The Pennsylvania State University

The Graduate School

College of Agricultural Sciences

INFLUENCE OF STREAM CHANNEL MORPHOLOGY, STREAM HABITAT, AND LANDSCAPE FEATURES ON BROOK TROUT DENSITIES IN CENTRAL PENNSYLVANIA STREAMS

A Thesis in

Wildlife and Fisheries Science

by

Doris A. Mason

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2009

The thesis of Doris A. Mason was reviewed and approved* by the following:

C. Paola Ferreri
Associate Professor of Fisheries Management
Thesis Advisor

Tyler Wagner
Adjunct Assistant Professor of Fisheries Ecology

Victoria A. Braithwaite
Professor of Fisheries and Biology

John A. Sweka, Special Signatory
Fish Biologist – U.S. Fish and Wildlife Service

Michael G. Messina
Director, School of Forest Resources

*Signatures are on file in the Graduate School

ABSTRACT

The brook trout (*Salvelinus fontinalis* (Mitchill)) is the only stream salmonid native to Pennsylvania and is considered an important indicator of high quality coldwater streams. However, recent studies have shown that brook trout populations have declined throughout much of Pennsylvania due to increased sedimentation, increasing water temperatures, and competition with non-native species. The goal of this study was to evaluate the effectiveness of using thalweg profile metrics and other habitat features to predict brook trout density and to determine what factors may be limiting brook trout density in Pennsylvania streams.

Twenty eight study streams located within the Susquehanna River Basin in central Pennsylvania were selected using information from the Pennsylvania Fish and Boat Commissions' (PFBC) fisheries management database. At each stream, a reach at least 250m in length was surveyed to measure the thalweg profile as described by Mossop and Bradford (2006). From the thalweg profile, metrics describing length in residual pool, mean maximum residual pool depth, variation index, and mean square error were calculated. Number of pools per kilometer and gradient were also calculated for each study reach from the thalweg profile. Substrate composition, bank erosion, cover, and large woody debris were evaluated at twenty evenly-spaced transect throughout the study reach. Water quality parameters including pH, temperature, and alkalinity were recorded at the downstream end of the study reach. Drainage area and land use composition were determined for the watershed area upstream of the study reach using GIS.

Fish were sampled at each study reach using backpack electrofishing. Two streams were sampled using mark-recapture techniques and 26 were sampled using multiple pass removal in the same reach where the thalweg profile was measured. Brook trout density was estimated using appropriate multiple pass removal estimators or the Petersen mark-recapture estimator. Brook trout were measured (TL, mm) and a sub-sample was weighed (g). All other species were recorded as present.

Brook trout density was highly variable among physiographic provinces and among streams. I did not find a significant difference between brook trout densities between the Appalachian Plateau and Ridge and Valley physiographic province. The results indicate that the thalweg metrics were not strong predictors or limiting factors of brook trout populations. Using simple linear regression percent residual ($r^2 = 0.33$, $p \leq 0.01$) and mean maximum depth ($r^2 = 0.16$, $p \leq 0.05$) were significantly correlated with $\log_{10}$- brook trout density. Mean wetted width ($r^2 = 0.47$, $p \leq 0.01$), percent gradient ($r^2 = 0.25$, $p \leq 0.01$), non-brook trout species ($r^2 = 0.25$, $p \leq 0.01$), and drainage area ($r^2 = 0.16$, $p \leq 0.05$) were significantly correlated with $\log_{10}$- brook trout density using simple linear regression. Using quantile regression mean wetted width, gradient, pools per kilometer, and non brook trout species were significant limiting factors for brook trout densities.

Although the percent residual pool and mean maximum depth explained some variation in brook trout densities, the predictive power of these variables was not strong. These results indicate that brook trout restoration and protection has its highest potential in smaller higher gradient streams. Also, the addition of many smaller pools rather than a few large pools would provide a greater benefit for brook trout restoration.

TABLE OF CONTENTS

LIST OF FIGURES vii

LIST OF TABLES ix

ACKNOWLEDGEMENTS x

Chapter 1 INTRODUCTION 1

Chapter 2 METHODS 5

- Study Sites 5
- Thalweg Profiling 7
- Determination of Study Reach Length 10
- Water Quality 14
- Large Woody Debris and Overhead Cover 14
- Substrate Composition and Erosion 15
- Drainage Area and Land Use 16
- Fish Sampling and Density Estimates 18
- Statistical Analysis 19

Chapter 3 RESULTS 22

- Thalweg Profiles 22
- Thalweg Metrics and Brook Trout Density 24
- Additional Habitat Variables and Brook Trout Density 30
- Correlations Among Thalweg Metrics and Stream Habitat Variables 40
- Regression Tree Analysis 41

Chapter 4 DISCUSSION 42

- Management Implications 45

Bibliography 47

Appendix A: Thalweg profiles of five 1 km stream reaches sampled to determine appropriate reach length for the thalweg metrics. 50

Appendix B: Length frequency histograms for brook trout captured using multiple pass depletion from summer 2008 to fall 2008 56

Appendix C: Thalweg profiles of study streams sampled in summer and fall 2008 in the Ridge and Valley and Appalachian Plateau physiographic provinces. Graphs are scaled based on stream gradient and reach length. 70

Appendix D: Landscape level and in stream habitat characteristics for 15 Appalachian Plateau and 13 Ridge and Valley physiographic province streams of central Pennsylvania sampled in summer and fall 2008. 81

Appendix E: Plots of non significant variables and log_{10}- brook trout densities in central Pennsylvania Streams 86

LIST OF FIGURES

Figure 1: Study stream location in the Appalachian Plateau and Ridge and Valley provinces within central Pennsylvania. 6

Figure 2: Hypothetical thalweg profile illustrating how the length of residual pool and residual pool depth are determined from relative elevation change along the stream channel length (adapted from Mossop and Bradford 2006)........ 9

Figure 3: Percent change in the thalweg metrics (percent pool length, mean maximum pool depth, and the variation index) as the thalweg profile is increased from 50 to 500 m using bootstrap simulation........ 11-13

Figure 4: Comparison of the thalweg profile of two streams with differ ent gradients, but similar number of residual pools. 23

Figure 5: Plots comparing brook trout density and thalweg metrics to determine the relationships. Plots had a significant relationship ($p<0.05$)........ 26

Figure 6: Plots comparing log10- brook trout density and thalweg metrics to determine the relationships. None of the plots have a significant relationship (p<0.05) 27

Figure 7: Estimates of slope (β_1) for the thalweg metrics (percent residual pool, mean maximum pool depth, mean square error, and the variation index. The dotted line represents the slope and the shaded area represents the 90% confidence intervals for the slope........ 29

Figure 8: Plots comparing $\log_{10}$- brook trout density and significant ($p<0.05$) variables including mean wetted width, percent gradient, total non brook trout species and drainage area to determine the relationships........ 32-33

Figure 9: Estimates of slope (β_1) for the mean wetted width, percent gradient, non brook trout species and pools/km. The dotted line represents the slope and the shaded area represents the 90% confidence intervals for the slope........ 35

Figure 10: Quantile regression plot of brook trout density and the mean wetted width and the total number of non brook trout species with significant limiting factors at the 70^{th} and 80^{th} quantile 37

Figure 11: Quantile regression plot of brook trout density and pools/km and percent gradient with significant limiting factors at the 75^{th} and 85^{th} quantile 38

Figure 12: a. Quantile regression plot of brook trout density and the average bank score with significant limiting factors at the 80th and 90th quantile b. Quantile regression plot of brook trout density and the percent silt with significant limiting factors at the 90th quantile 39

Figure 13: Regression tree analysis for all of the variables in one model. If the mean wetted width is ≥ 4.022 the mean brook trout density is 5. 41

LIST OF TABLES

Table 1: Location (latitude and longitude, date of fish sampling (fish date), date of habitat assessment (habitat date), and length of study reach with the stream (survey length) in meters) for 28 study streams. Streams are grouped according to the physiographic province in which they are located. Shaded area represents streams that were sampled on separate days for habitat and fish. 7

Table 2: Pennsylvania Fish and Boat Commission's stream classification trout streams (PFBC 1997) and number of streams per class within each province..... 7

Table 3: The thalweg profile length with < 5% percent change from the previous 50 meter increment for percent pool length, mean maximum pool depth, and the variation index, based on bootstrap simulations. 13

Table 4: Classification of LWD (Flebbe and Dolloff 1995) 15

Table 5: Sediment classifications (Modified Platts et al. 1983) 16

Table 6: Bank erosion classification (Platts et al. 1983) 16

Table 7: Classifications for land cover types 17

Table 8: Brook trout density/100m^2 estimates and variables derived from the thalweg profile of the 28 streams located in central Pennsylvania (15 in the Appalachian Plateau and in the 13 Ridge and Valley physiographic province streams).Stream location and sample dates in Table 1. 25

Table 9: Simple linear regression values for thalweg metrics and $\log_{10}$- brook trout densities. Shading represents variables with a $p \leq 0.05$. 28

Table 10: Simple linear regression values for stream habitat features and $\log_{10}$- brook trout density. Shading represents variables with a $p \leq 0.05$. 34

Table 11: Confidence intervals and slopes for the significant quantiles of percent silt and average bank score variables, which could not be graphed due to values approaching infinity (Inf). 36

Table 12: Correlation coefficients comparing thalweg metrics and variables that were significant with quantile regression. Grey shaded area represents coefficients with a $p \leq 0.05$ 40

ACKNOWLEDGEMENTS

I would like to thank the US Fish and Wildlife Service Northeast Fishery Center for the use of equipment and staff hours to complete the project. I thank the College of Agricultural Sciences at Penn State University for providing a tuition waiver during the first year of my program. Animal use for this project was approved under IACUC. I thank my advisor Paola Ferreri and the members of my committee John Sweka, Tyler Wagner, and Victoria Braithwaite for their assistance and support for my project and pursuit of a degree at Penn State.

I appreciate the help of the US Fish and Wildlife Service staff and volunteers who assisted with the project including Tom Kehler, Steve Davis, Jerre Mohler, Jeff Kalie, Patrick Farrell, Bill Quartz, Steve and Bryce Bason, Jillian Best, Ashley Lenig, and Colten Rager. I also thank the Clinton County Conservation district summer interns including Sam Kutskels and Josh Furl and the Pennsylvania Department of Environmental Protection including Jerry Miller, John Ryder, and Jared Dressler for assistance with field work. I also appreciate the assistance from fellow Penn State graduate students Briana Hutchison and Brooks Fost. I would also like to extend my thanks to Jason Detar, Dave Kristine, and John Frederick of the Pennsylvania Fish and Boat Commission for assistance with project planning and field work. I also appreciate the permission to use state forest land by the Pennsylvania Department of Natural Resources.

I also extend my deepest thanks to my family, especially my parents George and Ardelle Mason who have supported me in pursuit of all of my goals.

Chapter 1

INTRODUCTION

Introduction

The brook trout (*Salvelinus fontinalis* (Mitchill)) is the only stream salmonid native to Pennsylvania (Cooper 1983). Historically, the brook trout's range in the United States extended from Maine to Georgia, but deterioration of stream habitat has led to a decline in populations throughout much of the Northeastern United States (Hudy et al. 2005). In Pennsylvania, brook trout are generally found in small mountain streams where they reach sizes of 200 to 250 mm and live 3 to 4 years (Raleigh 1982). Brook trout spawn in the fall; females excavate redds in areas with reduced sediment and upwelling ground water that increases flow to the eggs (Raleigh 1982). In comparison to other trout species, brook trout are relatively intolerant of high temperature. They can withstand temperatures from 0 to 24 ºC, but survive and grow best between 11 and 16 ºC. Some populations of brook trout are also tolerant of pH below 5.0, but most survive and grow best at a pH of 6.5 to 8 (Raleigh 1982). Brook trout populations have declined within Pennsylvania due to increased sedimentation, increasing water temperatures, and competition with exotic species (Hudy et al. 2005).

Understanding the role of habitat in determining the abundance or density of salmonids has been the focus of many studies (Bovee et al. 1998; Flebbe and Dolloff 1995; Mossop and Bradford 2006). Some studies have shown a relationship between habitat complexity and brook trout abundance; for example, Sweka (2003) found that as the number of distinct pools, riffles, and runs increased per unit length of stream, so did brook trout density. Pool area is generally considered an important component of brook trout habitat. In the habitat suitability models for brook trout developed by Raleigh (1982), percent pools is an important variable for the adult, juvenile, and fry stages, and pool class (describing the length and depth of pools) is important for the adult and juvenile stages. Logan (2003) found that brook trout used pool habitat most frequently. Flebbe and Dolloff (1995) showed that all trout preferred pool habitat and had a greater preference for pools that contained woody debris. Pools provide habitat and refugia in times of drought when the riffles of the stream have been reduced (Hakala and Hartman 2004). Although pools have been documented as an important habitat feature, methods to quantify and describe the amount of pool habitat in a stream are often debated (Mossop and Bradford 2006).

Mossop and Bradford (2006) found that juvenile chinook salmon (*Oncorhynchus tshawytsha)* prefer pool habitat and were most abundant in pools. In their study, density of juvenile chinook salmon was correlated with metrics determined by surveying the thalweg or deepest part of the channel. The thalweg profile describes relative elevation changes along the length of a stream channel and provides a repeatable and objective way to quantify the amount of pool habitat in a stream reach that is independent of flow conditions. Mossop and Bradford (2006) defined a residual pool as an area within a stream profile that has a > 0.1 m elevation decrease and increase between three points measured along the thalweg. From the thalweg profile, variables such as length of residual pool, mean maximum residual pool depth, and the variation index can be calculated. Mossop and Bradford (2006) found that density of juvenile chinook salmon was correlated with length of residual pool, mean maximum residual pool depth, and the variation index.

Large woody debris (LWD) increases habitat complexity in a stream by promoting the formation of pools (Neumann and Wildman 2002). In addition, large woody debris can provide overhead cover (Berg et al. 1998; Gurnell et al. 1995) and sediment and organic matter storage (Bilby 1981). Salmonid abundance is generally positively correlated with the abundance of LWD (Flebbe and Dolloff 1995; Cederholm et al. 1997). However, some artificial additions of LWD have not shown significant results in modifying stream habitat and have not significantly increased salmonid abundance (Sweka and Hartman 2006), while others have shown increases (Neumann and Wildman 2002). The mixed results of LWD additions could be a result of fluctuations in salmonid populations over time or the result of additional limiting factors within these streams.

Land use practices can influence brook trout populations by changing stream habitat features. Historic and current practices can contribute to channelization, sediment deposition, increased temperature, and changes in the biological community within the stream. Harding et al. (1998) found that historical land use practices in areas that are currently forested may still be affecting the structure of macroinvertebrate communities. Lenat and Crawford (1994) found significant differences between the macroinvertebrate communities when comparing streams with three dominant land use types: forested, agricultural, and urban. Macroinvertebrate communities were significantly different among land use types with the largest difference occurring between the urban and forested streams. The differences in macroinvertebrate communities may be attributed to increased sedimentation and also represent changes in the forage base available to brook trout. Land use impacts and the size of a stream can increase stream temperatures, which results in changes in species composition from salmonids to minnows (Smith and Kraft 2005 and Taniguchi et al. 1998). Taniguchi et al. (1998) found that as the temperature of streams increased, brown trout and creek chubs would out-compete brook trout for habitat and food. As the temperature of streams increase, brook trout become less efficient and therefore cannot compete for food resources.

Erosion resulting from land management practices such as logging, roads, and agriculture can affect the quality of brook trout habitat in a stream. The result of increased erosion may be increased turbidity and suspended material (Bash et al. 2001). Turbidity may decrease fitness in brook trout by decreasing foraging efficiency and increasing the energy required for foraging (Sweka and Hartman 2001). The presence of fine sediment within a stream can affect salmonid populations through decreased egg survival (Argent and Flebbe 1998), changes in available forage (Kaller and Hartman 2004), and changes in physical habitat due to sedimentation (Lisle and Hilton 1992).

The overall goal of my study was to evaluate the effectiveness of using thalweg profile metrics and other habitat features to predict brook trout density in Pennsylvania streams. The first objective was to determine if a relationship exists between brook trout density and the thalweg metrics. The second objective is to evaluate the relationship between brook trout and additional stream habitat and landscape level factors. The third objective was to determine what factors may be limiting brook trout density in Pennsylvania streams.

Chapter 2

METHODS

Study Sites

Twenty eight study streams located within the Susquehanna River Basin in central Pennsylvania were selected using information from the Pennsylvania Fish and Boat Commissions' (PFBC) fisheries management database (Figure 1). Based on previous surveys by the PFBC, brook trout comprised > 75% of the total salmonid biomass (including brown trout and rainbow trout) in the selected streams. Fifteen streams were within the Appalachian Plateau and 13 in the Ridge and Valley provinces (Table 1). Streams were selected to span a range of historical brook trout biomass based on PFBC trout stream classification (Table 2). To ensure that study streams were not highly impacted by acid deposition, only the streams with historic alkalinity values of >5 mg/L were selected. The sample site in each stream was selected based on the state's historic site and locations where access could be obtained. A sample site consisted of a representative reach of approximately 250 meters in length (Table 1). This representative reach length was determined based upon preliminary surveys of five one kilometer sections of stream as described below. All but one of the sample sites was at least 250 m. Stony Run was the only stream where less than 250 m was sampled because the stream went underground within the study reach. Some of the sites were longer because they were sampled by the PFBC for a replicate of a previously established site length.

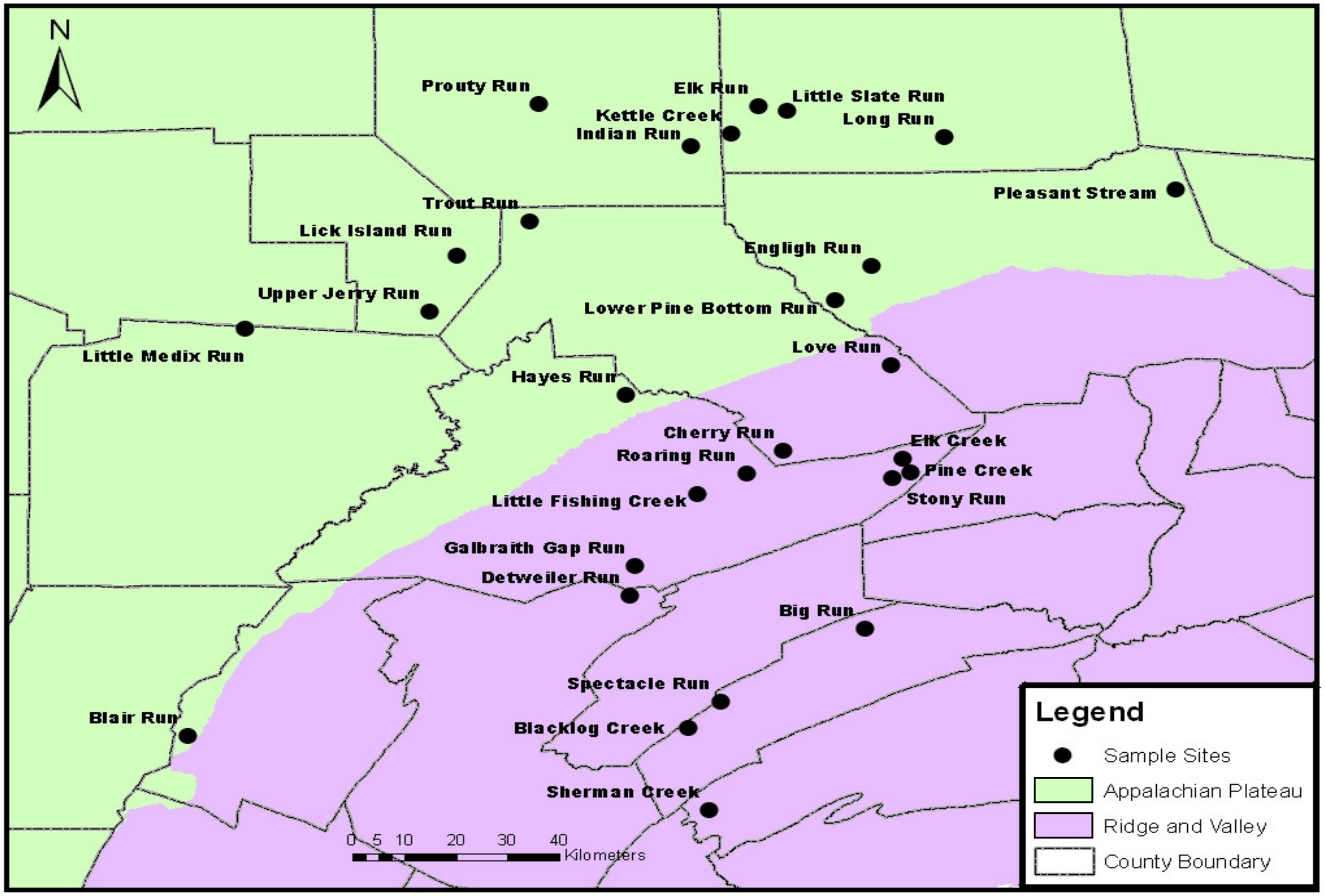


Figure 1: Study stream location in the Appalachian Plateau and Ridge and Valley provinces within central Pennsylvania.

Table 1: Location (latitude and longitude, date of fish sampling (fish date), date of habitat assessment (habitat date), and length of study reach with the stream (survey length) in meters) for 28 study streams. Streams are grouped according to the physiographic province in which they are located. Shaded area represents streams that were sampled on separate days for habitat and fish.

Stream	Latitude	Longitude	Fish Date	Habitat Date	Survey Length (m)
Appalachian Plateau					
Blair Run	40.43	-78.53	7/9/08	7/9/08	257
Elk Run	41.67	-77.54	7/29/08	7/29/08	258
Hayes Run	41.10	-77.77	7/7/08	7/16/08	256
Indian Run	41.59	-77.65	8/19/08	9/12/08	352
Little Medix Run	41.23	-78.43	7/3/08	7/3/08	253
Lower Pine Bottom Run	41.29	-77.40	8/13/08	8/13/08	260
Prouty Run	41.68	-77.92	8/14/08	8/14/08	264
Trout Run	41.45	-77.93	9/4/08	8/15/08	308
Kettle Creek	41.62	-77.58	8/6/08	8/15/08	360
Lick Island Run	41.38	-78.06	9/4/08	9/4/08	259
Little Slate Run	41.67	-77.49	8/22/08	8/22/08	282
Pleasant Stream	41.51	-76.81	9/2/08	9/2/08	258
Upper Jerry Run	41.27	-78.11	8/28/08	8/28/08	256
English Run	41.36	-77.34	9/11/08	9/11/08	252
Long Run	41.61	-77.21	7/1/08	7/1/08	257
Ridge and Valley					
Love Run	41.16	-77.30	7/22/08	7/22/08	262
Stony Run	40.94	-77.30	9/16/08	9/16/08	231
Galbraith Gap Run	40.76	-77.75	8/12/08	8/12/08	260
Detweiler Run	40.71	-77.76	8/5/08	8/5/08	253
Pine Creek	40.95	-77.27	7/14/08	6/26/08	263
Roaring Run	40.95	-77.56	9/15/08	9/15/08	243
Spectacle Run	40.49	-77.60	7/10/08	7/10/08	266
Cherry Run	40.99	-77.49	8/6/08	8/6/08	260
Elk Creek	40.98	-77.29	7/25/08	6/26/08	250
Little Fishing Creek	40.91	-77.64	6/23/08	9/5/08	257
Blacklog Creek	40.44	-77.66	7/28/08	7/28/08	271
Sherman Creek	40.28	-77.62	7/11/08	7/11/08	256
Big Run	40.64	-77.35	8/27/08	8/27/08	261

Table 2: Pennsylvania Fish and Boat Commission's stream classification trout streams (PFBC 1997) and number of streams per class within each province.

Class	Historic Biomass (kg/ha)	Ridge and Valley	Appalachian Plateau
A	>30	4	5
B	20 – 30	4	4
C	10 – 20	4	5
D	<10	1	1

Thalweg Profiling

The thalweg profile of each stream was assessed using laser level survey equipment following the methods of Mossop and Bradford (2006). The laser level was set at the downstream end of a reach and an initial elevation was taken at distance zero. An elevation reading was taken every five meters or at apparent changes in streambed slope (Mossop and Bradford 2006). When the level could no longer be seen, a turning point was established, the equipment was moved, and another elevation was taken at the same location as the last elevation. Sherman Creek, Blair Run, Spectacle Run, and Stony Run were missing the first point in the new level location, which was not recorded at the time of sampling. For these four streams, the level of the first measured point within the section was used as the initial elevation for that level location, which resulted in a complete profile for each of these streams.

The thalweg profile data (relative elevation change along the stream channel length; Figure 2) was used to determine the thalweg metrics described in Mossop and Bradford (2006). The metrics include the variation index, mean maximum residual pool depth, length in residual pool, and mean square error (MSE) of a least-squares regression line for the profile. The MSE of the regression line represents profile variability, the greater the MSE, the more variability in the thalweg profile. The maximum residual pool depth is the difference between the deepest part of the pool and the height at the crest of the downstream riffle; this variable provides an index of pool depth. Pools $\leq$ 0.1 m deep were not counted to ensure only morphological changes were recorded. The variation index represents the variation in morphology of the residual pools and was calculated as the standard deviation of the residual depths of the pools (Madej 1999). The length of stream reach in residual pool is calculated by summing the total length of pools for the entire reach, and the percent residual pool is calculated as the proportion of the reach length that was pool habitat (Mossop and Bradford 2006). Additional features that were determined using the thalweg profile were percent gradient and the number of pools per kilometer. The percent gradient was equal to the slope of the least-squares regression line through the profile. The thalweg profile was used to calculate the total number of pools in the reach over 0.1 m residual pool depth. The total number of pools was converted to number of pools per kilometer of stream.

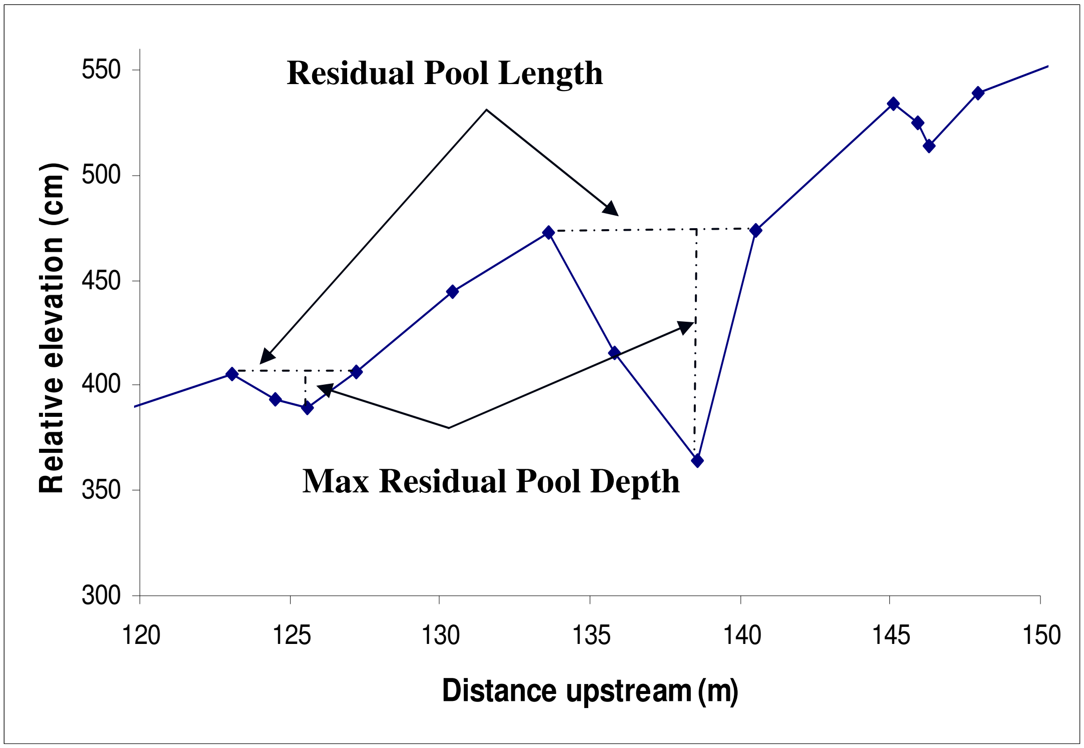
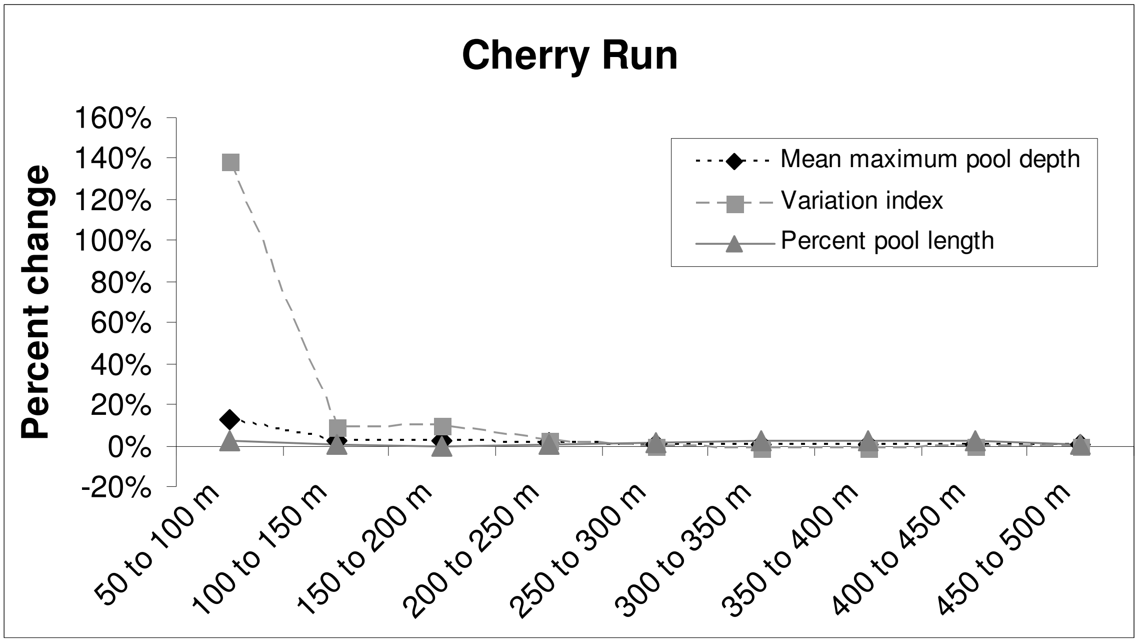


Figure 2: Hypothetical thalweg profile illustrating how the length of residual pool and residual pool depth are determined from relative elevation change along the stream channel length (adapted from Mossop and Bradford 2006).

Determination of Study Reach Length

To determine appropriate length of each reach to sample, I measured the thalweg profile for a 1 km section of five streams. A bootstrap simulation coded in SAS® (Version 9.1) was then used to determine the appropriate representative length of stream. In each simulation, a random starting point along the stream reach was selected and thalweg data for various stream reach lengths (50 – 500 m in 50 m increments) beginning at the starting point were used to estimate thalweg profile metrics (length in residual pool, mean residual pool depth, and the variation index). Ten thousand simulations were conducted for each reach length. I determined the percent change from the previous 50 meter increment based on the thalweg profile metrics. The percent change in the variables from one increment to the next decreased as the distance increased from 0 to 500 meters. I assumed a representative reach was the survey length where the percent change from one increment to the next was less than 5%. The profiles for the 1 km sections of stream were graphed to show a representation of the thalweg profile (Appendix A).

Four of the five streams had a less than 5% change from the previous simulation at reach lengths $\leq$ 200 m. Trout run had $\leq$ 5% error at 450 meters (Figure 3). The average length where the percent change in the thalweg variables was less than 5% was 220 m and the median was 200 m (Table 3). Based on these results, I set the representative reach length for thalweg profiling at 250 m.



