparisons by the second analytical method are presented in Tables 3.4 through 3.6.

In the first analysis, Wilcoxon tests of all reaches combined, d50 and d84 values were not significantly different ($p>|Z|=0.05$ or less) between mussel density groups (Table 3.1). Similar results were observed upon initial transect analyses in the Little River pilot study (Appendix A). However, upon reanalysis following removal of Little River point bar transects, d50 and d84 values were significantly different between groups. Therefore, d50 and d84 values were compared again with the five point bar transects removed from analyses. The variables PBR, d50*adj.*, d84*adj.*, MDEP, DMAX, WDR, and DH were significantly different between groups regardless of which analysis method was used. Cross-sectional area (XSEC) was significantly different between groups only when the first analysis method was used. Direction of streamflow was significantly different between groups only when the second analysis method was employed. Of the two analysis methods, the second is thought to be more valid due to differences in mussel recruitment among reaches (Chapter 2). The second analysis method will therefore be used in the following summary of results.

In the second analysis, Wilcoxon tests utilizing all reaches combined (Table 3.4), the following significant results ($p>|Z|=0.05$ or less) were

Table 3.1. Mean values of habitat parameters for high and low mussel density groups for all reaches (n = 66 transects, first analysis method).

Habitat Parameter	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>z
substratum characteristics			
PBR (%)	18.06 (4.86)	41.03 (6.84)	0.005*
d50 (mm)	76.75 (4.72)	93.17 (9.05)	0.127
d50*adj.*[1]	76.75 (4.72)	107.28 (8.18)	0.0036*
d84 (mm)	145.39 (14.37)	160.43 (16.87)	0.285
d84*adj.*[1]	145.39 (14.37)	185.24 (15.89)	0.0165*
GSD	1.85 (0.06)	1.74 (0.05)	0.309
channel cross-section morphology			
MDEP (m)	0.303 (0.016)	0.494 (0.026)	0.0001*
BWID (m)	25.27 (1.98)	30.52 (2.53)	0.151
XSEC (m^2)	7.92 (0.91)	15.21 (1.56)	0.0003*
DMAX (m)	0.440 (0.022)	0.710 (0.040)	0.0001*
WDR	89.81 (7.34)	64.65 (5.62)	0.023*
DH	0.089 (0.006)	0.146 (0.012)	0.0001*
BHT (m)	1.28 (0.12)	1.29 (0.09)	0.593
stream valley characteristics			
DIR[2]	175.64 (10.11)	187.00 (11.12)	0.387
MFLO (cm/s)	36.40 (3.87)	35.47 (4.60)	0.689

* Denotes differences significant at the 95 percent confidence level.

[1] d50*adj.* and d84*adj.* values are from analyses without point bars.

[2] DIR is measured in azimuth degrees.

Table 3.2. Mean values of habitat parameters for high and low mussel density groups for unbraided reaches (n = 43 transects, first analysis).

Habitat Parameter	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>z
substratum characteristics			
PBR (%)	27.08 (6.58)	60.84 (7.39)	0.002*
d50 (mm)	86.21 (5.60)	94.95 (13.30)	0.541
d50*adj.*[1]	86.21 (5.60)	120.79 (11.41)	0.013*
d84 (mm)	171.29 (19.28)	166.63 (24.84)	0.942
d84*adj.*[1]	171.29 (19.28)	213.14 (22.51)	0.069
GSD	1.96 (0.07)	1.79 (0.07)	0.186
channel cross-section morphology			
MDEP (m)	0.295 (0.021)	0.536 (0.031)	0.0001*
BWID (m)	27.73 (2.64)	35.57 (3.11)	0.082
XSEC (m^2)	8.59 (1.26)	18.34 (1.88)	0.0001*
DMAX (m)	0.445 (0.031)	0.794 (0.048)	0.0001*
WDR	101.10 (9.49)	71.35 (7.94)	0.042*
DH	0.094 (0.008)	0.166 (0.016)	0.0002*
BHT (m)	1.00 (0.07)	1.23 (0.10)	0.120
stream valley characteristics			
DIR[2]	169.10 (14.80)	189.05 (22.83)	0.218
MFLO (cm/s)	30.14 (3.14)	25.27 (3.64)	0.345

* Denotes differences significant at the 95 percent confidence level.

[1] d50*adj.* and d84*adj.* values are from analyses without point bars.

[2] DIR is measured in azimuth degrees.

Table 3.3. Mean values of habitat parameters for high and low density groups for braided reaches (n = 23 transects, first analysis method).

Habitat Parameter	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>z
substratum characteristics			
PBR (%)	0.00 (0.00)	6.82 (3.98)	0.066
d50 (mm)	57.83 (5.74)	90.09 (9.85)	0.0106*
d84 (mm)	93.58 (7.24)	149.73 (17.72)	0.0115*
GSD	1.64 (0.04)	1.66 (0.07)	0.975
channel cross-section morphology			
MDEP (m)	0.320 (0.023)	0.421 (0.040)	0.079
BWID (m)	20.35 (2.19)	21.80 (2.89)	0.951
XSEC (m^2)	6.56 (1.02)	9.80 (1.92)	0.372
DMAX (m)	0.431 (0.030)	0.575 (0.053)	0.045*
WDR	67.28 (8.28)	53.06 (5.69)	0.309
DH	0.078 (0.009)	0.111 (0.015)	0.103
BHT (m)	1.85 (0.25)	1.38 (0.15)	0.124
stream valley characteristics			
DIR[1]	188.70 (6.08)	183.45 (10.39)	0.644
MFLO (cm/s)	46.41 (7.99)	48.74 (7.98)	0.762
PROX	1.58 (0.19)	2.09 (0.28)	0.184

* Denotes differences significant at the 95 percent confidence level.

1 DIR is measured in azimuth degrees.

Table 3.4. Mean values of habitat parameters for high and low mussel density groups for all reaches (n = 66 transects, second analysis method).

Habitat Partameter	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>z
substratum characteristics			
PBR (%)	12.84 (4.18)	42.37 (6.39)	0.0006*
d50 (mm)	74.37 (4.14)	92.57 (8.38)	0.139
d50*adj.*[1]	74.37 (4.14)	101.39 (8.11)	0.016*
d84 (mm)	130.71 (7.92)	171.29 (18.93)	0.163
d84*adj.*[1]	130.71 (7.92)	188.16 (19.28)	0.021*
GSD	1.80 (0.04)	1.80 (0.06)	0.753
channel cross-section morphology			
MDEP (m)	0.332 (0.020)	0.441 (0.028)	0.007*
BWID (m)	29.12 (2.19)	26.36 (2.31)	0.290
XSEC (m^2)	10.19 (1.18)	12.16 (1.50)	0.635
DMAX (m)	0.480 (0.031)	0.640 (0.041)	0.005*
WDR	94.84 (7.52)	63.79 (5.58)	0.002*
DH	0.091 (0.006)	0.135 (0.012)	0.007*
BHT (m)	1.35 (0.13)	1.23 (0.08)	0.700
stream valley characteristics			
DIR[2]	4.81 (0.234)	3.89 (0.231)	0.008*
MFLO (cm/s)	38.00 (3.82)	33.85 (4.56)	0.161

* Denotes differences significant at the 95 percent confidence level.

[1] d50*adj.* and d84*adj.* values are from analyses without point bars.

[2] DIR is measured in azimuth degrees.

Table 3.5. Mean values of habitat parameters for high and low mussel density groups for unbraided reaches (n = 43 transects, second analysis method).

Habitat Parameter	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>z
substratum characteristics			
PBR (%)	19.90 (5.94)	61.22 (6.73)	0.0001*
d50 (mm)	81.05 (4.53)	97.91 (11.57)	0.223
d50*adj.*[1]	81.05 (4.53)	118.83 (9.94)	0.014*
d84 (mm)	146.25 (9.02)	231.67 (26.37)	0.219
d84*adj.*[1]	146.25 (9.02)	231.67 (26.37)	0.015*
GSD	1.88 (0.05)	1.89 (0.09)	0.817
channel cross-section morphology			
MDEP (m)	0.317 (0.027)	0.475 (0.035)	0.002*
BWID (m)	32.15 (2.88)	30.36 (3.02)	0.688
XSEC (m^2)	10.86 (1.58)	14.68 (1.99)	0.210
DMAX (m)	0.474 (0.042)	0.708 (0.052)	0.001*
WDR	110.00 (9.64)	68.79 (7.33)	0.002*
DH	0.094 (0.008)	0.154 (0.014)	0.002*
BHT (m)	0.99 (0.09)	1.20 (0.09)	0.192
stream valley characteristics			
DIR[2]	5.05 (0.34)	3.83 (0.34)	0.013*
MFLO (cm/s)	32.38 (3.05)	23.83 (3.19)	0.023*

* Denotes differences significant at the 95 percent confidence level.
[1] d50*adj.* and d84*adj.* values are from analyses without point bars.
[2] DIR is measured in azimuth degrees.

Table 3.6. Mean values of habitat parameters for high and low density mussel groups for braided reaches (n = 43 transects, second analysis method).

Habitat Parameter	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>z
substratum characteristics			
PBR (%)	0.00 (0.00)	6.25 (3.68)	0.090
d50 (mm)	63.36 (6.77)	82.33 (10.25)	0.166
d84 (mm)	102.45 (11.20)	136.92 (17.17)	0.123
GSD	1.65 (0.06)	1.65 (0.06)	0.999
channel cross-section morphology			
MDEP (m)	0.359 (0.030)	0.377 (0.040)	0.926
BWID (m)	23.62 (2.66)	18.68 (2.21)	0.185
XSEC (m^2)	8.97 (1.71)	7.33 (1.42)	0.282
DMAX (m)	0.490 (0.044)	0.509 (0.050)	0.878
WDR	67.32 (6.47)	54.21 (7.87)	0.186
DH	0.088 (0.009)	0.099 (0.016)	0.829
BHT (m)	2.00 (0.24)	1.28 (0.15)	0.021*
stream valley characteristics			
DIR[1]	4.36 (0.15)	4.00 (0.21)	0.223
MFLO (cm/s)	45.15 (7.42)	50.54 (8.59)	0.543
PROX	1.27 (0.14)	2.33 (0.22)	0.001*

* Denotes differences significant at the 95 percent confidence level.

[1] DIR is measured in azimuth degrees.

observed. PBR values for high mussel density transects (mean=12.84%) were lower than PBR values for low density ones (mean=42.37%). The d50 values (excluding point bars) for high density transects (mean=74.37 mm) were lower than d50 values for low density transects (mean=101.39 mm). High density transect d84 values also were lower (mean=130.71 mm) than low density transect d84 values (mean=188.6 mm). Mean depths (MDEP) of high density transects (mean=0.332 m) were less than mean depths of low density ones (mean=0.441). Maximum depths (DMAX) of high density transects (mean=0.480) also were lower than maximum depths of low density ones (mean=0.640). Width to depth ratios (WDR) of high density transects (mean=94.84) were greater than WDR values for low density ones (mean=63.79). Depth heterogeneity (DH) values for high density transects (mean=0.091) were lower than DH values for low density ones (mean=0.135). The direction of streamflow (DIR) of high density transects (mean=4.81 azimuth units) was different than the direction of streamflow of low density transects (mean=3.89 azimuth units).

When unbraided transects were compared (Table 3.5), the following significant results were observed. Percent bedrock (PBR) was lower in high density transects (mean=19.90%) than in low density ones (mean=61.22%). The d50 particle size was smaller in high density transects (mean=81.05 mm) than in low density ones (mean=118.83 mm). The d84 particle size also was smaller in high density transects (mean=146.25 mm) than in low density ones (mean=231.67 mm). The mean depth (MDEP) was less in high density transects (mean=0.317 m) than in low density ones (mean=0.475 m). The maximum depth (DMAX) of high density transects (mean=0.474 m) was also less than in low density ones (mean=0.708 m). Width to depth ratios were greater in high density transects (mean=110.00) than in low density transects (mean=68.79). Depth heterogeneity (DH) was lower in high density transects (mean=0.094) than in low density ones (mean=0.154). Streamflow direction (DIR) in high density ones (mean=5.05 azimuth units) was different than in low density ones (mean=3.83 azimuth units). Mean flow velocity (MFLO) was greater in high density transects (mean=32.38 cm/s) than in low density ones (mean=23.83 cm/s).

In comparisons of braided reach transects (Table 3.6), only bank height (BHT) and proximity to floodplain (PROX) were significantly different between groups at the 95 percent confidence level. Streambanks of high density transects (mean=2.00 m) were significantly higher than the banks of low density transects (mean=1.28 m). High density transects were further removed from the flood plain (mean=1.28 units) than low density transects (mean=2.33 units). Percent bedrock ($p>|Z|=0.090$) was the most significant of the remaining variables. As in all reaches combined, and unbraided reaches, PBR was lower in high density transects (mean=0.00%) than in low density transects (mean=6.25%).

The best variables identified by stepwise discriminant analysis (SDA), F statistics, average squared canonical correlation values, and p>F values for all transects, unbraided transects, and braided transects are listed in Table 3.7. Cumulative ASCC values increased from 0.30, to 0.52 and 0.61, when all transects were split into unbraided and braided transect groups. Frequency distributions of variables selected by SDA for high and low density groups are presented in Figures 3.6 through 3.10. The following text is a summary of observations on the frequency distributions for each selected variable.

Table 3.7. Variables selected by stepwise discriminant analysis to predict habitat quality group from 14 Study A habitat variables. ASCC = average squared canonical correlation.

Variables	F Statistic	ASCC	p>F
all transects, n = 66			
PBR (percent bedrock)	10.4	0.18	0.002
d50 (median particle size)	4.8	0.26	0.03
MDEP (mean depth)	2.7	0.30	0.11
unbraided transects, n = 43			
PBR (Percent Bedrock)	20.6	0.33	0.0001
d84	4.3	0.40	0.0
MDEP (mean depth)	4.9	0.47	0.03
DIR2 (direction of flow)	3.0	0.52	0.05
braided transects, n = 23			
PROX (proximity to floodplain)	15.3	0.42	0.0008
PBR (percent bedrock)	10.0	0.61	0.0049

Percent bedrock

Percent bedrock was the only variable selected by SDA for all, unbraided, and braided transects. The highest frequency of high and low density transects occurred in the 0-10 percent bedrock class for all transects combined (Figure 3.6.A). This was also the case in the braided transects (Figure 3.6.C). However only three braided transects, all of which were low density, occurred outside the 0-10% class. In the unbraided transects (Figure 3.6.B) the highest frequency of high density transects occurred in the 0-10% class. The highest frequency of low density unbraided transects, however, occurred in the 91-100% class, with only one transect in the 0-10% class.

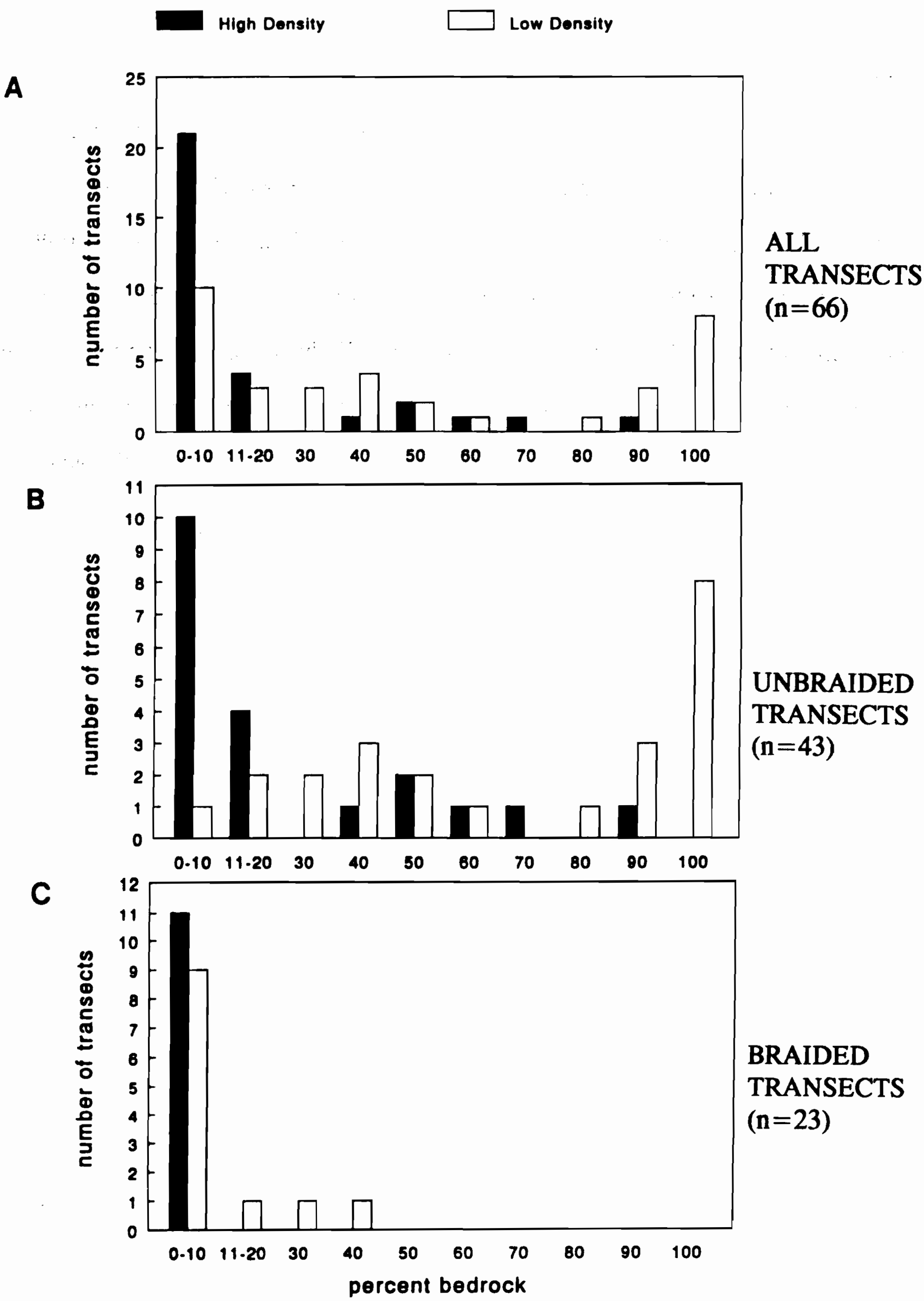

Figure 3.6. Percent bedrock (PBR) frequency distributions of high and low mussel density transects. A. All transects. B. Unbraided transects. C. Braided transects. Point bar transects are not included.

