A Physical and Chemical Assessment of Presque Isle Bay Watershed Streams

Report to the Erie County Conservation District
Waterford, Pennsylvania

Harry R. Diz, Ph.D.
Principal Investigator

Ronald G. Johnson, M.S.
Research Assistant

Department of Environmental Science and Engineering
Gannon University
Erie, PA 16541

June, 2002

Abstract

A physicochemical assessment of the Presque Isle Bay (PIB) watershed was conducted as part of a comprehensive watershed assessment project. Seventeen sites along Mill Creek, Cascade Creek, Garrison Run, Scott Run, were studied as well as seven reference sites outside the watershed. Selected water and sediment quality parameters were also measured.

Sites along Cascade Creek received lower habitat scores than the Mill Creek sites. This appeared to be linked to the higher degree of urbanization which was associated with loss of riparian buffer zones, resulting in loss of vegetation and increased bank instability.

Sediments from Cascade Creek and Garrison Run were contaminated with heavy metals while Mill Creek sediments generally contained higher levels of oil and grease.

Acknowledgment

We would like to thank the Erie County Conservation District and the Pennsylvania Sea Grant Program for the opportunity to conduct this research by providing financial assistance through funding from the PADEP Growing Greener program.

TABLE OF CONTENTS

List of Figures

List of Tables

1. Introduction

The U.S. Department of State designated Presque Isle Bay (PIB) as an Area of Concern in January of 1991. As an Area of Concern, PIB receives priority attention from the Pennsylvania Department of Environmental Protection (DEP). This attention resulted in a PIB ecosystem study and background report in June of 1991. The purpose of the report was to identify any impairment of PIB's beneficial uses. It was determined that the two major impairments were the contamination of the bay sediment, which causes restrictions on dredging, and the increased incidence of tumors in fish (GLNPO, 2000). This impairment is thought to be caused by activities within the watershed. Almost two thirds of the water discharged into PIB comes from two sources, Mill Creek (including Garrison Run), and Cascade Creek (Potomac-Hudson, 1991). Other minor contributors include Scott Run as well as sewer discharges and overflows.

A physicochemical assessment of the PIB watershed was conducted during the summer of 2001. This study included the examination of seventeen sites along Mill Creek, Cascade Creek, Garrison Run, Scott Run, as well as seven reference sites outside the watershed using the EPA Rapid Bioassessment Protocol (Barbour et al., 1999), land use patterns, stream type and origin, riparian and in-stream features, as well as *in-situ* measurements of stream physical and chemical parameters. Also, water and/or sediments were analyzed for certain heavy metals, oil and grease, organic carbon, and biochemical oxygen demand.

2. Background

2.1 Study Area

Presque Isle Bay (PIB) watershed is located in Erie County Pennsylvania within the City of Erie and Millcreek Township (Figure 1). The drainage basin is about 25 square miles, which is relatively small in comparison to the volume of PIB, which is nearly 14,000 million gallons (Potomac-Hudson, 1991).

The watershed is about 80% urban and 20% rural. According to the Potomac-Hudson study, about 57% of the watershed is residential, 16 % open area, 11% commercial, 8 % public, and only 7 % is industrial.

The PIB watershed can be divided into three smaller watersheds. Cascade Creek, Mill Creek (including Garrison Run), and Scott Run, all of which drain into the PIB. The smallest is Scott Run, which is about 1.2 miles in length. The two branches of Cascade Creek total about 5.2 miles, and Mill Creek is the largest at 7 miles in length. A major tributary to Mill Creek is Garrison Run, with a length of 2 miles. Cascade Creek drains an area of about 6 square miles and Mill Creek drains about 13 square miles (Potomac-Hudson, 1991).

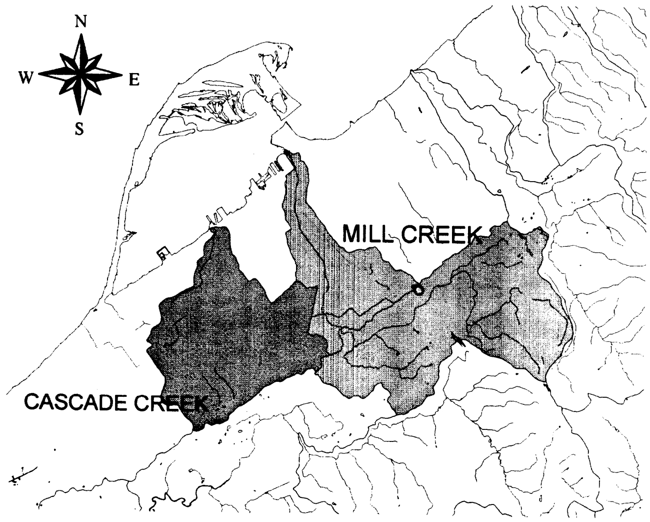

Figure 1. Mill Creek and Cascade Creek watersheds and Presque Isle Bay. Map courtesy of PADEP.

2.2 Contaminants of Concern

While some pollutants are found dissolved in water, most contaminants of concern in PIB are typically associated with the sediment phase. These contaminants include certain toxic heavy metals, polycyclic aromatic hydrocarbons (PAHs), and oil and grease.

It was beyond the scope of this study to assess the occurrence of PAHs, but sediments were collected from the study sites for the measurement of selected heavy metals (cadmium, copper, lead, nickel, and zinc) and oil & grease. A variety of methods is used to set levels of concern for each of these substances.