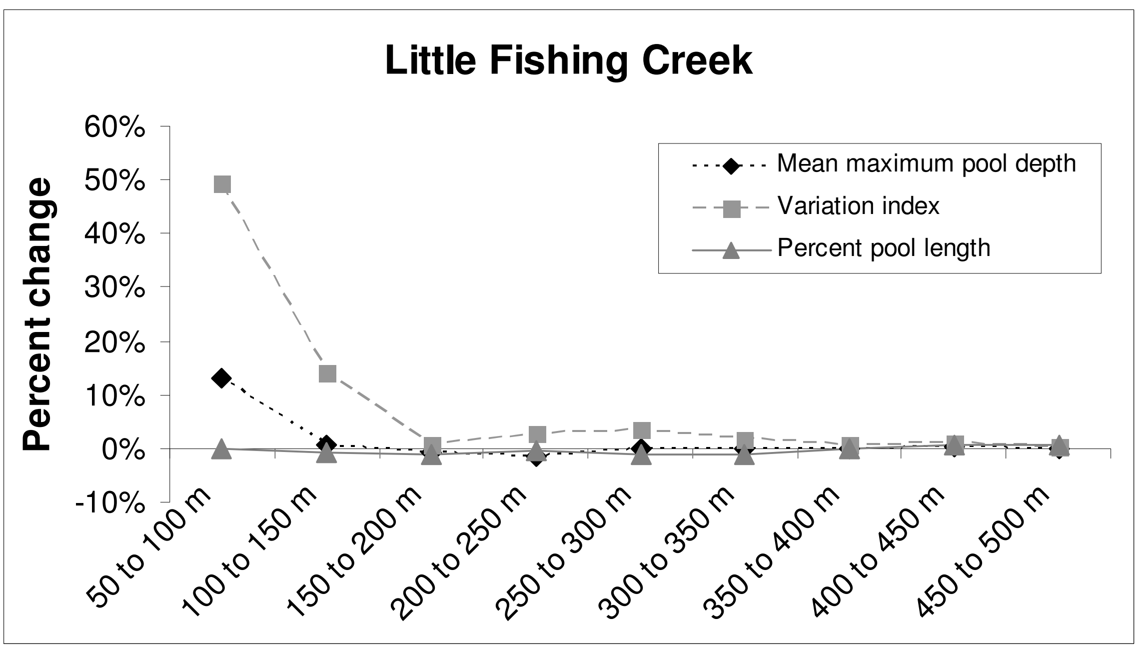
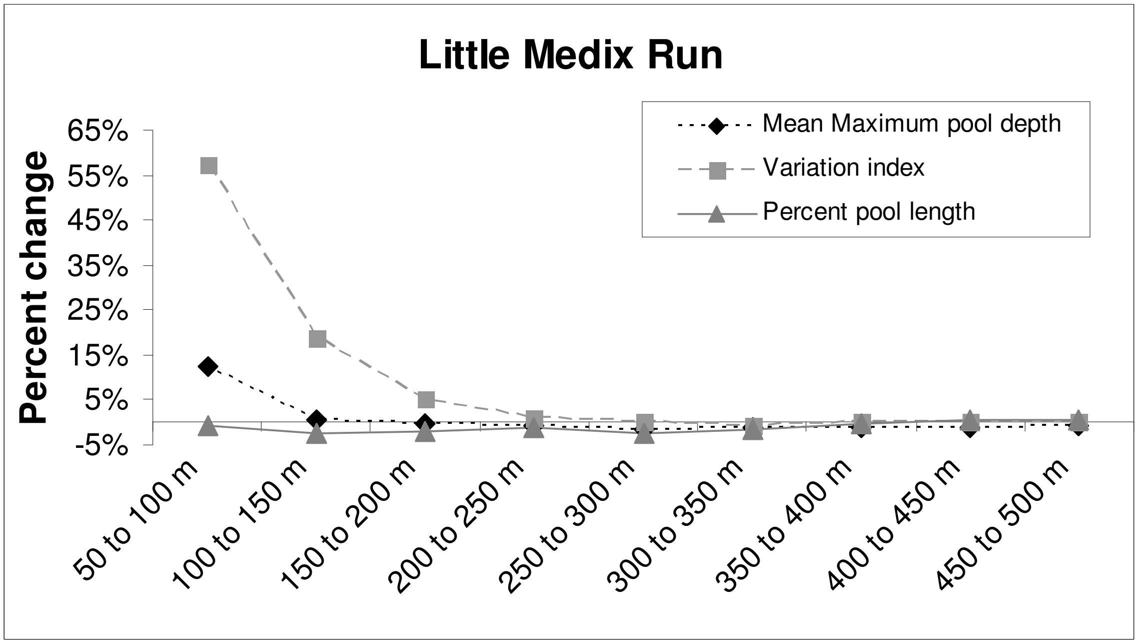


Figure 3: Percent change in the thalweg metrics (percent pool length, mean maximum pool depth, and the variation index) as the thalweg profile is increased from 50 to 500 m using bootstrap simulation.



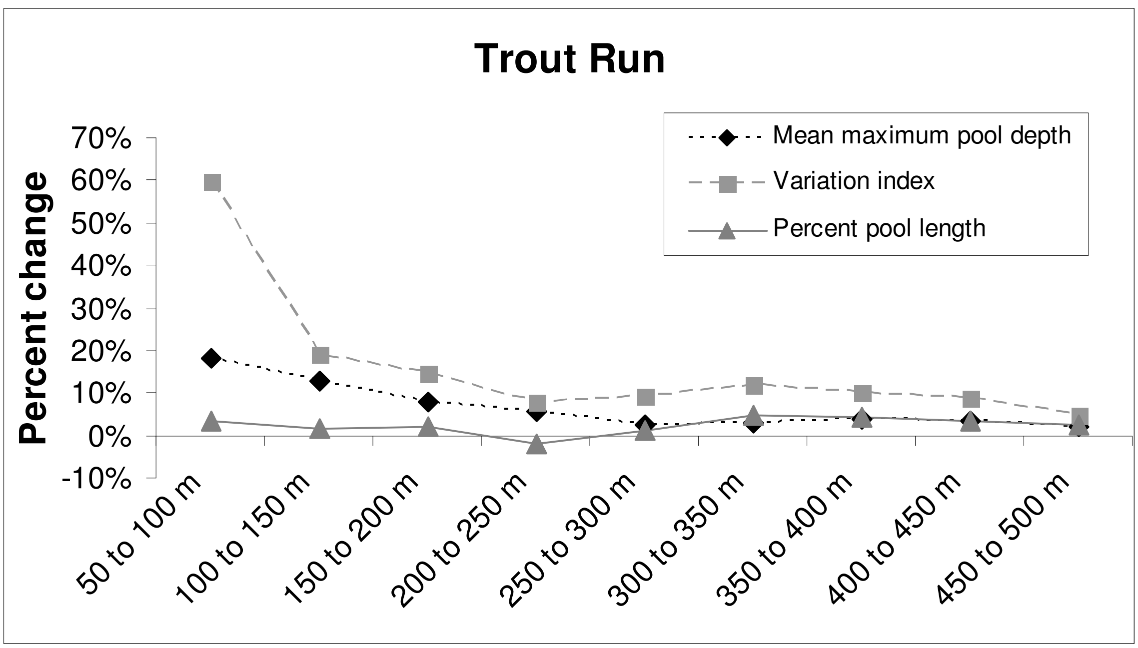


Figure 3 (Continued): Percent change in the thalweg metrics (percent pool length, mean maximum pool depth, and the variation index) as the thalweg profile is increased from 50 to 500 m using bootstrap simulation.

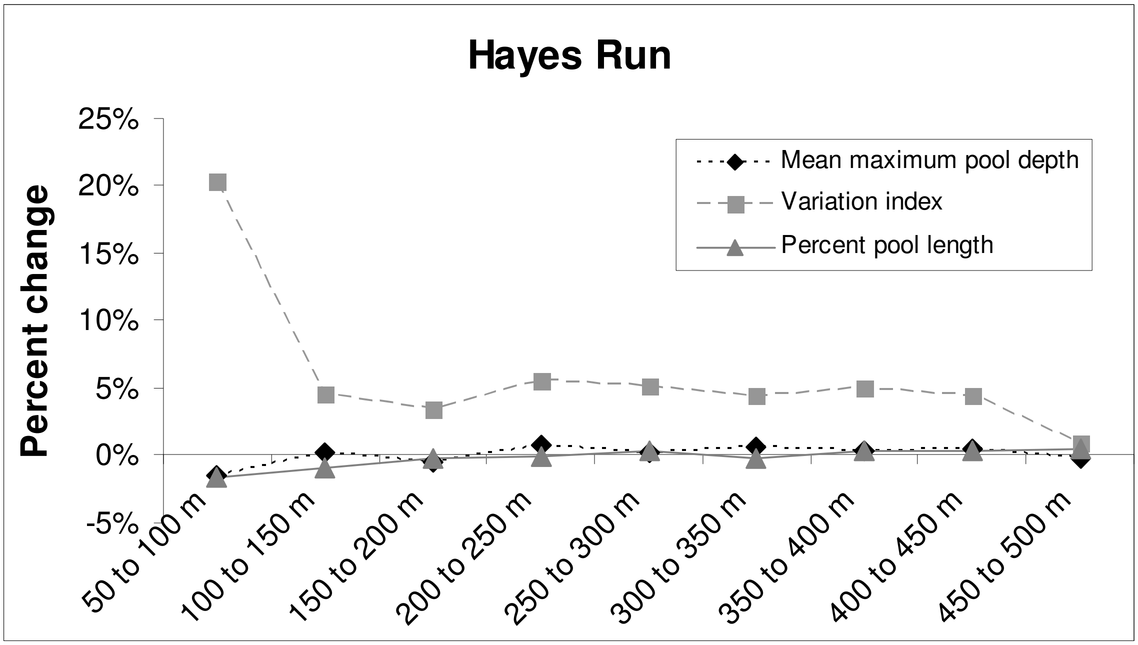


Figure 3 (Continued): Percent change in the thalweg metrics (percent pool length, mean maximum pool depth, and the variation index) as the thalweg profile is increased from 50 to 500 m using bootstrap simulation.

Table 3: The thalweg profile length with < 5% percent change from the previous 50 meter increment for percent pool length, mean maximum pool depth, and the variation index, based on bootstrap simulations.

Stream	Length (m)
Cherry Run	200
Little Fishing Creek	150
Little Medix Run	200
Trout Run	450
Hayes Run	100
Average	**220**
Median	**200**

Water Quality

Water quality parameters including temperature, pH, and conductivity were recorded within the stream reach at the same time the thalweg profile was completed. The temperature and conductivity were measured using a YSI 30 meter and the pH was measured using a WTW pH 315i Meter or YSI pH 10 pen. The WTW pH meter was calibrated for each use and the YSI pen was calibrated a few times during the field season.

Large Woody Debris and Overhead Cover

Large woody debris was identified within the bankfull channel while the thalweg profile was being surveyed. Each piece of LWD was classified using the methods from Flebbe and Dolloff (1995) (Table 4). The total number of pieces of woody debris per 250m was calculated to compare values between streams. The total number of pieces ≥ 5 on the classification scale was also determined.

Overhead cover was observed at 20 equally spaced transects along the reach length. Overhead cover included woody debris, undercut bank, bedrock ledges, aquatic vegetation, and terrestrial vegetation within one meter of the water. The percentage of overhead cover from each stream reach was calculated based on the number of transects with overhead cover out of the total number of transects on the stream.

Table 4: Classification of LWD (Flebbe and Dolloff 1995)

	Diameter			
Length	5-10 cm	> 10-50 cm	>50 cm	Rootwads
1-5 m	Class 1	Class 2	Class 3	Class 7
>5 m	Class 4	Class 5	Class 6	Class 7

Substrate Composition and Erosion

Substrate composition was determined using pebble counts (Bain and Stevenson 1999). Pebble counts were taken at the 20 evenly spaced transects along the reach length. At each transect, five pieces of substrate were taken at equal distances along the transect and measured using a ruler at the intermediate axis. The intermediate axis would determine if the particle would fit through a sieve (Bain and Stevenson 1999). The size of the particles was recorded for all pieces above 0.83mm, and the smaller pieces were classified as silt, sand, or clay. The classifications from Platts et al. (1983) were used to classify substrate types (Table 5). A total of 100 particles were measured in each stream and the percentage of each substrate type was determined by the number within each class.

At each of the pebble count transects, the percent erosion on each bank was visually estimated. The right and left bank (determined facing upstream) were classified according to Platts et al. (1983) for five meters upstream and downstream from the intersection of each transect (Table 6). The scores for each stream were totaled and an average bank score was determined for the entire reach.

Table 5: Sediment classifications (Modified Platts et al. 1983)

Particle diameter size (mm)	Sediment Classification
>610.0	Large Boulder
305.0-609.0	Small Boulder
76.1-304.0	Rubble (cobble)
4.81-76.0	Gravel
0.83-4.71	Fine Sediment (Large)
<0.83	Fine Sediment (silt, sand, or clay)

Table 6: Bank erosion classification (Platts et al. 1983)

Rating	Description
4 (Excellent)	Over 80 % of the streambank surfaces are covered by vegetation in vigorous condition or by boulders and rubble. If the streambank is not covered by vegetation, it is protected by materials that do not allow bank erosion.
3 (Good)	Fifty to 79 % of the streambank surfaces are covered by vegetation or by gravel or larger material. Those areas not covered by vegetation are protected by materials that allow only minor erosion.
2 (Fair)	Twenty-five to 49 % of the streambank surfaces are covered by vegetation or by gravel or larger material. Those areas not covered by vegetation are protected by materials that give limited protection.
1 (Poor)	Less than 25 % of the streambank surfaces are covered by vegetation or by gravel or larger material. That area not covered by vegetation provides little or no control over erosion and the banks are usually eroded each year by high water flows.

Drainage Area and Land Use

I used ArcHydro with digital elevation models (DEM) to determine the watershed boundaries for each of my study reaches. There were several steps within the ArcHydro program used to delineate watershed boundaries. Sinks within the DEM were filled to determine where each drop of water that enters the terrain would eventually flow. The flow direction was determined for each cell within the DEM. This was determined based on the largest change in elevation of the surrounding cells. Flow accumulation was determined by summing the number of cells that are drained into each single cell. The next step, stream definition, took all the cells that drain a large enough area and define them separately. Next, I ran stream segmentation which split the stream definition output into smaller units. Catchment grid delineation gave all the cells in a drainage area of a particular stream segment a unique value. The resulting raster catchment grid was converted to a shapefile that was used to draw the drainage area of a particular stream. If watershed boundaries from ArcHydro did not cross at the beginning of my stream reach, I used GIS editing tools and topographic maps to estimate the boundary around this point. This process resulted in a shapefile that was used to represent the drainage area above the stream reach that I sampled. The calculate geometry function in ArcGIS was used to calculate the total drainage area from the drainage area shapefile for each of the streams. The watershed area shapefile was then used to determine land use percentages from the Pennsylvania land cover map (2000). The land uses were deciduous, coniferous, mixed forest, row crop, hay pasture, low density urban, quarries, transitional, emergent wetlands, woody wetlands, and water. I grouped these into 5 categories including: forested, agriculture, developed, water and wetlands, and barren (Table 7).

Table 7: Classifications for land cover types

Category	Classifications from land cover dataset
Forested	Coniferous, Deciduous, and Mixed Forest
Agriculture	Row Crops and Hay Pasture
Developed	Low Density Urban
Water and Wetlands	Water, Woody Wetlands, and Emergent Wetlands
Barren	Quarries and Transitional

Fish Sampling and Density Estimates

Fish were sampled using Appalachian Aquatics (AA-24) or Smith-Root (LR-24 Electrofisher) backpack electrofishing gear using pulsed DC current with 2 to 3 person crews depending on the size of the stream. Two streams were sampled by PFBC personnel as part of their routine sampling using mark recapture methods. I sampled the remaining 26 streams using multiple pass depletion. Twenty-five streams were sampled using the following methods. Length (TL, mm) and weights (g) were recorded for the first 10 brook trout and brown trout within each 25 mm size class. Once there were 10 weights in a size class, just length was recorded for the remaining fish. Indian Run was sampled using a multiple pass depletion and the first 10 brook trout and brown trout were weighed and measured for each 25 mm size class. The remaining fish were grouped into the 25 mm size classes and the total number of each class was determined. Trout Run and Kettle Creek were sampled by PFBC personnel using mark recapture. The crews electrofished and marked all the trout captured on the first day. On the following day the crew electrofished and recorded the number of marked fish and unmarked fish that were captured. All of the trout for Trout Run and Kettle Creek were measured (TL, mm) and grouped into 25 mm size classes. Additional species of fish were collected, and the total number of non-trout species was determined for each study site. Because temperatures can vary throughout the year, the non brook trout species variable may provide an indicator of temperature when the temperature is not recorded over a long time period (Smith and Kraft 2005 and Taniguchi et al. 1998).

Multiple pass removal estimators or the Petersen mark-recapture estimates were used to estimate brook trout density in the same reach where the thalweg profile was measured. During multipass electrofishing, block nets were placed at the upstream and downstream ends of the reach to ensure a closed population. The population estimates were determined for age 1+ brook trout; the length cutoff for 1+ individuals was determined from length frequency histograms (Appendix B). The minimum length for mark recapture streams and Indian Run where the fish were grouped into 25 mm size classes was set at 75mm based on a length frequency histogram with all the data from the first 25 streams (Appendix B). Population estimates within a stream reach were estimated in 25 of the streams using the generalized removal estimator in the program CAPTURE (White et al. 1982). Indian run, which only had a two pass depletion was completed using the Zippin method in the program CAPTURE (White et al. 1982). Density was calculated by dividing the population estimate by the wetted area of the sampling reach. The wetted area was determined at the time of sampling by averaging the wetted width from approximately 20 evenly spaced transects along the reach length and multiplying it by the length of representative reach. Brook trout densities were recorded as number of brook trout density per 100 m^2.

Statistical Analysis

I used a two sample t-test to determine if differences existed in brook trout density between the two physiographic provinces. This step was necessary to determine if the data from the 28 streams could be pooled for further analysis. Brook trout densities were transformed using a $\log_{10}$- transformation to better meet the assumption of normally distributed residuals. To evaluate the relationship between $\log_{10}$- brook trout density and the habitat variables that were recorded, I used simple linear regression using MINITAB statistical software (MINITAB 2003).

Mossop and Bradford (2006) found that a length in residual pool, mean maximum pool depth, and the variation index metrics that were related to juvenile chinook salmon were also correlated with one another. To determine if multiple linear regression could be used Petersen correlation coefficients were determined for the thalweg metrics and the significant habitat variables. Due to the large amount of correlation between variables a multiple regression could not be used (See results).

Within biological systems, many unmeasured variables can create error when simple linear regression is used. Simple linear regression assumes a normal distribution of errors, which is not true of most biological data, and may lead to insignificant relationships when the variable could be having an effect on the response. Quantile regression does not have such an assumption and can be used with data that do not meet the assumption of normal linear regression (Cade and Noon 2003). Quantile regression examines a particular section of the data, which is called a quantile. When the upper quantiles of a particular data set is measured, the results will show where the population is limited by that variable allowing for a better examination of the effect of a single variable on the response parameter. I used quantile regression to analyze the upper quantiles of the habitat variables and brook trout density (# brook trout/100 m^2) to determine the level at which the variable may be limiting. To determine the significance of each of the quantiles, the 90 % confidence intervals were determined for the slope for quantiles 0.1 to 0.9 in 0.02 increments. Graphs were constructed for each metric that had significant upper quantiles and confidence intervals that were not outside the range that could be graphed. I used the cut-off of quantiles $\geq$ 0.80 to designate a variable as a limiting factor. Each of the variables was examined to determine if they were significant at the upper quantiles. The statistical program R 2.8.1 and the quantreg package were used for the quantile regression analysis (R Development Core Team 2008). I then used a two sample t-test to compare habitat variables that were significantly correlated with brook trout density using quantile regression to determine if differences existed between physiographic provinces.

Finally, I used regression tree analysis to evaluate all habitat variables as a single group. Regression tree analysis splits the data into the two most homogenous groups by analyzing the entire set of variables and examines the significance of each of the variables in the model. The size of the tree was determined based the “1-standard error rule”. The regression tree approach gives the mean value for the brook trout density for each of the splits created by the predictor variable. I used the statistical program R 2.8.1 and the rpart package for the regression tree analysis (R Development Core Team 2008).

Chapter 3

RESULTS

Brook trout density was not significantly different between streams located in the Appalachian Plateau and Ridge and Valley Provinces (two sample t-test, p=0.06). As a result, I pooled data from both physiographic provinces for all statistical analyses of brook trout density.

Thalweg Profiles

The thalweg profiles of the study streams showed a range of variation in shapes of the stream channels (Appendix C). Graphs of the profiles helped visualize and compare the differences among streams;(Appendix C) for example, Prouty Run had a much lower gradient, but similar total number of residual pools as Long Run (Figure 4).

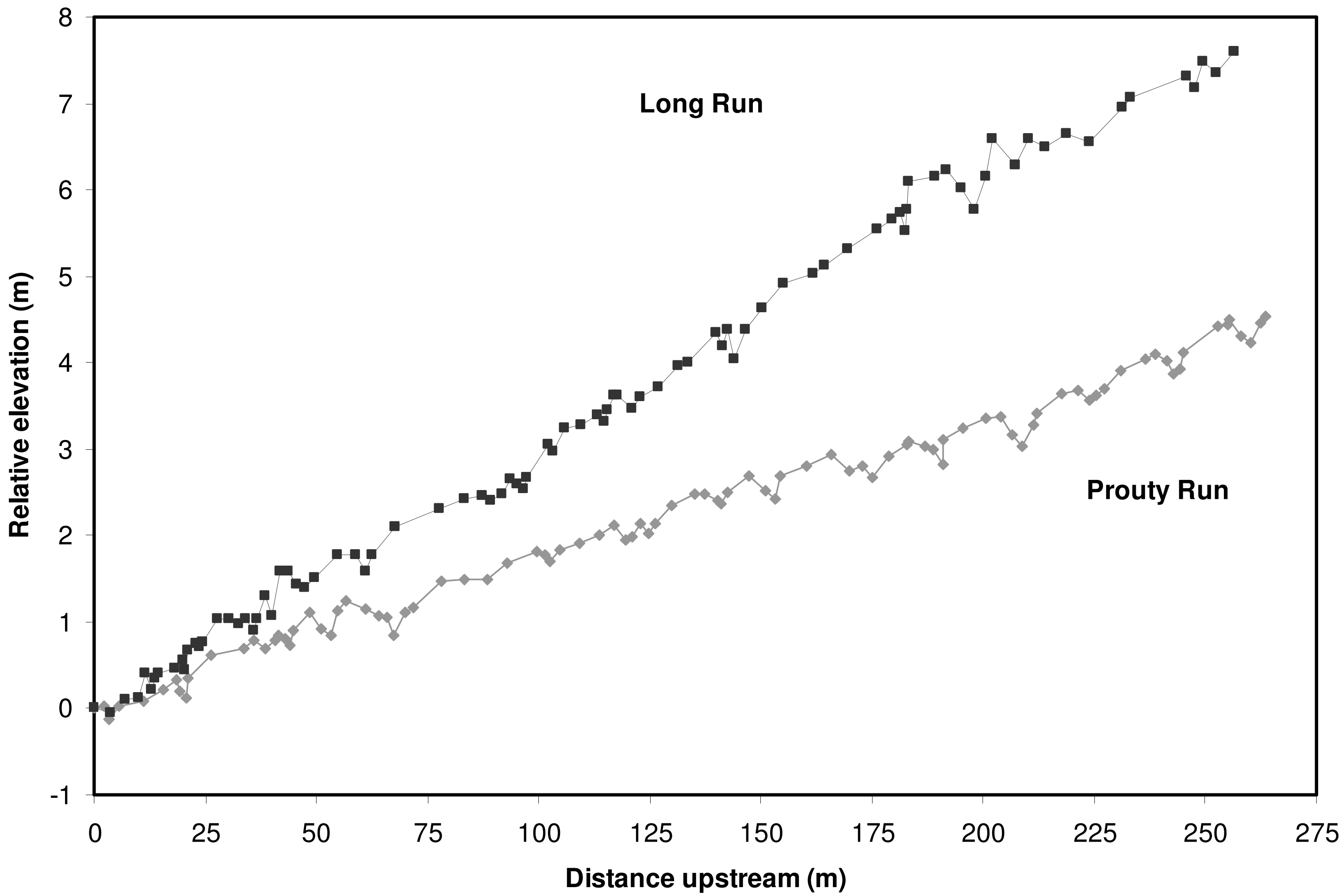


Figure 4: Comparison of the thalweg profile of two streams with different gradients, but similar number of residual pools.

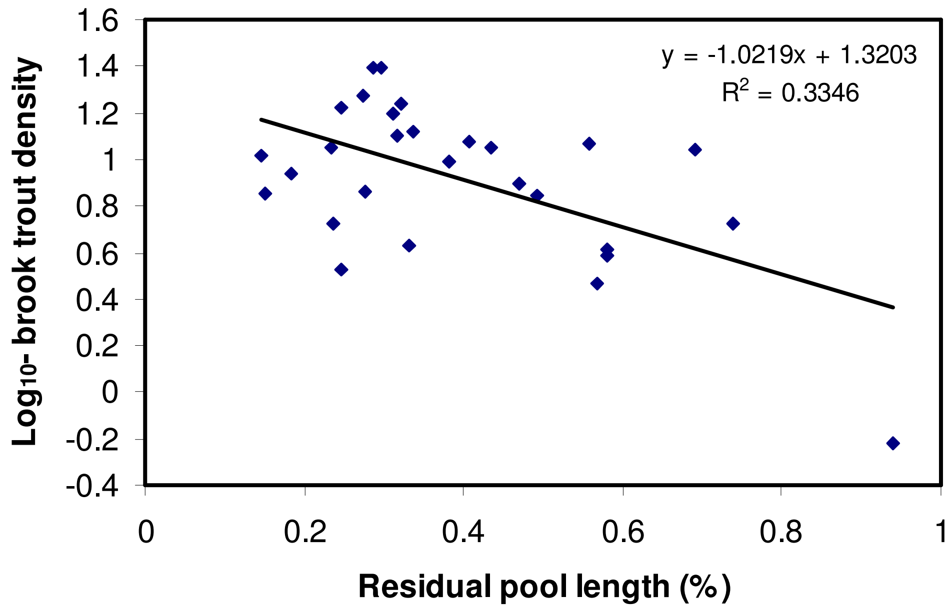
Thalweg Metrics and Brook Trout Density

The thalweg metrics that were calculated from the profile for each stream were highly variable (Table 8). Using simple linear regression, I analyzed the relationship between each thalweg metric and log_{10}- brook trout density (Figure 5). Percent residual pool and mean maximum depth, were both negatively correlated with log_{10}- brook trout density ($p < 0.05$, Figure 5). Percent residual pool explained 33% of the variation in log_{10}- brook trout density and mean maximum depth explained 16% of the variation in log_{10}- brook trout density (Table 9). Mean square error and the variation index were not correlated with log_{10}- brook trout density (Figure 6, Table 9).

Percent residual pool was significantly correlated with brook trout density at the 0.1 to 0.46 and 0.68 to 0.72 quantiles and mean maximum depth was significantly correlated from 0.1 to 0.32 quantiles (Figure 7). The variation index and mean square error were not significantly correlated with brook trout density at any quantile (Figure 7). Although the percent residual pool and mean maximum depth were significantly correlated to log_{10}- brook trout density using simple linear regression, none of the thalweg metrics were significant at the upper quantiles (> 0.8) to evaluate them as limiting factors using quantile regression.

Table 8: Brook trout density/100m^2 estimates and variables derived from the thalweg profile of the 28 streams located in central Pennsylvania (15 in the Appalachian Plateau and in the 13 Ridge and Valley physiographic province streams).Stream location and sample dates in Table 1.

Stream	Brook trout density/ 100m^2	Residual pool length (%)	Mean max depth (m)	Variation index	Mean square error
Appalachian Plateau					
Blair Run	7.3	28	0.26	0.19	0.077
Elk Run	18.7	27	0.27	0.20	0.035
Hayes Run	17.5	32	0.20	0.11	0.036
Indian Run	7.1	15	0.17	0.09	0.068
Little Medix Run	11.3	23	0.19	0.07	0.025
Lower Pine Bottom Run	16.5	25	0.22	0.11	0.056
Prouty Run	11.9	41	0.21	0.09	0.021
Trout Run	13.2	34	0.22	0.10	0.060
Kettle Creek	8.7	18	0.15	0.03	0.030
Lick Island Run	11.3	44	0.26	0.16	0.077
Little Slate Run	10.3	15	0.18	0.08	0.033
Pleasant Stream	4.3	33	0.19	0.10	0.031
Upper Jerry Run	12.7	32	0.22	0.22	0.084
English Run	24.9	29	0.18	0.11	0.044
Long Run	9.8	38	0.20	0.10	0.033
Ridge and Valley					
Love Run	15.8	31	0.21	0.12	0.051
Stony Run	3.3	25	0.20	0.10	0.075
Galbraith Gap Run	11.6	56	0.33	0.21	0.081
Detweiler Run	3.9	58	0.37	0.27	0.107
Pine Creek	11.0	69	0.26	0.11	0.055
Roaring Run	0.6	94	0.33	0.12	0.016
Spectacle Run	24.8	30	0.21	0.03	0.048
Cherry Run	2.9	57	0.27	0.17	0.052
Elk Creek	7.9	47	0.23	0.09	0.017
Little Fishing Creek	7.0	49	0.18	0.08	0.022
Blacklog Creek	5.3	74	0.25	0.15	0.017
Sherman Creek	4.1	58	0.28	0.11	0.088
Big Run	5.3	24	0.17	0.07	0.021



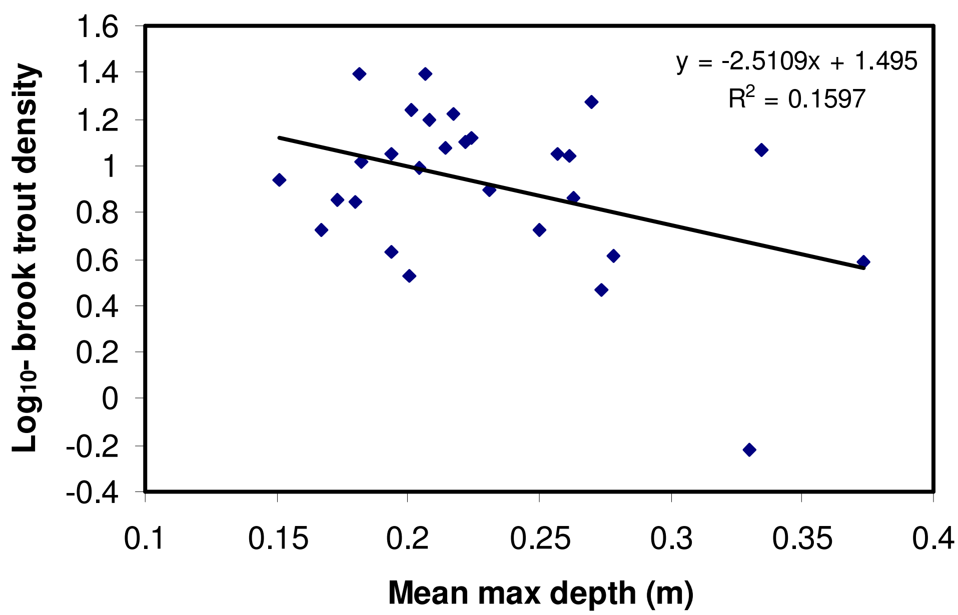
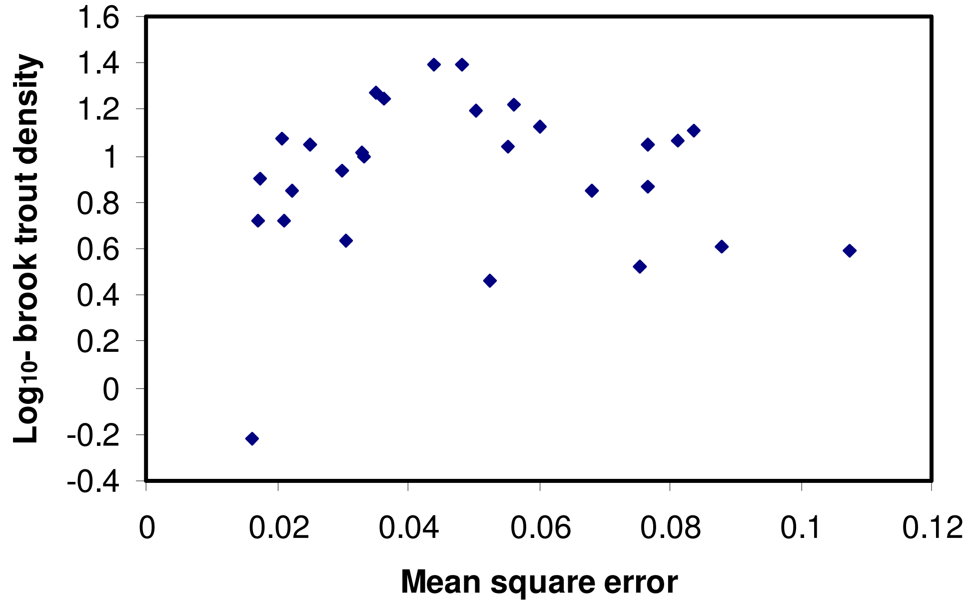


Figure 5: Plots comparing brook trout density and thalweg metrics to determine the relationships. Plots had a significant relationship (p<0.05).



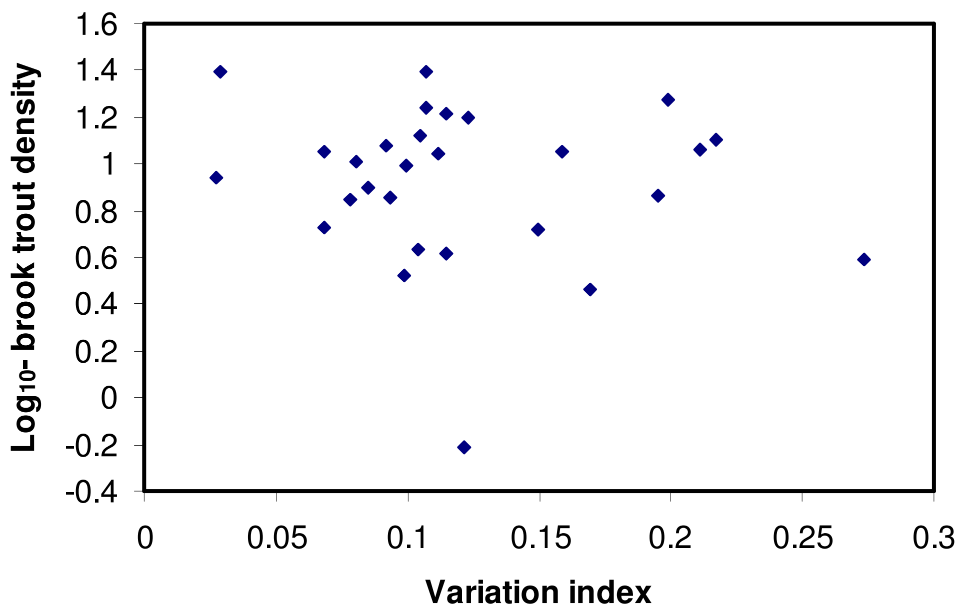


Figure 6: Plots comparing $\log_{10}$- brook trout density and thalweg metrics to determine the relationships. None of the plots have a significant relationship (p<0.05).