Particle size

Frequency distributions of median particle size (d50), selected by SDA for all transects combined, are shown in Figure 3.7.A. The high density transect group exhibited a unimodal distribution, with most d50 values occurring in the 61-80 mm size class. No high density transect d50 value exceeded 120 mm. The low density group exhibited a bimodal distribution, with frequency peaks occurring in the 41-60 mm and 121-140 mm size classes. The range of values for the low density group was greater than the high density group. The d84 particle size variable was selected by SDA for unbraided transects (Figure 3.7.B). The frequency peak of the unimodally distributed high density group occurred in the 101-150 mm size class. The d84 values of the low density transect group exhibited a greater range of values with a frequency peak in the 251-300 mm size class. Neither particle size variable (d50 or d84) was selected by SDA in braided transect analyses.

Mean depth

Mean depth was selected by SDA for unbraided transects and all transects combined. High density transects exhibited a distinctly unimodal distribution with the peak frequency in the 0.21-0.30 meter depth class (Figure 3.8.A and B). The peak frequency for low density transects was also in the 0.21-0.30 meter depth class. However, there were no low density transects in shallower depth classes and low density transects occurred at mean depths greater than 0.60 meters. There was no clear peak in frequency among low density unbraided transects, but the distribution

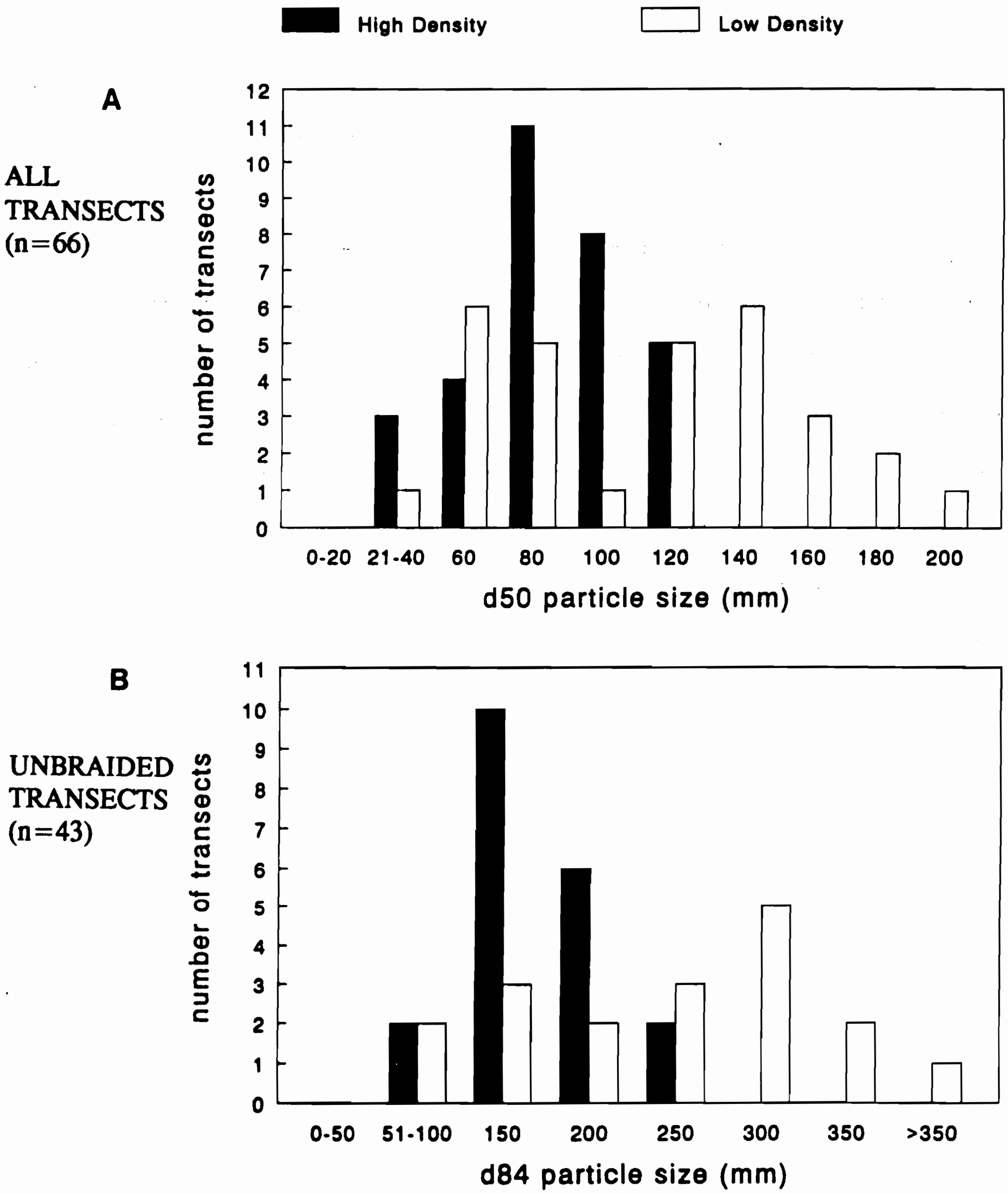

Figure 3.7. Particle size distributions of high and low mussel density transects. A. All transects (d50). B. Unbraided transects (d84).

was shifted toward greater mean depths relative to the high density transects.

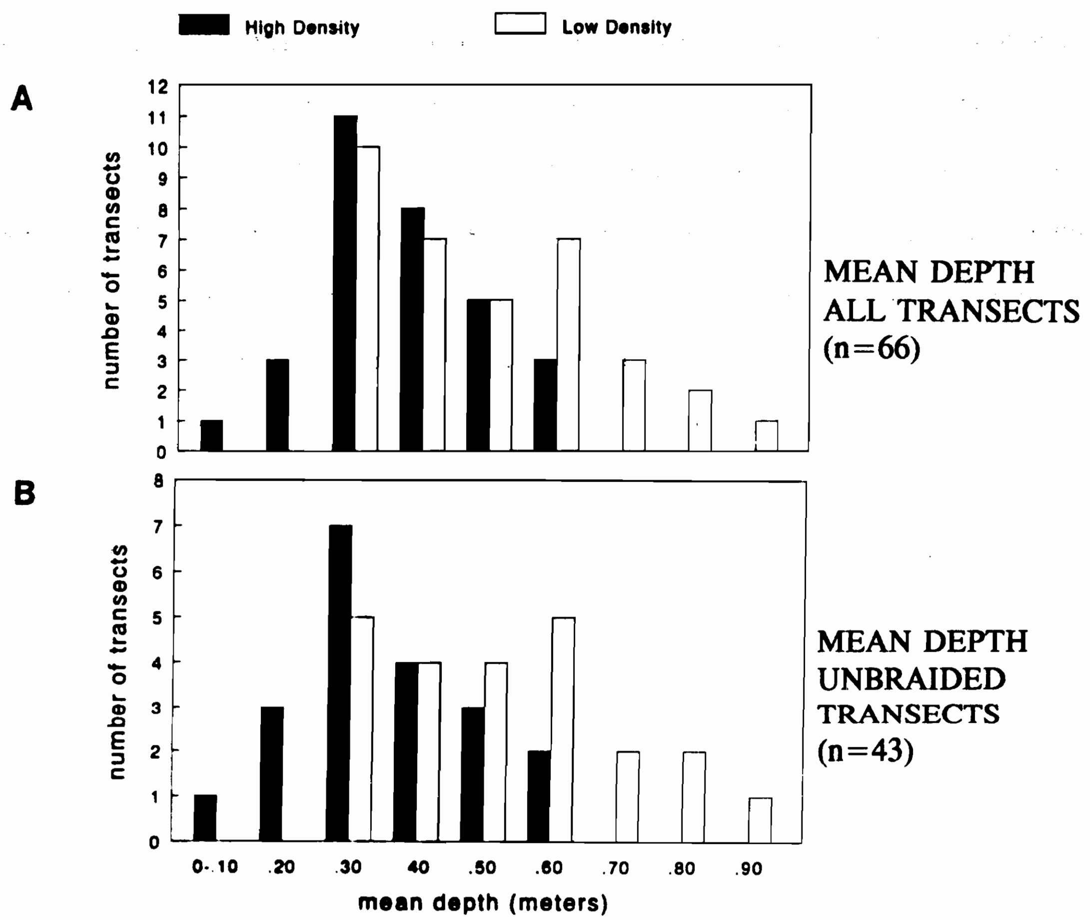

Figure 3.8. Mean depth distributions of high and low mussel density transects. A. All transects. B. Unbraided transects.

Proximity to floodplain

Proximity to floodplain (PROX) was a variable used only among braided transects and was selected by SDA as an important variable among braided transects (refer to Figure 3.4, page 50). High density transects occurred only in PROX classes 1 and 2, with the greatest frequency in PROX class 1 (Figure 3.9). Low density transects occurred in all PROX classes, with the peak frequency found in PROX class 2. High density transects occurred more frequently in channels nearer steep slopes, or channels farther removed from the flood plain.

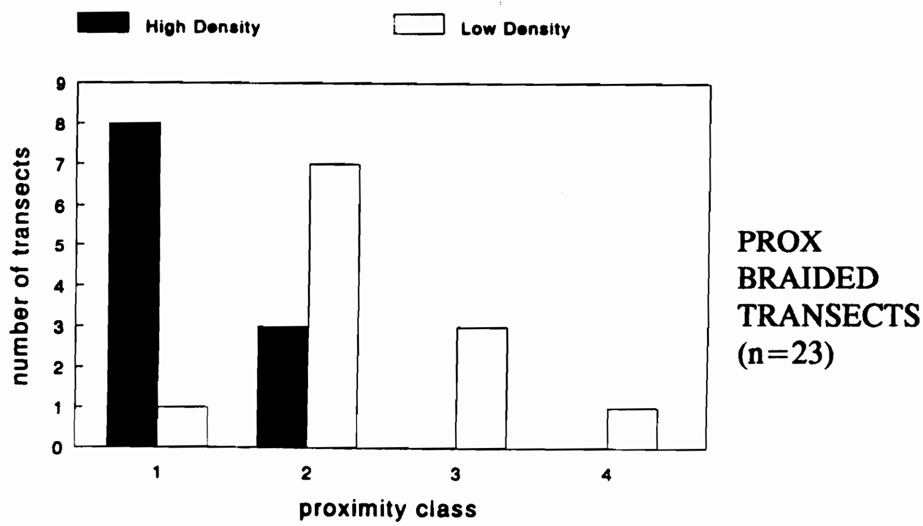

Figure 3.9. Proximity to floodplain (PROX) of high and low mussel density transects in braided reaches.

Direction of streamflow

Direction of streamflow was selected by SDA only in unbraided transects (Figure 3.10). The highest frequency of high density transects occurred in azimuth unit 6 (South flowing), while the highest frequency of low density transects occurred in azimuth unit 2 (North flowing). However, there were comparatively high frequencies of low density transects in azimuth units 4 (West) and 6 (South). There were no transects in azimuth units 1 (Northeast), 7 (Southeast), or 8 (East) as the river did not flow in these directions in any the study reaches.

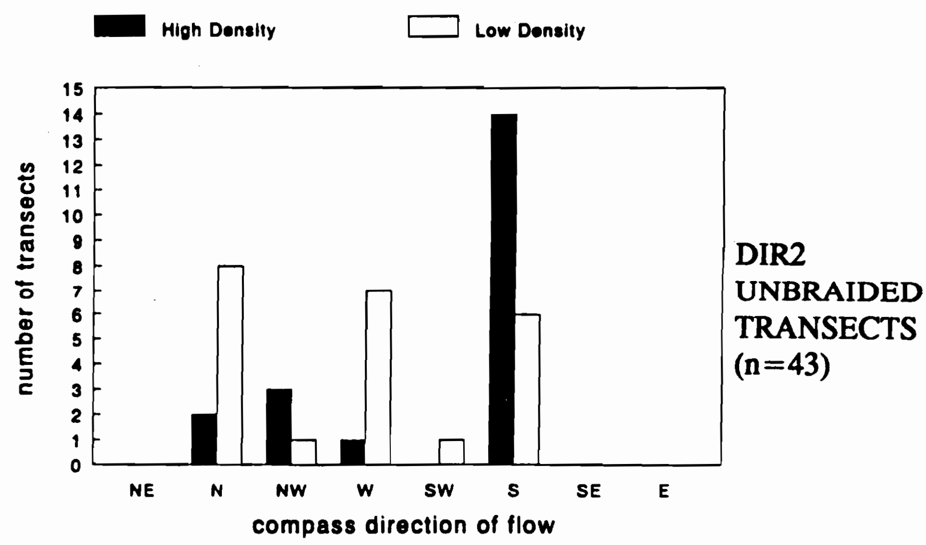

Figure 3.10. Direction of streamflow (DIR2) of high and low mussel density transects in unbraided channels.

Discussion

Unbraided reaches

The four habitat variables selected by SDA in unbraided reaches were percent bedrock, d84 particle size, mean depth, and direction of flow. High density transects were characterized by low PBR values. Therefore, large contiguous areas of alluvium, with little or no exposed bedrock, appear to be conducive to the development of high mussel density. Stanford and Gaufin (1974) observed that rivers with a deep hyporheos of coarse particles offer the greatest resistance to washout during high discharges. According to Resh et al. (1988), streams characterized by sparse bedload (high PBR) are disturbed more by high discharge. I am unaware of other mussel habitat studies in which percent bedrock of stream cross-sections was used as a variable. This parameter appears to be a useful indicator of mussel density in the Clinch River, where much of the streambed is unfractured bedrock, and may provide utility in other bedrock-dominated streams.

Transects with high mussel densities were characterized by smaller particles than low density transects. Streambed areas characterized by large particles (large cobbles and boulders) are often associated with higher percent bedrock, and are usually indicative of higher gradient and increased hydraulic stress during high discharge. Additionally, there may be fewer suitable places for mussels to burrow amidst coarser particles. Strayer and Ralley (1993) suggest that in rocky rivers, mussels may be limited by the number of small, protected patches of fine sediments. A number of researchers have reported sediment granulometry to be of limited value in explaining the distribution of riverine mussels (Holland-Bartels, 1990; Strayer and Ralley, 1993; Di Maio and Corkum, 1995; Layzer and Madison, 1995). Strayer et al. (1994) doubted the usefulness of focusing on sediment granulometry in future studies of unionid habitat ecology. However, the studies referenced differ from this one in at least two important respects. With the exception of Layzer and Madison (1995), particle size ranges documented in the referenced studies were less than 16 mm in diameter, compared to median particle sizes of 81 mm (high density group) and 119 mm (low density group) in the unbraided transects of this study. Layzer and Madison (1995) identified a broad range of particle sizes (silt to boulders) in Horse Lick Creek, Kentucky, but used a visual technique, rather than sieve analyses, to classify substrata. This study also differs from those referenced in the methods used to sample sediment particles. Most researchers (Holland-Bartels, 1990; Strayer and Ralley, 1993; Strayer et al., 1994; Di Maio and Corkum, 1995) collected volumetric samples via cores or PONAR grab samples, followed by sieve analyses. In this study, only the pavement or surface layer was sampled by using a modification of the grid-by-number technique that has been used in hydraulic engineering and sediment transport studies (Wolman, 1954; Kellerhals and Bray, 1971; Hey and Thorne, 1983). The streambed alluvium of gravel bed streams is usually stratified vertically, and consists of a surface layer composed of coarser particles than the underlying sediments (Wolman, 1954; Kellerhals and Bray, 1971; Parker , 1980; Diplas and Parker, 1985; Diplas and Sutherland, 1988).

Transects characterized by low mean and maximum depth, low depth heterogeneity, and moderate flow velocities were characteristic of high mussel density. This suite of conditions describe the glide, which is intermediate between riffle and pool conditions. Glides are often referenced as high quality mussel habitat, but are not described in terms of measurable descriptors of channel shape. Riffles are generally less uniform in depth than glides, and are characterized by larger particles and swifter, more turbulent flows. Pools, which are depositional during low discharge and erosional during high discharge, are the areas of greatest physical disturbance during high discharge events (Resh et al. 1988). Given the extreme longevity of most mussel species, substratum stability during high discharge events may be the most important attribute of high quality mussel habitat in unregulated rivers.

Direction of flow as an important variable in unbraided reaches was a somewhat unexpected outcome. I speculate that bedrock strata orientation, relative to flow direction, may determine bedload retention or scour during periods of high discharge. A closer examination of two of the study reaches will help to elucidate this proposed relationship. Study reaches LR1 and CR3 are comprised of a North flowing reach, a tight bend, and a South flowing reach (Figure 3.1). The mussel density in South flowing reaches is much greater than in North flowing reaches in both LR1 and CR3. Mean mussel density in North and South flowing reaches at LR1 is 6.33 and 12.87 mussels/m^2, respectively. The mean mussel density in North and South flowing reaches at CR3 is 2.07 and 5.83 mussels/m^2, respectively.

These differences may be explained in terms of geologic strike and dip, which were measured on bedrock outcrops at both sites. Stratigraphy and bed load (alluvium) at CR3 are mapped schematically in Figure 3.11. The mean of geologic strike measurements was N75° E. Dip was approximately 30° in the SE direction (perpendicular to the line of strike). Therefore, South flowing reaches are flowing in the approximate direction of dip, while North flowing ones are roughly opposite the direction of dip. Retention of alluvium by the gently dipping strata encountered as the river flows North is therefore less than alluvium retained by the nearly vertical ledges encountered as the river flows South. As long as the orientation of bedrock strata are so aligned, one would expect greater retention of alluvium (lower percent bedrock) in South flowing reaches. Vannote and Minshall (1982) hypothesized that large boulders protect areas of mussel habitat from bed scour in the Snake River. Orientation of bedrock strata may similarly affect substratum retention or removal during high discharge periods. Further testing of this hypothesis is conducted in Chapter 4.

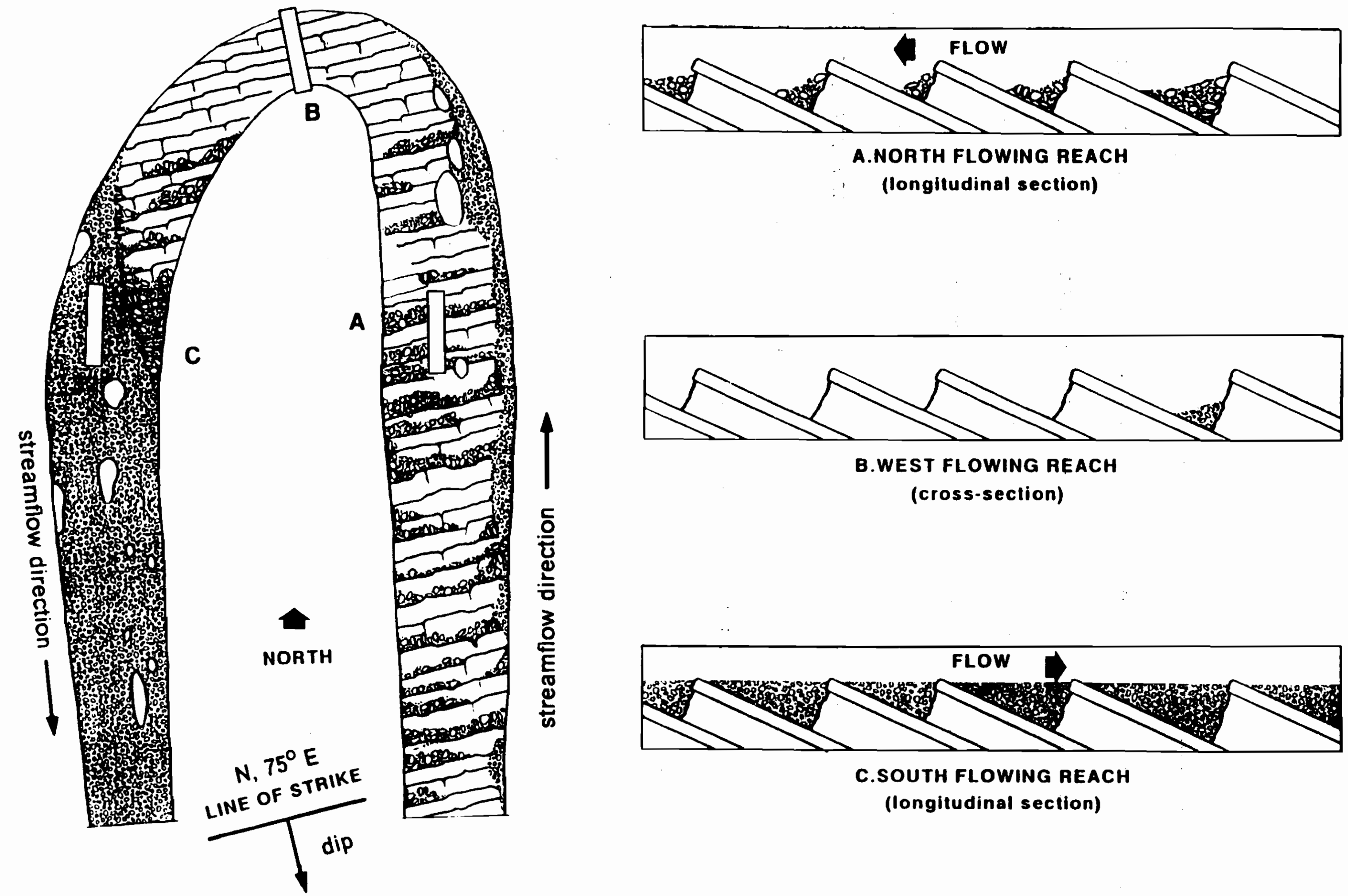

Figure 3.11. Schematic diagram of stratigraphy and bed load at CR3.

Braided reaches

Most of the best mussel sites sampled during the TVA survey (TVA 1986a) occur in braided channels. Holland-Bartels (1990) also documented high mussel densities in a braided reach of the upper Mississippi River. Channel braiding occurs where more bedload material enters the stream than it is competent to remove (Leopold and Wolman 1957, Resh et al. 1988). Braided channels usually lie in flood plain areas which permit high discharge volumes to spill over the banks, dissipating residual energy with little increase in hydraulic stress along the streambed.

In the braided reaches, all transects were relatively shallow with low depth heterogeneity, which may explain why channel morphology variables were not significantly different between high and low mussel density transects. The range of particle sizes was smaller among braided transects, resulting in no significant difference between low and high density transects. The mean particle size of the high density group was smaller than that of the low density group, which was consistent with observations from unbraided reaches. Reduced hydraulic stress in braided channels may permit the retention of smaller cobbles, which probably would be scoured during high discharge in unbraided channels carrying an equivalent discharge volume. Generally, greater mussel densities were observed in substrata composed of smaller cobbles, which occurred more frequently in braided channels than in unbraided channels.

Proximity to floodplain and percent bedrock were selected by SDA as the most important variables in braided channels. All high density braided transects had less than 10 percent bedrock. However, there was much less exposed bedrock throughout the braided reaches than in the unbraided ones. Knighton (1984) has observed that braided channels are characterized by large bed loads (and consequently low bedrock), erodible banks, highly variable discharge, and high gradient. Proximity to floodplain appeared to be important in the braided reaches studied, with the greatest occurrence of high density transects in channels farthest removed from the floodplain. According to Knighton (1984), braided channels are usually composed of a dominant, containing channel with a relatively straight alignment, and a variable number of lesser sinuous channels. Rapid shifts in the position of the lesser channels may occur during high discharges due to the erodibility of their banks. I suggest that the containing channels at CR4 and CR5 are more fixed in position, due to the steep bedrock comprising their left descending banks, than the secondary channels with their banks of more erodable alluvium. The greatest mussel densities were observed in the containing channels at CR4 and CR5. These channels may be less subject to bed scour during high discharges, and therefore are more likely to contain stable mussel habitat than the secondary channels.

Conclusions

In unbraided reaches of the Clinch River, the direction of flow relative to geologic dip may be an important factor determining the distribution of habitats with high densities of mussels. Reaches which flow in the direction of geologic dip (approximately south in this study) appear to be characterized by lower percent bedrock and smaller particle sizes associated with areas of high mussel density. This is probably due to enhanced retention of alluvium by bedrock ledges, which retain the sediments from bed scour during high discharges. Increased stability of the substratum enables mussels to colonize more effectively, with the consequent development of greater mussel density within these streambed areas.

Orientation of bedrock strata may be less important in the retention of streambed particles in highly braided channels. Braided channels typically occur where the stream channel and valley floor are wide, resulting in a reduction of stream competence to transport particles. These conditions permit the retention of smaller particles, which often occur in high density mussel habitat, than would be retained in unbraided channels carrying equivalent discharge volumes.

CHAPTER 4. HABITAT ANALYSES USING SITES FROM THE 1986 TVA MUSSEL SURVEY OF THE CLINCH RIVER

Introduction

In Chapter 3 a number of habitat variable measurements were found to be significantly different between transect groups of high and low mussel density. In this chapter, further analyses are conducted to test these variables using a larger number of Clinch River sites. Two landscape or macro-scale variables were included in addition to the variables measured in Chapter 3.

These analyses would not have been possible without the large data base compiled by Steve Ahlstedt and other TVA biologists between 1979 and 1984 (TVA 1986a). Prior to qualitative sampling, the entire free-flowing Clinch River downstream of Pounding Mill, Virginia was canoed by experienced TVA mussel biologists. Virtually every site seemingly favorable for mussel habitat was included in the survey (Steven Ahlstedt, USGS, personal communication). Each sampling crew consisted of three to five divers equipped with SCUBA gear and/or snorkels. Sampling time at each site averaged between one and two hours (TVA 1986a). The survey included qualitative sampling data from 141 sites on the Clinch River upstream of Norris Reservoir (CRK 241.0), and is certainly the most comprehensive mussel survey of the river.

Mussel site quality, as indicated by the number of mussels reported in the TVA survey, was used as the dependent variable in this study. This is different from the Chapter 3 study, in which excavated quadrat samples were used to determine in-stream mussel densities (mussels/m^2). In the Section 1 study of this chapter, on-site measurements at 20 high quality and 23 low quality TVA sites were compared. In the Section 2 study, patterns of site distribution were examined in terms of direction of stream flow and geological characteristics.

Section 1. Comparisons of habitat variables associated with high quality and low quality mussel sites.

Study Site Selection

Study sites were selected from the free-flowing Clinch River between CRK 274.0 near Swan Island in Hancock County, Tennessee and CRK 473.0 near the confluence of Lewis Creek in Russell County, Virginia (Figures 4.1 and 4.2). Twenty high quality sites were selected from the 21 best (sites with the greatest numbers of mussels reported) TVA sites (Table 4.1). One high quality site, from which 944 mussels were reported, was excluded due to accessibility problems. At least 130 mussels were reported from each site in the high quality group.

Precautions were taken to include only relatively undisturbed sites in the low quality group. As in the preceding habitat study (Chapter 3), sites within reaches of documented anthropogenic disturbance (CRK 482.0-515.0 and CRK 407.0-431.0) were excluded. Additionally, only low quality sites immediately downstream of intermediate or high quality sites were selected, in order to minimize the likelihood of including sites impacted by undocumented point and non-point source pollution. Less than

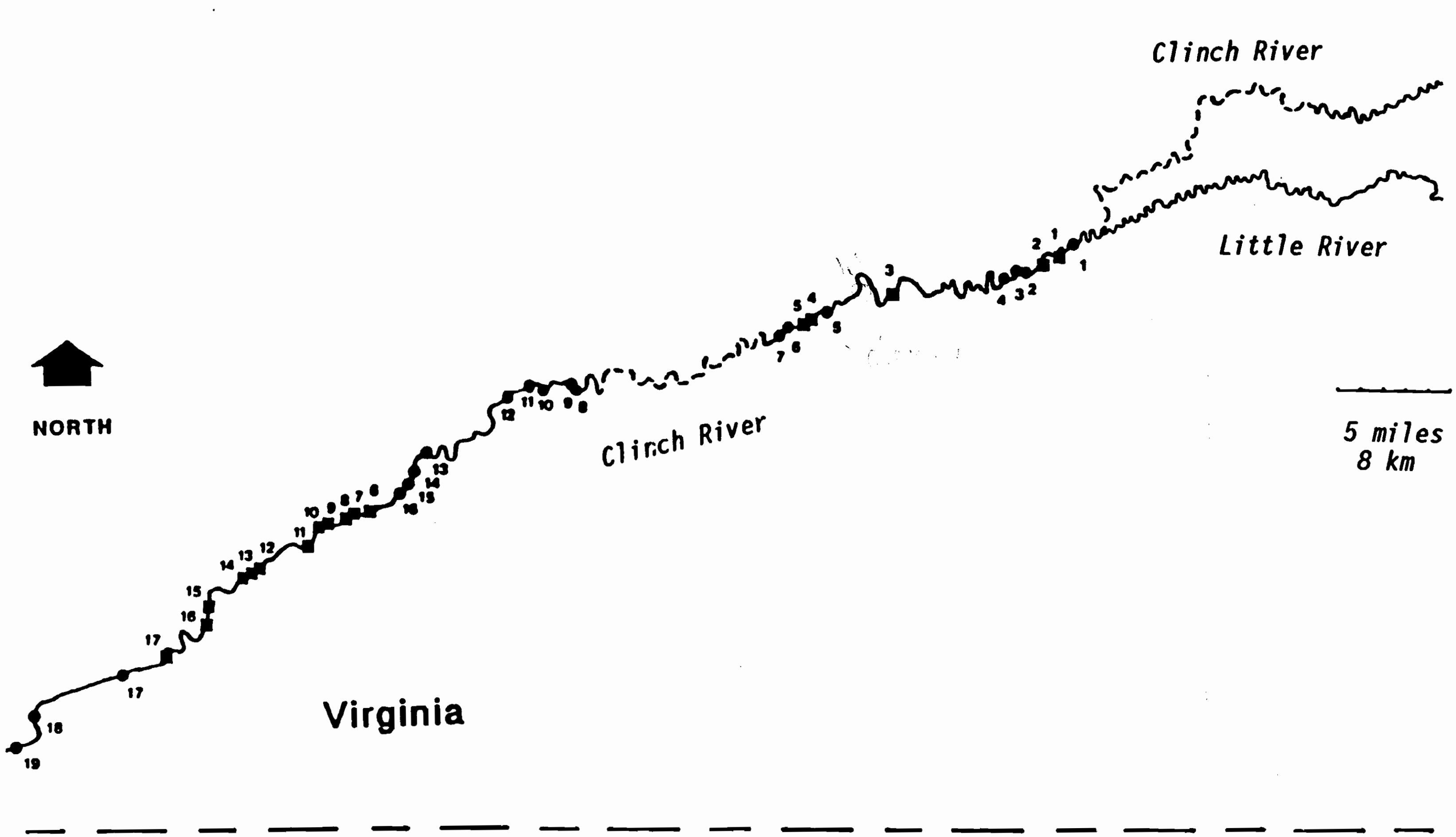

Figure 4.1. Chapter 4: Section 1 study sites in Virginia. High quality sites are indicated by square symbols and are numbered above the river. Low quality sites are indicated by round symbols and are numbered below the river. River kilometer location of sites are listed in Tables 4.1 and 4.2. Reaches of documented impact are indicated by dashed lines.

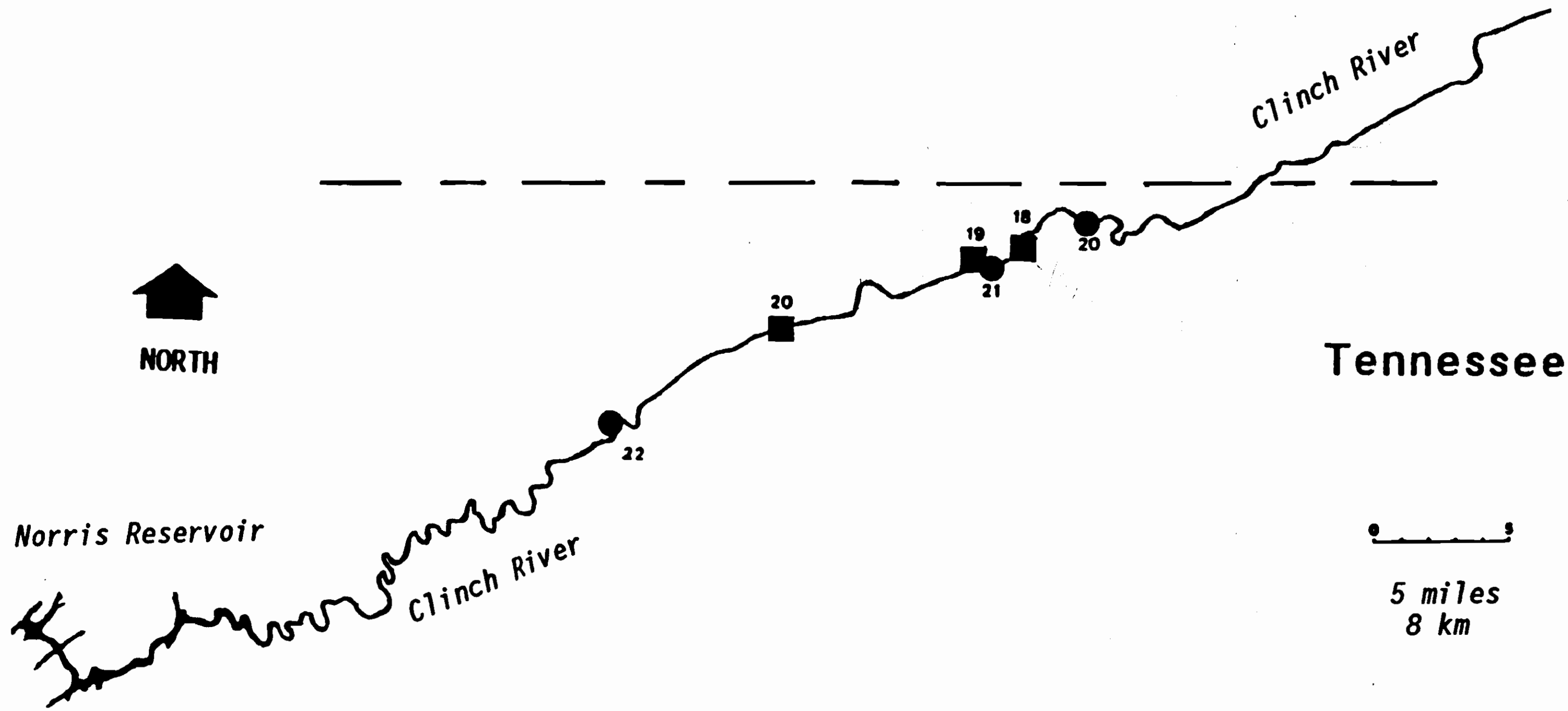

Figure 4.2. Chapter 4: Section 1 study sites in Tennessee. High quality sites are indicated by square symbols and are numbered above the river. Low quality sites are indicated by round symbols and are numbered below the river. River kilometer location of sites are listed in Tables 4.1 and 4.2.

Table 4.1. High quality mussel sites selected from TVA survey (TVA 1986).

TVA Site Number[1]	CRK Location	Mussels Reported	Site Morphology
23	287.5	139	braided
39	301.0	132	braided
43	304.6	150	unbraided
68	352.9	132	braided
69	359.3	365	unbraided
70	360.6	155	unbraided
73	364.1	1182	braided
74	364.3	505	braided
75	364.6	600	braided
77	374.3	220	braided
79	376.5	482	braided
80	377.3	539	braided
82	378.0	509	braided
84	378.4	145	braided
85	378.9	227	unbraided
118	435.7	139	braided
120	436.0	249	braided
125	447.3	208	braided
132	470.3	154	unbraided
133	471.4	136	unbraided

[1] Sites were selected from the TVA report entitled "Cumberlandian Conservation Program, Activity 1: Mussel Distribution Surveys" prepared by Steven A Ahlstedt January, 1986.

Table 4.2. Low quality mussel sites selected from TVA survey (TVA 1986).