Table 9: Simple linear regression values for thalweg metrics and $\log_{10}$- brook trout densities. Shading represents variables with a $p \leq 0.05$.

	Intercept	**Slope**	**r^2**	**p-value**
% residual pool length	1.3	-1.0	0.33	0.00
Mean maximum pool depth	1.5	-2.5	0.16	0.04
Variation index	1.0	-0.8	0.02	0.51
Mean square error	0.9	0.5	0.00	0.85

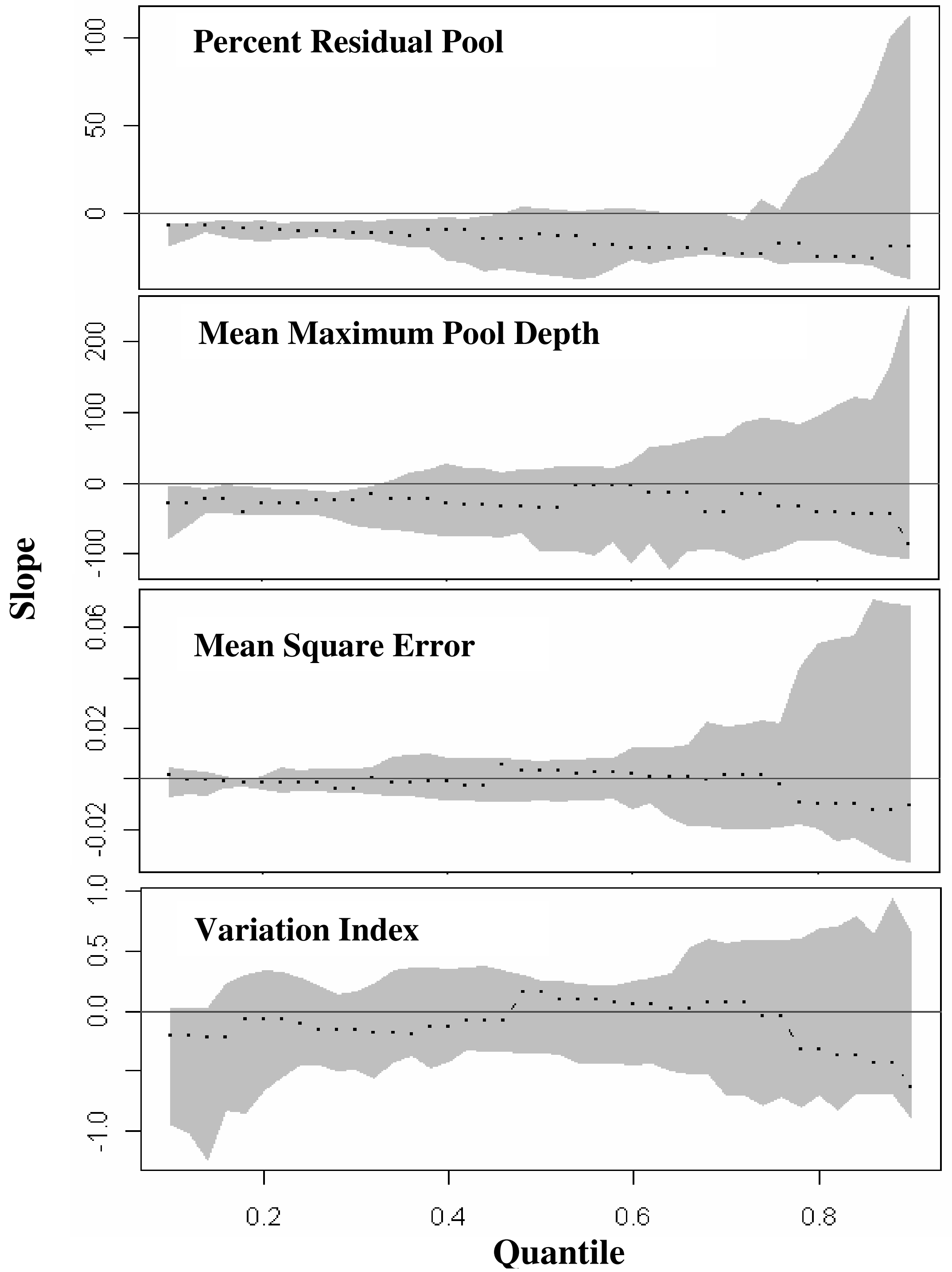


Figure 7: Estimates of slope (β_1) for the thalweg metrics (percent residual pool, mean maximum pool depth, mean square error, and the variation index. The dotted line represents the slope and the shaded area represents the 90% confidence intervals for the slope.

Additional Habitat Variables and Brook Trout Density

Mean wetted width, percent gradient, non-brook trout species, and drainage area were significantly correlated with log_{10}- brook trout density (Figure 8, Table 10, Appendix D). Mean wetted width was negatively correlated with log_{10}- brook trout density ($r^2 = 0.47$, $p \leq 0.01$) indicating that as stream size increased, brook trout density decreased. Gradient was positively correlated with log_{10}- brook trout density ($r^2 = 0.25$, $p \leq 0.01$) and drainage area was negatively related to log_{10}- brook trout density ($r^2 = 0.16$, $p \leq 0.05$) indicating that smaller streams with higher gradients had higher densities of log_{10}- brook trout. The number of non-brook trout species was also negatively correlated to log_{10}- brook trout density ($r^2 = 0.25$, $p \leq 0.01$). As the number of non-brook trout species serves as a surrogate for stream temperature, the negative relationship indicates that brook trout density decreases as temperature (and the number of other fish species in the stream) increases. The remaining habitat and landscape variables were not significantly correlated with log_{10}- brook trout density (Table 10, Appendix D and E).

Mean wetted width had a negative correlation with brook trout density and was significant from approximately the 0.1 to 0.82 quantiles (Figures 9 and 10). Gradient had a positive correlation with brook trout density and was significant at the 0.24-0.34, 0.4-0.86, and 0.9 quantiles (Figures 9 and 11). Pools/km was significant from 0.52 to 0.85 and had a positive correlation with brook trout density at these quantiles (Figures 9 and 11). Non brook trout species had a negative correlation with brook trout density and was significant from approximately 0.18 to 0.82 quantiles (Figures 9 and 10). Percent silt and average bank score were significant at the 90^{th} quantile and may be described as limiting values (Table 11) even though they were not correlated with log_{10}- brook trout density using simple linear regression. Average bank score and percent silt were significant at a small number of the upper quantile, but had a large confidence interval around the slope that could not be graphed. The percent silt variables showed a positive correlation at the upper quantiles while average bank score had a negative correlation (Figure 12).

Mean wetted width was significantly different between the Ridge and Valley and Appalachian Plateau (two sample t-test, p=0.03); streams in the Ridge and Valley province had greater mean wetted widths than those in the Appalachian Plateau province. Gradient was also lower for streams in the Ridge and Valley province than those in the Appalachian Plateau provinces (two sample t-test, p=0.01). Non brook trout species, pools/km, silt, and average bank score were not significantly different between the Ridge and Valley and Appalachian Plateau provinces (two sample t-test, p>0.05).

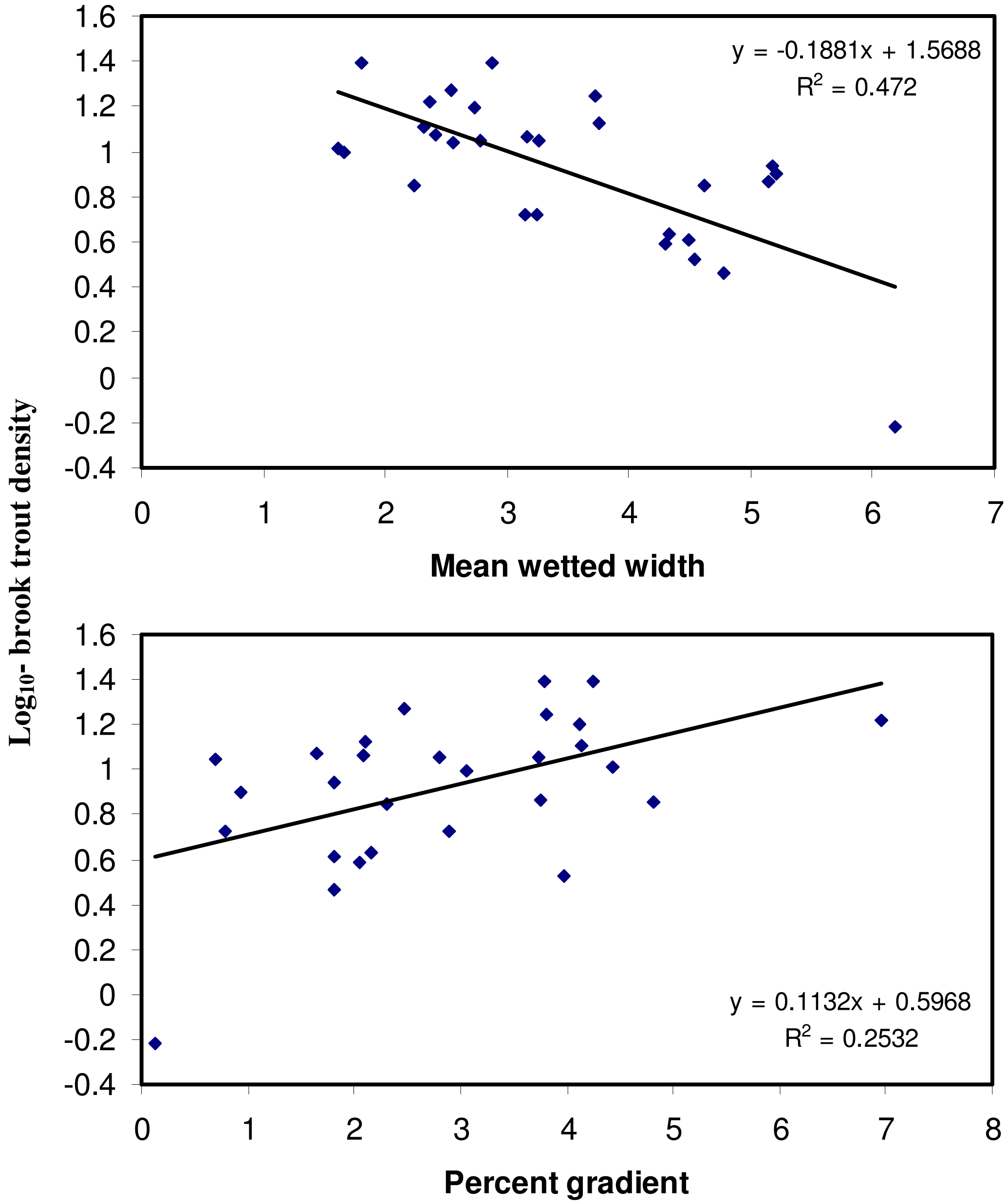


Figure 8: Plots comparing $\log_{10}$- brook trout density and significant (p<0.05) variables including mean wetted width, percent gradient, total non brook trout species and drainage area to determine the relationships.

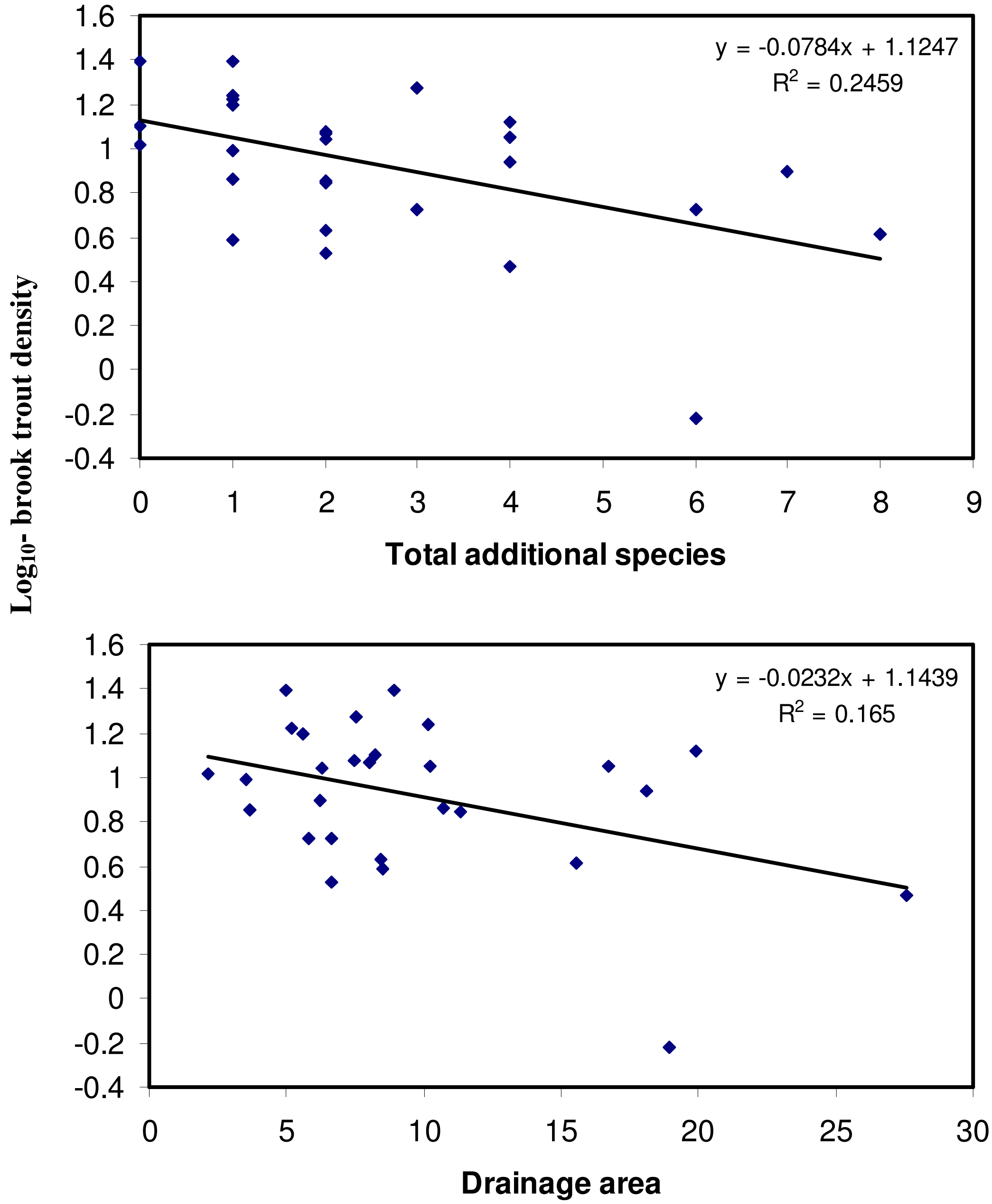


Figure 8 (Continued): Plots comparing $\log_{10}$- brook trout density and significant (p<0.05) variables including mean wetted width, percent gradient, total non brook trout species and drainage area to determine the relationships.

Table 10: Simple linear regression values for stream habitat features and $\log_{10}$- brook trout density. Shading represents variables with a $p \leq 0.05$.

	Intercept	Slope	r^2	p-value
Substrate Composition				
% large fines	0.84	0.05	0.06	0.22
% sand	0.96	-0.01	0.03	0.36
% cobble	0.74	0.00	0.02	0.46
% large boulder	0.93	-0.01	0.01	0.61
% small boulder	0.89	0.01	0.01	0.69
% silt	0.90	0.01	0.01	0.70
% gravel	0.97	0.00	0.00	0.80
% bedrock	0.91	0.01	0.00	0.86
Watershed Level				
Drainage area	1.14	-0.02	0.16	0.03
% water and wetlands	0.94	-0.13	0.02	0.53
% agriculture	0.94	-0.01	0.00	0.75
% developed	0.91	1.90	0.00	0.79
% forested	0.59	0.00	0.00	0.86
% barren	0.91	0.01	0.00	0.88
Water Quality				
Conductivity	1.11	0.00	0.12	0.07
pH	1.60	-0.09	0.02	0.53
Temperature	1.20	-0.02	0.01	0.64
Additional Stream Features				
Mean wetted width	1.57	-0.19	0.47	0.00
% gradient	0.60	0.11	0.25	0.01
Non brook trout species	1.12	-0.08	0.25	0.01
Pools per km	0.53	0.01	0.11	0.08
Woody debris ≥ 5	1.06	0.00	0.06	0.23
% overhead cover	0.97	0.00	0.00	0.73
Large woody debris	0.95	0.00	0.00	0.77
Bank erosion	1.03	-0.03	0.00	0.83

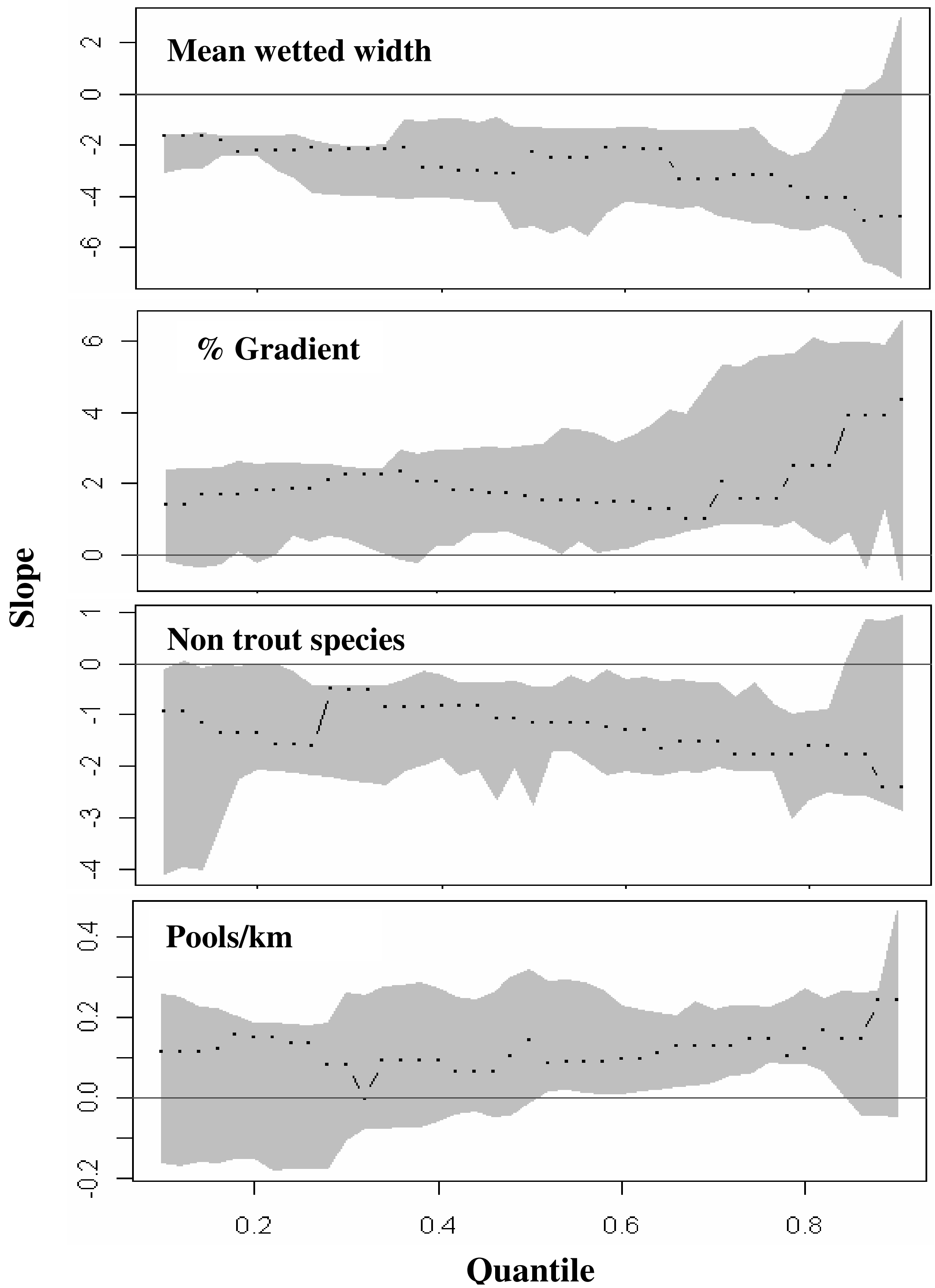
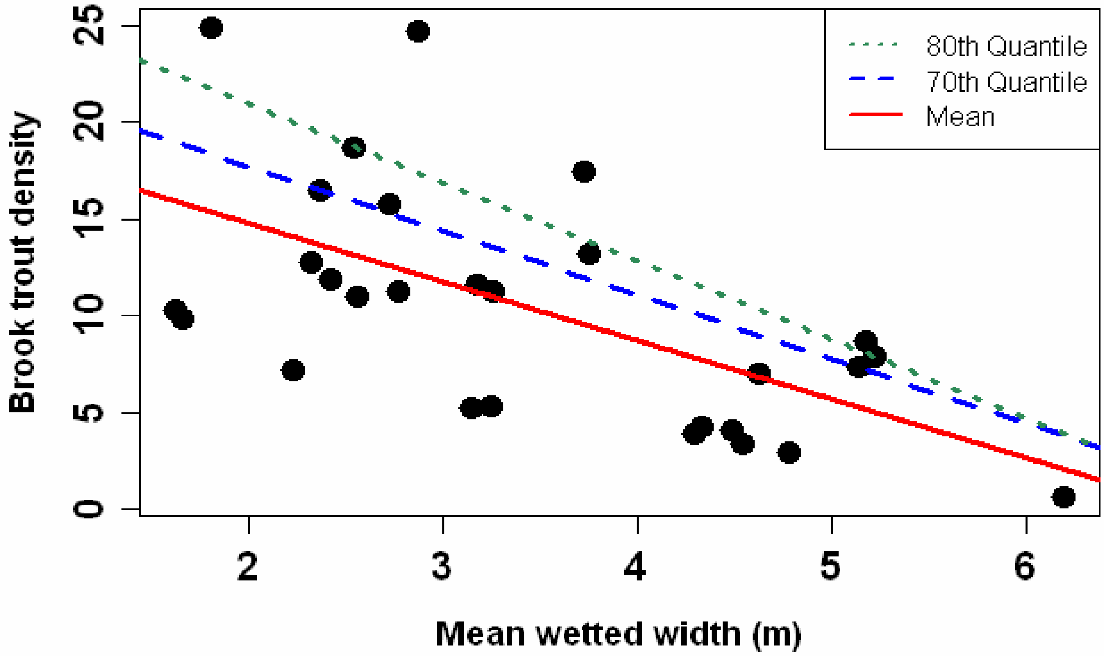


Figure 9: Estimates of slope (β_1) for the mean wetted width, percent gradient, non brook trout species and pools/km. The dotted line represents the slope and the shaded area represents the 90% confidence intervals for the slope.

Table 11: Confidence intervals and slopes for the significant quantiles of percent silt and average bank score variables, which could not be graphed due to values approaching infinity (Inf).

Average bank score				***Silt***			
Quantile	**Slope**	**Lower CI**	**Upper CI**	**Quantile**	**Slope**	**Lower CI**	**Upper CI**
0.76	-8.4	-16.2	-2.7	0.86	0.37	0.18	Inf
0.78	-7.5	-17.1	-2.8	0.88	0.37	0.35	Inf
0.8	-7.5	-19.1	-3.8	0.9	0.35	0.32	Inf
0.82	-7.3	-18.2	-1.9				
0.84	-7.3	-19.0	-5.3				
0.86	-12.9	-18.7	-6.0				
0.88	-12.8	-58.7	-5.3				
0.9	-12.9	Inf	-5.0				



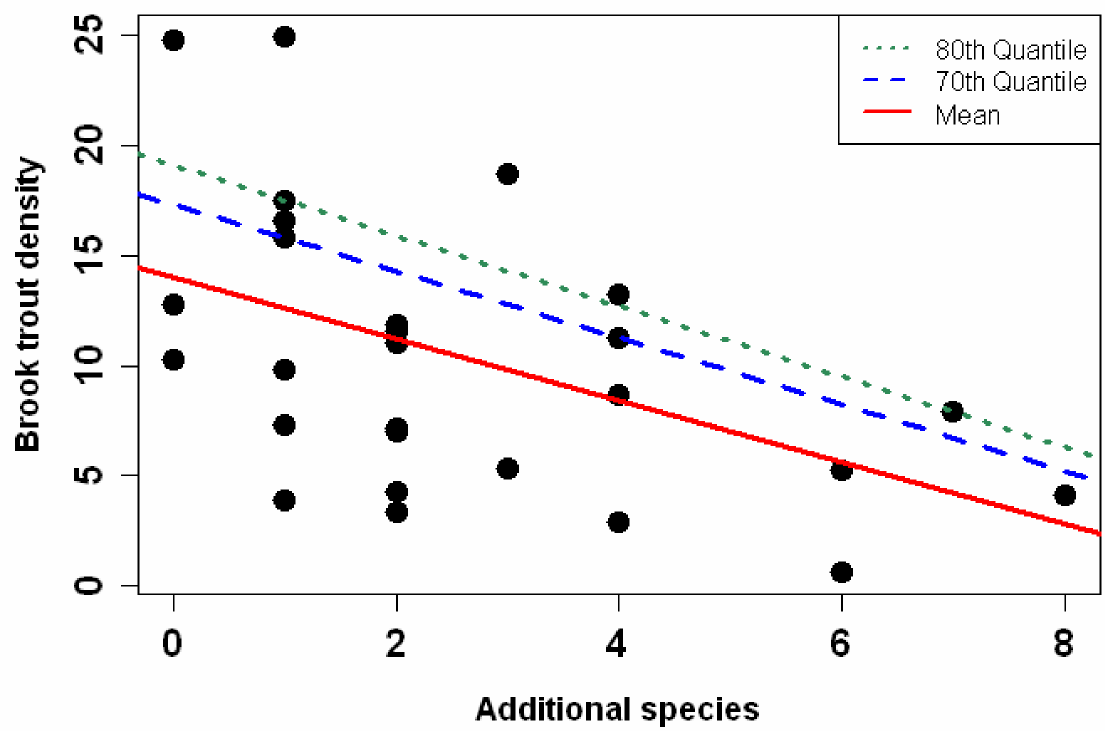


Figure 10: Quantile regression plot of brook trout density and the mean wetted width and the total number of non brook trout species with significant limiting factors at the 70th and 80th quantile

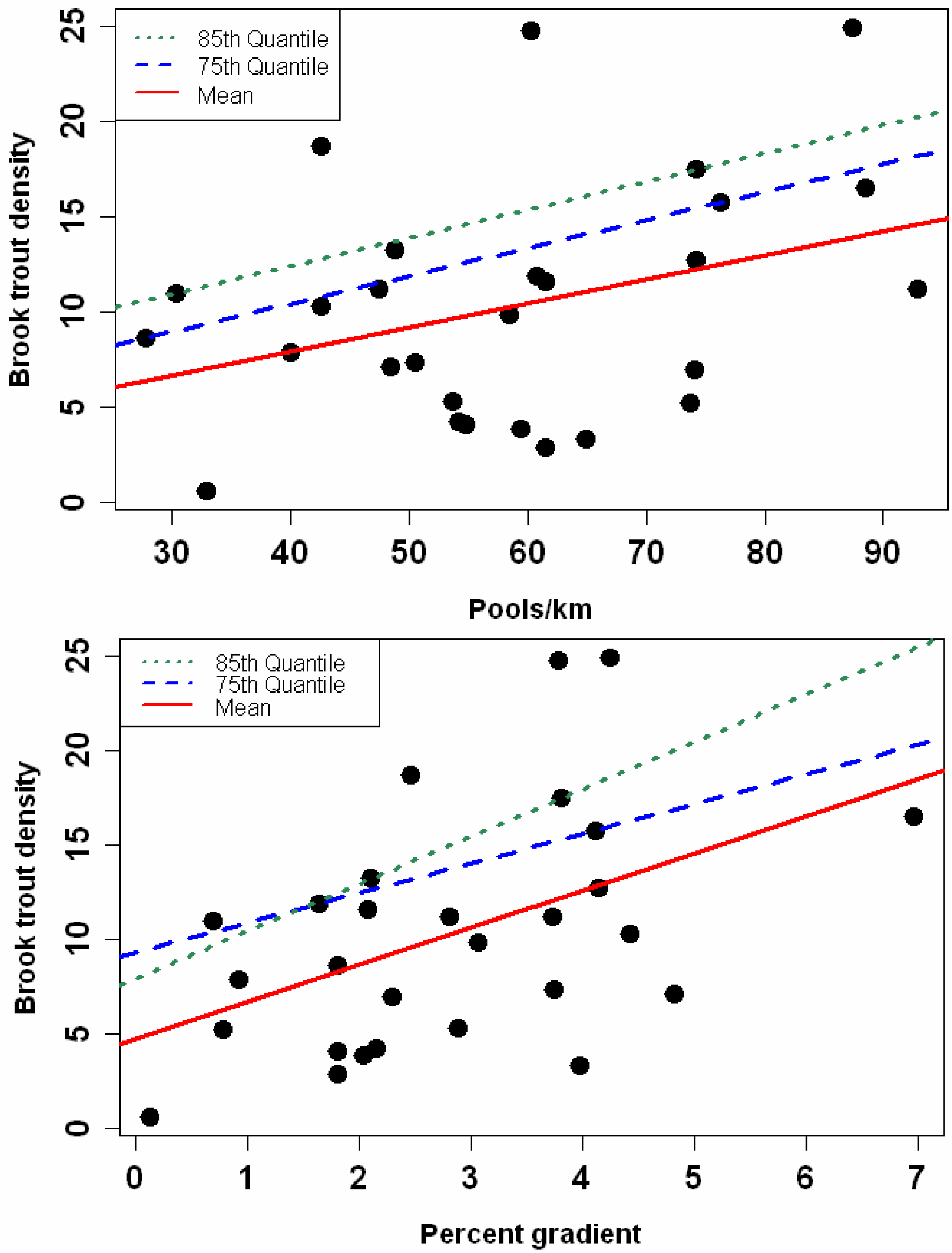


Figure 11: Quantile regression plot of brook trout density and pools/km and percent gradient with significant limiting factors at the 75th and 85th quantile

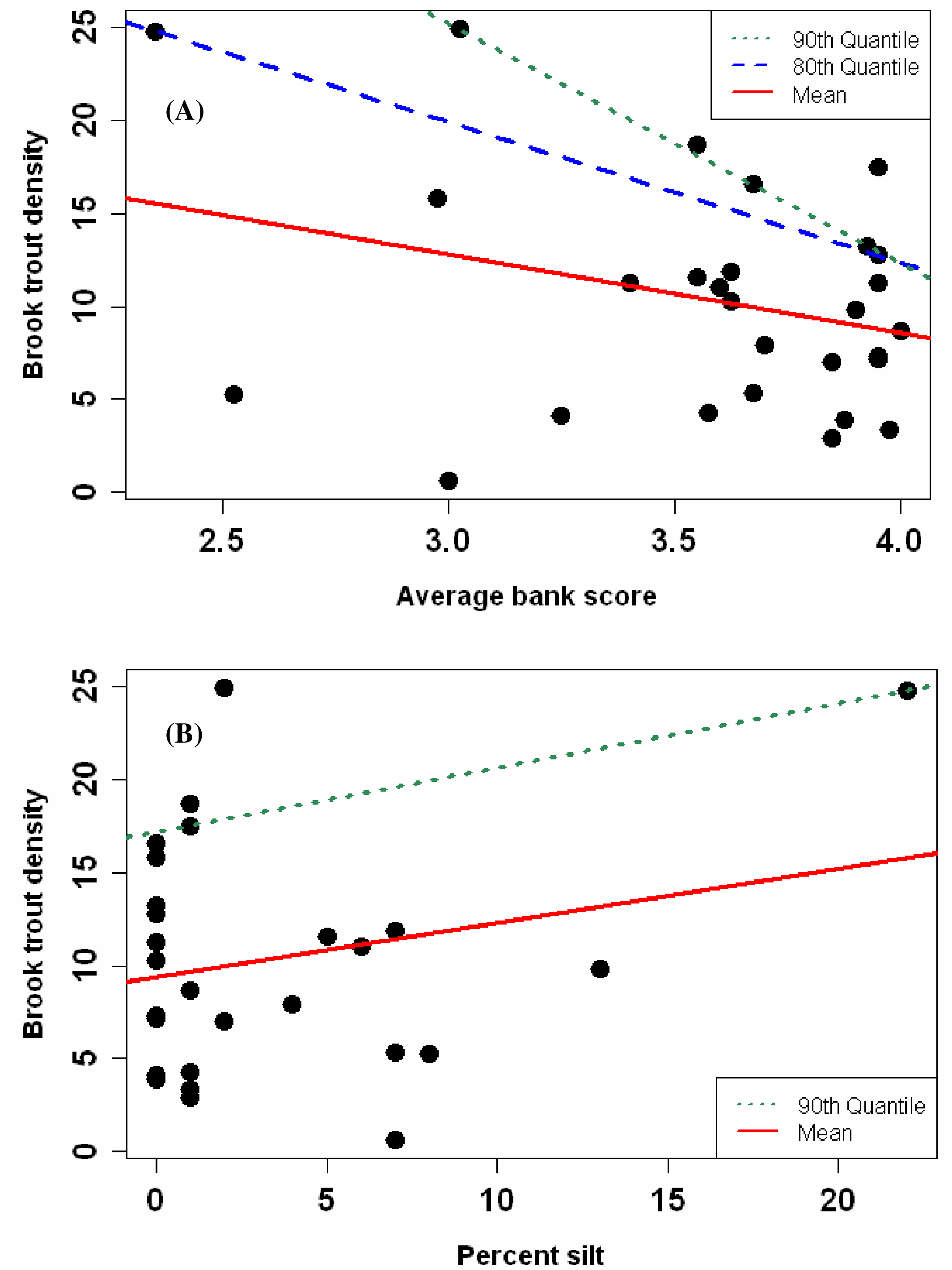


Figure 12: a. Quantile regression plot of brook trout density and the average bank score with significant limiting factors at the 80th and 90th quantile b. Quantile regression plot of brook trout density and the percent silt with significant limiting factors at the 90th quantile

Correlations Among Thalweg Metrics and Stream Habitat Variables

Several of the thalweg metrics and variables that were related to brook trout were correlated with one another. Gradient was negatively correlated with the majority of variables, but positively correlated with the pools per kilometer (Table 12).