TVA Site Number[1]	CRK Location	Mussels Reported	Site Morphology
15	274.3	4	unbraided
40	301.4	17	braided
49	310.5	3	unbraided
59	337.9	14	unbraided
63	340.8	4	unbraided
65	349.2	9	unbraided
87	381.3	0	unbraided
88	381.7	0	unbraided
89	382.5	0	unbraided
90	383.4	0	braided
96	395.0	1	unbraided
97	397.3	10	unbraided
98	398.2	10	unbraided
100	401.6	1	unbraided
101	401.8	14	unbraided
115	433.5	4	unbraided
117	434.8	2	unbraided
122	437.6	16	braided
129	467.1	4	unbraided
130	467.9	5	unbraided
131	468.7	3	unbraided
134	473.0	12	unbraided

[1] Sites were selected from the TVA report entitled "Cumberlandian Conservation Program, Activity 1: Mussel Distribution Surveys" prepared by Steven A Ahlstedt January, 1986.

18 mussels were reported (TVA 1986) from each of the 22 sites selected as low quality sites (Table 4.2).

Habitat Measurement Methods

The methods used to measure substratum characteristics (PBR, d50, d84) were the same as those described in Chapter 3. The channel morphology characteristics mean depth (MDEP), bed width (BWID), cross-sectional area (XSEC), maximum depth (DMAX), width to depth ratio (WDR), depth heterogeneity (DH), and bank height (BHT) were measured at the stream cross-section level as in Chapter 3. Of the 20 high quality sites, 14 occurred in braided channels. Only three of the 22 low quality sites occurred in braided channels. Proximity to floodplain (PROX) was not evaluated in this study for lack of mussel density data to substantiate the habitat quality of specific areas of streambed.

In addition to direction of stream flow (DIR), the macro-scale valley characteristics, valley floor width (VFW) and flood plain location (FPL) were measured for each site. Valley floor width (VFW) was the distance in meters across the valley, perpendicular to the direction of stream flow, measured on USGS 7.5 minute topographic maps. Valley floor width at each site was measured as the distance in meters between the first contour line encountered on opposite sides of the river for USGS maps with 12.2 m (40 ft.) contour intervals (Coeburn, St. Paul, Carbo, Lebanon, Elk Garden, Honaker and Richlands). The distance between the second contour line encountered on opposite sides of the river was used for USGS maps with 6.1 m (20 ft.) contour intervals (Sneedville, Kyles Ford, Looneys Gap, Plum

Grove, Duffield, Clinchport, Gate City, Fort Blackmore and Dungannon).

Flood plain location (FPL) refers to which side of the river the flood plain lies on as one faces downstream. Sites in which the flood plain occurred to the right of the river were coded as 1, 2 if the flood plain occurred on both sides of the river, and 3 if the flood plain occurred to the left of the river. The geologic features, dip and strike, were measured wherever practical, as in Chapter 3, but were not treated as variables.

Results of Quality Group Comparisons

Wilcoxon rank-sum tests

Comparisons of habitat parameter values associated with high and low quality groups for all sites (Table 4.3) and unbraided sites (Table 4.4) were made using Wilcoxon two-sample tests (PROC NPAR1WAY, SAS, 1985). Comparisons between high and low quality site groups were not conducted for braided sites, as there were only three low quality braided sites.

All three substratum variables were significantly different (alpha = 0.05) between quality groups for all sites combined (Table 4.3), and for unbraided sites (Table 4.4). Four of the seven channel cross-section variables (MDEP, XSEC, DMAX, and DH) were significantly different between quality groups. However, none of the channel cross-section variables were significantly different between quality groups for unbraided sites only. The stream valley variables BRD and VFW were significantly different between quality groups for all sites combined. Of the stream valley

Table 4.3. Mean values of habitat parameters for high and low quality site groups (all sites, n = 42 sites).

Habitat Parameter	High Quality Sites Mean (SE)	Low Quality Sites Mean (SE)	Wilcoxon Sign. p>Z
substratum characteristics			
PBR (%)	4.00 (2.09)	41.82 (6.19)	0.0001*
d50 (mm)	77.75 (4.13)	133.91 (12.59)	0.001*
d84 (mm)	119.15 (6.06)	221.18 (20.75)	0.0002*
channel cross-section morphology			
MDEP (m)	0.317 (0.012)	0.402 (0.020)	0.001*
BWID (m)	40.23 (3.47)	43.02 (2.94)	0.890
XSEC (m^2)	13.07 (1.38)	17.20 (1.35)	0.043*
DMAX (m)	0.478 (0.027)	0.684 (0.047)	0.0001*
WDR	127.44 (10.16)	112.00 (9.05)	0.162
DH	0.092 (0.010)	0.152 (0.014)	0.0003*
BHT (m)	1.48 (0.17)	1.39 (0.14)	0.641
stream valley characteristics			
DIR1[1]	225.10 (12.57)	221.00 (18.87)	0.614
DIR2[1]	150.10 (12.57)	178.73 (14.06)	0.141
VFW (m)	395 (58)	184 (26)	0.004*
FPL	1.68 (0.15)	1.60 (0.19)	0.661

* denotes differences significant at the 95 percent confidence level or greater.

[1] measured in azimuth degrees.

Table 4.4. Mean values of habitat parameters for high and low quality site groups for unbraided sites (n = 25 sites).

Habitat Parameter	High Quality Sites Mean (SE)	Low Quality Sites Mean (SE)	Wilcoxon Sign. p>Z
substratum characteristics			
PBR (%)	13.00 (5.68)	46.84 (6.41)	0.017*
d50 (mm)	89.17 (7.85)	137.68 (12.94)	0.042*
d84 (mm)	139.83 (9.94)	226.42 (20.26)	0.033*
channel cross-section morphology			
MDEP (m)	0.344 (0.023)	0.405 (0.022)	0.143
BWID (m)	49.07 (4.66)	44.25 (3.15)	0.111
XSEC (m^2)	17.07 (2.20)	17.78 (1.45)	0.874
DMAX (m)	0.580 (0.060)	0.703 (0.053)	0.239
WDR	144.48 (13.02)	114.61 (9.75)	0.092
DH	0.124 (0.026)	0.158 (0.015)	0.215
BHT (m)	1.13 (0.16)	1.36 (0.16)	0.587
stream valley characteristics			
DIR1[1]	176.17 (4.42)	212.32 (20.64)	0.080
DIR2[1]	101.17 (4.42)	175.21 (15.41)	0.009*
VFW (m)	233 (86)	172 (24)	0.873
FPL	1.80 (0.37)	1.58 (0.19)	0.643

* denotes differences significant at the 95 percent confidence level.
[1] measured in azimuth degrees.

variables, only DIR2 was significantly different betweeen high and low quality unbraided sites.

Stepwise discriminant analysis and comparison with Chapter 3 results

The variables selected by stepwise discriminant analysis (SDA) from the 14 habitat variables were PBR, d84, DIR2, and VFW for all sites combined, and PBR, d84, d50, and DIR2 for unbraided sites (Table 4.5). In order to compare the SDA results of Chapter 3 with the SDA results of Chapter 4, SDA was repeated for the Chapter 4 study using only the 12 habitat variables common to both studies (PBR, d50, d84, MDEP, BWID, XSEC, DMAX, WDR, DH, BHT, DIR1, and DIR2). These results are reported as Chapter 4′ in Tables 4.6 and 4.7. The two macrohabitat variables, VFW and FPL, were not included in this analysis because they were not measured in Chapter 3. Variables selected by SDA from the 12 variables common to Chapters 3 and 4 were PBR, d84, and DIR, for all sites combined, and PBR, d84, d50, and DIR for unbraided sites (Table 4.6).

The variables PBR, d50, and MDEP were selected by SDA as the variables which provide the greatest discrimination between low and high density transects in Chapter 3 for all transects combined. In the Chapter 4′ analysis, PBR, d84, and DIR were selected by SDA for all sites. There is agreement between the analyses in that percent bedrock and a metric of particle size were selected by SDA in both Chapter 3 and Chapter 4′. When the landscape variables BRD, VFW, and FPL were added to the stepwise discriminant analysis in the Chapter 4 study for all transects combined, the variable VFW was selected by SDA in addition to PBR, d84, and DIR

(Table 4.7).

In the unbraided transects of the Chapter 3 study, PBR, d84, MDEP, and DIR were selected by SDA as the habitat variables yielding the greatest discrimination between low and high quality transect groups. In the Chapter 4' analysis, MDEP was replaced by d50. The same variables (PBR, d84, d50, and DIR) were selected by SDA following inclusion of the two landscape variables VFW and FPL in the Chapter 4 analysis (Table 4.7).

Table 4.5. Variables selected by stepwise discriminant analysis to predict habitat quality group (from all 14 Chapter 4 variables). ASCC = average squared canonical correlation.

Variables	F Statistic	ASCC	p>F
all sites, n = 42			
PBR (percent bedrock)	25.0	0.40	0.0001
d84 (84% finer particle size)	21.8	0.63	0.0001
DIR2 (flow direction)	3.0	0.66	0.09
VFW (valley floor width)	4.1	0.69	0.05
unbraided sites, n = 25			
PBR (Percent Bedrock)	8.1	0.26	0.0095
d84 (84% finer particle size)	10.6	0.50	0.004
d50 (median particle size)	2.3	0.55	0.15
DIR2 (flow direction)	3.6	0.62	0.07

Table 4.6. Chapter 4' Study: Variables selected by stepwise discriminant analysis to predict habitat quality group from 12 variables common to Chapter 3 and Chapter 4 studies (excluding VFW, and FPL). ASCC = average squared canonical correlation.

Variables	F Statistic	ASCC	p>F
all sites, n = 42			
PBR (percent bedrock)	30.9	0.44	0.0001
d84 (84% finer particle size)	21.2	0.63	0.0001
DIR2 (flow direction)	3.3	0.66	0.0784
unbraided sites, n = 25			
PBR (Percent Bedrock)	8.0	0.26	0.001
d84 (84% finer particle size)	10.6	0.50	0.004
d50 (median particle size)	2.3	0.55	0.15
DIR2 (flow direction)	3.6	0.62	0.07

Table 4.7. Variables Selected by Stepwise Discriminant Analysis for Chapter 3 and Chapter 4' studies (12 variables common to Study A and B), and the Chapter 4 study (15 variables).

	Chapter 3	Chapter 4'	Chapter 4
all sites/transects			
	PBR	PBR	PBR
	d50	d84	d84
	MDEP	d50	VFW
		DIR	DIR
		MDEP	
unbraided sites/transects			
	PBR	PBR	PBR
	d84	d84	d84
	MDEP	d50	d50
	DIR	DIR	DIR

Percent bedrock was consistently selected by stepwise discriminant analysis as a variable separating high quality mussel sites from low quality ones for all sites combined and for unbraided ones. High quality riverine mussel habitat typically occurred where areas of exposed bedrock are minimal, concealed by a layer of gravel/cobble alluvium. At least one descriptor of particle size (d50 or d84) was consistently selected by SDA as important between low and high quality mussel sites for all sites combined, and for unbraided sites alone. The descriptor most frequently selected was d84 particle size. However, in one instance (Chapter 3; all transects) d50 particle size was selected. Both d50 and d84 particle size were selected by SDA in two instances (Table 4.7).

Direction of streamflow (DIR) was selected by SDA in Chapter 3, Chapter 4, and Chapter 4′ analyses for unbraided transects/sites. DIR was not selected for all transects in Chapter 3, but was selected for all sites in Chapter 4 and Chapter 4′ analyses. High quality unbraided sites typically occurred where the river flows in the direction of dip. High quality braided sites generally occurred where the river flows along the line of strike.

Valley Floor Width (VFW) was selected by SDA for all sites in the Chapter 4 analysis. Most of the high quality sites are braided and typically occur where the valley floor is wide. This variable is important mainly because braided reaches tend to be associated with high VFW values, and high quality mussel sites often occurred within braided reaches. Mean Depth (MDEP) was selected by SDA for all transects and unbraided transects in Chapter 3, but not in Chapter 4 or Chapter 4' analyses. Optimal stream cross-sections are of uniformly shallow depth; however, there was less variability in the depth of cross-sections in the Chapter 4 study than in Chapter 3. This difference between studies was probably because all of the sites sampled in the TVA survey (Chapter 4) were subjectively judged by mussel biologists to be suitable mussel habitat. Shallowness was likely an attribute that the experienced TVA team associated with suitable mussel habitat. Transects in Chapter 3, however, were deliberately selected to encompass a broad range of channel forms including deeper cross-sections. Consequently, cross-sections of the low density transect group were significantly deeper than cross-sections of the high density group in Chapter 3.

Discussion

The habitat variables selected by SDA with all sites combined were percent bedrock (PBR), d84 particle size, direction of flow (DIR), and valley floor width (VFW).

High quality sites were usually located in stream cross-sections of unconsolidated alluvium, characterized by very low PBR values. Stanford and Gaufin (1974) and Resh et al. (1988) observed that streams with sparse bedload (high PBR) are indicative of greater washout during high discharges. I am unaware of other mussel habitat studies in which percent bedrock in stream cross-sections was measured as a variable. This parameter appears to be a useful indicator of mussel habitat quality in the Clinch River, where much of the streambed is consolidated bedrock, and may be of use in other bedrock-dominated streams.

High quality sites were also characterized by smaller particles lining the surface of the streambed than low quality sites. Streambed areas with larger particles (large cobbles and boulders) were usually associated with greater percent bedrock, and are usually indicative of higher gradient or increased hydraulic stress during high discharge. Additionally, there may be fewer suitable places for mussels to burrow amidst coarser particles. Strayer and Ralley suggest that in rocky rivers, mussels may be limited by the number of small, protected patches of fine sediments. Many researchers have found sediment granulometry to be of limited value in explaining the distribution of riverine unionids (Holland-Bartels, 1990; Strayer and Ralley, 1993; Strayer et al., 1994; Di Maio and Corkum, 1995; Layzer and Madison, 1995). These studies differ from this one in two important respects. With the exception of the Layzer and Madison (1995) study, particle sizes involved in the referenced studies were less than 16 mm in diameter, compared to median particle sizes of 78 mm (high quality sites) and 134 mm (low quality sites) in this study (all sites). This study also differs from those referenced in the methods used to sample sediment particles. Layzer and Madison (1995) sampled a broad range of particle sizes (silt to boulders) in Horse Lick Creek, Kentucky, but used a visual technique to classify substrata. Most researchers (Holland-Bartels, 1990; Strayer and Ralley, 1993; Strayer et al., 1994; Di Maio and Corkum, 1995) collected volumetric samples via cores or PONAR grab samples, followed by sieve analyses. Only the pavement, or surface layer of particles, was sampled in this study using a modification of the grid-by-number technique used in hydraulic engineering and sediment transport studies (Wolman, 1954; Kellerhals and Bray, 1971; Hey and Thorne, 1983). The streambed alluvium of gravel bed streams is usually stratified vertically, and consists of a surface layer composed of coarser particles than the underlying sediments (Wolman, 1954; Kellerhals and Bray, 1971; Parker, 1980; Diplas and Parker, 1985; Diplas and Sutherland, 1988).

Direction of flow was also an important variable in this study, yet I am unaware of other studies which have included this factor in analyses. I speculate that the orientation of bedrock strata relative to flow direction, may determine bedload retention or scour during high discharges. As in the Chapter 3 study, most high quality unbraided sites occurred where the river flows in the direction of geologic dip. Retention of alluvium by the gently dipping rock strata encountered as the river flows opposite the direction of dip, is less than alluvium retained by the nearly vertical ledges encountered as the river flows in the direction of dip. Vannote and Minshall (1982) hypothesized that large boulders protect small areas of mussel habitat from bed scour in the Snake River. Orientation of bedrock strata, relative to stream flow, may similarly affect substratum retention or removal during high discharge periods. Distribution patterns of 141 mussel sites are examined in Section 2 of this chapter.

Valley floor width (VFW) was selected by SDA when all sites were included, but was not selected when only unbraided sites were analyzed. Many of the best mussel sites in the TVA (1986a) survey occur in braided channels, which typically develop where the valley floor is wide. Channel braiding occurs where more bedload material enters the stream than it is competent to remove (Leopold and Wolman, 1957; Knighton, 1984; Resh et al., 1988). Based on observations from Chapter 3, the quality of mussel habitat in individual channels within braided reaches may vary enormously. According to Knighton (1984), braided channels are usually consist of a dominant, containing channel, and a variable number of lesser, more sinuous channels. Depending on the erodability of their banks, rapid shifts in the position of lesser channels may occur during high discharges. Substrata in the dominant channels may be more stable during high discharges and, based on in-stream mussel sampling of two braided reaches in Chapter 3, may contain higher quality mussel habitat. Patterns of braided site occurrence, relative to underlying geologic formations, are briefly examined in Section 2 of this chapter.

Section 2. Site location patterns: Relationship to streamflow direction and geology

Introduction

Two landscape scale variables (direction of streamflow and valley floor width) were identified as important parameters in discriminating between high and low quality mussel habitat in Chapter 4: Section 1. The relationship of these parameters to bedrock strata orientation was assumed to affect the retention and long-term stability of stream bed alluvium. An additional study was conducted using the entire TVA upper Clinch data set (n=141 sites). The purpose of the study was to examine spatial patterns of mussel site occurrence relative to these two variables. Twelve of the 141 sites were within reaches of documented disturbance. They were included in plots of all sites, but not in plots of high quality (n=50) and low quality sites (n=50).

Methods

In order to determine the orientation and variability of geologic dip and strike along the entire river, 101 measurements of strike orientation were taken from geologic maps provided by the Virginia Department of Mines, Minerals, and Energy in Abingdon, Virginia. The angle and direction of dip were also indicated for each mapped strike symbol. The mean direction of strike was North, 72.6 degrees East (standard error = 1.1 degrees). This was very close to the mean direction of strike of North, 75 degrees East measured in-stream in Chapter 3. The mean declination of dip was 36.2 degrees Southeast (standard error = 1.3 degrees). Geologic formations underlying the river were also determined from geologic maps for most of the upper Clinch (CRK 277 to 521).

Sites were located on USGS 7.5 minute topographic maps using river mile locations referenced in the TVA survey (1986). The planimetric form (braided or unbraided) of sites was determined from large format infrared aerial photographs which were provided by the Maps and Surveys Department of TVA in Chattanooga, Tennessee. Of the 141 sites, 93 were unbraided and 48 were braided.

Fifty sites were assigned to both high and low quality site groups from the 129 sites remaining after exclusion of impacted sites. The number of mussels reported from the sites was the criterion used to assign sites to high and low quality groups. At least 60 mussels were reported from each of the 50 high quality sites, while low quality sites had fewer than 22. Of the 50 high quality sites, 26 occurred in braided channels, whereas of the 50 low quality sites, only 8 occurred in braided channels.

Based on the results from Chapters 3 and 4, the greatest frequency (sites/km) of high quality unbraided sites was expected in reaches flowing in the direction of dip. The greatest frequency of high quality braided sites was expected to occur where the valley floor is wide and the river flows along the line of strike.

In order to determine site frequencies, it was necessary to determine the number of river kilometers flowing in various directions from CRK 241 to CRK 482. This was accomplished using a transparent plexiglass plate on which the compass azimuth was divided into eighteen 20 degree arc segments. The plate was placed over topographic maps aligned with a T-square for correct directional orientation. On each map, river reaches flowing within arc segments were marked at each end and labelled with respect to arc segment numbers. Upon completion of this process, river segment lengths were measured in centimeters and summed for each arc segment. The topographic map scale was used to convert centimeter distances to kilometers. The high quality (n=50), low quality (n-50), and total sites (n=141) occurring within each arc segment were enumerated. The frequency of occurrence of high quality, low quality, and total sites per km were then determined for each arc segment.

Results

Circular "radar" plots, in which values are plotted radially from the central origin, were used to examine patterns of high quality, low quality, and total site frequency (sites/km) relative to stream flow direction. Figure 4.3.A is a radar plot of the number of river kilometers flowing within each twenty degree arc segment (AS). It is readily apparent that the river most often flows in the direction of AS13 and 14 (51.8 and 33.5 km respectively). The mean line of strike lies approximately equidistant between these two axes. The river rarely flows in the opposite direction of AS3 through 6 (cumulative 1.3 km). The cumulative length of reaches occurring in the remaining 10 arc segments ranged from 1.5 to 23.3 km.

The frequency of TVA mussel sites (n=141) occurring within each arc segment is plotted in Figure 4.3.B. as sites per kilometer. The greatest site frequencies occur around the direction of geologic dip in AS7 through 11 with a maximum of 1.53 sites/km in AS7. The direction of dip is in the approximate position of the AS9 axis. A high frequency of sites also occurs in AS1, which is roughly opposite the direction of dip. Lower site frequencies occur along the line of strike in AS12 through 18. No sites occur in AS3 through 6.

Frequencies of unbraided mussel sites (n=93) are plotted in Figure 4.4.A. As in the plot of all sites (Figure 4.3.B), the greatest site frequencies occur around the direction of dip, in AS7 through 11, and opposite the direction of dip in AS1. Unbraided site frequencies along the line of strike in AS12 through 18 were considerably lower than total site frequencies were in these arc segments, indicating a greater proportion of braided sites in these arc segments.

Frequency patterns of braided sites (Figure 4.4.B) are quite different from unbraided site frequencies (Figure 4.4.A). Site frequencies were lower around the direction of dip (AS9 through 11) than along the line of strike (AS13 through 16). There were no braided sites in AS1 through 8, or in AS18.

Frequencies of good (>60 mussels) unbraided sites were greatest in the direction of dip (AS8, 9, 10) and intermediate opposite the direction of dip (AS18), and in AS11 (Figure 4.5.A). There were very few good unbraided sites observed in arc segments along the line of strike (AS12 through 16).

Frequency patterns of good braided sites (Figure 4.5.B) are quite different than the frequency pattern of good unbraided sites (Figure 4.5.A). Frequencies of good braided sites were greatest along the line of strike in AS13 and 14. Site frequencies were low in AS 1 through 12, and in AS16 and 18. Intermediate frequencies were observed in AS15 and 17.

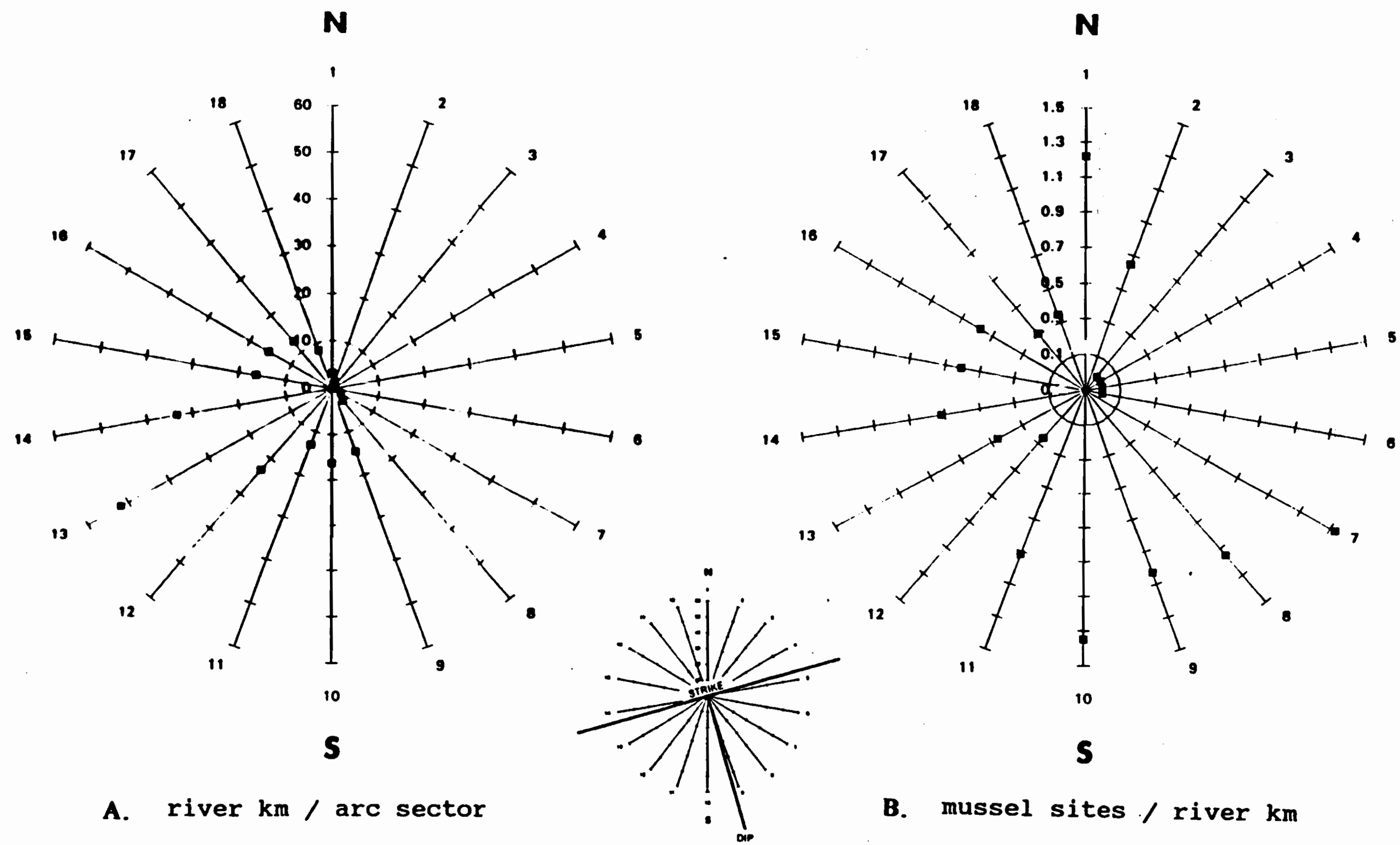

Figure 4.3. A. The number of Clinch River kilometers flowing in each of 18 20-degree arc sectors. The origin for all axes is the center of the radar plot and N and S indicate the directions north and south. B. TVA mussel sites per river kilometer occurring in each 20 degree arc sector (n = 141 sites). Orientation of dip and strike are indicated on the small radar plot.

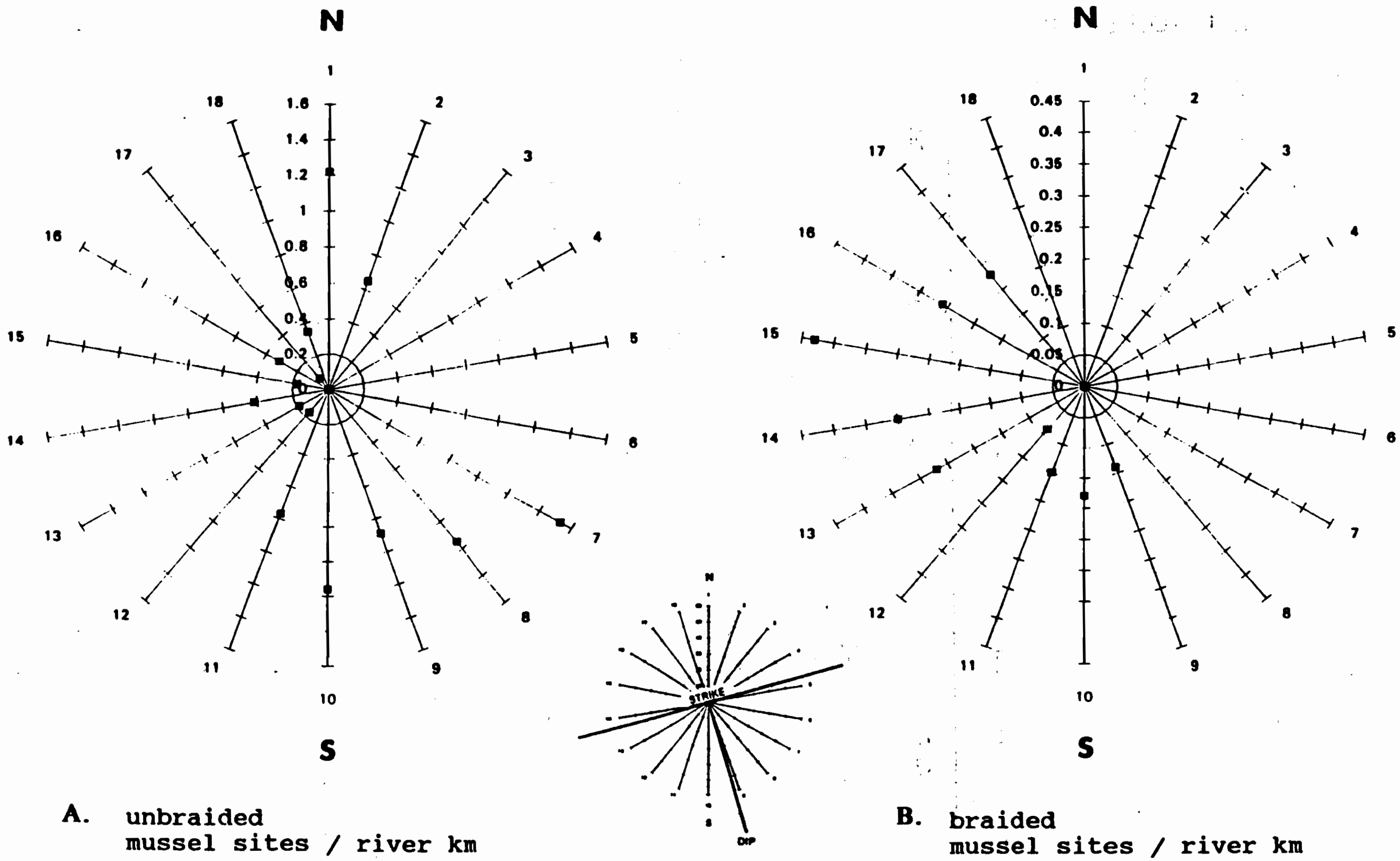

Figure 4.4. Frequency of TVA mussel sites per river kilometer occurring in each of 18 20-degree arc sectors. The origin for all axes is the center of the radar plot and N and S indicate the directions north and south. A. Unbraided sites (n = 93 sites). B. Braided sites (n = 48 sites). Orientation of dip and strike are indicated on the small radar plot.

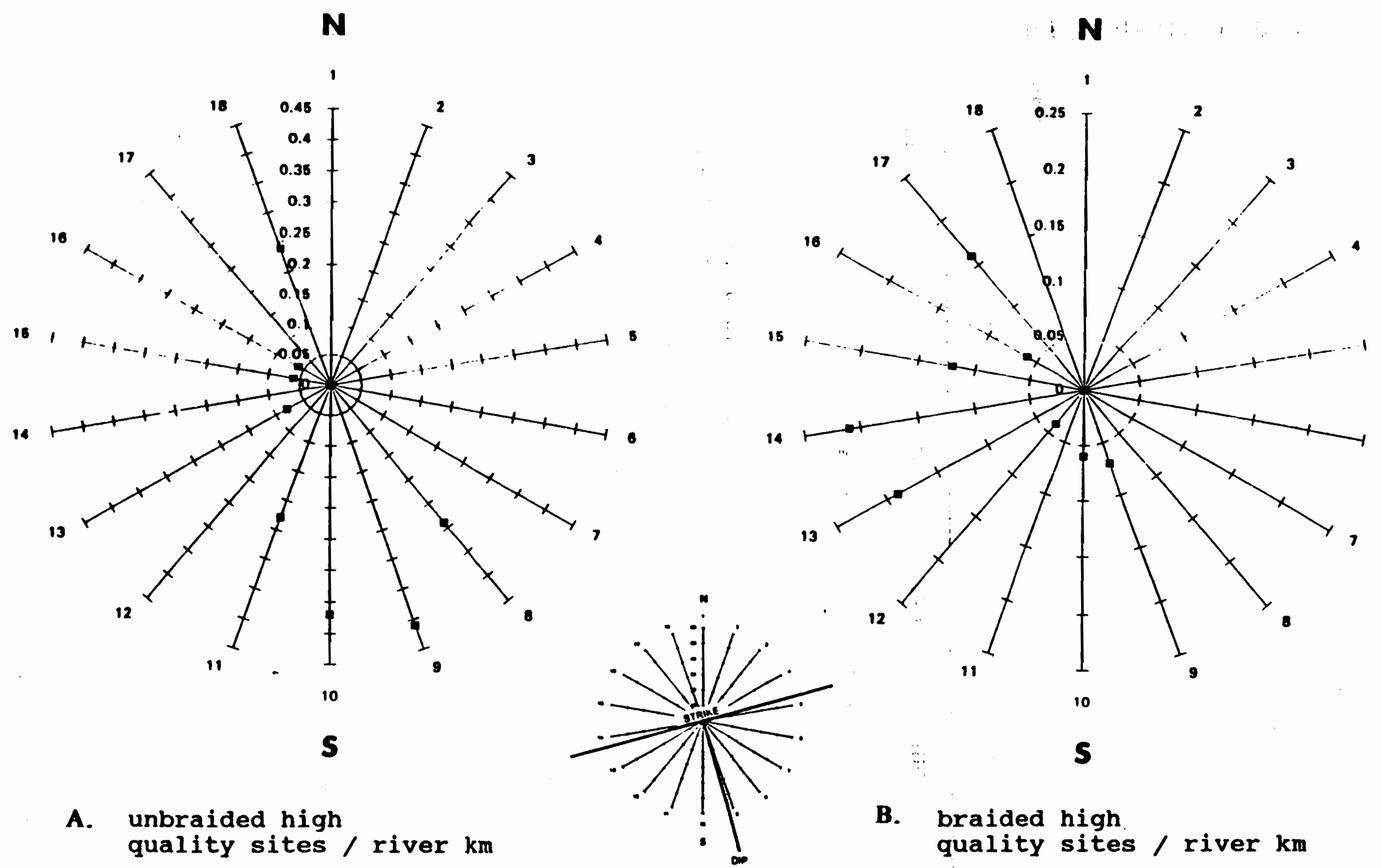

Figure 4.5. Frequency of high quality (>130 mussels reported) TVA mussel sites per river kilometer occurring in each of 18 20-degree arc sectors. The origin for all axes is the center of the radar plot and N and S indicate the directions north and south. A. Unbraided high quality sites (n = 24 sites). B. Braided high quality sites (n = 26 sites). Orientation of dip and strike are indicated on the small radar plot.

Discussion

Important mussel habitat characteristics were identified in Chapter 4: Section 1, and included percent bedrock, d84 particle size, direction of flow, and valley floor width. The Chapter 4: Section 2 study was undertaken to examine patterns of mussel site distribution, relative to direction of stream flow. As predicted from the results of on-site habitat studies in Chapter 3 and Chapter 4: Section 1, the greatest frequency of good unbraided sites occurred in the direction of geologic dip (arc segments 9 and 10), while the greatest frequency of good braided sites occurred along the line of strike in arc segments 13 and 14.

The occurrence of high quality unbraided sites in the direction of dip is perhaps more intuitively obvious than the greater occurrence of high quality braided sites along the line of strike. Enhanced retention of alluvium by the fractured ledges of rock strata in south-flowing reaches is certainly easy to visualize (Figure 3.11). However, it is less clear why good braided reaches should also be confined to a small portion of the azimuth. Characteristics of valley morphology and geology appear to support a possible explanation for the observed distribution pattern of good braided sites.

The geologic formations underlying the Clinch River are numerous, but can be generally considered as limestone-dolomite formations and softer, more erodable shale-siltstone formations (7.5 minute geologic quadrangles, scale 1:24,000, Virginia Department of Mines, Minerals, and Energy). Of the 24 high quality unbraided sites, 16 occur on limestone-dolomite formations. The remaining 8 sites occur on shale formations. Of the 26 high quality braided sites, 24 occur on shale formations, while only 2 sites occur on limestone-dolomite formations. This may indicate a fundamental difference between high quality braided and unbraided sites, in that high quality braided sites almost always occurred over shale formations. These differences in the occurrence of braided sites are probably due to the greater erodability of shale-siltstone formations, compared to limestone-dolomite formations. Differences in the thickness and erodability of these formations result in corresponding differences in the valley floor width and gradient of river reaches flowing through these rock formations.

Reaches of the river occurring over shale formations are relatively linear and usually follow the line of strike. However, long linear sections are comparatively rare in the meandering reaches which flow through limestone-dolomite formations. Additionally, the gradient of limestone-dolomite reaches is greater than that of shale reaches (Figure 4.6).