All of the significant relationships among the thalweg metrics had a positive relationship. Mean wetted width had a positive relationship with percent residual pool and the number of non brook trout species (Table 12).

Table 12: Correlation coefficients comparing thalweg metrics and variables that were significant with quantile regression. Grey shaded area represents coefficients with a $p \leq 0.05$

	Gradient	Mean wetted width	Percent residual pool	Non brook trout species	Mean maximum depth	Variation index	Mean square error
Mean wetted width	-0.51	-					
Percent residual pool	-0.72	0.42	-				
Non brook trout species	-0.63	0.54	0.51	-			
Mean maximum depth	-0.42	0.32	0.72	0.25	-		
Variation index	-0.05	0.04	0.33	-0.10	0.76	-	
Mean square error	0.30	-0.01	-0.02	-0.22	0.47	0.61	-
Pools/km	0.55	-0.32	-0.10	-0.30	-0.08	0.23	0.24

Regression Tree Analysis

The regression tree analysis split the data based on the mean wetted width of the stream and gives the mean values for streams within each group. It grouped the remaining data based on a wetted width ≥ 4.022 m or < 4.022 m (Figure 13). The regression tree analysis showed that the mean brook trout density all the streams with a wetted width ≥ 4.022 was 5 brook trout / 100m^2. The mean brook trout density is lower for streams with a large wetted width.

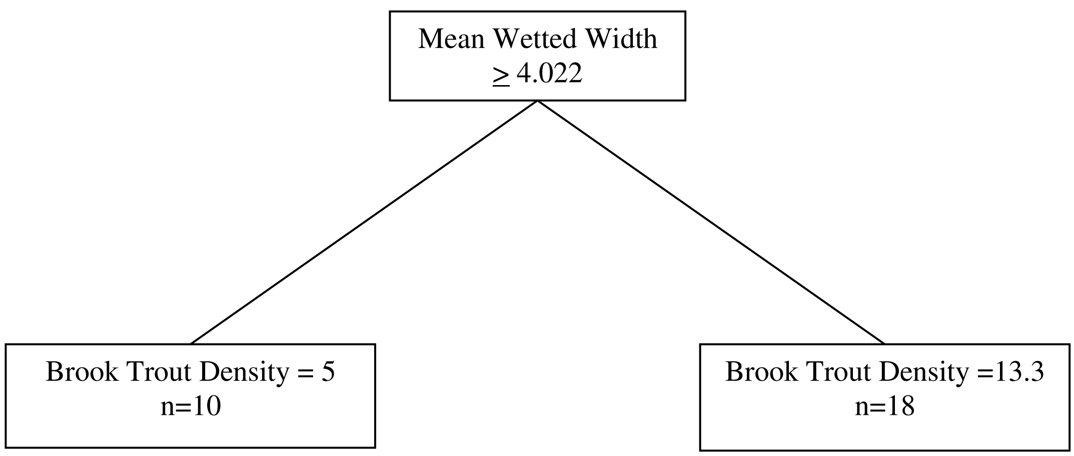


Figure 13: Regression tree analysis for all of the variables in one model. If the mean wetted width is ≥ 4.022 the mean brook trout density is 5.

Chapter 4

DISCUSSION

Brook trout densities were not significantly different between streams located in the Appalachian Plateau and Ridge and Valley physiographic provinces. Kocovsky and Carline (2006) found higher brook trout densities in the Ridge and Valley province, and they attributed the difference to land features that caused the streams to have lower pH in the Appalachian Plateau. The streams I chose for my study were selected based on higher alkalinities to ensure they were not impacted by acid mine drainage and acid deposition. The lack of these impacted streams in my study may account for the difference in my findings.

Mean wetted width and gradient were significantly different between the physiographic provinces. Mean wetted width and gradient were also two of the most significant variables in relation to brook trout density. These results would indicate that there may be a difference between the physiographic provinces. The sample size of 28 streams may not have been large enough to show a significant relationship with brook trout for streams with an alkalinity > 5mg/L.

In biological systems some factors may not be good predictors of a particular response variable, but could still be limiting that response variable. The six measured variables that were significant limiting factors in my study were wetted width, gradient, pools per kilometer, non brook trout species, percent silt, and the average bank score. The wetted widths of the streams in this study have a negative relationship at the upper quantiles with brook trout density meaning that brook trout density will decrease as the stream size increases as measured by wetted width. These results may be the result of increased stream temperature and changes in gradient, which results in wider slower streams. Gradient has a positive relationship with brook trout densities indicating that as gradient decreases brook trout become more limited by this variable. The pool per kilometer variable showed a positive relationship with brook trout density indicating that the number of pools within a stretch of stream may be more important than the size of the pools. This finding is consistent with results from Sweka (2003) that showed a significant positive correlation with discrete habitat units of riffle, run, and pool. My results indicate that brook trout may prefer a stream with numerous smaller pools and less long pools. The non brook trout species variable that provides an indication of the year round stream temperature had a negative relationship with brook trout. This would indicate that as the number of species and likely temperature increase brook trout become more limited. The relationship between percent silt and the average bank score are the opposite of the expected results and may be due to the small number of streams with large amounts of sediment or highly eroded banks. Due to the concentrated range of data for these specific variables conclusions should not be drawn without further examination.

The Mossop and Bradford (2006) thalweg metrics do not appear to be good predictors of adult brook trout densities in the central region of Pennsylvania. Although percent residual pool and the residual pool depths were significantly correlated with $\log_{10}$- brook trout density, they described only a small percentage of the variation in $\log_{10}$- brook trout densities ($r^2 = 0.33$ and $r^2 = 0.16$ respectively). Mossop (2003) found a strong positive relationship between juvenile Chinook salmon and with percent residual pool length ($r^2 = 0.64$) and maximum pool depth ($r^2 = 0.61$) while adult brook trout appear to have a weak negative relationship. The variation index and mean square error were not correlated with brook trout densities.

Several factors may explain why these metrics do not effectively explain variation in brook trout densities among streams. First, the streams that I selected for my study based on historical brook trout biomass had higher gradients than those examined by Mossop and Bradford (2006) (two-sample t-test, $p<0.01$). In their study, juvenile Chinook salmon showed a negative relationship with gradient and appeared to prefer lower gradient streams. The thalweg metrics of length of residual pool and residual pool depth were negatively correlated with brook trout densities, but were positively correlated with juvenile Chinook salmon density in the Mossop and Bradford (2006) study. It appears that the habitat requirements or preferences for juvenile chinook salmon in the Yukon Territory and adult brook trout in central Pennsylvania streams are different. These differences may explain why the thalweg metrics were not strong predictors of adult brook trout density while they were for juvenile Chinook salmon. Within Pennsylvania these metrics may be more suitable for brown trout, which generally inhabit larger lower gradient streams.

There were a large number of variables in my analysis that did not show a relationship with brook trout densities. None of the land use factors showed a significant relationship with brook trout densities. Over 90% of my streams had a percent forested >90% so there may not have been enough variation in these variables to show a relationship. Neither of the LWD variables showed a significant relationship with brook trout densities. Sweka and Hartman (2006) found that additions of LWD did not increase brook trout densities in West Virginia streams. Some studies have shown that salmonid abundance and pool area increased with the addition of LWD (Cederholm et al. 1997 and Neumann and Wildman 2002).

The water quality parameters did not show a significant relationship with the brook trout densities. All of the parameters were taken as a one time snap shot when the stream was sampled and do not account for variation throughout the year. Stream pH was also not significant and may be the result of selecting only high alkalinity streams for this study. The temperature variable was not correlated with density, but the number of non-brook trout species were correlated. Because the number of non-brook trout species may indicate warmer temperatures it may be affecting the brook trout densities. Various land use practices along with the natural warming as the stream gets larger may be affecting brook trout densities as you move downstream.

Management Implications

This study indicates that Pennsylvania brook trout restoration and protection has its highest potential in small high gradient streams. In order to determine the site of brook trout restoration, my quantile regression results may provide some guidance. For example, if the stream has a wetted width of 5 m it will be limited 80% of the time to only 8 or 9 brook trout per 100 m^2. If it has a wetted width of 2.5m, it is much less limited by this variable and would be limited to 18 or 19 brook trout per 100 m^2 80% of the time. If a stream has a gentle gradient of 1% it will be limited to approximately 10 brook trout per 100 m^2 85% of the time. If the gradient is steeper at 5%, the brook trout will be limited to 19 to 20 brook trout per 100m^2. Brook trout density is also limited by pools per kilometer. If this factor is not the primary limiting factor, there may be another factor that is limiting brook trout abundance, and the addition of more pools may not result in more fish. The number of non brook trout species or a year round temperature may also be a limiting factor. If the number of other species is found to be limiting, it may be difficult to increase brook trout density without addressing the increased water temperature. When deciding on a habitat manipulation site, the number of fish should be compared to these limiting factors. If the stream is very shallow with few pools due to land use practices, the wetted width may be altered by habitat structures. If the stream is much larger with a gentle gradient and the width cannot be altered, the density of brook trout should be compared to the limiting factors. If the brook trout are limited by an aspect of the stream that cannot be altered, another site should be considered for restoration. The addition of numerous small pools will also be more beneficial than a small number of large pools as indicated by the pools per kilometer variable. The selection of a site and method of restoration should be based on numerous factors to get the best improvement in brook trout habitats and densities.

Bibliography

Argent, D.G. and P.A. Flebbe. 1998. Fine sediment effects on brook trout eggs in laboratory streams. Fisheries Research 39:253-262.

Bain, M.B. 1999. Substrate. Pages 95-103 in M.B. Bain and N.J. Stevenson, editors. Aquatic habitat assessment: common methods. American Fisheries Society, Bethesda, Maryland.

Bash, J., C. Berman, and S. Bolton. 2001. Effects of turbidity and suspended solids on salmonids. Center for Streamside Studies, University of Washington.

Berg, N., A. Carlson, and D. Azuma. 1998. Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California. Canadian Journal of Fisheries and Aquatic Sciences 55:1807-1820.

Bilby, R.E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology 62:1234-1243.

Bovee, K.D., B.L. Lamb, J.M. Bartholow, C.B. Stalnaker, J. Taylor, and J. Henriksen. 1998. Stream habitat analysis using the Instream Flow Incremental Methodology. Information and Technology Report USGS/BRD/ITR-1998-0004. Fort Collins, CO: U.S. Geological Survey-BRD. 130 p.

Cade, B.S. and B.R. Noon. 2003. A gentle introduction to quantile regression for ecologists. Frontiers in Ecology 1:412-420.

Cederholm, C.J., R.E. Bilby, P.A. Bisson, T.W. Bumsteam, B.R. Fransen, W.J. Scarlett, J.M. Ward. 1997. Response of juvenile coho salmon and steelhead to placement of large woody debris in a coastal Washington stream. North American Journal of Fisheries Management 17:947-963.

Cooper, E. L. 1983. Fishes of Pennsylvania. Pennsylvania State University Press, University Park, PA.

Flebbe, P.A. and C.A. Dolloff. 1995. Trout use of woody debris and habitat in Appalachian Wilderness streams of North Carolina. North American Journal of Fisheries Management 15:579-590.

Gurnell, A.M., K.J. Gregory and G.E. Petts. 1995. The role of coarse woody debris in forest aquatic habitats: implications for management. Aquatic Conservation: Marine and Freshwater Ecosystems 5:143-166.

Hakala, J.P. and K.J. Hartman. 2004. Drought effect on stream morphology and brook trout (Salvelinus fontinalis) populations in forested headwater streams. Hydrobiologia 515:203-213.

Harding, J.S., E.F. Benfield, P.V. Bolstad, G.S. Helfman, and E.B.D Jones III. 1998. Stream biodiversity: The ghost of land use past. Production of the National Academy of Sciences USA 95:14843-14847.

Hudy, H., T.M. Thieling, N.G. Gillespie, and E.P. Smith. 2005. Distribution, status and perturbations to the brook trout within the eastern United States. Final Report: Eastern Brook trout Joint Venture.

Kaller, M.D. and K.J. Hartman. 2004. Evidence of a threshold level of fine sediment accumulation for altering benthic macroinvertebrate communities. Hydrobiologia 518:95-104.

Kocovsky, P.M. and R.F. Carline. 2006. Influence of landscape-scale factors in limiting brook trout populations in Pennsylvania streams. Transactions of the American Fisheries Society 135:76-88.

Lenat, D.R. and J.K. Crawford. 1994. Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams. Hydrobiologia 294:185-199.

Lisle, T.E. and S. Hilton. 1992. The volume of fine sediment in pools: An index of sediment supply in gravel-bed streams. Water Resources Bulletin 28:371-383.

Logan, M.N. 2003. Brook trout (*Salvelinus fontinalis*) movement and habitat use in a headwater stream of the Central Appalachian Mountains of West Virginia. Master's Thesis. West Virginia University, Morgantown, WV.

Madej, M.A. 1999. Temporal and spatial variability in thalweg profiles of a gravel-bed river. Earth Surface Processes and Landforms. 24:1153-1169.

Mossop, B. 2003. Monitoring salmon habitat in small streams using streambed profiling and the importance of large woody debris for juvenile chinook salmon habitat in small Yukon streams. Master's Thesis. Simon Fraser University, Burnaby, BC.

Mossop, B. and M.J. Bradford. 2006. Using thalweg profiling to assess and monitor juvenile salmon (Oncorhynchus spp.) habitat in small streams. Canadian Journal of Fisheries and Aquatic Sciences 63(7):1515-1525.

Neumann, R.M. and T.L Wildman. 2002. Relationships between trout habitat use and woody debris in two southern New England streams. Ecology of Freshwater Fish 11:240-250.

Pennsylvania Fish and Boat Commission (PFBC). 1997. Management of trout fisheries in Pennsylvania waters. Pennsylvania Fish and Boat Commission, Harrisburg, PA.

Platts, W.S., W.F. Megahan, and G.W. Minshall. 1983. Methods for evaluating stream, riparian, and biotic conditions. General Technical Report INT-138, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Raleigh, R. F. 1982. Habitat suitability index models: brook trout. U.S. Department of the Interior, Fish and Wildlife Service, FWS/OBS-82/10.24.

Smith, T.A. and C.E. Kraft. 2005. Stream fish assemblages in relation to landscape position and local habitat variables. Transactions of the American Fisheries Society 134:430-440.

Sweka, J.A. 2003. Aquatic-terrestrial linkages in Appalachian streams: influence of riparian inputs on stream habitat, brook trout populations, and trophic dynamics

Sweka, J.A. and K.J. Hartman. 2001. Effects of turbidity on prey consumption and growth in brook trout and implications for bioenergetics modeling. Canadian Journal of Fisheries and Aquatic Sciences 58:386-393.

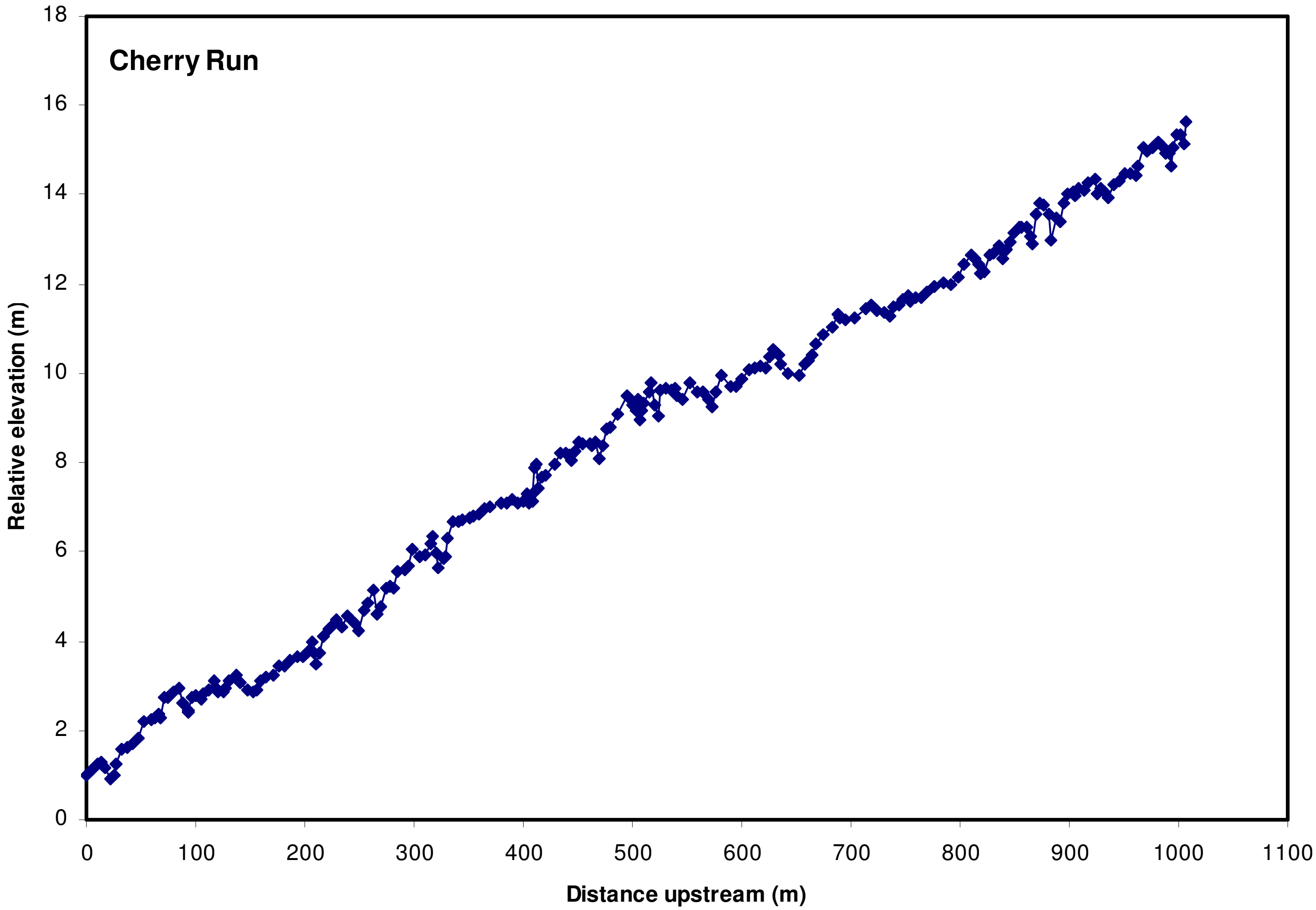
Sweka, J.A. and K.J. Hartman. 2006. Effects of large woody debris addition on stream habitat and brook trout populations in Appalachian streams. Hydrobiologia 559:363-378.

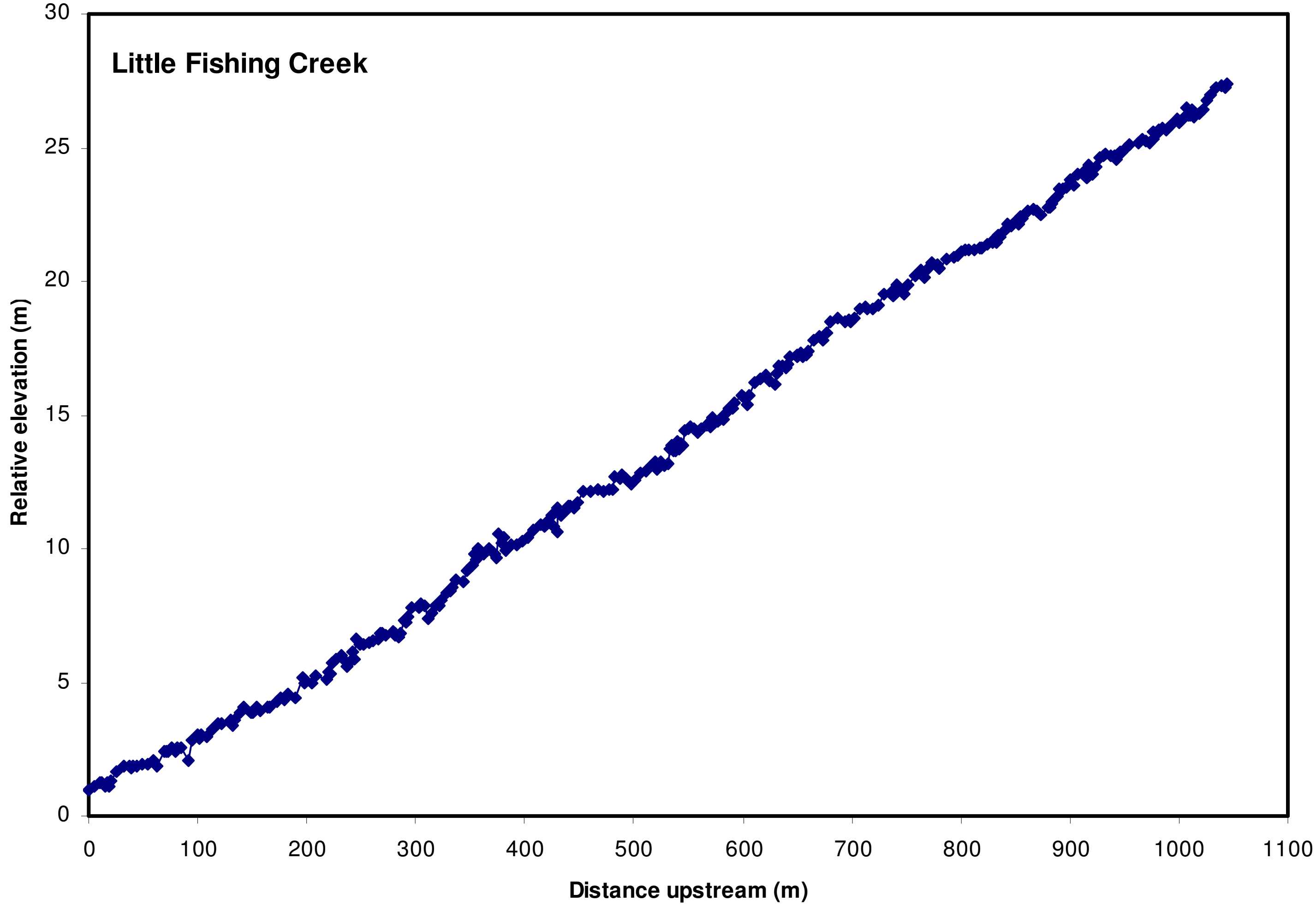
Taniguchi, Y., F.J. Rahel, D.C. Novinger, and K.G. Gerow. 1998. Temperature mediation of competitive interactions amoung three fish species that replace each other along longitudinal stream gradient. Canadian Journal of Fisheries and Aquatic Sciences 55:1894-1901.

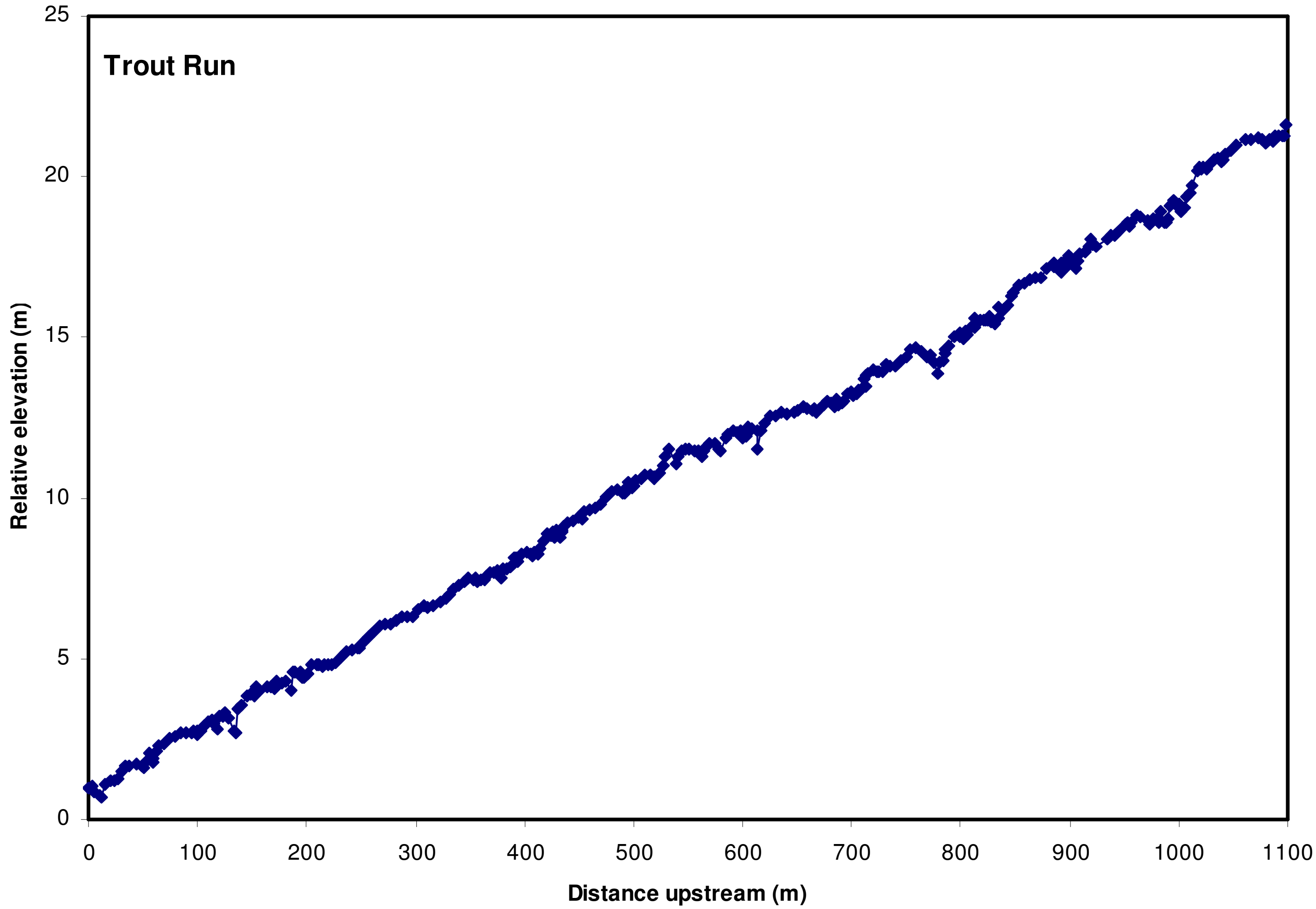
White, G. C., D. R. Anderson, K. P. Burnham, and D. L. Otis. 1982. Capture-recapture and removal methods for sampling closed populations. Los Alamos National Laboratory, LA-8787-NERP, Los Alamos, New Mexico.

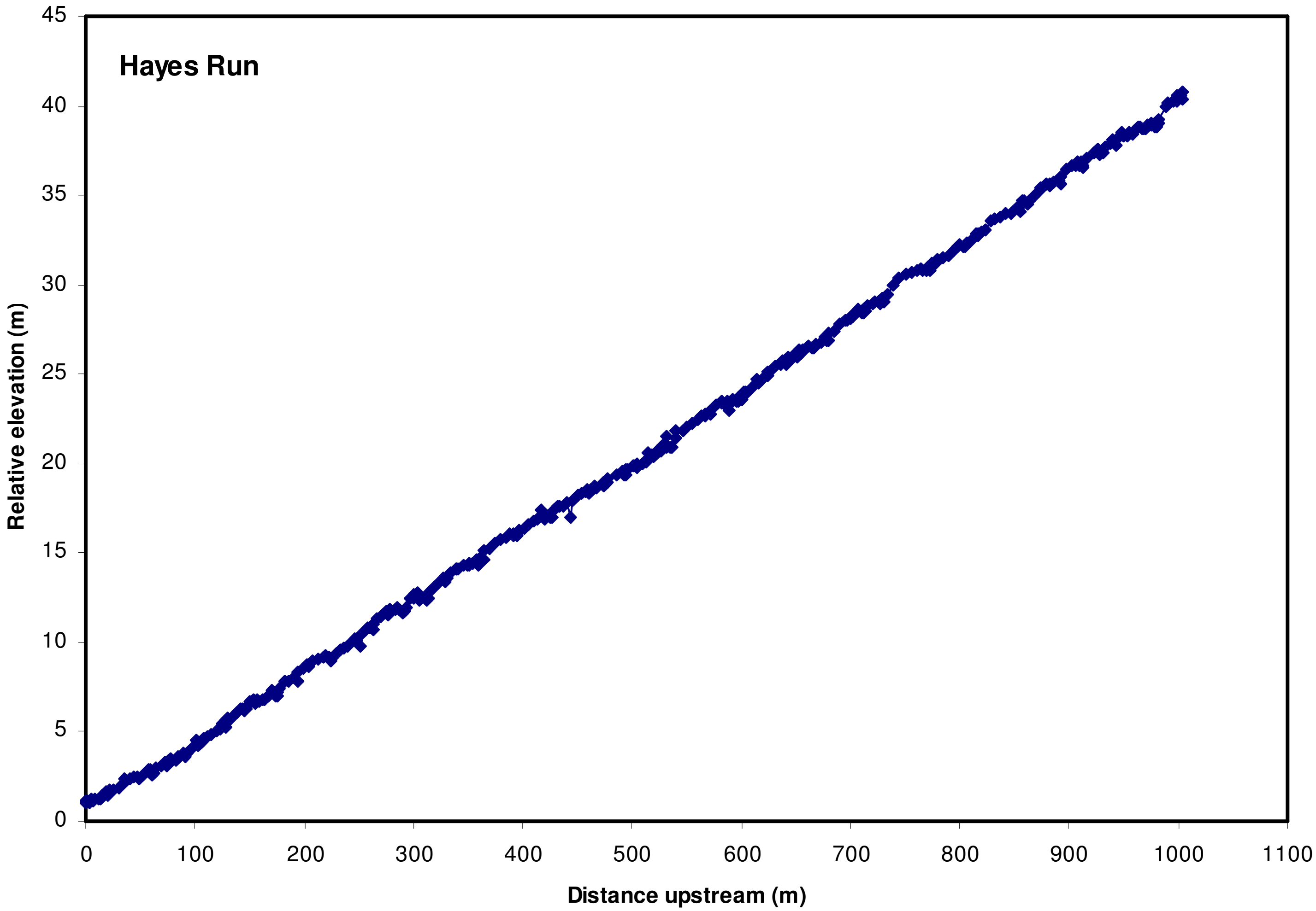
Appendix A

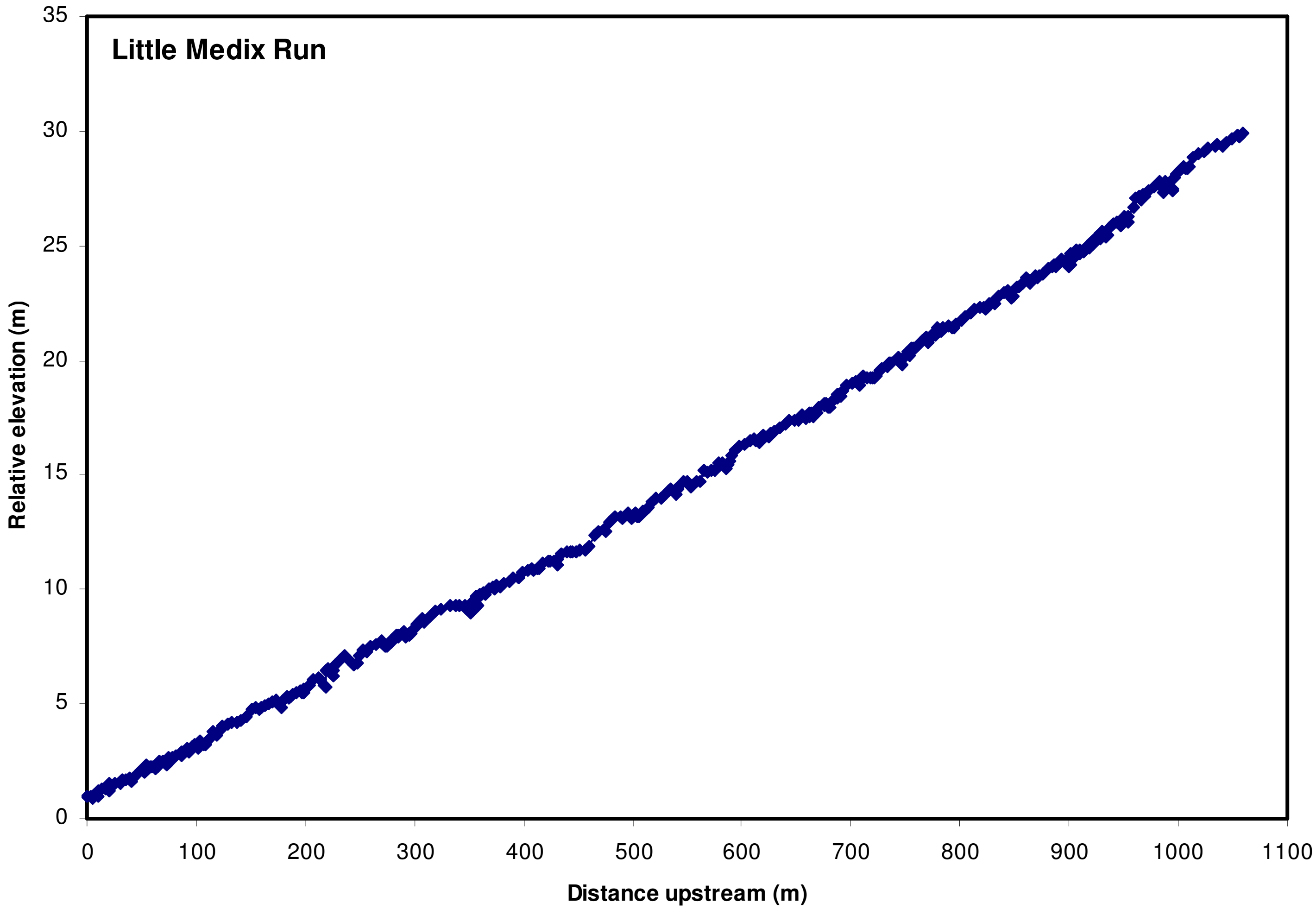
Thalweg profiles of five 1 km stream reaches sampled to determine appropriate reach length for the thalweg metrics.