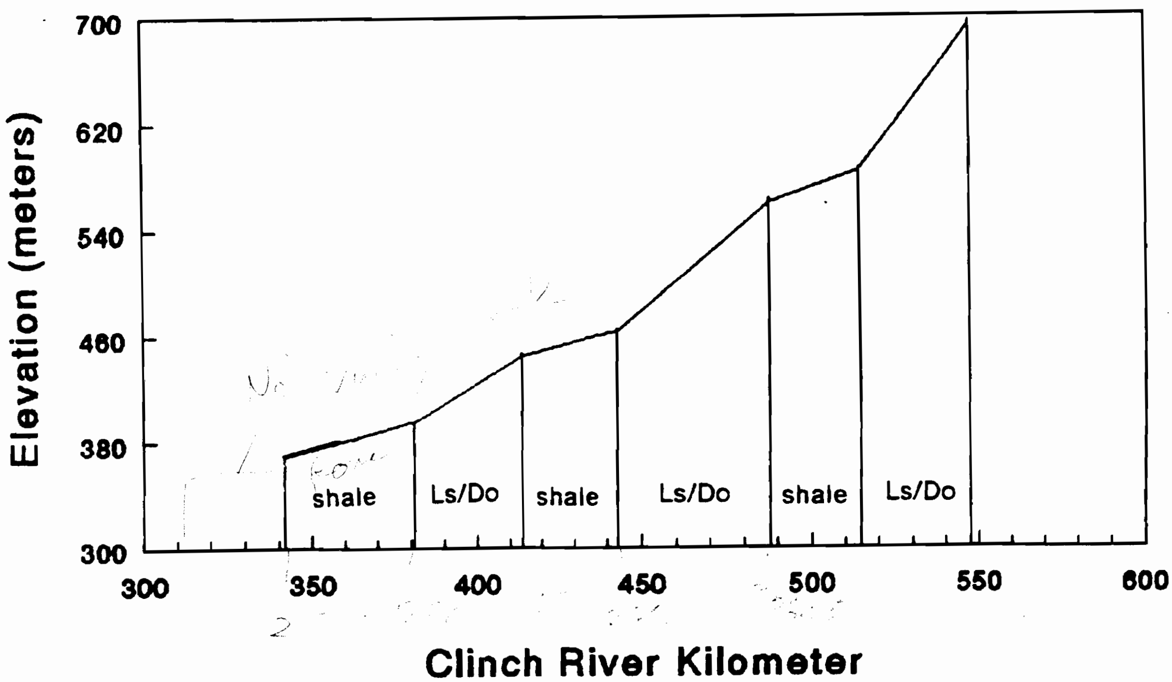

Figure 4.6. Plot of Clinch River kilometers against elevation. Note that limestone/dolomite (Ls/Do) reaches are characterized by higher gradient than shale reaches.

River reaches flowing through shale formations are not always characterized by high quality braided sites. The greatest concentration of high quality sites (most of which are braided) occur in the Rome Formation (shale) between CRK 343 and CRK 381. Fourteen of the 23 sites in this reach are high quality sites (>60 mussels reported) occurring in braided reaches. However, in the Nolichucky Shale just downstream between CRK 310 and 339, only two out of 12 sites are high quality sites occurring in braided reaches. The direction of stream flow is predominantly along the line of strike in both the Rome Formation and in the Nolichucky Shale. The thickness of these formations, however, is quite different. The Rome

Formation ranges from 366 to 457 m in thickness, while the Nolichucky Formation is only 156 m thick (as measured in the Clinchport 7.5 minute geologic quadrangle). Consequently, the valley floor width, which was identified as an important habitat variable in Chapter 4: Section 1, is also different between the two formations. The mean VFW of sites over the Rome Formation is 477 m (SE=48 m), while the mean VFW of sites over the Nolichucky Shale is only 167 m (SE=10 m).

The greatest occurrence of high quality braided sites in the Clinch River appears to be where the river flows along the line of strike, and both the streambed and valley floor are wide. These conditions usually occur over thick shale formations. High quality unbraided sites occur more frequently where the river flows in the direction of dip through limestone-dolomite formations. Valley floor width as a factor affecting mussel site quality is apparently less important in unbraided than in braided reaches.

Differential stability of stream bed alluvium during high discharge is likely the major factor responsible for patterns of occurrence of high quality sites observed in the Clinch River. I propose that mussel assemblages characterized by high density and old-aged individuals are most likely to develop in riverine sediments that are resistant to bed scour during flood events. Two plausible mechanisms of alluvium retention (i.e., substratum stability) are supported by observations in these studies. One mechanism is the physical retention of alluvium by bedrock ledges, which appears to be particularly important in the development of high quality unbraided sites. Retention of coarse alluvium is apparently enhanced where the river flows in the direction of dip, and rock strata are moderately to steeply inclined. The second mechanism of alluvium retention appears to be due to reduced hydraulic stress in the stream channel as a consequence of changes in channel and valley morphology, and stream gradient. In the Clinch River, high quality mussel sites were associated with smaller particles (excluding point bars) than low quality mussel sites. In highly-braided shallow reaches with broad flood plains, the river's competence to transport bedload particles during floods is reduced, resulting in retention of smaller particles than can be retained in unbraided reaches with narrow flood plains. Indeed, Leopold and Wolman (1957) hypothesized that a local reduction in stream competence, relative to the rate of sediment delivery, is the primary mechanism responsible for the development of braided channels.

An observation made during the Chapter 4: Section 1 study lends additional support to the hypothesis of substratum stability as an important factor affecting the distribution of high quality mussel habitat. During visits to some of the 22 sites designated as low quality sites, I found moderate mussel densities in-stream, in addition to abundant evidence of mussel recruitment in the form of fresh mussel shells in muskrat foraging middens. I wondered how a team of trained biologists could visit these sites and overlook so many living mussels. It then occurred to me that the TVA survey began in 1979, only two years after the flood of 1977, which was the highest discharge recorded in USGS records of the Clinch River. In all likelihood, the bed load at those sites, along with their mussel assemblages, was completely scoured by the flood. Any mussels present at the time of the 1979 TVA survey would have been too young to observe qualitatively. Indeed, upon counting the shell annuli of several living mussels at these sites, there appeared to be no individuals greater than 14 years of age (these observations were made in 1991). Substrata at these sites, now characterized by moderate mussel densities, have probably remained intact during subsequent discharges of lesser magnitude. Many of the other low quality TVA sites have probably been scoured by more recent floods, and remained as low mussel density sites in 1991.

The conclusions reached during this study concur with those of Kat (1982); namely, that high quality mussel microhabitats are characterized by stable substrata and protection from bed scour. The present study also lends support to the suggestion by Vannote and Minshall (1982) that local lithology and fluvial processes interact to regulate the density and size-class structure of mussel populations. Strayer and Ralley (1993) suggest that descriptors of the streambed based on fluvial geomorphology may offer a better understanding of mussel distribution. Strayer and Ralley (1993) further suggest that models using larger spatial scales may be of more predictive power than microhabitat models. The results of this study support the usefulness of considering large scale measurements (percent bedrock, channel cross-section, valley floor width, and direction of stream flow relative to rock strata) in addition to traditional aquatic habitat measurements such as substratum granulometry and depth, when assessing the relative suitability of stream sites as habitat for long-lived sedentary benthic organisms.

APPENDIX A

APPENDIX A: SUBSTRATUM CHARACTERIZATION AND MUSSEL ABUNDANCE IN THE LITTLE RIVER

Introduction

Freshwater mussels are burrowing organisms that require clastic sediments (alluvium) in which to burrow. While this may appear an obvious point, it is an important one, considering that most of the streambed area of the Clinch River is exposed bedrock. The ambiguity inherent in certain methods of substratum characterization was discussed in Chapter 1. The objective of this study was to characterize high and low quality mussel substratum using objective, quantitative methods. A 1.4 km reach of the Little River, a relatively unimpacted stream, was selected for study. The utility of using substratum characteristics (percent bedrock, median particle size, and d84 particle size) to predict densities of unionids was examined. Individual samples as well as pooled transect samples were analyzed.

The study area

The Little River is a short (52 km), fourth-order tributary of the upper Clinch River that enters at CRK 482.2. Most of the Little River's annual discharge is provided by Maiden Spring, which flows from a cavern 1.5 km below the confluence of Liberty Creek and Maiden Spring Creek in Tazewell County, Virginia. A mill dam impounds the first 1 km of the Little River below Maiden Spring. The Little River watershed is a mosaic of forested tracts and pasture, with limited residential development and no industrial development. Row crops, while present in the watershed, are usually not in close proximity to the river. During the summer of 1990, a mussel survey was conducted within the upper Clinch River and the entire Little River below the mill dam at Maiden Spring (Church 1991). During the survey, middens of fresh-dead mussel shells from the foraging activities of muskrats, *Ondatra zibethicus*, were collected as the primary source of information about in-stream mussel assemblages. Prior to collection of shell middens, the entire Little River was reconnaissanced by canoe in order to select the best sampling sites. Sixteen sites, characterized by an abundance of fresh-dead mussel shells, were marked with flagging and sampled during subsequent collecting trips.

Selection of study reach

The 1990 survey results indicated that the Little River mussel fauna was less affected by anthropogenic impacts than the Clinch River fauna upstream and downstream of the Little River confluence. While certainly not pristine, the Little River presented an opportunity to study the distribution and abundance of mussels in a minimally disturbed state. A 1.4 km reach of the Little River, located 3.6 km upstream of the confluence with the Clinch River, was selected for study of in-stream mussel abundance. The south-flowing portion of this reach contained a long contiguous area of gravel and cobble substratum, and exhibited the greatest mussel abundance and diversity (10 unionid species) of any of the sites sampled during the 1990 Little River survey. Additionally, recruitment of young mussels appeared particularly high, as evidenced by the large proportion of young individuals in shell middens. Recruitment and size-class structure characteristics are elaborated further in Chapter 3.

Methods

Mussel sampling

A stratified random sampling design was used in which thirteen 3-meter wide transect zones (A through M), exhibiting a diverse array of substratum conditions, were selected (Figure 2.1). Each transect zone was subdivided into three equal sectors (Figure 2.2). A 1 m^2 quadrat frame was randomly tossed into each sector. The substratum within the quadrat frame was searched for mussels during a 15 minute excavation period. This search period resulted in sediment removal to a depth of 12-15 cm. In some bedrock-dominated transect zones, clastic sediments lay in linear recesses of bedrock strata. In these cases, an area equal to 1 m^2 was excavated for 15 minutes without using the quadrat frame. All mussels collected were enumerated, identified to species, and measured (mm) along their greatest longitudinal axes. Mussels were then returned to streambottom areas from which they were collected, following replacement of excavated sediments.

Additional sampling was conducted in the three point bar transects of the study reach (Figure 2.1, Transects A, G, and M) to facilitate comparison between point bar and main channel habitats. Eight randomly placed 1 m^2 quadrat samples were excavated in each of the three point bars (n=24).

Substratum characterization

Three substratum variables were measured in each sector. These were percent bedrock (PBR), median particle size (d50), and d84 particle size. Percent bedrock (PBR) was the percent area within each sector (Figure 2.2) comprised by bedrock (not covered by clastic sediments), and was visually estimated by the investigator. Median particle size (by number) is defined as the particle diameter at which 50 percent of the particles in the sample are of smaller diameter, whereas the d84 particle size is the diameter at which 84 percent of the sample particles are of smaller diameter. The d84 particle size value is sometimes used as a measurement of streambed roughness in hydraulic equations. Median particle size (d50) and d84 particle size were determined by a modification of the grid sampling technique used in gravel bed streams by Kellerhals and Bray (1971) and Wolman (1954), in which only the surface or pavement layer is sampled.

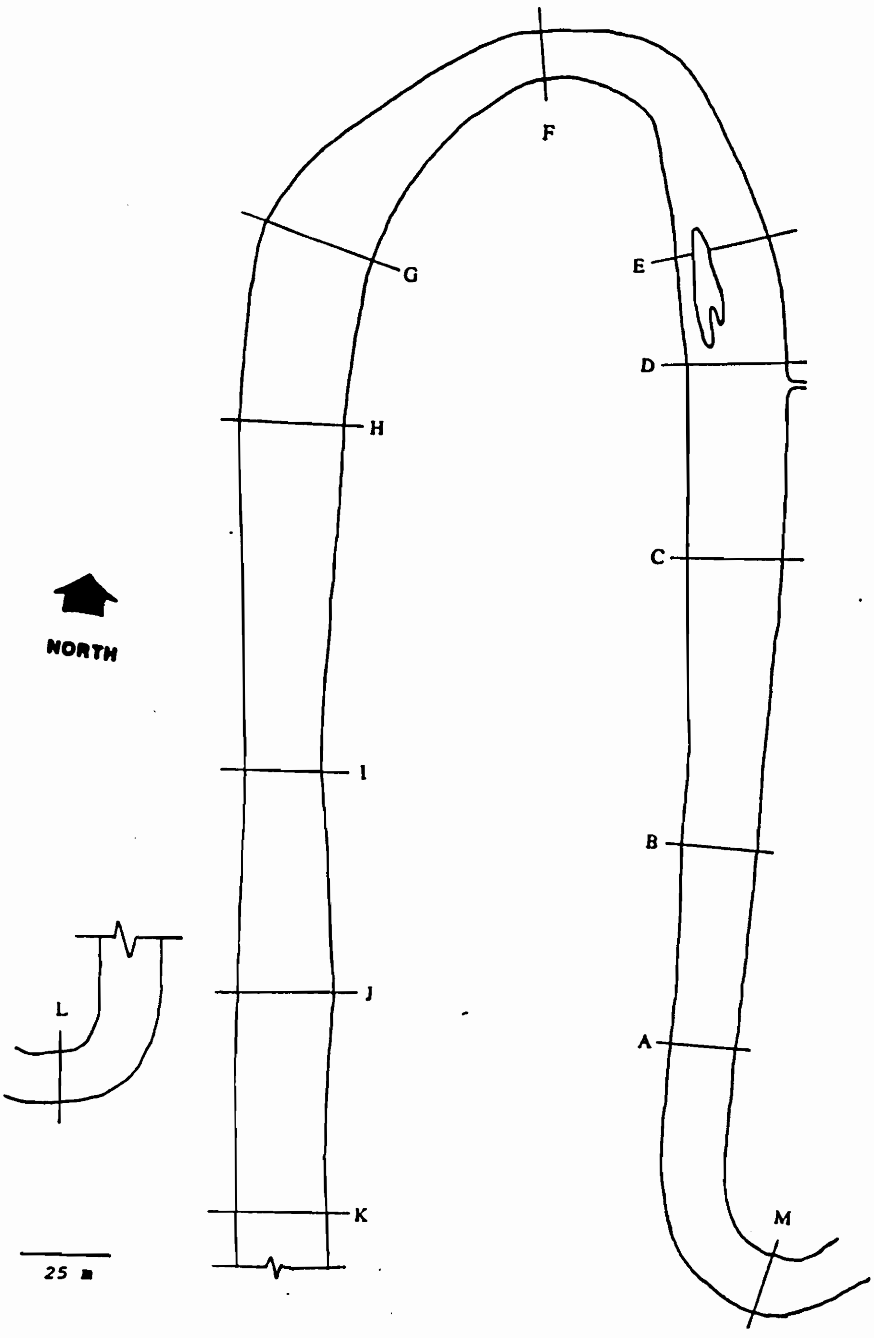

Figure A.1. Little River study reach with locations of sampling transects A - M.

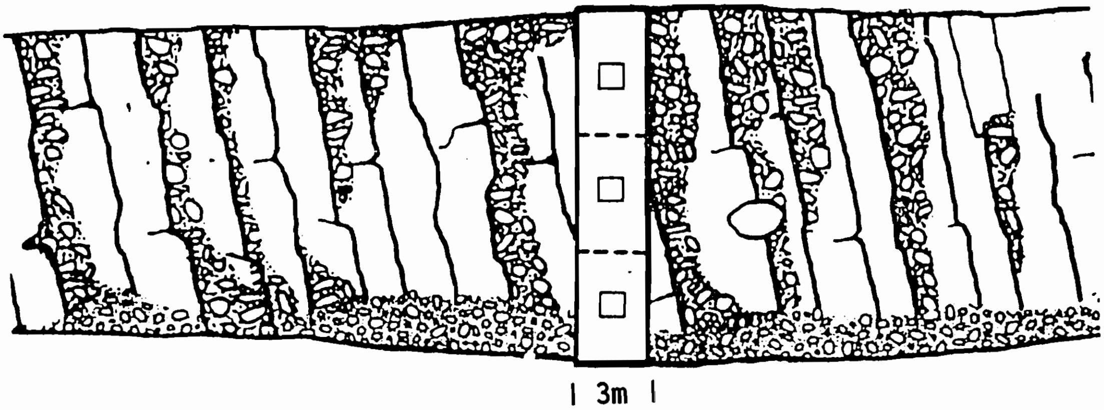

Figure A.2. Mussel density and percent bedrock (PBR) sampling methods. Three 1 m^2 quadrats were excavated in each 3 m wide transect zone. A visual estimate was made of the percent bedrock in each transect zone.

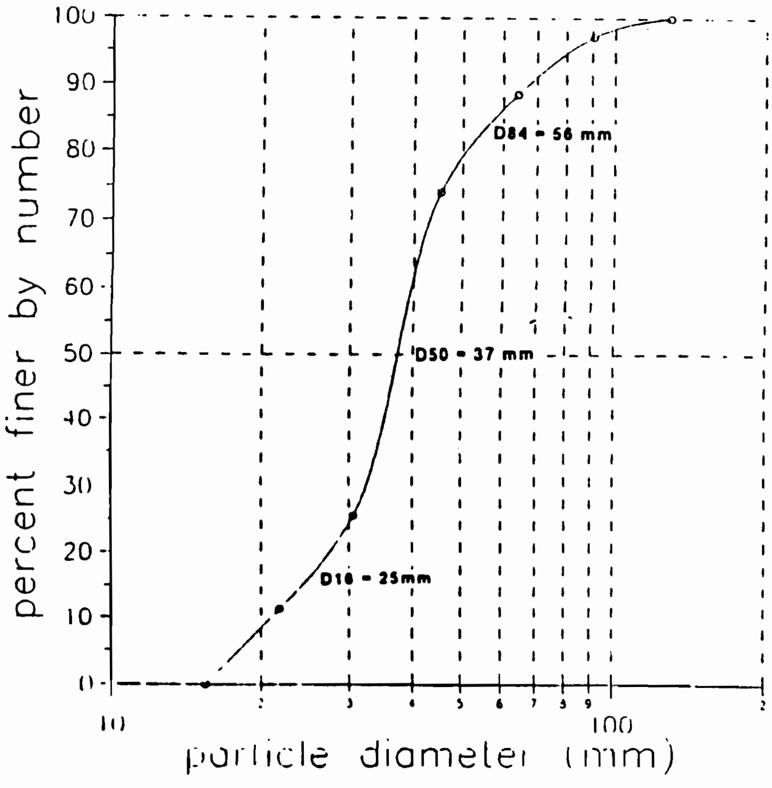

Figure A.3. A sample particle-size distribution curve from the Little River. D50 particle-size is also referred to as median particle size.