Cherry Run
Relative elevation (m)
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
600
700
800
900
1000
1100
Distance upstream (m)


Little Fishing Creek
Relative elevation (m)
0
5
10
15
20
25
30
Distance upstream (m)
0
100
200
300
400
500
600
700
800
900
1000
1100

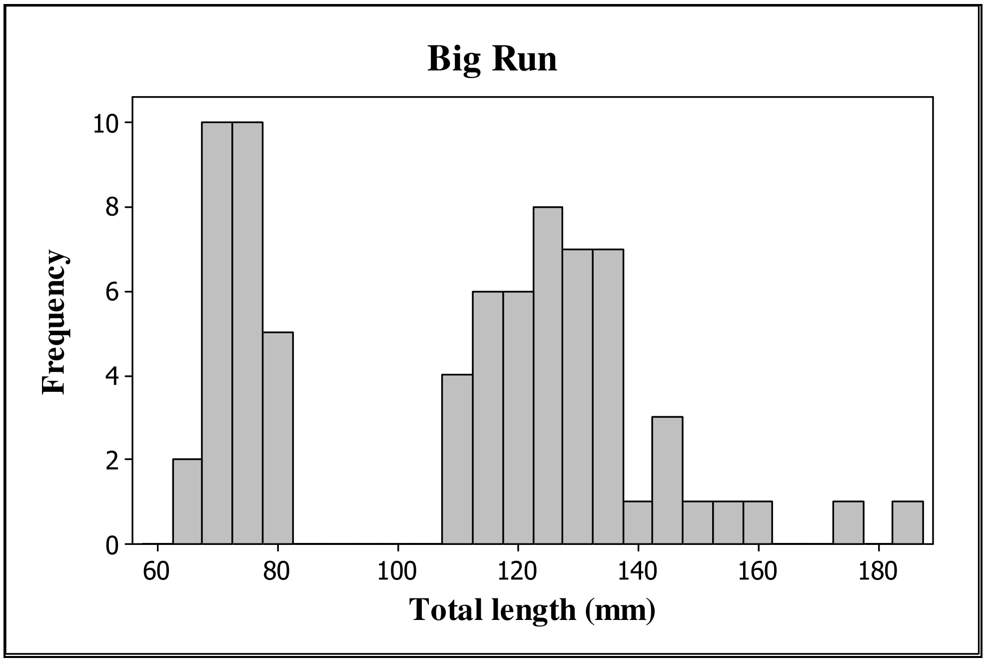

Trout Run
Relative elevation (m)
0
5
10
15
20
25
Distance upstream (m)
0
100
200
300
400
500
600
700
800
900
1000
1100

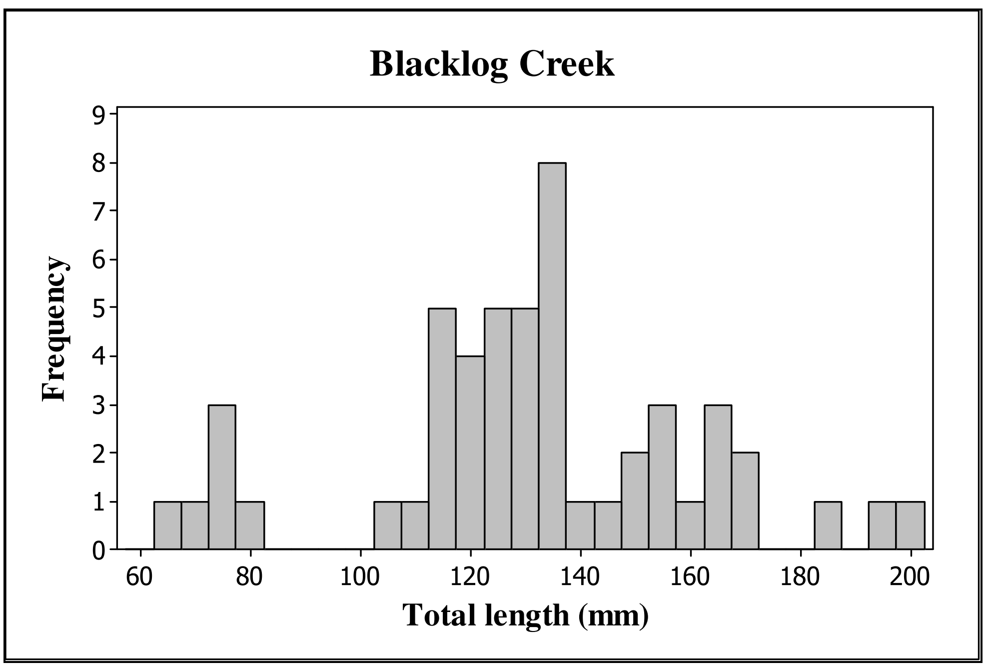

Hayes Run
Relative elevation (m)
0
5
10
15
20
25
30
35
40
45
0
100
200
300
400
500
600
700
800
900
1000
1100
Distance upstream (m)

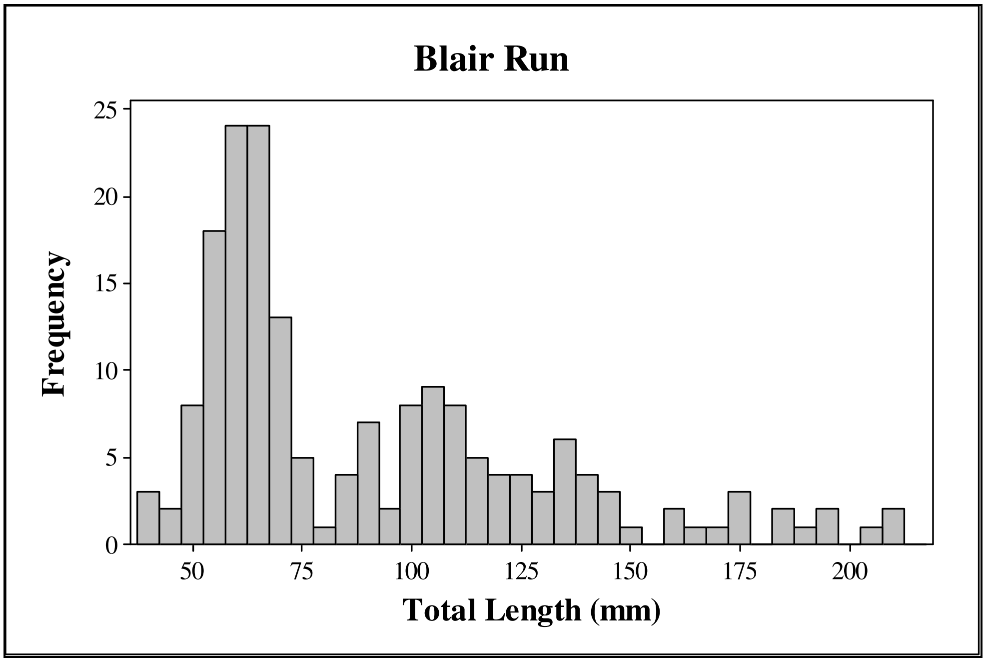

Little Medix Run
Relative elevation (m)
Distance upstream (m)
0
5
10
15
20
25
30
35
0
100
200
300
400
500
600
700
800
900
1000
1100

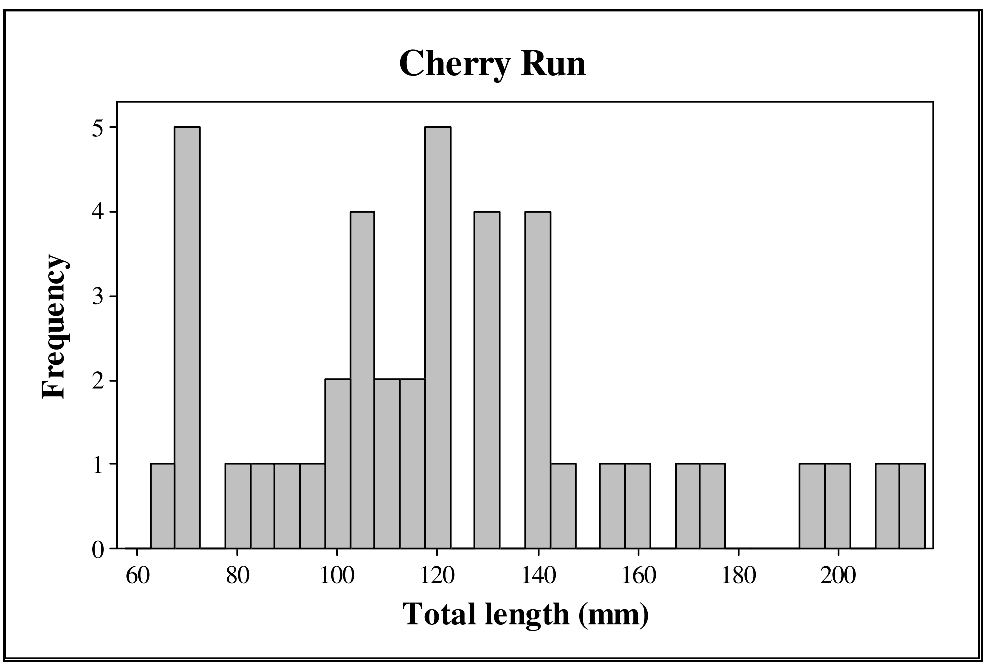
Appendix B

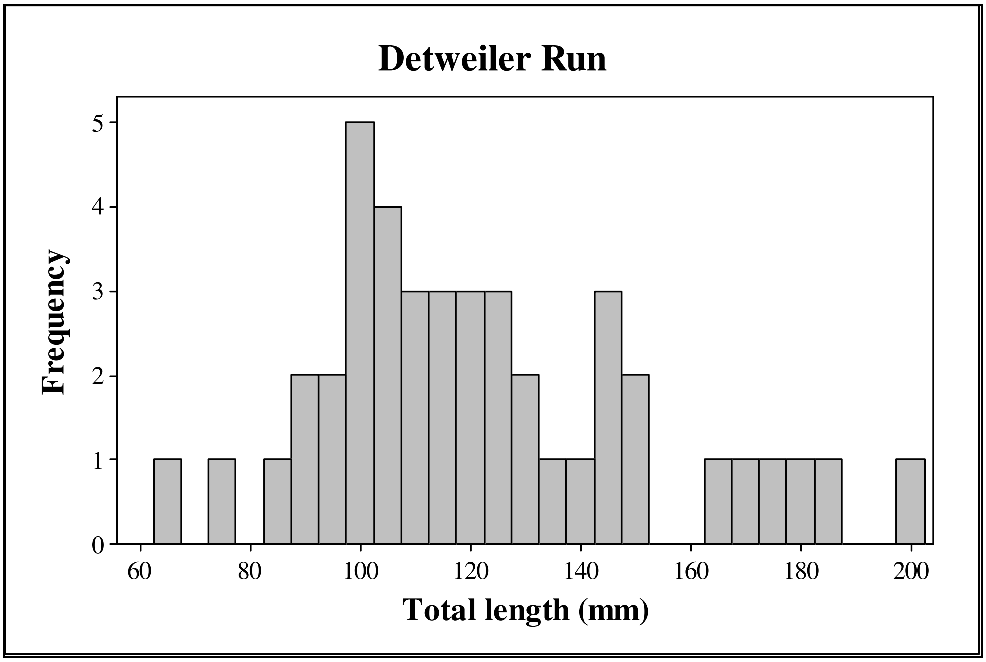
Length frequency histograms for brook trout captured using multiple pass depletion from summer 2008 to fall 2008

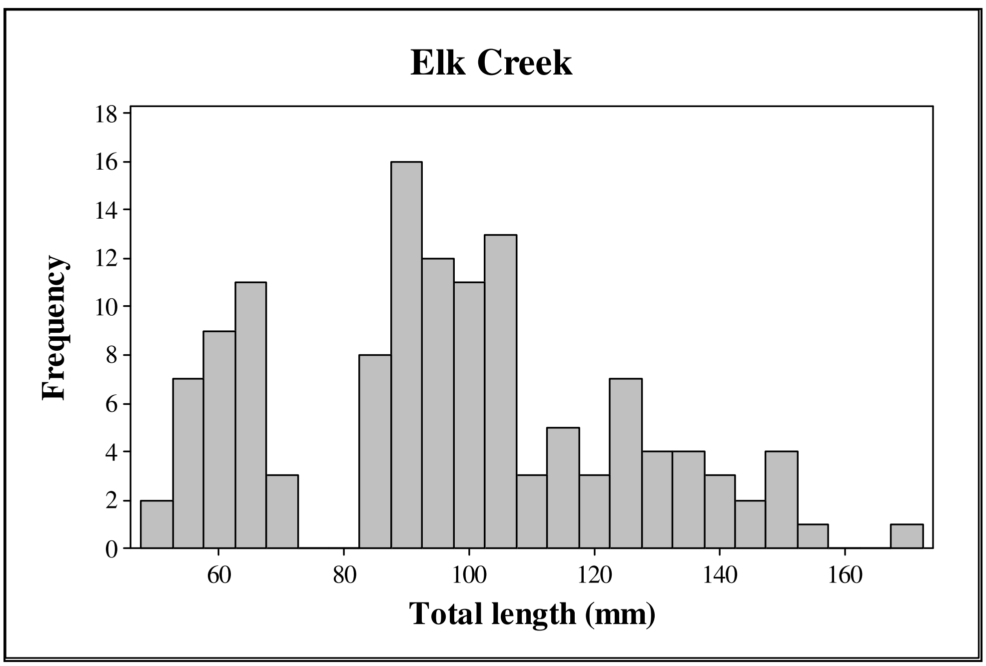

Big Run
Frequency
10
8
6
4
2
0
60
80
100
120
140
160
180
Total length (mm)

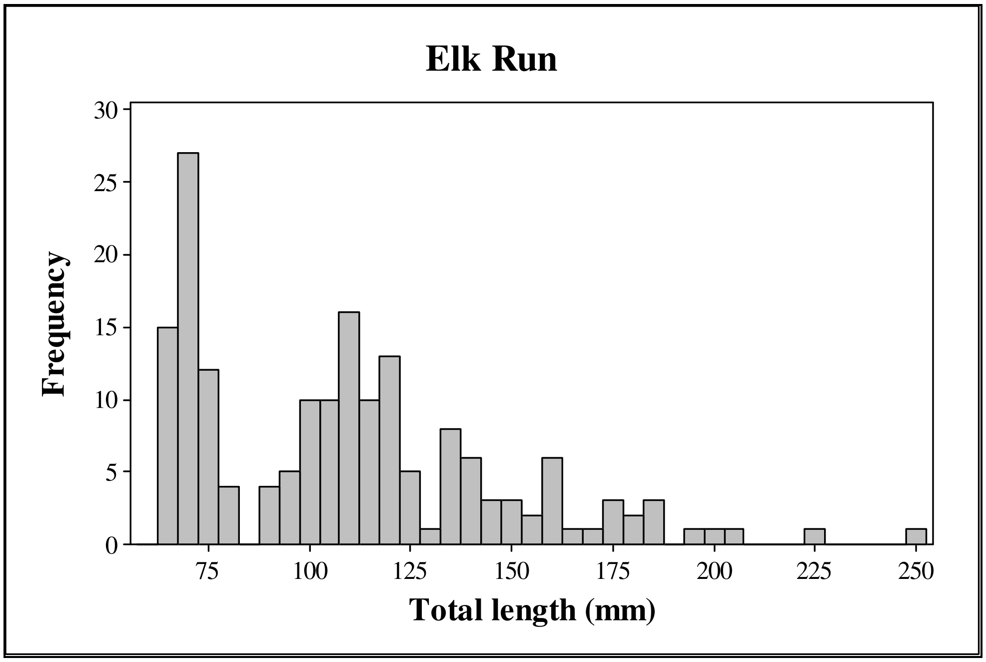

Blacklog Creek
Frequency
9
8
7
6
5
4
3
2
1
0
60
80
100
120
140
160
180
200
Total length (mm)

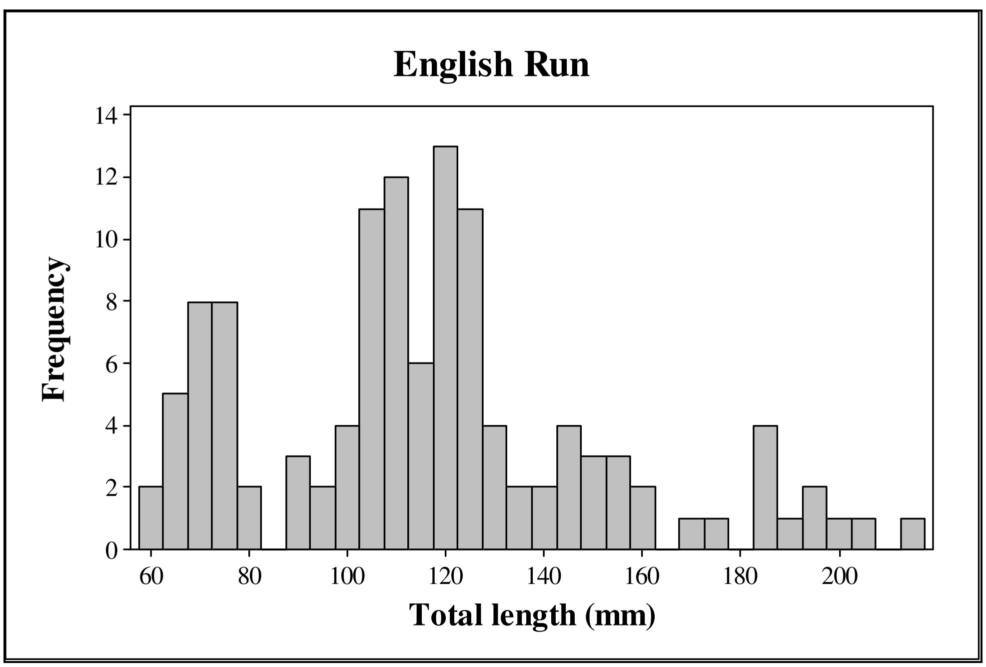

Blair Run
Frequency
0
5
10
15
20
25
50
75
100
125
150
175
200
Total Length (mm)

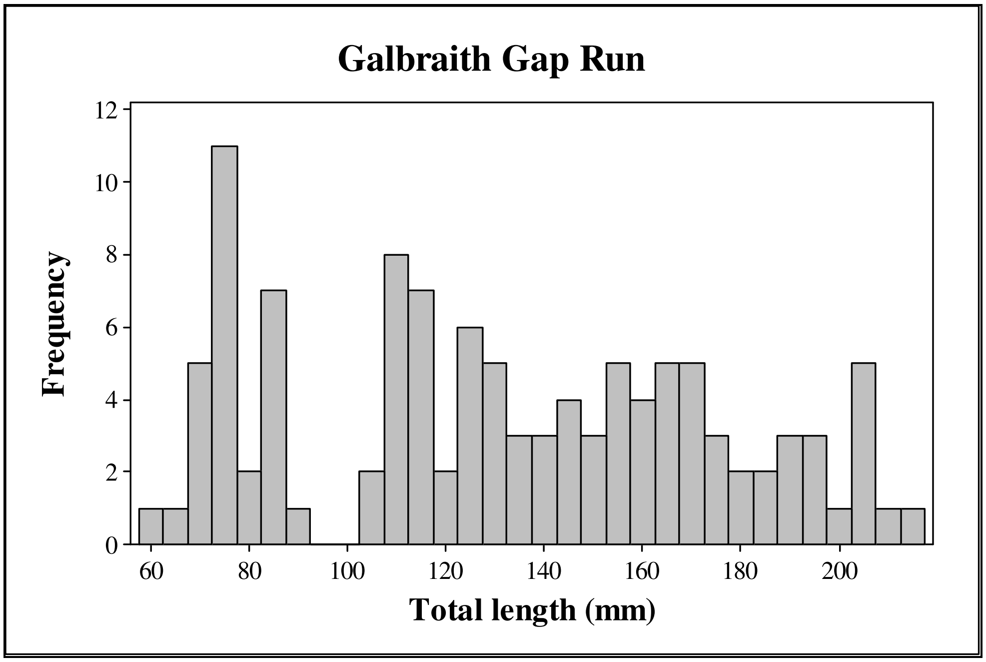

Cherry Run
Frequency
0
1
2
3
4
5
60
80
100
120
140
160
180
200
Total length (mm)

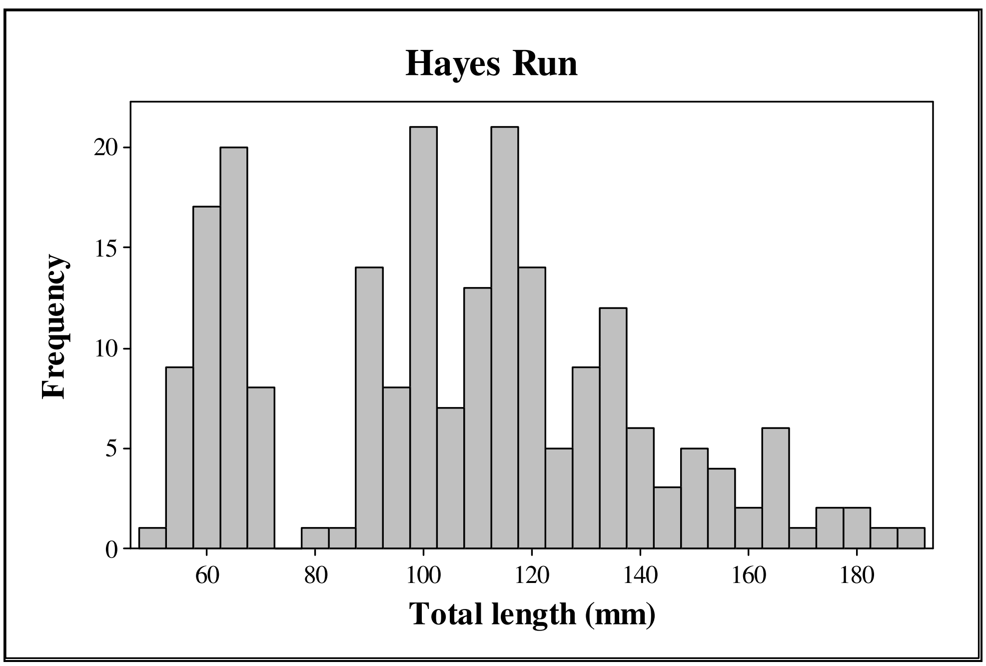

Detweiler Run
Frequency
0
1
2
3
4
5
60
80
100
120
140
160
180
200
Total length (mm)

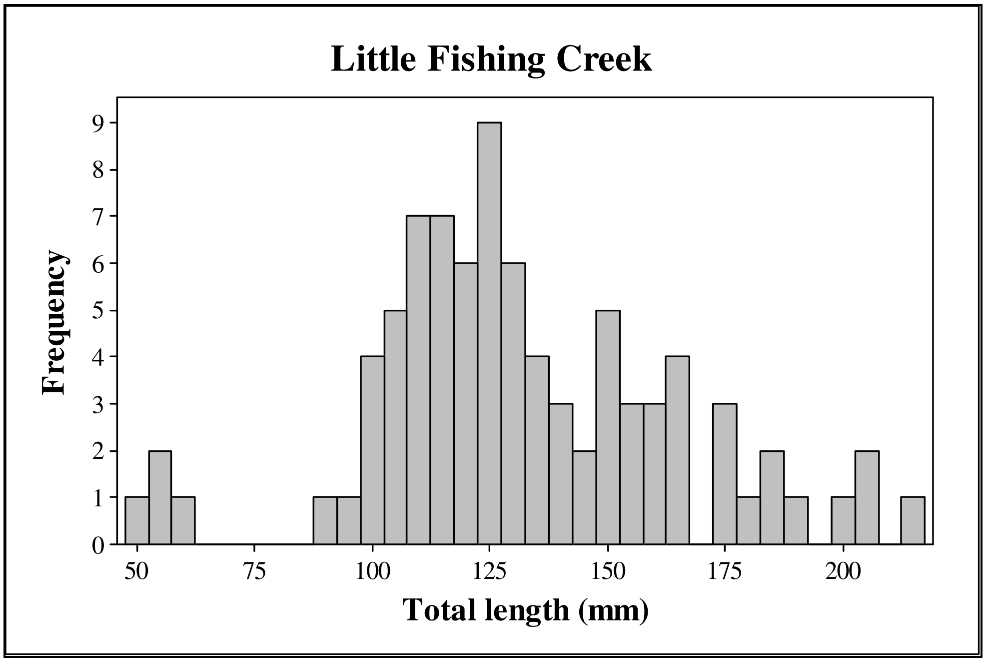

Elk Creek
Frequency
0
2
4
6
8
10
12
14
16
18
60
80
100
120
140
160
Total length (mm)

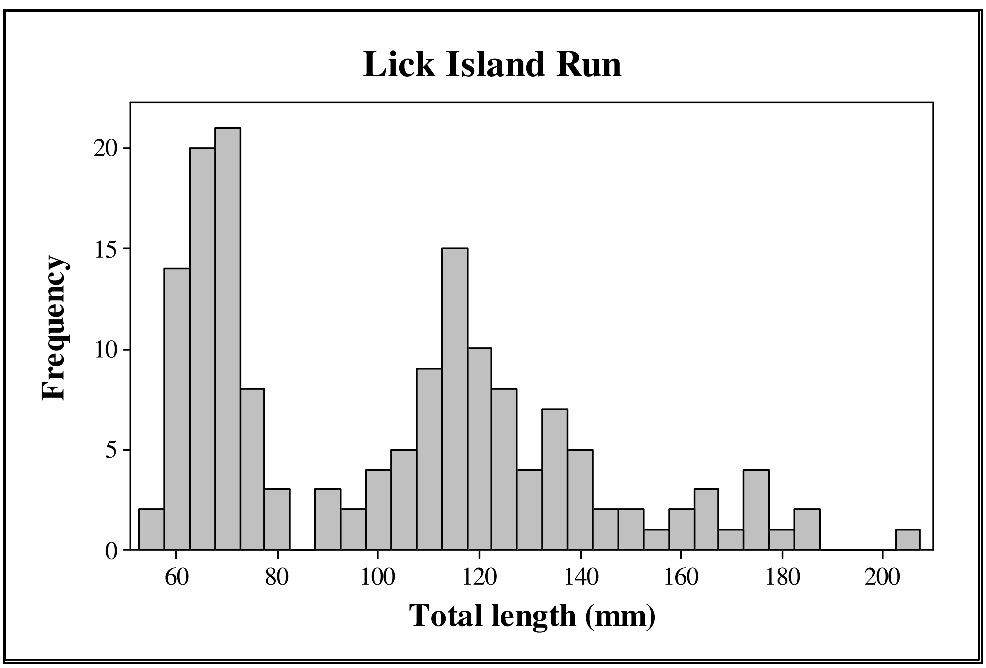

Elk Run
Frequency
30
25
20
15
10
5
0
75
100
125
150
175
200
225
250
Total length (mm)

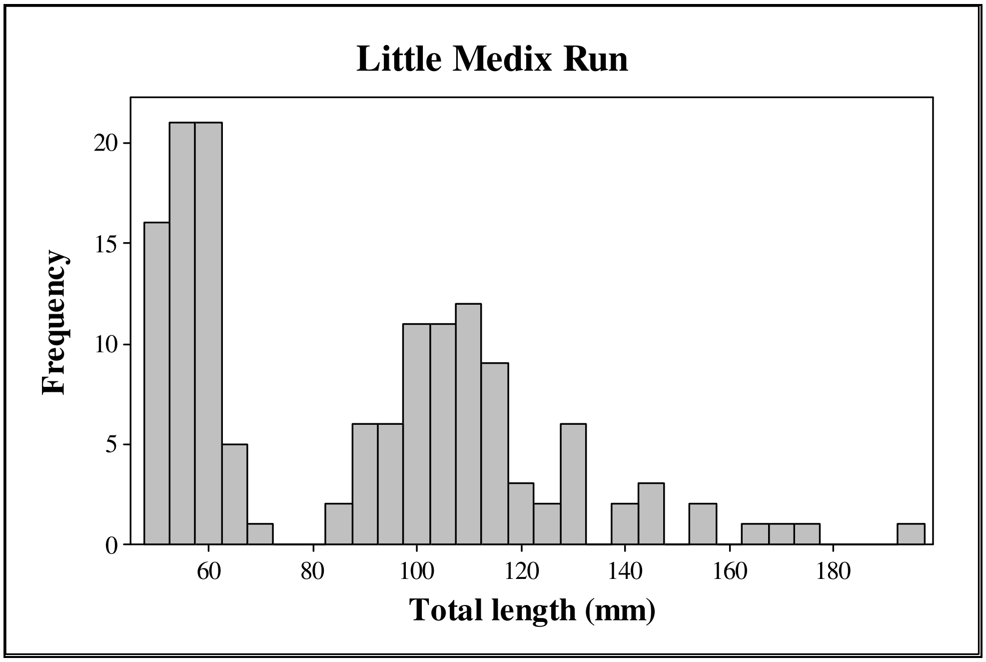

English Run
Frequency
14
12
10
8
6
4
2
0
60
80
100
120
140
160
180
200
Total length (mm)

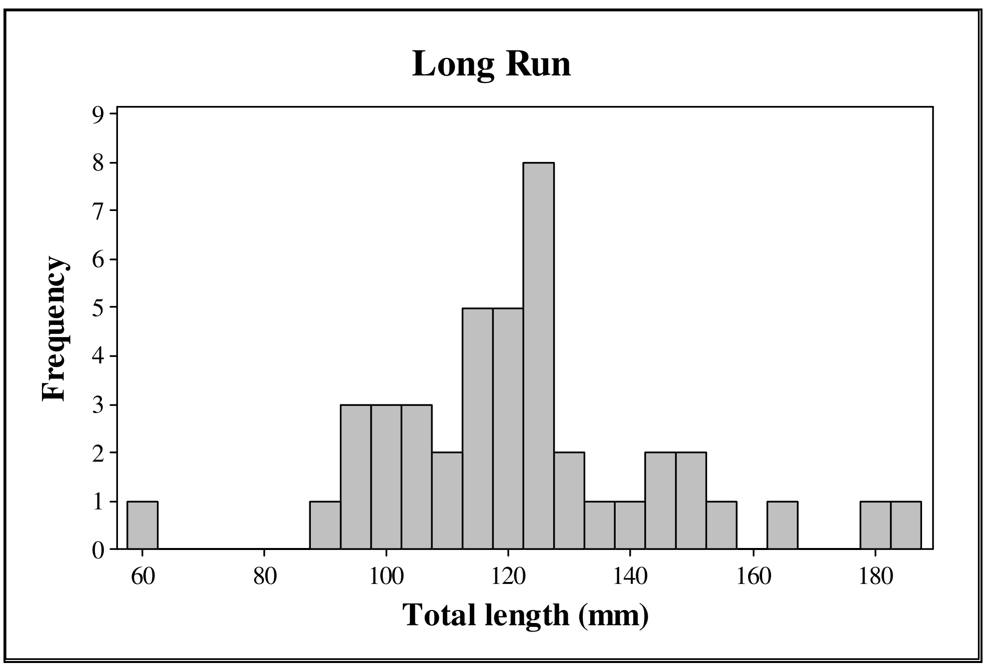

Galbraith Gap Run
Frequency
Total length (mm)
0
2
4
6
8
10
12
60
80
100
120
140
160
180
200

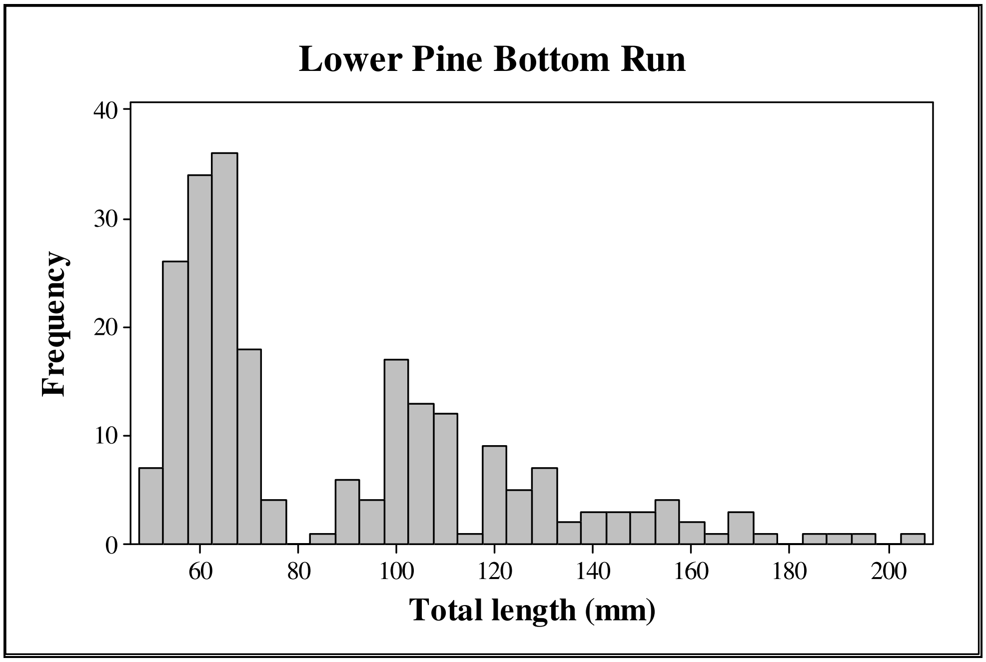

Hayes Run
Frequency
Total length (mm)
0
5
10
15
20
60
80
100
120
140
160
180

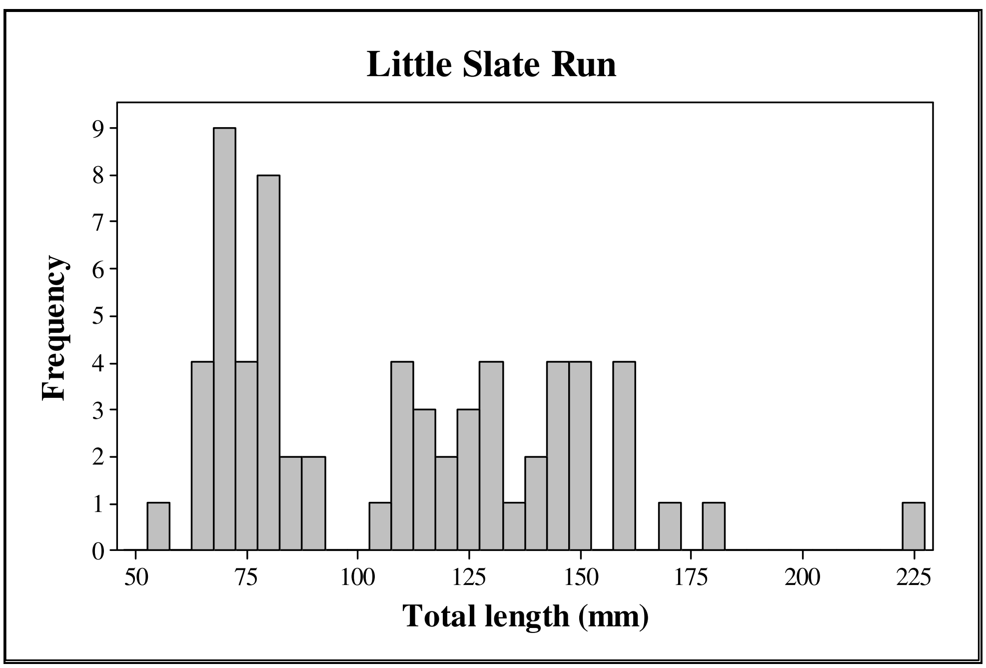

Little Fishing Creek
Frequency
0
1
2
3
4
5
6
7
8
9
50
75
100
125
150
175
200
Total length (mm)

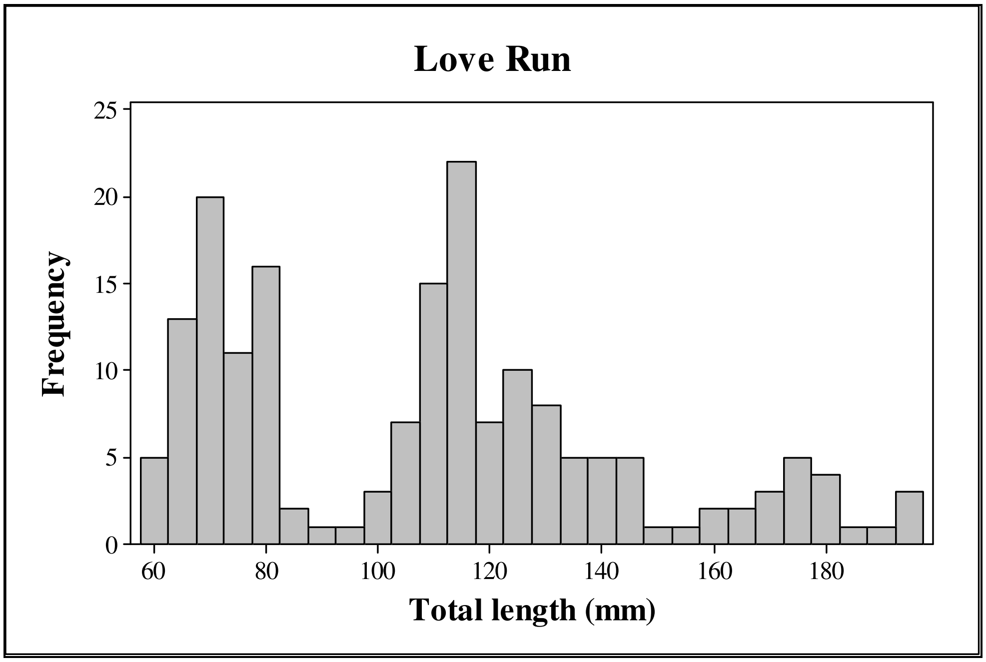

Lick Island Run
Frequency
0
5
10
15
20
60
80
100
120
140
160
180
200
Total length (mm)

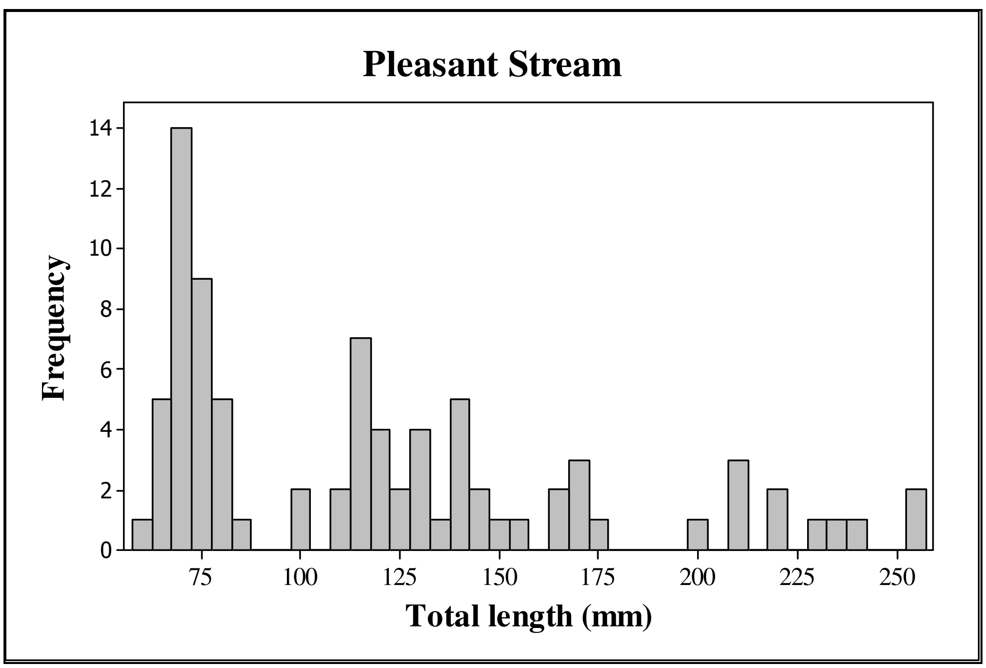

Little Medix Run
Frequency
0
5
10
15
20
60
80
100
120
140
160
180
Total length (mm)

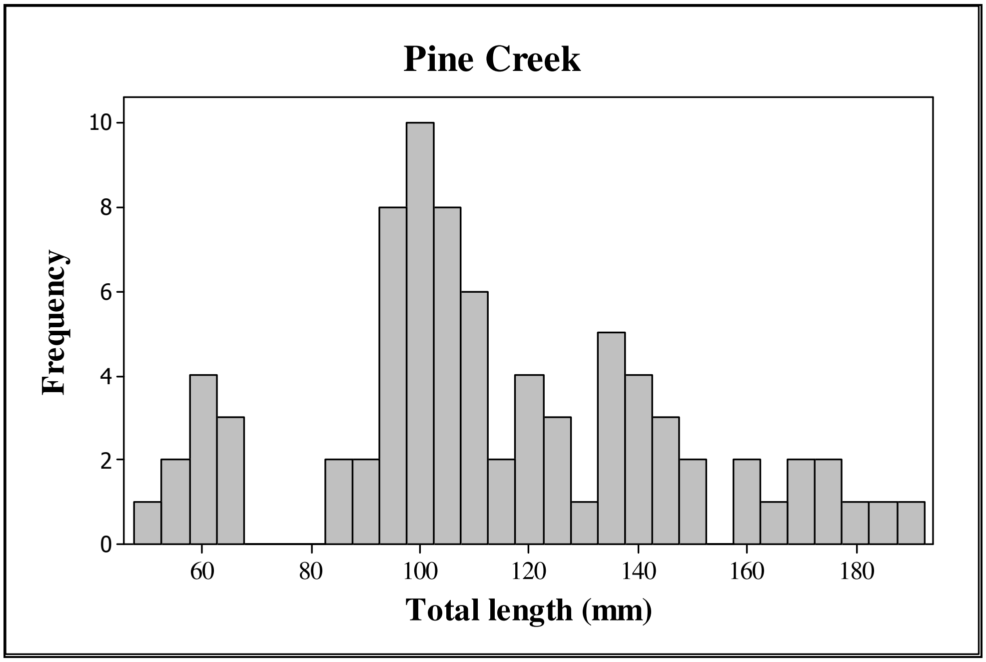

Long Run
Frequency
0
1
2
3
4
5
6
7
8
9
60
80
100
120
140
160
180
Total length (mm)

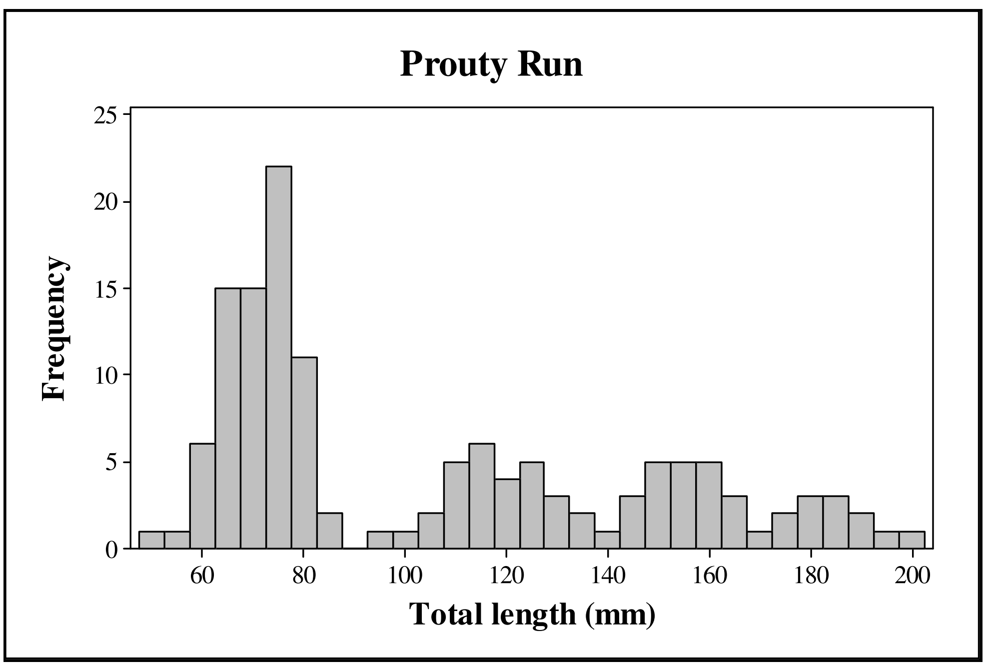

Lower Pine Bottom Run
Frequency
0
10
20
30
40
60
80
100
120
140
160
180
200
Total length (mm)

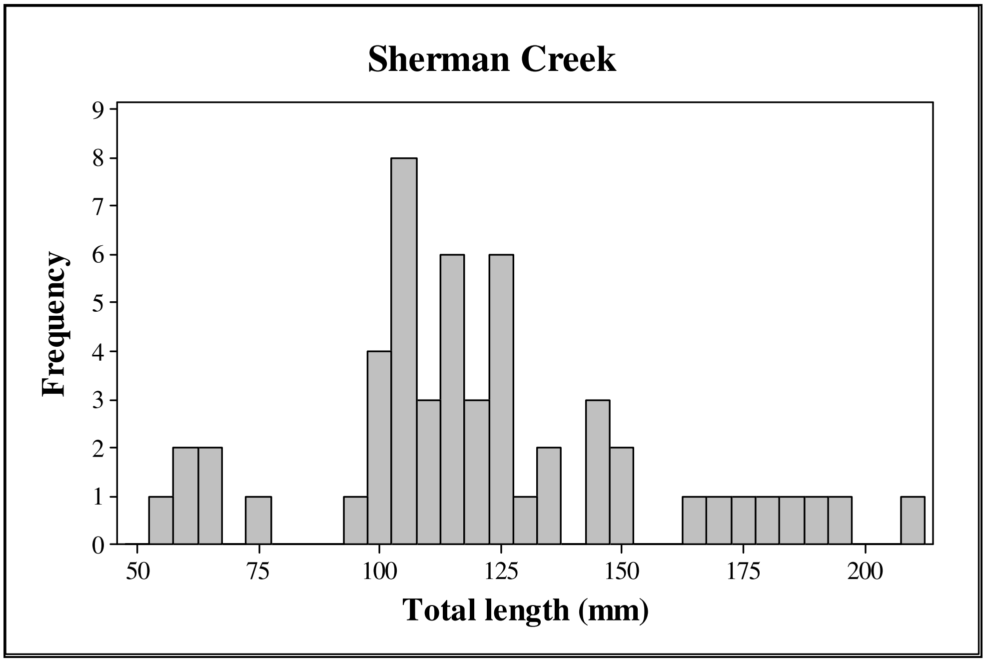

Little Slate Run
Frequency
0
1
2
3
4
5
6
7
8
9
50
75
100
125
150
175
200
225
Total length (mm)

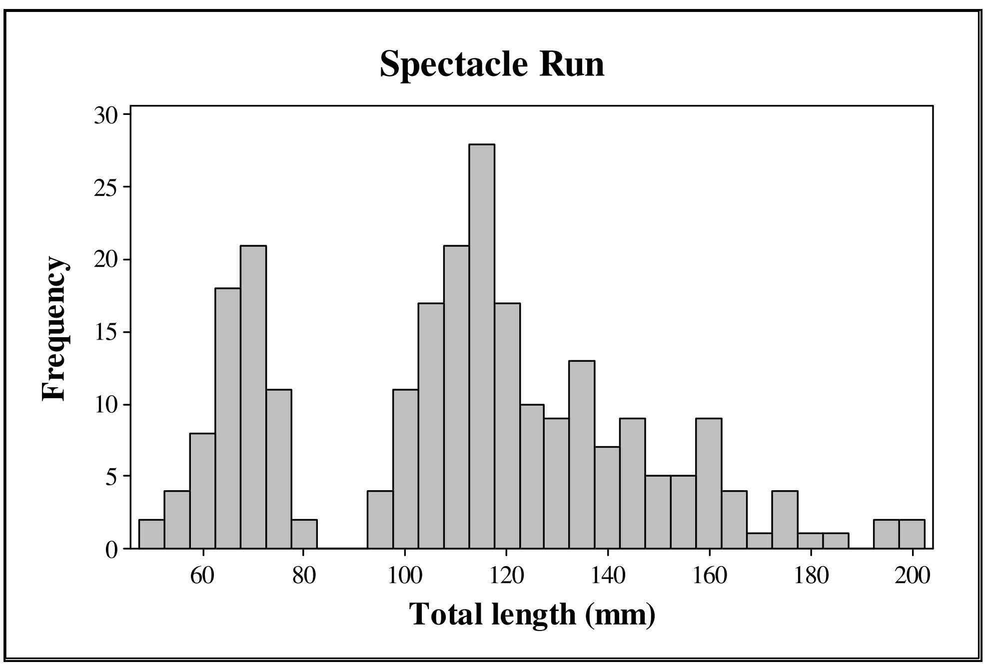

Love Run
Frequency
25
20
15
10
5
0
60
80
100
120
140
160
180
Total length (mm)

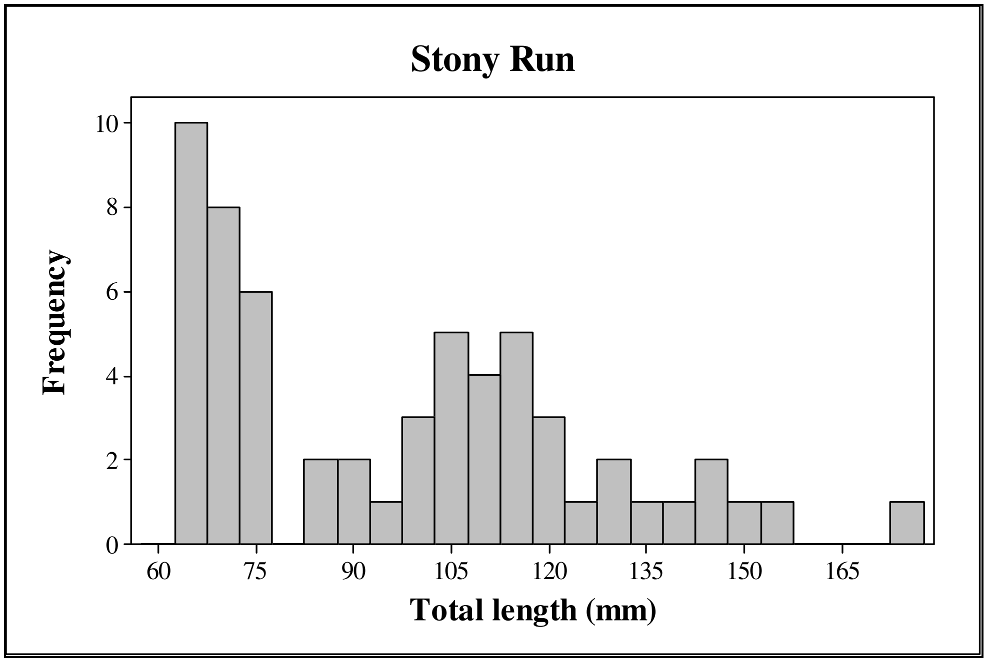

Pleasant Stream
Frequency
14
12
10
8
6
4
2
0
75
100
125
150
175
200
225
250
Total length (mm)

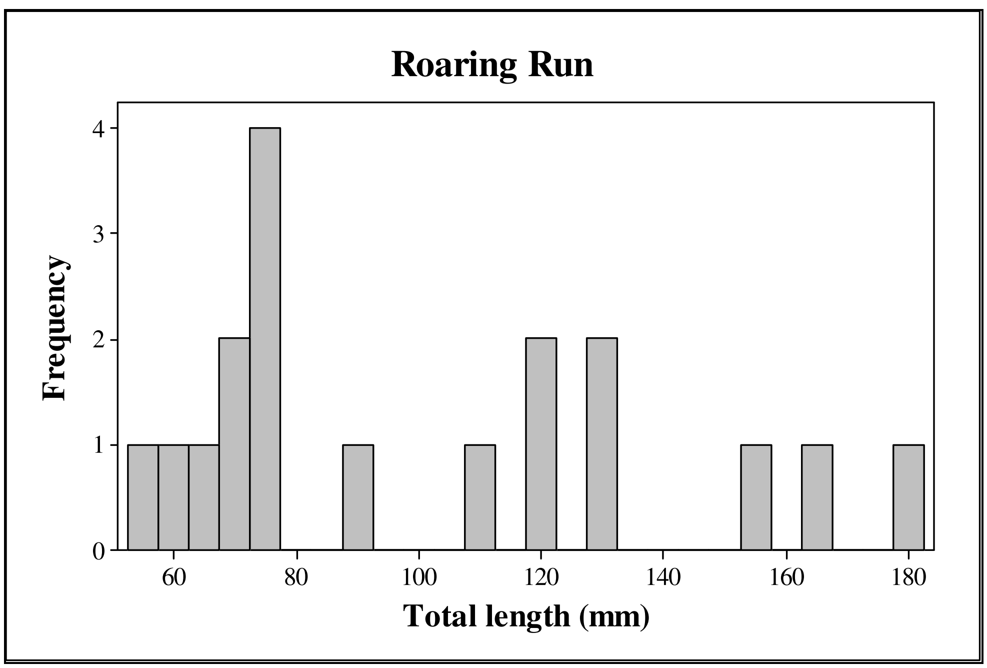

Pine Creek
Frequency
Total length (mm)
0
2
4
6
8
10
60
80
100
120
140
160
180

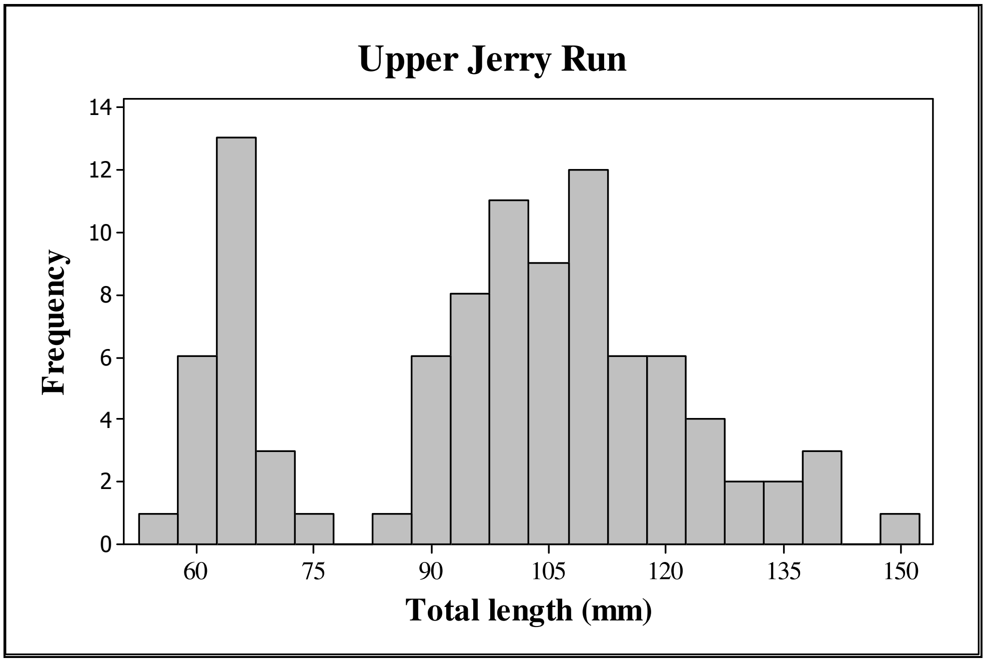

Prouty Run
Frequency
Total length (mm)
0
5
10
15
20
25
60
80
100
120
140
160
180
200

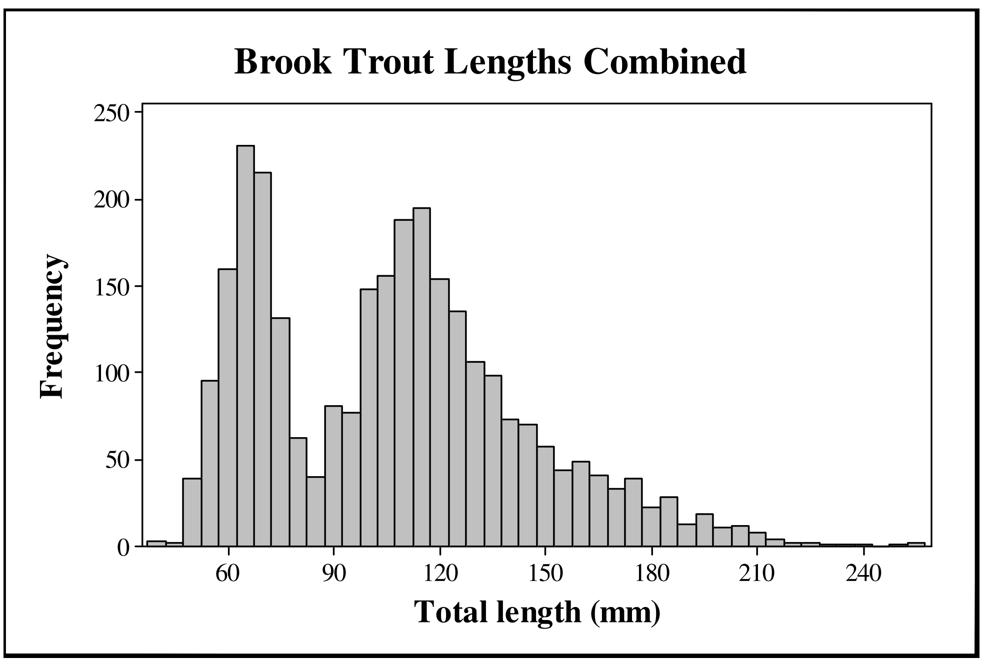

Sherman Creek
Frequency
0
1
2
3
4
5
6
7
8
9
50
75
100
125
150
175
200
Total length (mm)


Spectacle Run
Frequency
0
5
10
15
20
25
30
60
80
100
120
140
160
180
200
Total length (mm)


Stony Run
Frequency
0
2
4
6
8
10
60
75
90
105
120
135
150
165
Total length (mm)

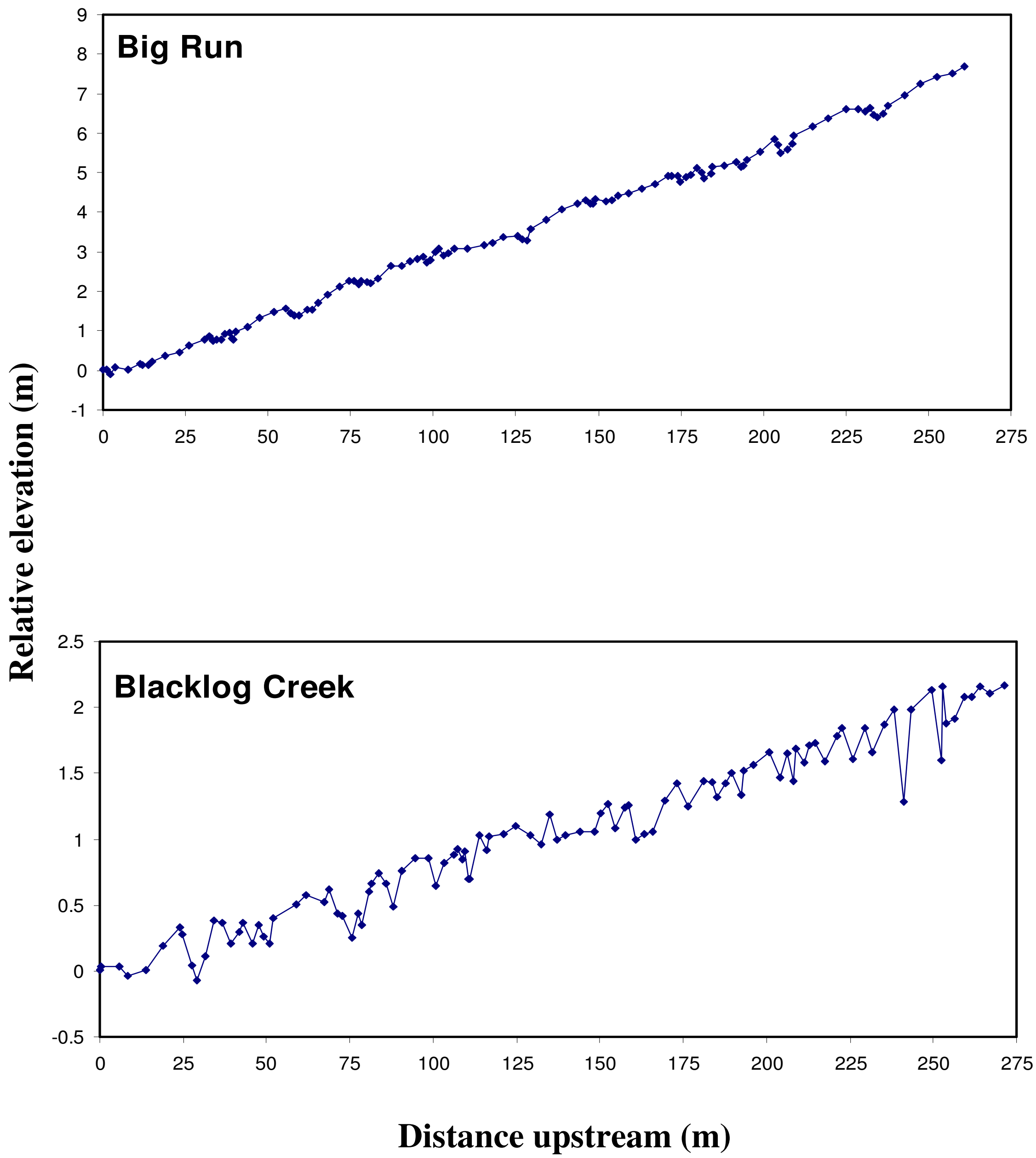

Roaring Run
Frequency
0
1
2
3
4
60
80
100
120
140
160
180
Total length (mm)

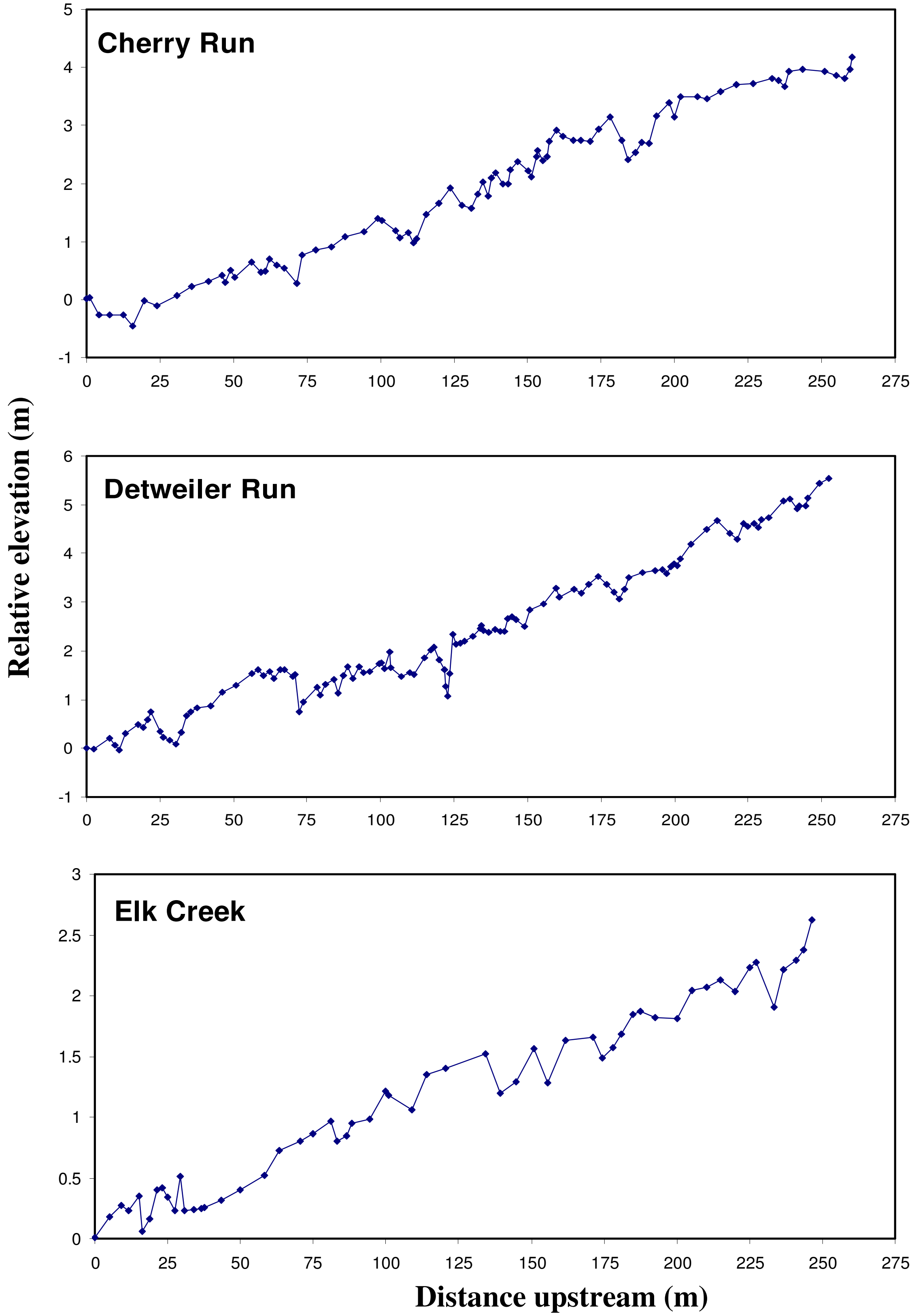

Upper Jerry Run
Frequency
0
2
4
6
8
10
12
14
60
75
90
105
120
135
150
Total length (mm)