Within each sector, 35 steps were taken in random directions. At each step, the particle beneath the toe of the investigator's shoe was collected and sized on a plexiglass template (gravelometer) with square openings corresponding to a progression of sieve sizes (Hey and Thorne 1983). Each sample of 35 particles was sorted into size-class categories, permitting a particle-size distribution curve to be plotted (Figure 2.3). From these curves, d50 and d84 particle diameter values for samples were determined.

Results

A tabulation of the number of individuals of each mussel species collected in the Little River Study Reach is included in Table 3.1 (Chapter 3). Sample densities of mussels ranged from 0 to $31/m^2$. Two sets of comparisons were made in this study. The first set analyzed samples by habitat type. The second set compared substratum values associated with high and low mussel density groups.

Habitat type comparisons

The three habitat types were point bars (n=24), channel center (n=10) comprised of the central samples of the remaining 10 transects, and channel edge (n=20) comprised of the lateral samples of these transects (Table 2.1).

Table A.1. Mean values of Little River parameters by habitat type (standard errors in parentheses).

Habitat Type	Mussels/m^2	PBR	d50 (mm)	d84 (mm)
Point Bars	1.17 (0.25)	53 (5.13)	26.67 (4.09)	42.66 (6.98)
Channel Center	8.30 (1.97)	16 (6.53)	115.86 (12.29)	216.55 (23.68)
Channel Edge	9.45 (1.38)	9 (4.53)	92.53 (6.13)	153.12 (12.46)

Table A.2. Significance levels (Wilcoxon p>Z) of habitat type comparisons.

Comparison	Mussel Density	PBR	d50	d84
Point Bars vs. Channel Center	0.0001	0.0007	0.0001	0.0001
Point Bars vs. Channel Edge	0.0001	0.0001	0.0001	0.0001
Channel Center vs. Channel Edge	0.7493	0.0638	0.0183	0.0020

Comparisons of parameters associated with each of the three habitat types were made using Wilcoxon two-sample tests (Table 2.2). Mussel density was significantly lower in point bar samples than in channel center or channel edge samples. While mussel density was greater in channel edge than in channel center samples, the difference was not significant at a p>Z level of 0.05. Percent bedrock was significantly greater in point bar sectors than in channel center or channel edge sectors. Percent bedrock was greater in channel center sectors than in channel edge sectors, but was not significant at a p>Z level of 0.05. Sediment surface particles, measured as d50 and d84 values, were significantly smaller in point bars than in channel center or channel edge sectors. Particle sizes from channel edge sectors were significantly smaller than those from channel center sectors (Figure 2.4).

Comparison by mussel density group

These analyses entailed the examination of substratum parameters associated with high and low mussel density groups. Therefore, in these comparisons mussel density is considered as the dependent variable, and habitat parameters (PBR, d50, and d84) are considered the independent variables. The value of substratum variables as predictors of mussel density group is therefore being tested, rather than differences between parameters associated with selected "habitat types". This analysis is in keeping with stated objectives to use only measurable habitat characteristics to explain the variable of interest (mussel density), and to minimize subjective or ambiguous habitat groupings. Quadrat sample data were split into two approximately equal groups on either side of the median mussel density value. Wilcoxon two-sample tests were used to test for significant differences between substratum values associated with high and low mussel density groups. These analyses were conducted using the entire data set (Table 2.3), and with point bar samples excluded (Table

2.4).

Table A.3. Mean Values of habitat parameters for high and low density groups in the Little River (all samples, n = 60).

Habitat Parameter (unit of measure)	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>Z
PBR (%)	11 (4.38)	51 (5.52)	0.0001
d50 (mm)	85 (3.57)	58.03 (10.68)	0.0004
d84 (mm)	150 (9.06)	92.79 (18.69)	0.0001

In comparisons using all samples (n=60), the 24 point bar samples dominated the low density group which, not surprisingly, exhibited significantly greater percent bedrock, and significantly smaller particle-size values (Table 2.3).

Point bar transects were characterized by high percent bedrock and fine sediments on the inside of bends, and were atypical of most of the streambed area. It was therefore desirable to compare substratum parameter values associated with density groups, with point bar transects excluded (n=36), in order to more rigorously test the efficacy of these methods (Table 2.4). Percent bedrock values were not significantly different between density groups in this comparison. Percent bedrock values associated with high and low mussel density samples were much lower than those associated with point bar samples. The high density sample group was characterized by significantly lower d50 and d84 values than the low mussel density group.

The opposite relationship was observed when point bar samples were included. Point bar sediments were consistently finer than alluvial sediments in other streambed areas, and were characterized by low mussel densities. High mussel densities typically occurred in sediments intermediate between the coarsest particle areas and fine-particle point bars.

Table A.4. Mean values of habitat parameters for high and low density groups in the Little River (point bar samples removed, n = 36).

Habitat Parameter (unit of measure)	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>Z
PBR (%)	13 (8.15)	23 (3.07)	0.076
d50 (mm)	81.39 (2.90)	115.24 (6.90)	0.05
d84 (mm)	140.88 (8.11)	252.51 (16.82)	0.035

Transect level of analysis

The relatively unimpacted Little River was perceived as an excellent stream in which to conduct pilot studies to evaluate substratum characterization methods before using them for a larger scale study on the main stem Clinch River (Habitat Study A; Chapter 4). In addition to substratum parameters, stream cross-section morphology parameters were also planned for Habitat Study A. Pooling sector sample data into transects permitted the computation of values more applicable at the stream cross-section level of analysis which is often used in fluvial geomorphological studies. Additionally, Wolman (1954) recommended using sediment particle samples of approximately 120 particles to adequately represent in-situ distributions. The procedure required to produce particle-size distribution curves is also time-consuming. If adequate resolution of mussel habitat quality can be gained from particle-size assessments at the level of the stream cross-section (transect), it is certainly more expeditious to use this level of scale.

Particles from the three sectors of each transect were pooled to generate a single sample of 105 particles for each transect, which were used to generate a transect particle-size curve (Figure 2.4). Transect PBR values are means of the three sector PBR values comprising each transect zone. Analyses were conducted using all transects (Table 2.5), and without point bar transects (Table 2.6), as in the preceding analyses at the sector level of comparison.

Table A.5. Mean Values of habitat parameters for high and low density groups at the transect (stream cross-section) level (all transects, n=13).

Habitat Parameter (unit of measure)	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>Z
PBR (%)	8 (7.75)	51 (13.11)	0.047
d50 (mm)	89.00 (3.33)	85.71 (23.94)	0.721
d84 (mm)	143.80 (8.98)	159.43 (46.95)	0.943

Table A.6. Mean Values of habitat parameters for high and low density groups at the transect level (point bar samples removed, n=10).

Habitat Parameter (unit of measure)	High Density Group Mean (SE)	Low Density Group Mean (SE)	Wilcoxon Sign. p>Z
PBR (%)	9 (9.40)	21 (8.50)	n.s.
d50 (mm)	86.20 (2.22)	124.60 (16.24)	0.05
d84 (mm)	137.80 (8.16)	232.40 (33.31)	0.022

The only significant difference observed when all transects were included in the analysis was percent bedrock. This is not surprising in that point bar transects (all of which were in the low mussel density transect group) were characterized by very high percent bedrock, whereas high mussel density transects were characterized by low percent bedrock. The poor Wilcoxon significance values (0.721 and 0.943) for particle-size comparisons between low and high density transect groups are easily understood if one examines plots of transect particle size curves (Figure 2.4). Lowest mussel densities occurred in point bars, followed by coarse particle transects; greatest mussel densities occurred in transects characterized by intermediate particle sizes. Therefore, the particle-size values for low density transects consisted of point bars and coarse sediment transects which, when averaged, resulted in particle-size mean values in the same range as particle-size values for the high mussel density transects. This is confirmed by reanalyzing the data with point bar transects excluded (Table 2.6), which resulted in significant differences between d50 and d84 values associated with high and low mussel density groups.

Discussion

The comparison of habitat parameter (PBR, d50, d84) values associated with transects having either high or low mussel density appears to be more valid than comparisons based on subjectively preselected "habitat types". With this approach, mussel density is the indicator of mussel habitat quality. Significant differences were observed between d50 and PBR values between high and low mussel density transect groups. Therefore, substratum granulometry and percent bedrock in the transect zone appear to be useful predictors of mussel habitat quality.

There appears to be a particle size range that is optimal for the development of high density mussel beds. In this study, the optimal range occured in transects characterized by d50 values between 80 and 90 mm (Figure 2.4). The particle size curves in Figure 2.4 also indicate a positive relationship between particle size and mussel density in the three point bars. The point bar with the lowest particle-size value (Transect A, d50 = 9 mm) exhibited the lowest mussel density. The point bar in Transect M (d50 = 17 mm) had a greater mussel density than Transect A, while the point bar with the coarsest particles (Transect M, d50 = 54 mm), exhibited the greatest mussel density. More particle-size and mussel data from point bars would be necessary to adequately test this perceived relationship.

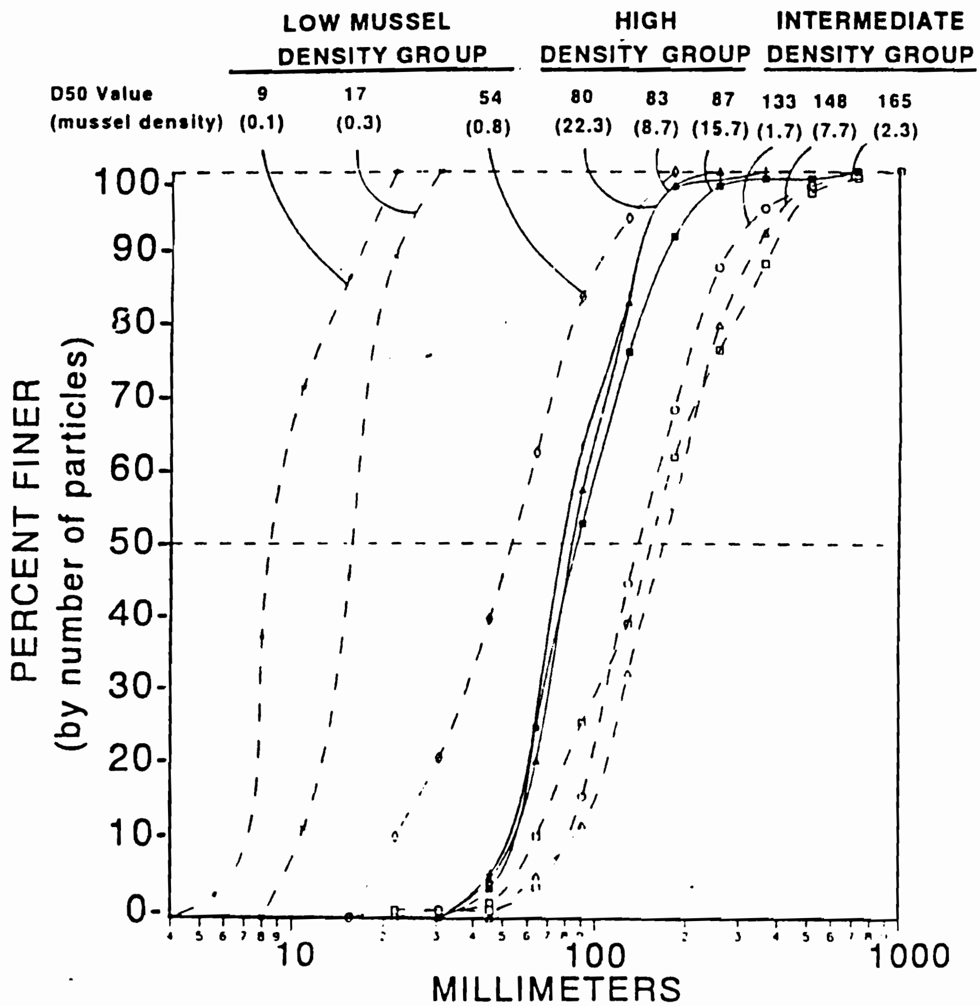

Figure A.4. Particle size distribution curves for nine Little River transects. Note that the high mussel density group (solid lines) occurs in a particle size range between low and intermediate mussel density groups.

The apparent relationship between mean particle size and mussel density can possibly be explained in terms of substratum stability during periods of high discharge. Point bars, characterized by finer sediments, are more likely to be entrained as stream competence increases, with the consequent displacement of mussels living in these habitats. The intermediate mussel densities associated with high d50 values is more difficult to interpret. It may be that these coarser particles occur in locations that become more turbulent and erosional during periods of high discharge. Further testing is necessary to determine if similar trends are observable in other river reaches.

Literature Cited

American Society of Civil Engineers. 1975. Sedimentation Engineering. Prepared by task committee on sedimentation of the hydraulics division. Edited by Vito A. Vanoni. ASCE, New York, New York. 745 pp.

Ahlstedt, S.A. 1984. Twentieth century changes in the freshwater mussel fauna of the Clinch River (Tennessee and Virginia). Unpublished M.S. thesis, Department of Zoology, University of Tennessee, Knoxville, 101 pp.

Baker, F.C. 1928. The fresh water Mollusca of Wisconsin. Part 2. Pelecypoda. Bulletin of the University of Wisconsin, Serial No. 1527, General Series No. 1301. pp. i-iv and 1-495, plates 29-105.

Bates, J.M. and S.D. Dennis. 1978. The mussel fauna of the Clinch River, Tennessee and Virginia. Sterkiana 69/70:3-23.

Bogan, A.E. and L.B. Starnes. 1982. The Little River unionid fauna and its implications for unionid biogeography. American Malacological Bulletin 1:93-94. [Abstract]

Bronmark, C. and B. Malmqvist. 1982. Resource partitioning between unionid mussels in a Swedish lake outlet. Holarctic Ecology 5:389-395.

Cairns, J.,Jr., J.S. Crossman, K.L. Dickson and E.E. Herricks. 1971. The recovery of damaged streams. ASB (Association of Southeastern Biologists) Bulletin 18: 79-106.

Church, G.W. 1991. Survey of the Family Unionidae in the upper Clinch and Little River, Virginia. Report to the Virginia Division of Natural Heritage, Richmond, Virginia, 23 pp.

Churchill, E.P., Jr. and S.I. Lewis. 1924. Food and feeding in freshwater mussels. Bulletin of the Bureau of Fisheries 39:439-471.

Cicerello, R.R., M.L. Warren, Jr. and G.A. Schuster. 1991. A distributional checklist of the freshwater unionids (Bivalvia:Unionidae) of Kentucky. American Malacological Bulletin 8(2):113-129.

Clarke, A.H. 1986. The mesoconch: a record of juvenile life in Unionidae. Malacology Data Net (Ecosearch Series) 1(2):21-36.

Dawley, C. 1947. Distribution of aquatic mollusks in Minnesota. American Midland Naturalist 38:671-697.

Dennis, S.D. 1984. Distributional analysis of the freshwater mussel fauna of the Tennessee River system with special reference to possible limiting effects of siltation. Unpublished Ph.D. dissertation, Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, 247 pp.

Dennis, S.D. 1987. An unexpected decline in populations of the freshwater mussel, *Dysnomia (=Epioblasma) capsaeformis*, in the Clinch River of Virginia and Tennessee. Virginia Journal of Science 38(4):281-288.

Dennis, S.D. 1989. Status of the freshwater mussel fauna at Pendleton Island Mussel Preserve, Clinch River, Virginia. Sterkiana 72:19-26.

Di Maio, J. and L.D. Corkum. 1995. Relationship between the spatial distribution of freshwater mussels (Bivalvia: Unionidae) and the hydrological variability of rivers. Canadian Journal of Zoology 73:663-671.

Diplas, P. 1989. Areal sampling techniques. Proceedings of the International Symposium on Sediment Transport Modeling, New Orleans, Louisiana 380-385.

Diplas, P. and G. Parker. 1985. Pollution of gravel spawning grounds due to fine sediment. Project Report No. 240, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, Minnesota.

Diplas, P. and A.J. Sutherland. 1988. Sampling techniques of gravel sized sediments. Journal of Hydraulic Engineering 114(5):484-501.

Dolan, R., A. Howard and D. Trimble. 1978. Structural control of the rapids and pools of the Colorado River in the Grand Canyon. Science 202:629-631.

Ellis, M.M. 1931. Some factors affecting the replacement of the commercial freshwater mussels. U.S. Department of Commerce Bureau of Fisheries. Circular No. 7.

Frierson, L.S. 1905. Notes on young Unionidae. The Nautilus 19(5):49-50.

Hey, R.D. and C.R. Thorne. 1983. Accuracy of surface samples from gravel bed material. Journal of Hydraulic Engineering 109(6):842-851.

Holland-Bartels, L.E. 1990. Physical factors and their influence on the mussel fauna of a main channel border habitat of the upper Mississippi River. Journal of the North American Benthological Society 9:327-335.

Howard, A.D. 1922. Experiments in the culture of freshwater mussels. Bulletin of the U.S. Bureau of Fisheries 38:1-89. [Also issued as U.S. Bureau of Fisheries Document No. 916]

Hynes, H.B.N. 1970. The ecology of running waters. Liverpool University Press, Liverpool, U.K.

Jacobson, P.J. 1990. Sensitivity of early life stages of freshwater mussels (Bivalvia: Unionidae) to copper. Unpublished M.S. thesis, Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, 162 pp.

Jacobson, P.J., J.L. Farris, R.J. Neves and D.S. Cherry. 1993. Juvenile mussel (Bivalvia: Unionidae) responses to acute toxicity testing with copper. Environmental Toxicology and Chemistry 12:879-883.

Jenkinson, J.J. 1974. The Fall Line as a barrier to the distribution of some unionids (Bivalvia: Unionidae). Bulletin of the American Malacolgical Union 1974:30-31.