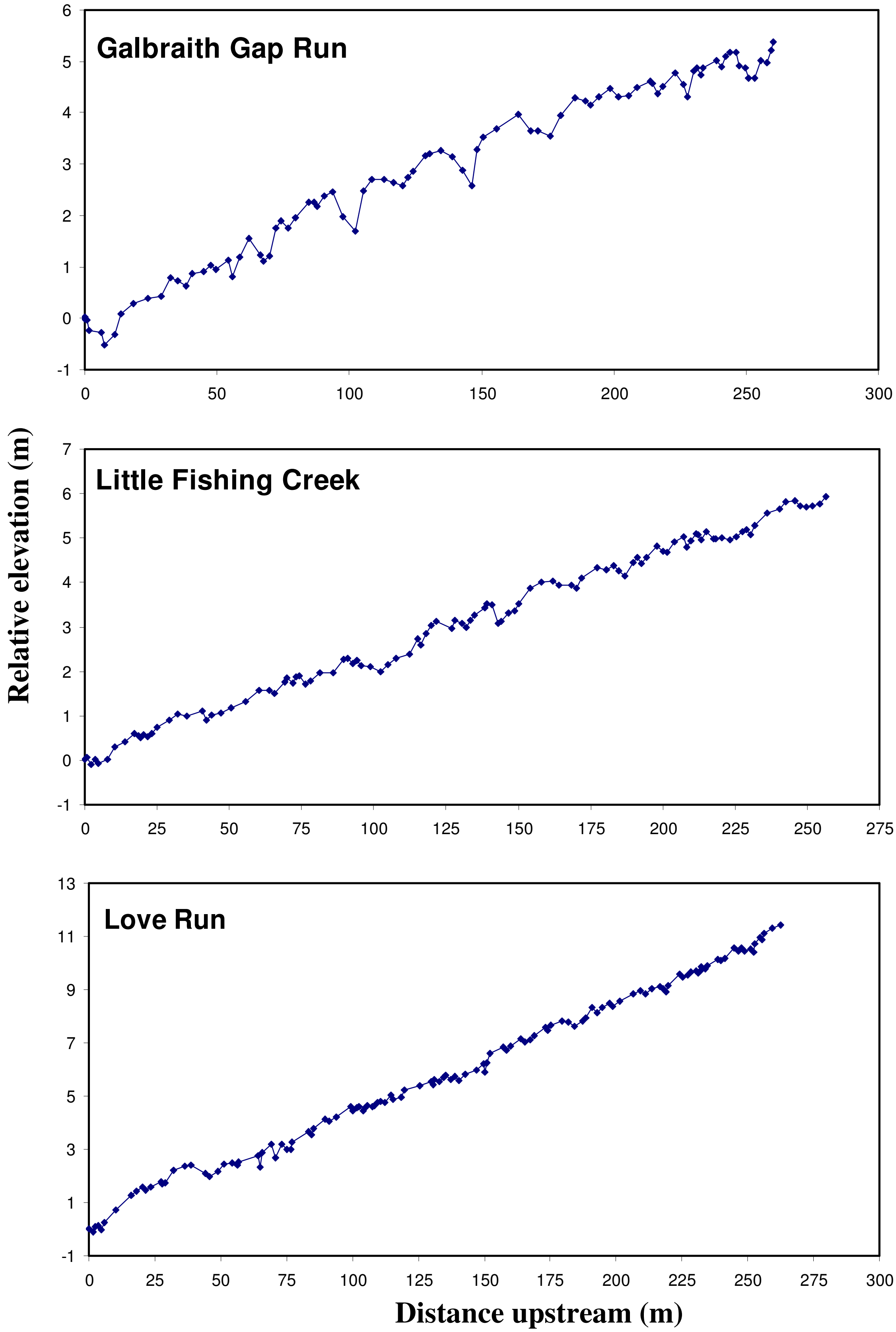

Brook Trout Lengths Combined
Frequency
0
50
100
150
200
250
60
90
120
150
180
210
240
Total length (mm)

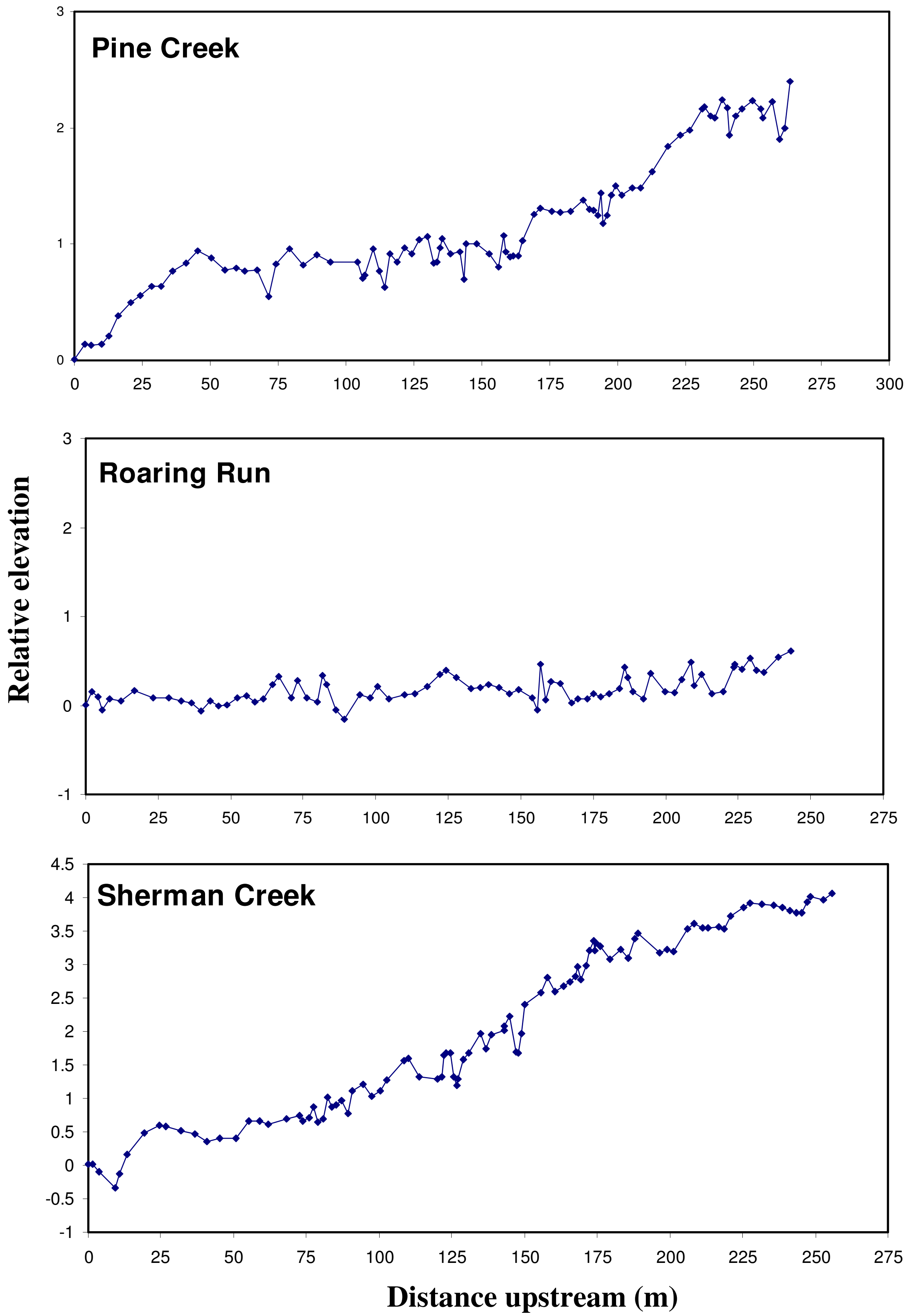
Appendix C

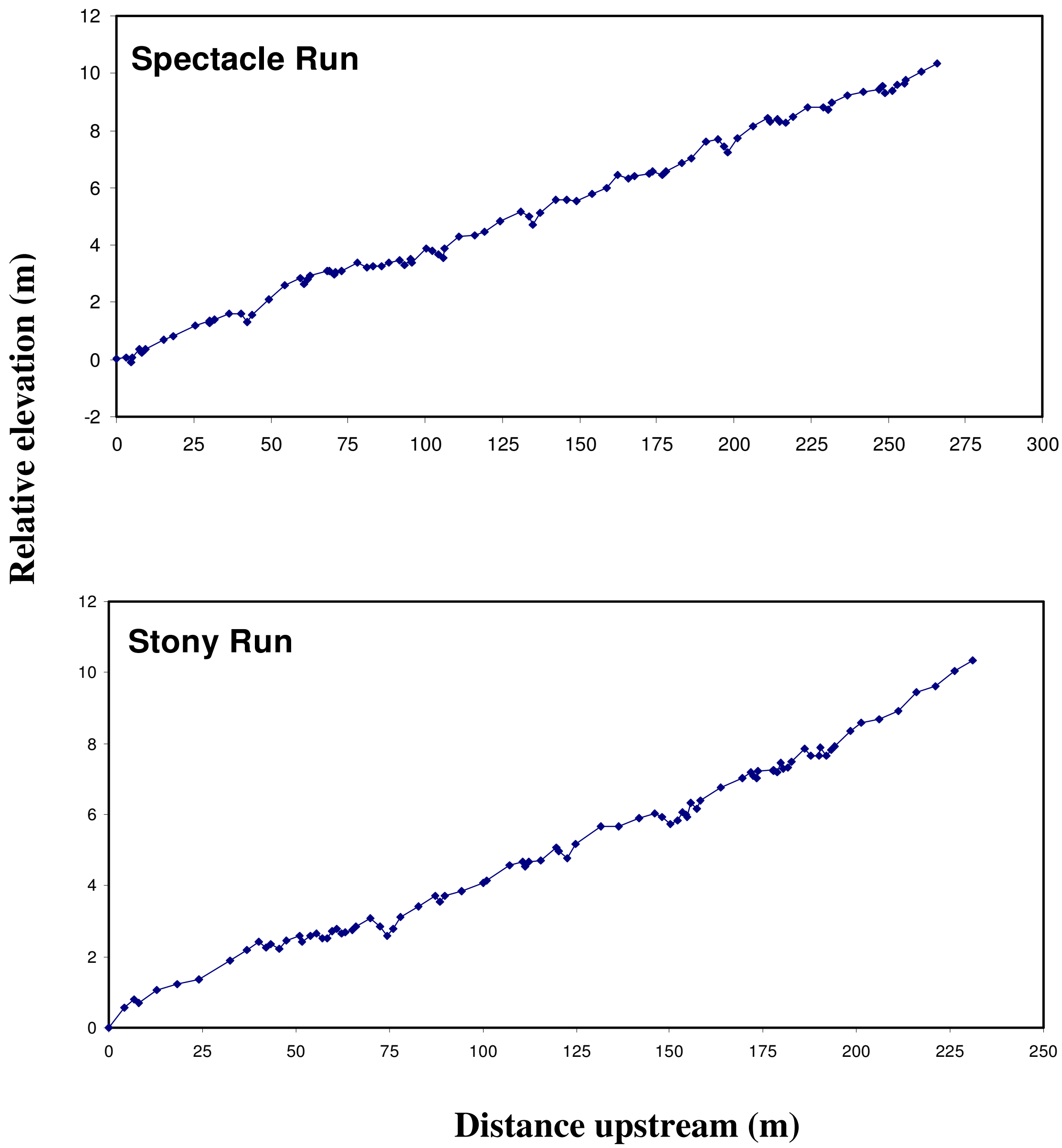
Thalweg profiles of study streams sampled in summer and fall 2008 in the Ridge and Valley and Appalachian Plateau physiographic provinces. Graphs are scaled based on stream gradient and reach length.

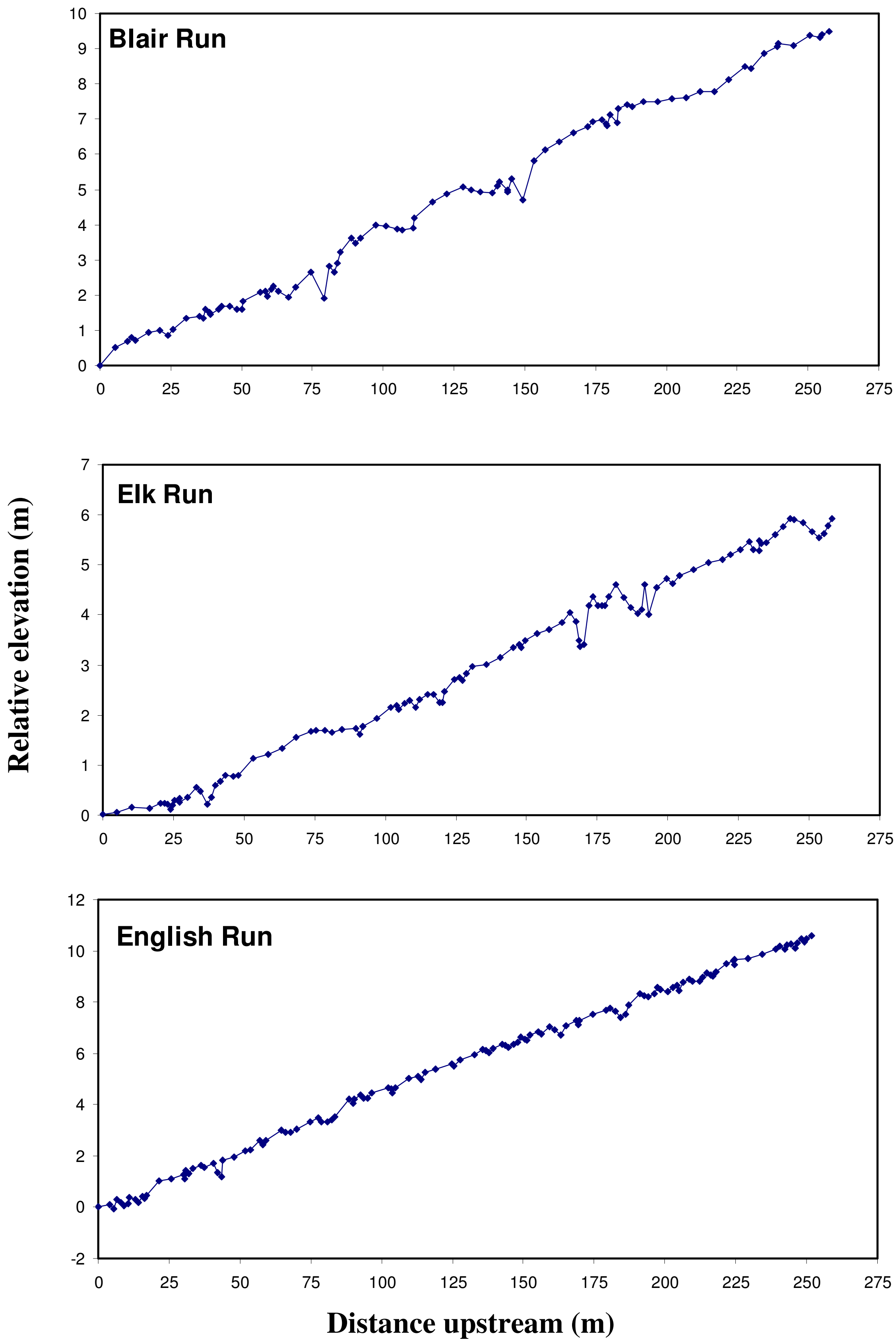

Big Run
Blacklog Creek
Relative elevation (m)
Distance upstream (m)
9
8
7
6
5
4
3
2
1
0
-1
2.5
2
1.5
1
0.5
-0.5
25
50
75
100
125
150
175
200
225
250
275

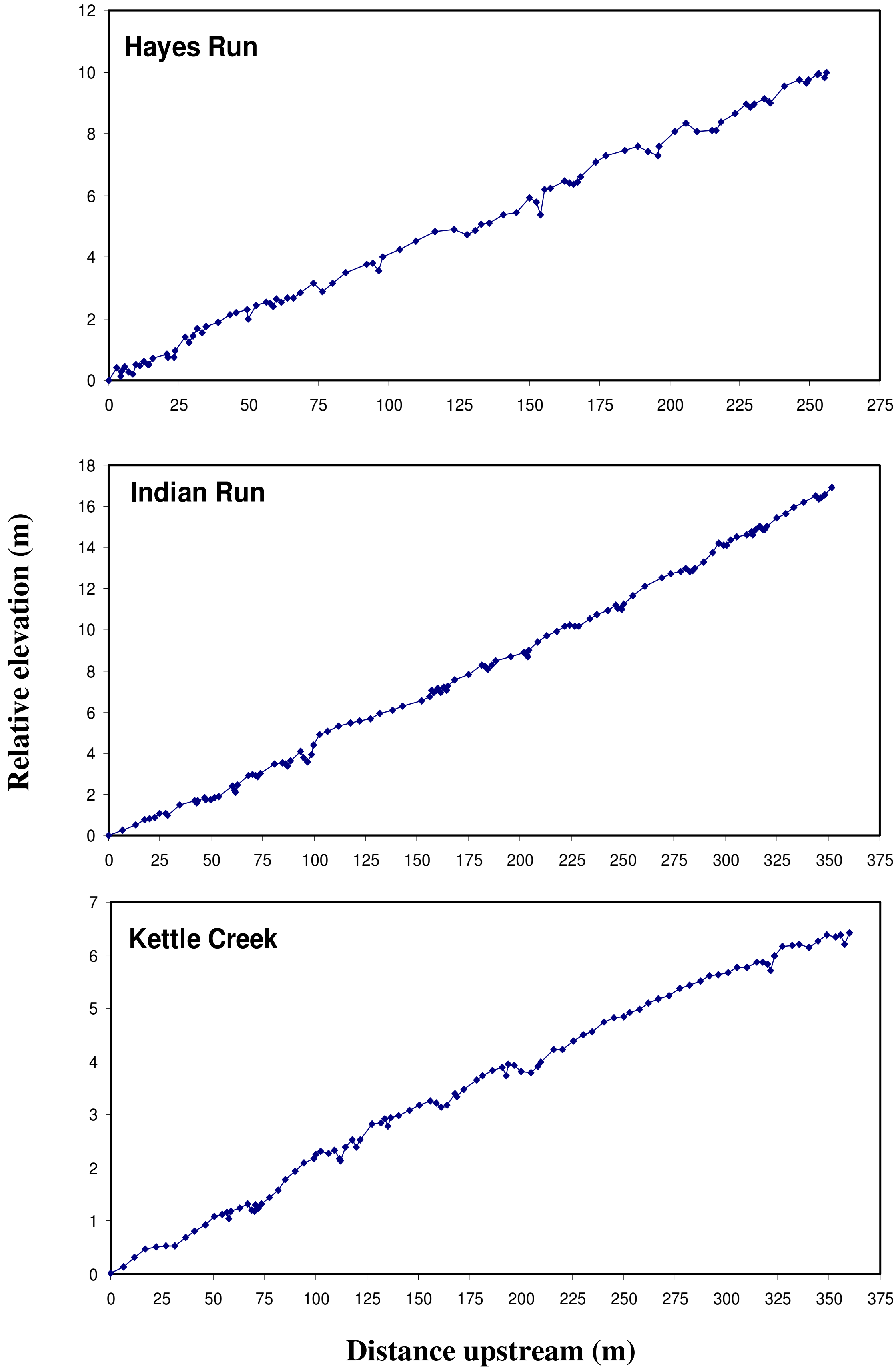

Cherry Run
Detweiler Run
Elk Creek
Relative elevation (m)
Distance upstream (m)
5
4
3
2
1
0
-1
6
2.5
1.5
0.5
0
25
50
75
100
125
150
175
200
225
250
275

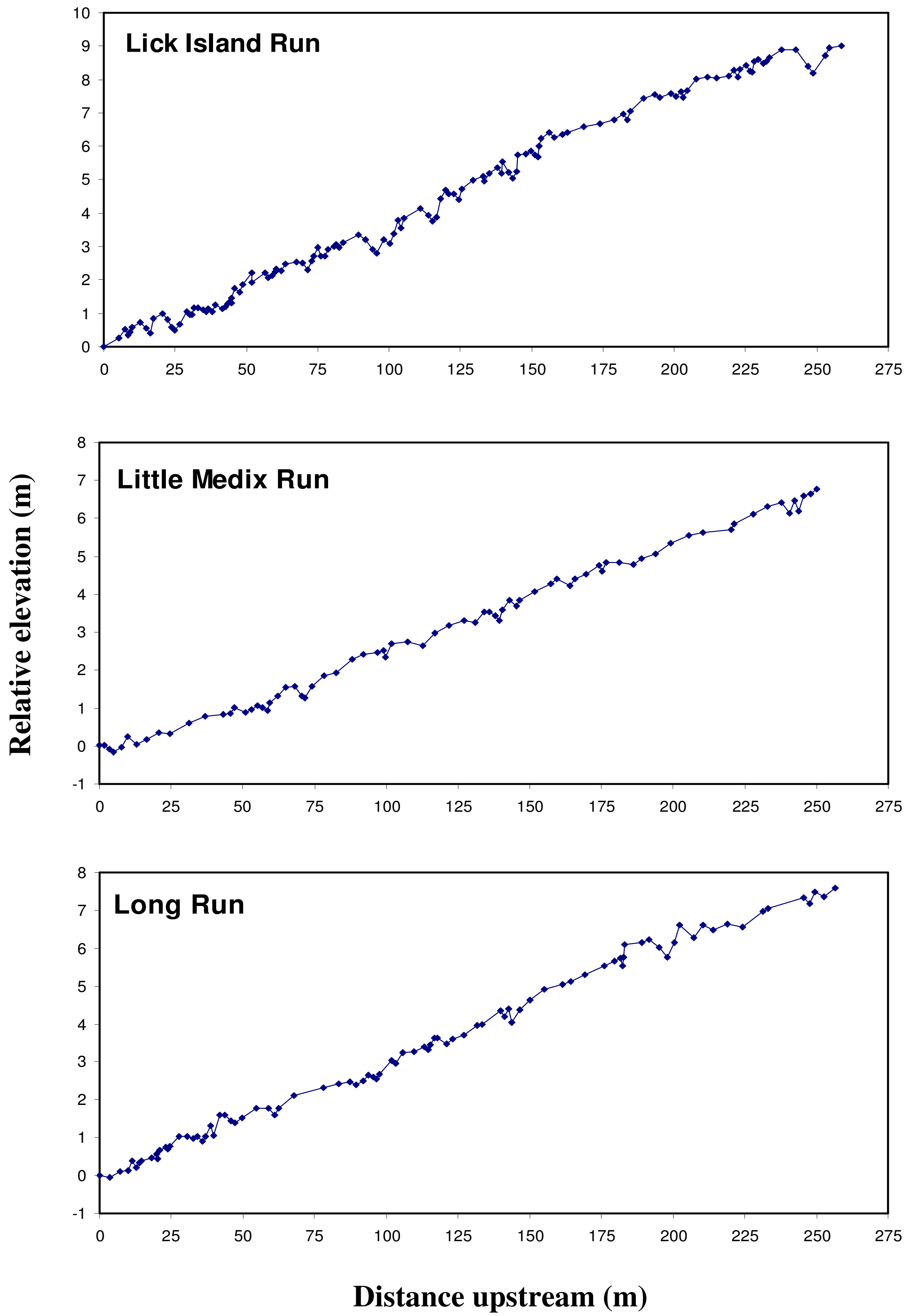

Galbraith Gap Run
Little Fishing Creek
Love Run
Relative elevation (m)
Distance upstream (m)

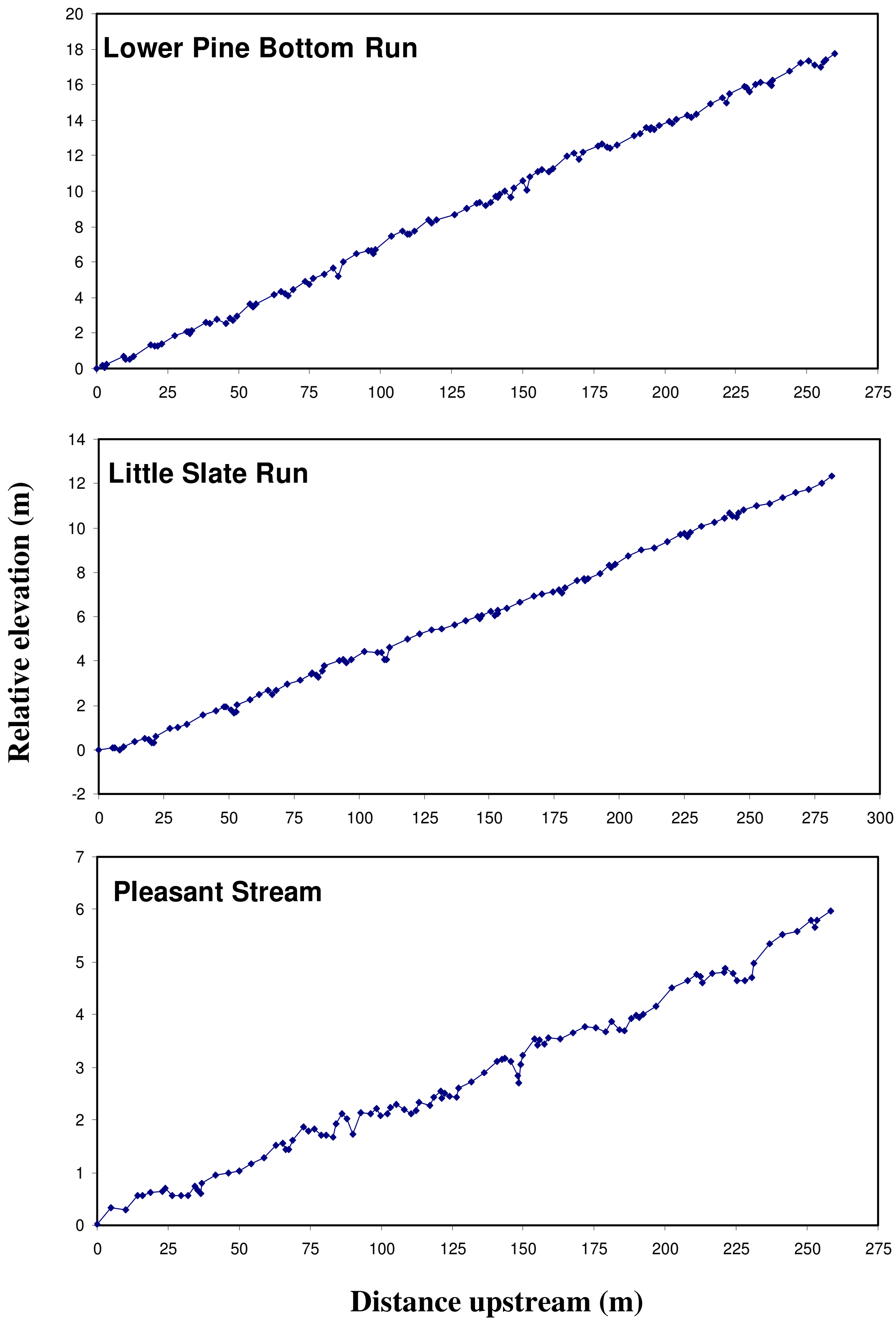

Pine Creek
Roaring Run
Sherman Creek
Relative elevation
Distance upstream (m)
0
25
50
75
100
125
150
175
200
225
250
275
300
-1
-0.5
0.5
1
1.5
2
2.5
3
3.5
4
4.5

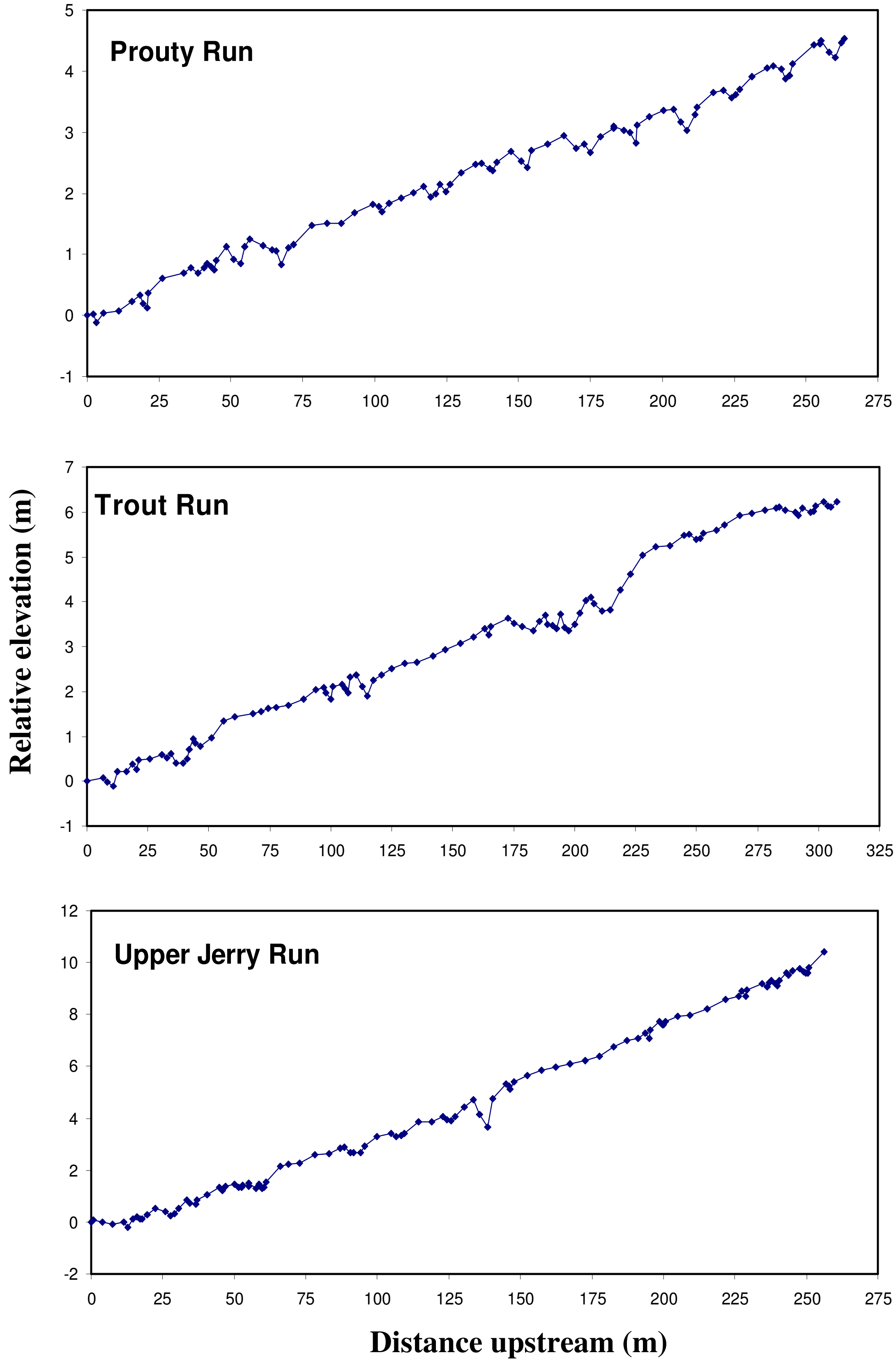

Spectacle Run
Stony Run
Relative elevation (m)
Distance upstream (m)
12
10
8
6
4
2
0
-2
0
25
50
75
100
125
150
175
200
225
250
275
300


Blair Run
Elk Run
English Run
Relative elevation (m)
Distance upstream (m)
0 25 50 75 100 125 150 175 200 225 250 275


Hayes Run
Indian Run
Kettle Creek
Relative elevation (m)
Distance upstream (m)
12
10
8
6
4
2
0
25
50
75
100
125
150
175
200
225
250
275
18
16
14
300
325
350
375
7
5
3
1


Lick Island Run
10
9
8
7
6
5
4
3
2
1
0
0 25 50 75 100 125 150 175 200 225 250 275
Little Medix Run
8
7
6
5
4
3
2
1
0
-1
0 25 50 75 100 125 150 175 200 225 250 275
Long Run
8
7
6
5
4
3
2
1
0
-1
0 25 50 75 100 125 150 175 200 225 250 275
Relative elevation (m)
Distance upstream (m)


Lower Pine Bottom Run
Little Slate Run
Pleasant Stream
Relative elevation (m)
Distance upstream (m)
0 25 50 75 100 125 150 175 200 225 250 275 300
-2 0 2 4 6 8 10 12 14 16 18 20


Prouty Run
Trout Run
Upper Jerry Run
Relative elevation (m)
Distance upstream (m)
5
4
3
2
1
0
-1
0 25 50 75 100 125 150 175 200 225 250 275
7
6
5
4
3
2
1
0
-1
0 25 50 75 100 125 150 175 200 225 250 275 300 325
12
10
8
6
4
2
0
-2
0 25 50 75 100 125 150 175 200 225 250 275

Appendix D

Landscape level and in stream habitat characteristics for 15 Appalachian Plateau and 13 Ridge and Valley physiographic province streams of central Pennsylvania sampled in summer and fall 2008.

Stream	Non Brook Trout Species	Mean Wetted Width (m)	Gradient (%)
Appalachian Plateau			
Blair Run	1	5.1	3.7
Elk Run	3	2.5	2.5
Hayes Run	1	3.7	3.8
Indian Run	2	2.2	4.8
Little Medix Run	4	2.8	2.8
Lower Pine Bottom Run	1	2.4	7.0
Prouty Run	2	2.4	1.6
Trout Run	4	3.8	2.1
Kettle Creek	4	5.2	1.8
Lick Island Run	4	3.3	3.7
Little Slate Run	0	1.6	4.4
Pleasant Stream	2	4.3	2.2
Upper Jerry Run	0	2.3	4.1
Engligh Run	1	1.8	4.2
Long Run	1	1.7	3.1
Ridge and Valley			
Love Run	1	2.7	4.1
Stony Run	2	4.5	4.0
Galbraith Gap Run	2	3.2	2.1
Detweiler Run	1	4.3	2.0
Pine Creek	2	2.6	0.7
Roaring Run	6	6.2	0.1
Spectacle Run	0	2.9	3.8
Cherry Run	4	4.8	1.8
Elk Creek	7	5.2	0.9
Little Fishing Creek	2	4.6	2.3
Blacklog Creek	6	3.2	0.8
Sherman Creek	8	4.5	1.8
Big Run	3	3.3	2.9

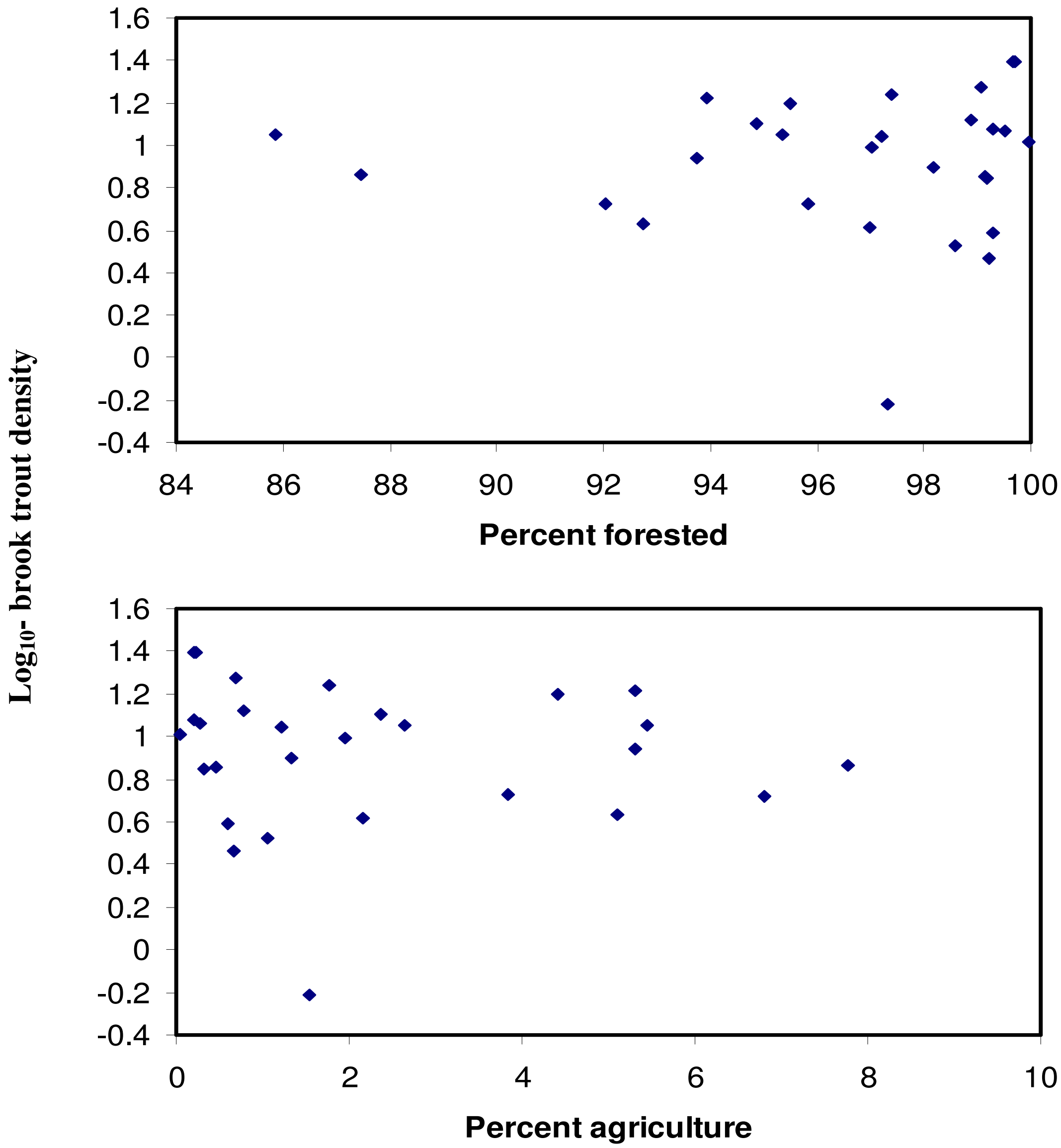
Stream	Silt (%)	Sand (%)	Large fines (%)	Gravel (%)	Cobble (%)	Small boulder (%)	Boulder (%)	Bedrock (%)
Appalachian Plateau								
Blair Run	0	0	1	42	54	1	2	0
Elk Run	1	0	0	52	46	0	1	0
Hayes Run	1	8	3	37	39	12	0	0
Indian Run	0	8	4	53	34	1	0	0
Little Medix Run	0	3	1	34	46	8	1	7
Lower Pine Bottom Run	0	1	4	62	30	2	1	0
Prouty Run	7	3	2	54	31	3	0	0
Trout Run	0	0	0	45	49	4	0	2
Kettle Creek	1	0	1	41	50	4	3	0
Lick Island Run	0	0	2	36	51	9	2	0
Little Slate Run	0	0	7	59	34	0	0	0
Pleasant Stream	1	0	3	37	54	5	0	0
Upper Jerry Run	0	2	1	52	40	2	3	0
English Run	2	1	2	55	35	3	2	0
Long Run	13	3	2	51	30	1	0	0
Ridge and Valley								
Love Run	0	0	1	48	50	1	0	0
Stony Run	1	11	0	19	47	7	15	0
Galbraith Gap Run	5	5	1	59	29	1	0	0
Detweiler Run	0	2	2	45	48	3	0	0
Pine Creek	6	44	0	8	36	6	0	0
Roaring Run	7	16	0	63	13	1	0	0
Spectacle Run	22	16	3	15	34	8	2	0
Cherry Run	1	3	0	43	44	7	0	2
Elk Creek	4	12	0	45	39	0	0	0
Little Fishing Creek	2	6	1	37	47	3	4	0
Blacklog Creek	8	29	0	50	13	0	0	0
Sherman Creek	0	8	0	35	55	2	0	0
Big Run	7	5	5	30	42	11	0	0

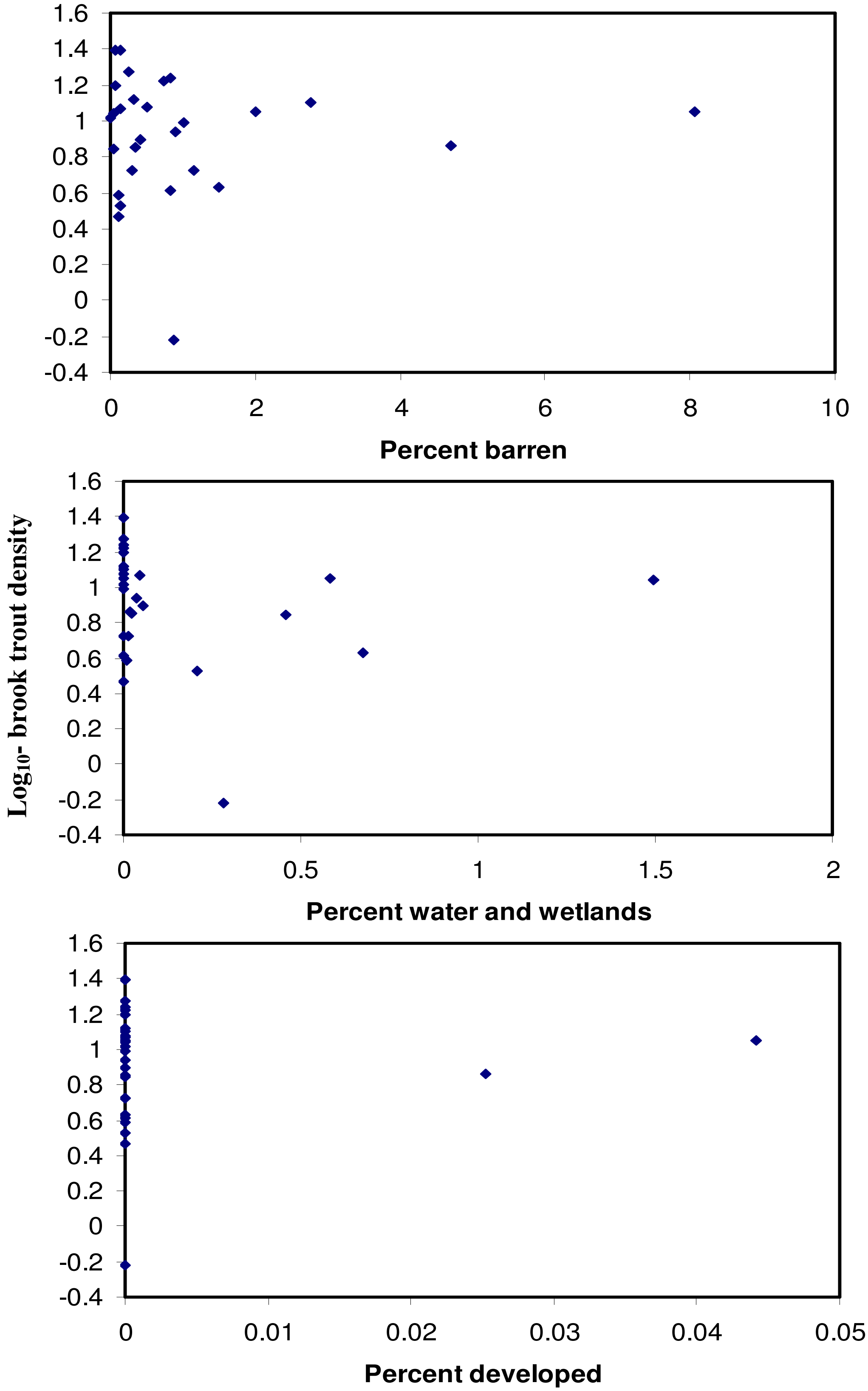
Stream	Drainage area	Forested (%)	Agriculture (%)	Barren (%)	Water and wetlands (%)	Developed (%)
Appalachian Plateau						
Blair Run	10.7	87.5	7.78	4.71	0.02	0.03
Elk Run	7.5	99.1	0.68	0.25	0.00	0.00
Hayes Run	10.2	97.4	1.78	0.84	0.00	0.00
Indian Run	3.6	99.2	0.47	0.34	0.02	0.00
Little Medix Run	10.2	85.9	5.45	8.07	0.58	0.04
Lower Pine Bottom Run	5.2	93.9	5.32	0.73	0.00	0.00
Prouty Run	7.4	99.3	0.21	0.50	0.00	0.00
Trout Run	19.9	98.9	0.79	0.33	0.00	0.00
Kettle Creek	18.1	93.8	5.30	0.90	0.03	0.00
Lick Island Run	16.7	95.3	2.65	2.01	0.00	0.00
Little Slate Run	2.2	100.0	0.04	0.00	0.00	0.00
Pleasant Stream	8.4	92.7	5.11	1.49	0.67	0.00
Upper Jerry Run	8.2	94.9	2.37	2.76	0.00	0.00
English Run	8.9	99.7	0.21	0.07	0.00	0.00
Long Run	3.5	97.0	1.94	1.02	0.00	0.00
Ridge and Valley						
Love Run	5.6	95.5	4.42	0.06	0.00	0.00
Stony Run	6.7	98.6	1.07	0.13	0.21	0.00
Galbraith Gap Run	8.0	99.5	0.28	0.15	0.04	0.00
Detweiler Run	8.5	99.3	0.59	0.12	0.01	0.00
Pine Creek	6.3	97.2	1.23	0.06	1.50	0.00
Roaring Run	18.9	97.3	1.53	0.87	0.28	0.00
Spectacle Run	4.9	99.7	0.22	0.13	0.00	0.00
Cherry Run	27.6	99.2	0.67	0.11	0.00	0.00
Elk Creek	6.2	98.2	1.33	0.42	0.06	0.00
Little Fishing Creek	11.4	99.2	0.33	0.04	0.46	0.00
Blacklog Creek	6.7	92.0	6.80	1.16	0.00	0.00
Sherman Creek	15.5	97.0	2.17	0.84	0.00	0.00
Big Run	5.8	95.8	3.84	0.30	0.02	0.00

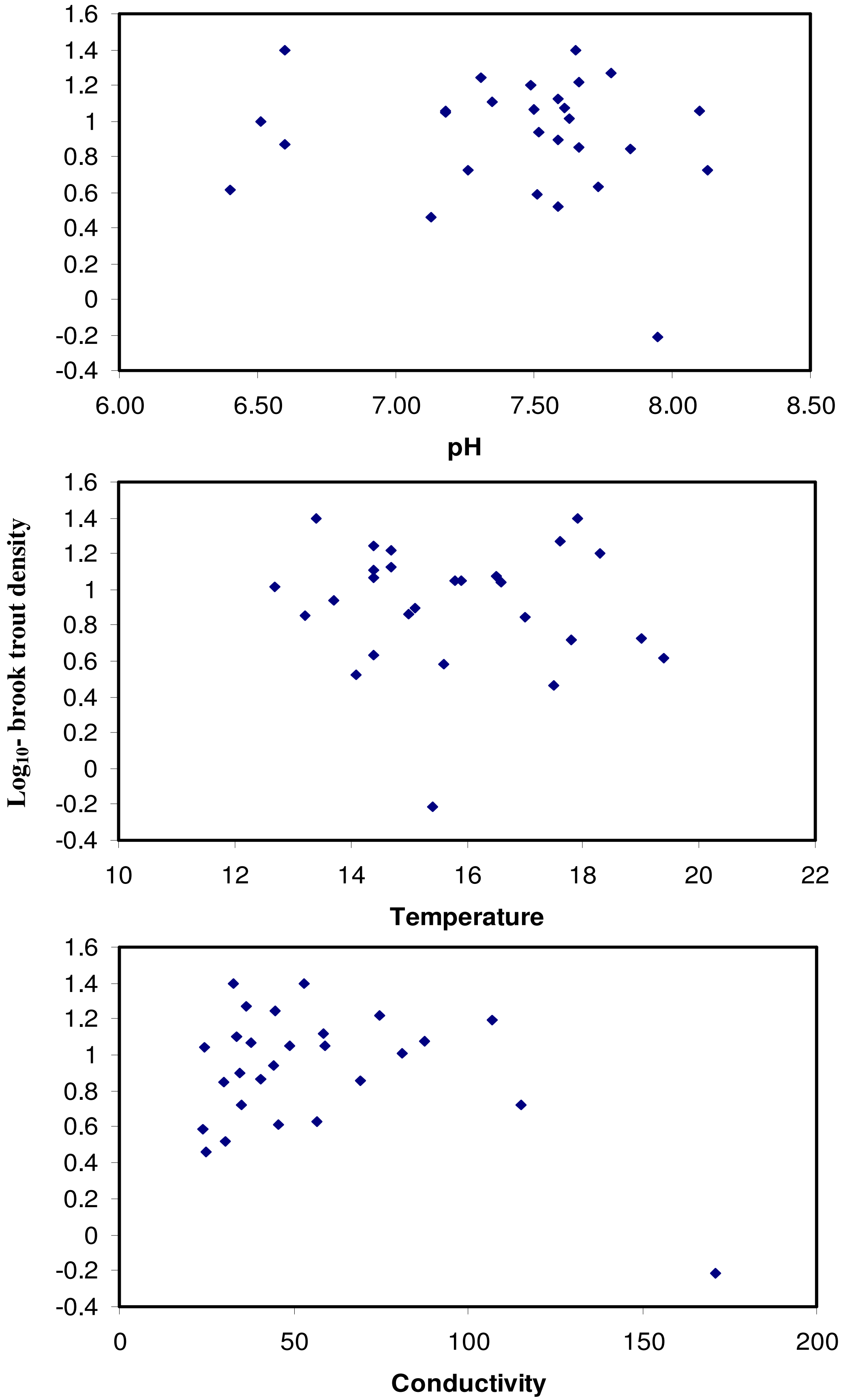
Stream	Temperature (°C)	pH	Conductivity (µS)	Overhead cover (%)	All LWD	LWD ≥ 5
Appalachian Plateau						
Blair Run	15	6.6	40.7	50	26.2	9.7
Elk Run	17.6	7.8	36.3	65	46.5	3.9
Hayes Run	14.4	7.3	44.8	40	68.4	11.7
Indian Run	13.2	7.7	69.3	20	43.4	10.7
Little Medix Run	15.8	7.2	59.1	55	44.4	16.8
Lower Pine Bottom Run	14.7	7.7	74.5	40	23.1	4.8
Prouty Run	16.5	7.6	87.6	25	35.1	13.3
Trout Run	14.7	7.6	58.7	10	18.7	6.5
Kettle Creek	13.7	7.5	44.4	25	13.2	4.2
Lick Island Run	15.9	8.1	49	50	19.3	6.8
Little Slate Run	12.7	7.6	80.9	40	96.8	36.4
Pleasant Stream	14.4	7.7	56.6	35	35.8	10.7
Upper Jerry Run	14.4	7.4	33.8	15	90.7	28.3
English Run	13.4	7.7	53.1	20	30.8	10.9
Long Run		6.5		35	40.9	19.5
Ridge and Valley						
Love Run	18.3	7.5	107.1	65	64.8	24.8
Stony Run	14.1	7.6	30.5	70	77.9	21.6
Galbraith Gap Run	14.4	7.5	37.8	60	78.8	22.1
Detweiler Run	15.6	7.5	23.9	70	47.5	16.8
Pine Creek	16.6	7.2	24.4	100	126.3	0.9
Roaring Run	15.4	8.0	170.8	50	120.3	12.3
Spectacle Run	17.9	6.6	32.5	75	59.3	5.6
Cherry Run	17.5	7.1	25	40	25.9	14.4
Elk Creek	15.1	7.6	34.6	65	100.0	10.0
Little Fishing Creek	17	7.9	30	60	51.7	22.4
Blacklog Creek	17.8	7.3	35	45	62.7	9.2
Sherman Creek	19.4	6.4	45.6	50	23.5	4.9
Big Run	19	8.1	115.2	35	73.8	11.5

Appendix E

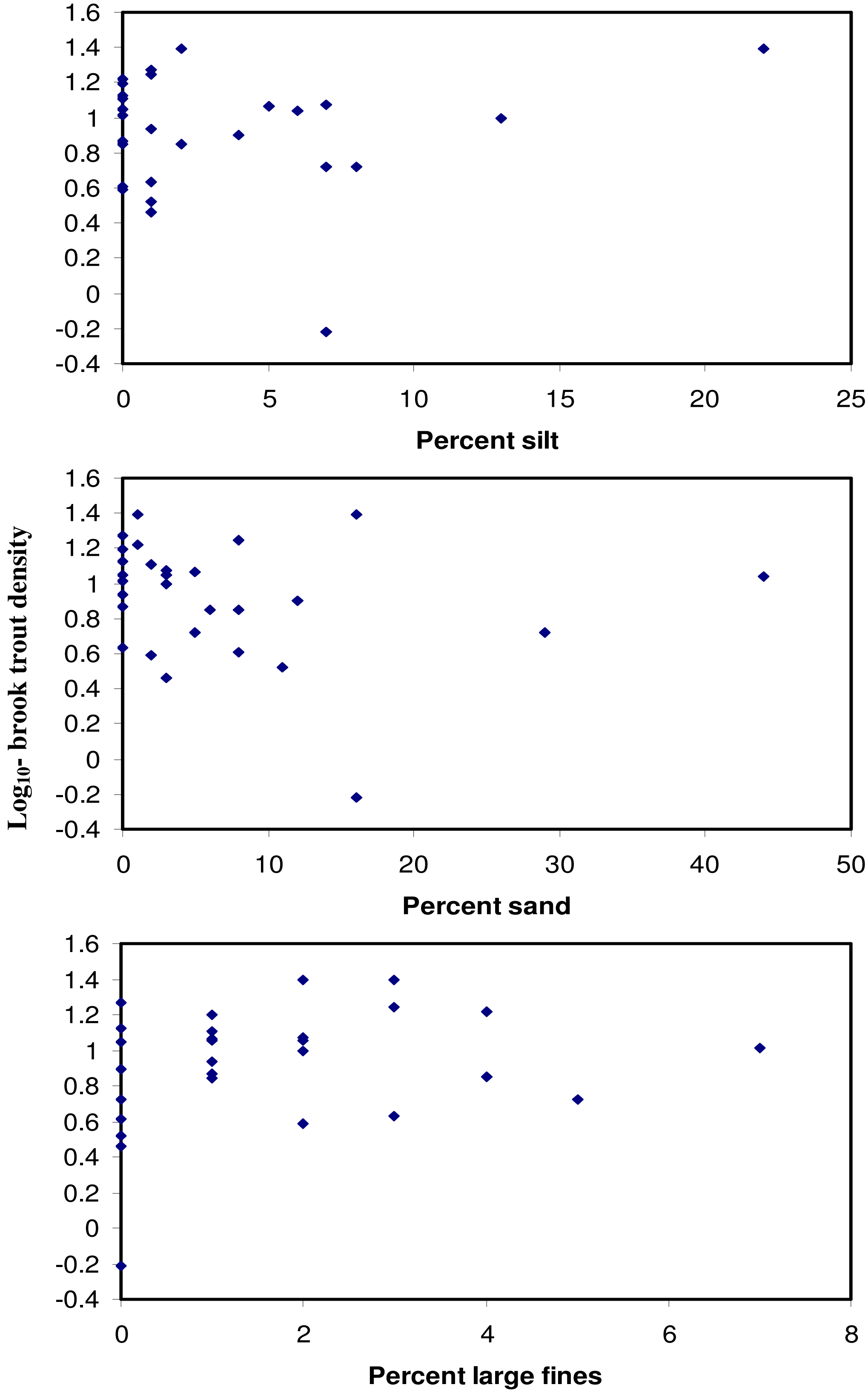
Plots of non significant variables and $\log_{10}$- brook trout densities in central Pennsylvania Streams

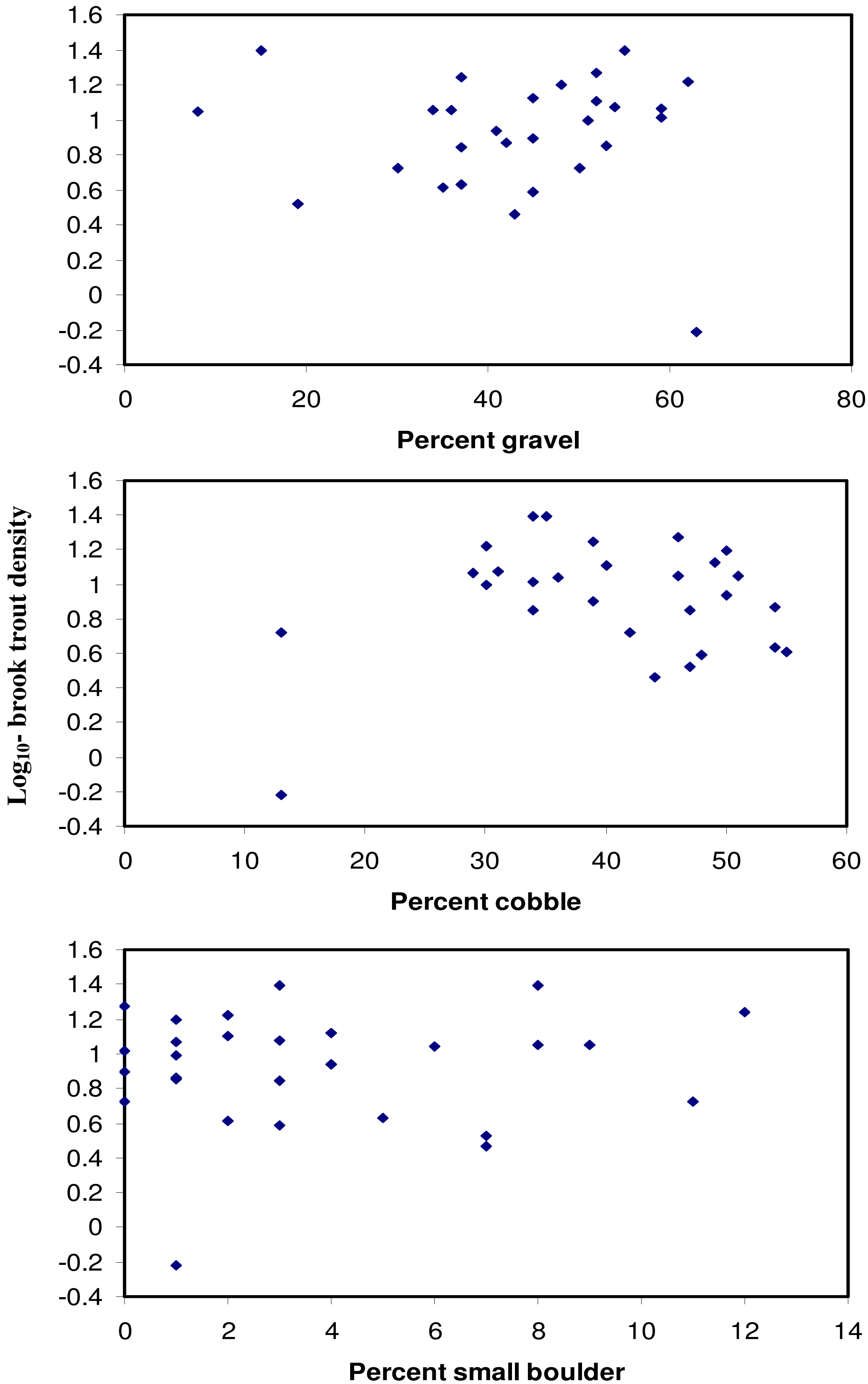

Log10- brook trout density
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
84
86
88
90
92
94
96
98
100
Percent forested
0
2
4
6
8
10
Percent agriculture

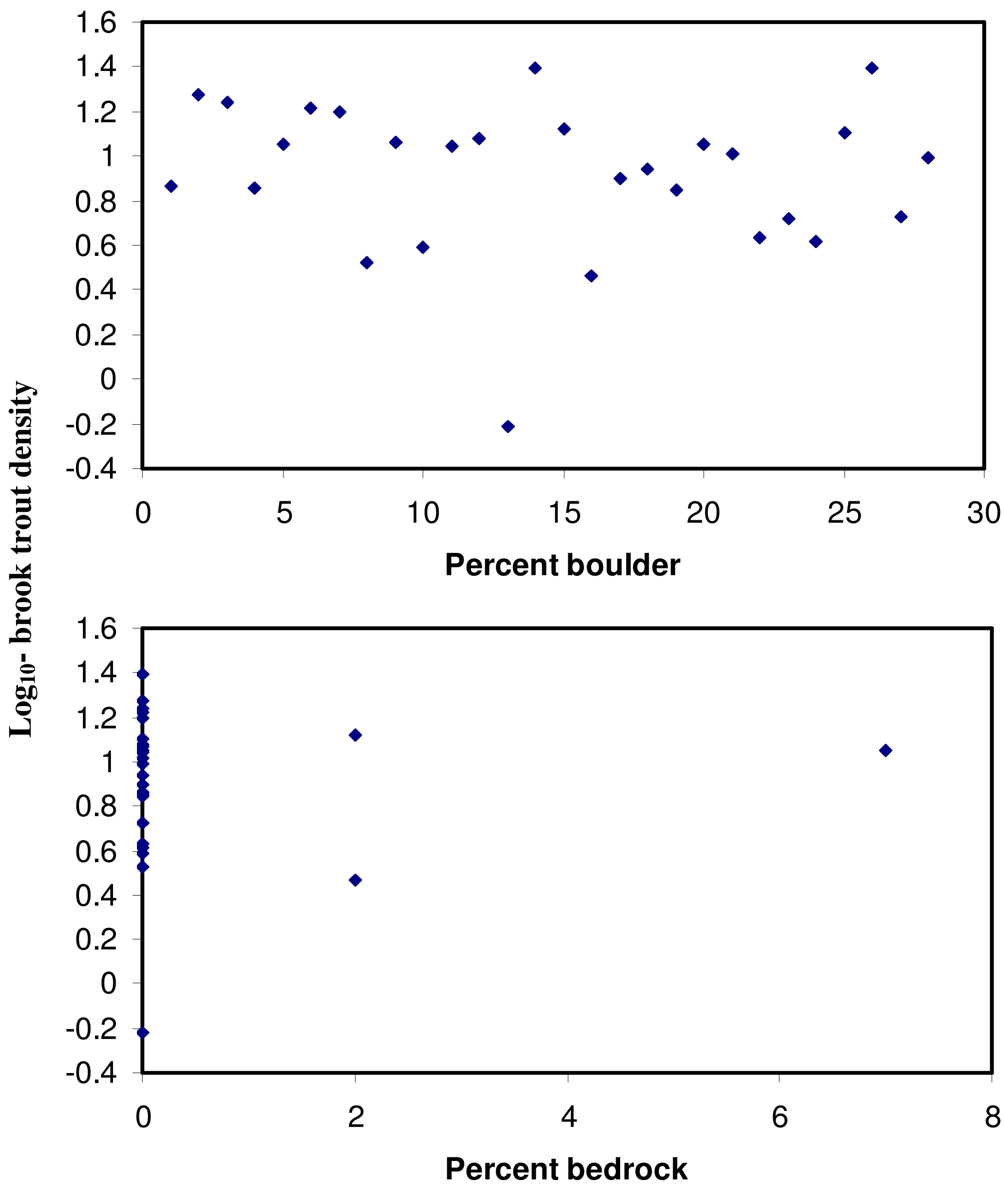

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
2
4
6
8
10
Percent barren
Log10- brook trout density
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.5
1
1.5
2
Percent water and wetlands
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.01
0.02
0.03
0.04
0.05
Percent developed

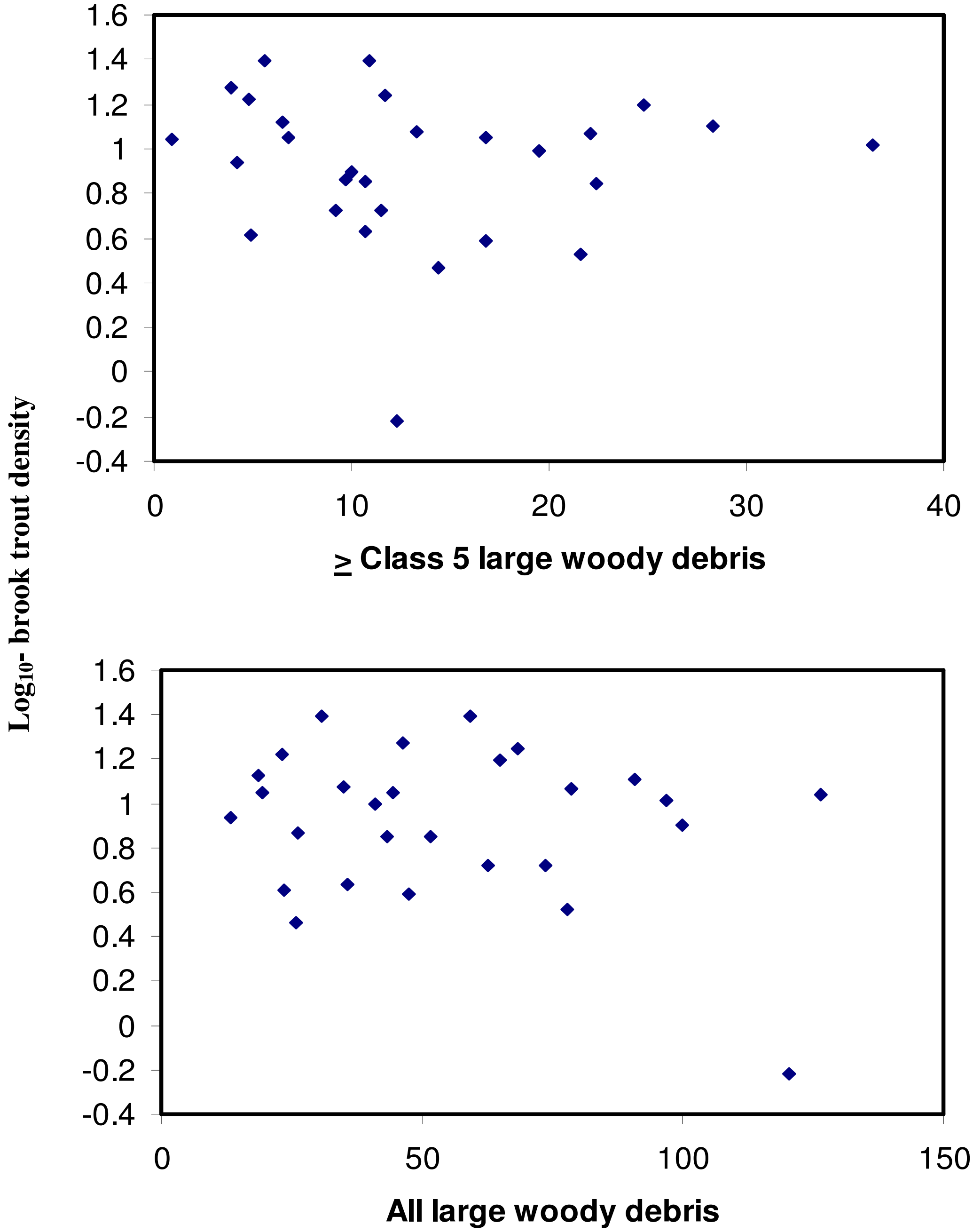


Log10- brook trout density
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
6.00
6.50
7.00
7.50
8.00
8.50
pH
10
12
14
16
18
20
22
Temperature
0
50
100
150
200
Conductivity


Log10- brook trout density
Percent silt
Percent sand
Percent large fines


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
20
40
60
80
Percent gravel
Log10- brook trout density
0
10
20
30
40
50
60
Percent cobble
0
2
4
6
8
10
12
14
Percent small boulder


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
30
Percent boulder
Log10- brook trout density
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
2
4
6
8
Percent bedrock


Log10- brook trout density
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
10
20
30
40
≥ Class 5 large woody debris
0
50
100
150
All large woody debris