Jenkinson, J.J. and S.A. Ahlstedt. 1988. Quantitative reassessment of the freshwater mussel fauna in the Clinch River, Tennessee and Virginia. Unpublished Tennessee Valley Authority study, Knoxville, Tennessee. 20 pp.

Kat, P.W. 1982. Effects of population density and substratum type on growth and migration of *Elliptio complanata* (Bivalvia: Unionidae). Malacological Review 15:119-127.

Kellerhals, R. and D.I. Bray. 1971. Sampling procedures for coarse fluvial sediments. Journal of the Hydraulics Division, ASCE, Vol. 97, No. HY8, Proceedings Paper 8279, August , 1971, pp. 1165-1180.

Knighton, D. 1984. Fluvial forms and processes. Edward Arnold (Publishers) Ltd, 41 Bedford Square, London WC1B 3DQ. 218 pp.

Layzer, J.B. and L.M. Madison. 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. Regulated Rivers: Research and Management, Vol. 10:329-345.

Leopold, L.B. and M.G. Wolman. 1957. River channel patterns - braided, meandering, and straight. United States Geological Survey Professional Paper 282B, pp. 39-85.

Lewis, J.B. and P.N. Riebel. 1984. The effect of substrate on burrowing in freshwater mussels (Unionidae). Canadian Journal of Zoology 62:2023-2025.

Miller, A.C., B.S. Payne and T. Siemsen. 1986. Description of the habitat of the endangered mussel, *Plethobasus cooperianus*. The Nautilus 100(1):14-18.

Neves, R.J., G.B. Pardue, E.F. Benfield and S.D. Dennis. 1980. An evaluation of endangered mollusks in Virginia. Final report for Virginia Commission of Game and Inland Fisheries, Project No. E-F-1, Richmond, Virginia. 140 pp.

Neves, R.J. and J.C. Widlak. 1987. Habitat ecology of juvenile freshwater mussels (Bivalvia: Unionidae) in a headwater stream in Virginia. American Malacological Bulletin 5:1-7.

Ortmann, A.E. 1918. The nayades (freshwater mussels) of the upper Tennessee drainage with notes on synonomy and distribution. Proceedings of the American Philosophical Society, Volume 62.

Ortmann, A.E. 1924. Mussel shoals. Science 60:565-566.

Ortmann, A.E. 1925. The naiad fauna of the Tennessee River system below Walden Gorge. American Midland Naturalist 9:1-47.

Parker, G. 1980. "Experiments on the formations of mobile pavement and static armor." Technical Report, Department of Civil Engineering, University of Alberta, Edmonton, Canada.

Parmalee, P.W. and A.E. Bogan. 1986. Molluscan remains from aboriginal middens at the Clinch River Breeder Reactor site, Roane County, Tennessee. American Malacological Bulletin 4(1):25-37.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace and R.C. Wissmar. 1988. The role of disturbance in stream ecology. Journal of the North American Benthological Society 7(4):433-455.

Salmon, A. and R.H. Green. 1983. Environmental determinants of unionid clam distribution in the Middle Thames River, Ontario. Canadian Journal of Zoology 61:832-838.

SAS Institute. 1985. SAS user's guide: statistics. Statistical Analysis System Institute, Cary, NC. 956 pp.

Scott, J.C. 1994. Population demographics of six freshwater mussel species (Bivalvia: Unionidae) in the upper Clinch River, Virginia and Tennessee. Unpublished M.S. thesis, Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, 142 pp.

Sepkoski, J.J., Jr. and M.A. Rex. 1974. Distribution of freshwater mussels: coastal rivers as biogeographic islands. Systematic Zoology 23:165-188.

Sheehan, R.J., R.J. Neves and H.E. Kitchel. 1986. An assessment of two techniques for re-establishing mussel populations in the Clinch and North Fork Holston Rivers, Virginia. Virginia Commission of Game and Inland Fisheries, Richmond, Virginia. 74 pp.

Sickel, J.B. 1980. Correlation of unionid mussels with bottom sediment composition in the Altamaha River, Georgia. Bulletin of the American Malacological Union 1980:10-13.

Simpson, C.T. 1896. The classification and geographical distribution of the pearly freshwater mussels. Proceedings of the U.S. National Museum. 18:295-343.

Stansbery, D.H. 1973. A preliminary report on the naiad fauna of the Clinch River in the southwestern Appalachian Mountains of Virginia and Tennessee (Mollusca: Bivalvia: Unionidae). Bulletin of the American Malacological Union, March 1973. [Abstract]

Stansbery, D.H., C.B. Stein and G.T. Watters. 1986. The distribution and relative abundance of unionid mollusks in the Clinch River in the vicinity of Appalachian Power Company's Clinch River Plant at Carbo, Virginia (Clinch River miles 264-270). The Ohio State University Research Foundation, Project 764801/717333. Columbus, Ohio. 184 pp.

Stanford, J.A., and A.R. Gaufin. 1974. Hyporheic communities of two Montana rivers. Science 185:700-702.

Stern, E.M. 1983. Depth distribution and diversity of freshwater mussels (Unionidae) collected with SCUBA from the lower Wisconsin and St. Croix Rivers. The Nautilus 97(1):36-42.

Strayer, D.L. 1981. Notes on the microhabitats of unionid mussels in some Michigan streams. American Midland Naturalist 106(2):411-415.

Strayer, D.L. 1993. Macrohabitats of freshwater mussels (Bivalvia: Uninionacea) in streams of the northern Atlantic Slope. Journal of the North American Benthological Society 12(3):236-246.

Strayer, D.L. and J. Ralley. 1993. Microhabitat use by an assemblage of stream-dwelling unionaceans (Bivalvia), including two rare species of *Alasmidonta*. Journal of the North American Benthological Society 12(3):247-258.

Strayer, D.L., D.C. Hunter, L.C. Smith, and C.K. Borg. 1994. Distribution, abundance, and roles of freshwater clams (Bivalvia, Unionidae) in the freshwater tidal Hudson River. Freshwater Biology 31:239-248.

Tennessee Valley Authority. 1986a. Cumberlandian mollusk conservation program, Activity 1: mussel distribution surveys. Tennessee Valley Authority, Field Operations, Eastern Area, Norris, Tennessee, 125 pp.

Tennessee Valley Authority. 1986b. Cumberlandian mollusk conservation program, Activity 5: analysis of physical habitat. Division of Air and Water Resources Engineering Laboratory, Norris, Tennessee, 159 pp.

Tennessee Valley Authority. 1988. Quantitative reassessment of the freshwater mussel fauna in the Clinch River, Tennessee and Virginia. River Basin Operations, Water Resources, Knoxville, Tennessee, 20 pp.

Tevesz, M.J.S. and P.L. McCall. 1979. Evolution of substratum preference in bivalves (Mollusca). Journal of Paleontology 53(1):112-120.

USFWS (U.S. Fish and Wildlife Service). 1982. Appalachian monkeyface pearly mussel (*Quadrula sparsa*) recovery plan. U.S. Fish and Wildlife Service, Atlanta, Georgia. 41 pp.

USFWS (U.S. Fish and Wildlife Service). 1983. Shiny pigtoe pearly mussel recovery plan. U.S. Fish and Wildlife Service, Atlanta, Georgia. 60 pp.

USGS (United States Geological Survey). 1991. Annual maximum stages and discharges of selected streams in Virginia through 1990. U.S.G.S. Open-File Report 90-587, Richmond, Virginia, 442 pp.

van der Schalie, H. 1938. The The naiades (freshwater mussels) of the Cahaba River in North Alabama. Occasional Papers of the Museum of Zoology, No. 392. University of Michigan Press, Ann Arbor, Michigan.

van der Schalie, H. and A. van der Schalie. 1950. The mussels of the Mississippi River. American Midland Naturalist 44:448-466.

Vannote, R.L. and G.W. Minshall. 1982. Fluvial processes and local lithology controlling abundance, structure, and composition of mussel beds. Proceedings of the National Academy of Science (Biological Science) 79(13):4103-4107.

Walker, B. 1918. A synopsis of the classification of the freshwater mollusca of North America, north of Mexico, and a catalogue of the more recently described species, with notes. Miscellaneous Publications of the Museum of Zoology, University of Michigan 6:1-213.

Warren, M.L., Jr., R.R. Cicerello, K.E. Camburn and G.J. Fallo. 1984. The longitudinal distribution of the freshwater mussels (Unionidae) of Kinnikonick Creek, northeastern Kentucky. American Malacological Bulletin 3(1):47-53.

Wolman, M.G. 1954. A method of sampling coarse river bed material. Transactions of the American Geophysical Union 35(6):951-956.

Yeager, M.M. 1994. Abiotic and biotic factors influencing the decline of native unionid mussels in the Clinch River, Virginia. Unpublished Ph.D. dissertation, Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg.

CURRICULUM VITAE

Gregory W. Church

October, 1997

MAILING ADDRESS: 9782 Kingsport Highway
Chuckey, Tennessee 37614

TELEPHONE: (423) 234-8122

EDUCATION:

Virginia Polytechnic Institute and State University, Blacksburg, Virginia. Ph. D. Degree, Zoology, pending dissertation defense in May, 1993. Dissertation Title, *Geomorphic Factors Affecting the Distribution and Abundance of Freshwater Mussels in the Clinch River, Virginia.*

East Tennessee State University, Johnson City, Tennessee. M. Sc. Degree, Environmental Health, Thesis Title, *Adsorption and Filtration of Pseudomonas and Coliforms by Two Selected Tennessee Soils.* 1981.

East Tennessee State University, Johnson City, Tennessee. B. Sc. Degree, Biology, 1977.

Sullivan Central High School, Blountville, Tennessee, 1973.

RELEVANT CURRICULUM: Transcripts available upon request.

Cell Biology
Genetics
Invertebrate Zoology
Vertebrate Zoology
Ornithology
Mammalogy
Environmental Animal Physiology
General Ecology
Animal Ecology
Topics in Aquatic Ecology
Ecosystem Dynamics
Ecological Community Analysis
Landscape and Restoration Ecology
Principles of Theoretical Ecology
Aquatic Biology
Aquatic Entomology
Fisheries Biology
Limnology
Hydrology
Environmental Geology
Environmental Chemistry
Environmental Microbiology
Environmental Health Practices
Environmental Health Law
Toxicology
Aquatic Ecotoxicology

Hazard Evaluation of Toxic Chemicals
Water Pollution
Water Pollution Control
Wildlife Conservation
Conservation of Natural Resources
Resource Problems
Human Ecology
Solid Waste Management
Plant Morphology
Plant Ecology
Plant Geography
Economic Botany
Trees of North America
Physiography of North America
Earth Materials
Soil Geography
New Developments in Biological Science
Seminar Laboratory
Biostatistics and Epidemiology
Biometry I, II and III

POSITIONS OF EMPLOYMENT HELD:

Assistant Professor/Director of Environmental Science

Tusculum College, Greeneville, Tennessee: Taught courses in Environmental Science, Biology, and Physical Science. Developed Environmental Science curriculum as well as curriculum for Environmental Management adult education program.

Graduate Teaching and Research Assistant

Virginia Polytechnic Institute and State University, Blacksburg, Virginia: (Biology Department) - 1987-present. Invertebrate Zoology Lab, Freshwater Ecology Lab, Ornithology Lab, Human Anatomy and Physiology, Principles of Biology Lab, General Biology Lab. Duties included lecture and exam preparation, laboratory supervision and assignment of course grades. Research Assistant: Conducted research on riverine mussel fauna during summers of 1988 and 1989.

Executive Director

Scott County Water and Sewerage Authority, Weber City, Virginia - 1984-1987. Responsible for managing all aspects of water and sewerage utilities including: selection and supervision of entire operations staff; grant management and financing of sewer and water construction projects; acquisition of easements and property; development of policy and procedures.

Environmental Planner

Central Virginia Planning District Commission, Lynchburg, Virginia - 1983-1984. Responsible for developing varied environmental projects: a volunteer-based water quality project; a hazardous waste management plan; performance of A-95 Regional Reviews; served in a staff capacity to a county litter control commission.

Environmental Scientist III

State of New Mexico, Environmental Improvement Division, Santa Fe, New Mexico - 1981-1982. Responsible for administration of New Mexico's Solid Waste Management Program; worked with Environmentalists throughout the state on specific solid waste problems; conducted training sessions and provided technical assistance to communities considering new solid waste facilities.

Environmentalist III

State of New Mexico, Environmental Improvement Division, Farmington, New Mexico - 1981. Major responsibility was enforcing state regulations in several environmental areas, including food service facilities, water supply, liquid waste and swimming pools.

Research and Laboratory Assistant

East Tennessee State University, Johnson City, Tennessee - 1979-1980. Conducted chemical and microbiological analyses for a water quality study on the Nolichucky River, Tennessee, funded by the US Dept. of Interior, entitled *Evaluation of the Impact Imposed upon Surface Water Sources by Implementation of the Federal Water Conservation and Reuse Policy in a River Basin with a Water Surplus*; Prepared microbiological media and chemical reagents for Environmental Chemistry and Microbiology classes.

Engineering Laboratory Technician

Soil and Materials Engineers, Inc., Blountville, Tennessee - 1978-79. Conducted physical tests on soils and building materials to facilitate sound engineering assessments used for structural planning; Performed field tests to insure contractor compliance with structural specifications.

PROFESSIONAL CONSULTING

Conducted survey of the mussel fauna of the Little and upper Clinch Rivers for the Virginia Nature Conservancy and Virginia Natural Heritage Program during 1990 (unpublished report).

Conducted benthic survey in Big Creek and Clinch River for Covenant Coal Corporation, Richlands, Virgina in January, 1993 prior to a stream relocation project.

PROFESSIONAL ORGANIZATION MEMBERSHIPS

American Malacological Union
Ecological Society of America
North American Benthological Society
Society of Environmental Toxicology and Chemistry

AVOCATIONS

Personal Computing
Canoeing
Hiking
Backpacking
Photography
SCUBA (PADI certification)
Natural History Studies

GRANT FUNDS APPLIED FOR

Virginia Polytechnic Institute and State University intradepartmental grant in amount of $2,000 to conduct Clinch River mussel fauna research during 1990. These funds have been awarded.

Virginia Natural Heritage Program grant in amount of $2,500 to conduct Clinch River mussel fauna research during 1990. These funds have been awarded.

National Audubon Society in amount of $5,600 to conduct Clinch River mussel fauna research during 1990. Funds were not awarded.

Conchologists of America in amount of $1,485.60 to conduct research on abiotic factors affecting distribution and abundance of native bivalves in the Clinch River, Virginia. Funds were not awarded.

The Nature Conservancy in amount of $7,485.60 to conduct research on abiotic factors affecting distribution and abundance of native bivalves in the Clinch River, Virginia. Funds were not awarded.

The Nature Conservancy in undetermined amount to conduct research on muskrat predation on native bivalves in the Clinch River, Virginia. Funds have not been awarded.

GRANT PROPOSALS IN PREPARATION

Assessment of Biotic Integrity Using the Extant Mussel Fauna: A Strategy for Identifying Source Areas of Impact to Rare and Endangered Mussel Species.

Currently submitted to:
The Nature Conservancy
Virginia Game and Fish Commission
United States Fish and Wildlife Service

INVITED SEMINARS AND PAPERS

Factors Affecting the Distribution and Abundance of Mussels in the Clinch River. G.W. Church, D.S. Cherry and J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Invited paper delivered at The Nature Conservancy Technical Conference, Abingdon, Virginia on December 5, 1991.

Lithological Factors Affecting the Distribution and Abundance of Mussels in the Clinch River. G.W. Church, D.S. Cherry, J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Invited seminar delivered in the Hydrosystems Division of the Department of Civil Engineering at Virginia Tech on December 11, 1991.

Factors Affecting the Distribution and Abundance of Mussels in the Clinch River. G.W. Church, D.S. Cherry, J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Siciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Invited seminar delivered to the Biology Department, East Tennessee State University, Johnson City, Tennessee on October 7, 1992.

The Cumberlandian Mussel Fauna: Appalachian legacy of biodiversity. G.W. Church, Department of Biology, Virginia Polytechnic Institute and State University, Blacksburg, VA. Invited seminar to be delivered to the Biology Department of Virginia Intermont College in April, 1993.

PUBLISHED ABSTRACTS

Decline of the Cumberlandian Mussel Fauna: A Strategy for Monitoring Changes in Mussel Shoal Communities. G.W. Church and D.S. Cherry, Biology, R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Poster paper presented at 1989 annual meeting of the North American Benthological Society at the University of Guelph, Guelph, Ontario.

Survey of the Family Unionidae in the Clinch and Little Rivers, Virginia. G.W. Church, D.S. Cherry and J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia. Poster paper presented at 1991 annual meeting of the North American Benthological Society at the College of Santa Fe, Santa Fe, New Mexico.

Characterization of Bivalve Habitat in the Little River, Virginia. M.P. Miller, G.W. Church, D.S. Cherry, J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Paper presented at 1992 annual meeting of the North American Benthological Society at the University of Louisville, Louisville, Kentucky on May 29, 1992.

Lithological and Geomorphic Factors Affecting the Abundance of Mussels in the Clinch River (Virginia, Tennessee). G.W. Church, D.S. Cherry, J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Paper presented at the annual meeting of the North American Benthological Society at the University of Louisville, Kentucky on May 29, 1992.

Factors Affecting the Distribution and Abundance of Mussels in the Clinch River (Virginia, Tennessee). G.W. Church, D.S. Cherry, J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Poster presentation presented at the Conservation and Management of Freshwater Mussels Symposium in St. Louis, MO on October 12, 1992.

Habitat Characterization and Assessment of Mussel Community Health in the Clinch River, Virginia. G.W. Church, D.S. Cherry, J.L. Farris, Biology; R.J. Neves, Fisheries and Wildlife Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA. Platform presentation delivered at the annual meeting of the Society of Environmental Toxicology and Chemistry meeting in Cincinnati, Ohio on November 12, 1992.

Assessment of Mussel Community Health in the Clinch River, Virginia. G.W. Church, D.S. Cherry and J.C. Fischer, Biology Department, and R.J. Neves, Virginia Cooperative Fisheries Research Unit, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061. Paper to be presented at the annual meeting of the North American Benthological Society in Calgary, Alberta, Canada on May 28, 1993.