2.3 Effects of Urbanization

Typical land uses in an urban setting include: residential land, commercial land, industrial land, other developed land such as parking lots, open lands such as parks and golf courses, and transportation (airports, highways and roads, railroads) (Novotny and Olem, 1994). Urbanization is a major source of non-point source pollution (NPS). NPS occurs when precipitation runs across land or percolates through it picking up pollutants and depositing them into water bodies (EPA, 1996a). Urbanization can also lower ground water levels due to inflow and infiltration into sewer lines and also from drainage below ground-level from the sub-structure of buildings (Novotny and Olem, 1994). Urbanization can degrade water bodies through the interactions of precipitation with impervious surfaces, runoff, and atmospheric deposition.

2.3.1 Impervious Surfaces

Urban settings tend to have a greater percentage of developed land than do rural areas. Nonporous urban landscapes such as roads, bridges, and parking lots, allow no infiltration. Runoff flows quickly into waterways and sewer systems (EPA, 1996b). Thus, urbanization shortens the time of concentration and overland flow, and reduces long-term upland sediment yield (Fischenich, et al., 2001). Thus, more water enters waterways at higher velocities over short periods of time, greatly increasing stream bank erosion and causing channel widening. Wider channels lead to lower water depths in dry periods, lowering habitat quality, and higher depths during wet periods, and increased sediment loads (EPA, 1996b).

2.3.2 Urban Pollution

Over long periods of time in areas with storm sewers, pollutants deposited onto impervious surfaces, excluding that removed by wind, decay, or street sweeping, will end up in surface runoff (Novotny, et al., 1994). Washout and runoff from urban areas such as construction sites, roadways, and other impervious surfaces introduce pollutants such as oil, grease, road salts, and heavy metals, and increase sediment loads (EPA, 1996b). Sediment delivered to streams can either be suspended and create turbid water, or settle to the bottom increasing embeddedness, which in excess can be detrimental to stream biota (Nerbonne and Vondracek, 2001).

In urbanized areas with high percentages of impervious land, runoff includes less sediment but higher levels of heavy metals, fecal coliforms, and other pollutants (Fischenich, et al., 2001). Trace metal concentrations are elevated in urban areas due to emissions from industrial and municipal activities as well as metals washed from roadways (USGS, 2001). Correlation between population density, traffic density, and total lead and zinc concentration indicate that population density is strongly related to traffic density and is an indicator of lead and zinc concentrations in the environment (Callender and Rice, 2000).

Motor vehicle traffic is directly responsible for the deposition of various pollutants including hydrocarbons, metals, and oils (Novotny and Olem, 1994). Zhou et al. (1997) concluded that trace metal concentrations in surface soil are considerably higher in areas of high vehicular traffic than in residential areas. Exhaust emissions, tire wear, solids transported by tires and underneath the frame, the wear and breakdown of parts, and the loss of lubrication fluids add to urban pollution (Novotny and Olem, 1994).

The use of salts on roadways for deicing is common in snow belt and mountain areas. The leading states in salt use on roadways are Michigan, Minnesota, Ohio, and Pennsylvania. High concentrations of salt on streets and in runoff is a major contributor to vehicular corrosion, and this metal loss is subsequently incorporated into snowmelt runoff (Novotny and Olem, 1994).

2.4. Study Goals and Objectives

The Goals of this study were:

- To document the general condition of streams in the PIB watershed.
- To document patterns of impairment in the watershed.
- To rank sites according to impairment, using both physical habitat and sediment quality.

3. Methods

3.1 Sampling Locations

Sampling sites were selected along Mill Creek (Figure 2), Cascade Creek (Figure 3), Garrison Run (Figure 4), and Scott Run (Figure 5). Reference sites in non-urbanized areas were located along 12-Mile and 7-Mile Creeks , as well as on Elk and French Creeks (not shown).

Table 1 provides the locations of the sites included in the study. Site ID's were assigned using the initials of the creek name and a number corresponding to the site's sequence from the mouth (one being closest to the mouth). All reference sites were given the initials RF, and were numbered according to the sequence they were studied.

Table 1. Study site locations.

Site ID	Creek Name	Coordinates
MC-1	Mill Creek	42 6' 20.05"N, 80 4' 23.04" W
MC-2	Mill Creek	42 5.19'N, 80 4.22' W
MC-3	Mill Creek	42 5' 11.61"N, 80 4' 14.58" W
MC-4	Mill Creek	42 4.64'N, 80 3.09' W
MC-5	Mill Creek	42 5.49'N, 80 3.41' W
MC-6	Mill Creek	42 6.18'N, 80 1.58' W
MC-7	Mill Creek	42 6.18'N, 80 1.66' W
MC-8	Mill Creek	42 5.40'N, 80 1.19' W
CC-1	Cascade Creek	42 7.60'N, 80 6.67' W
CC-2	Cascade Creek	42 7.03'N, 80 6.99' W
CC-3	Cascade Creek	42 6.81'N, 80 6.96' W
CC-4*	Cascade Creek	42 6.67'N, 80 7.26' W
CC-5*	Cascade Creek	42 6.38' N, 80 7.94' W
CC-6	Cascade Creek	42 6.10'N, 80 6.86' W
SR	Scott Run	42 6.62'N, 80 9.25' W
GR	Garrison Run	42 8.29'N, 80 4.29' W
MSS*	Myrtle St. sewer	42 7'59.3"N, 80 5'43.27"W
RF-1	7-Mile Creek	42 9.23'N, 80 56.53' W
RF-2	7-Mile Creek	42 10.90'N, 79 58.59' W
RF-3	12-Mile Creek	42 12.24'N, 79 54.74' W
RF-4	French Creek	41 54.56'N, 79 59.20' W
RF-5	French Creek	41 55.34'N, 79 53.99' W
RF-6	Elk Creek	42 0.39'N, 80 5.34' W
RF-7	Elk Creek	41 59.82'N, 80 9.89' W

*denotes water and sediment quality testing only.

Figure 2. Mill Creek study sites. Map courtesy of Maptech, 1997.

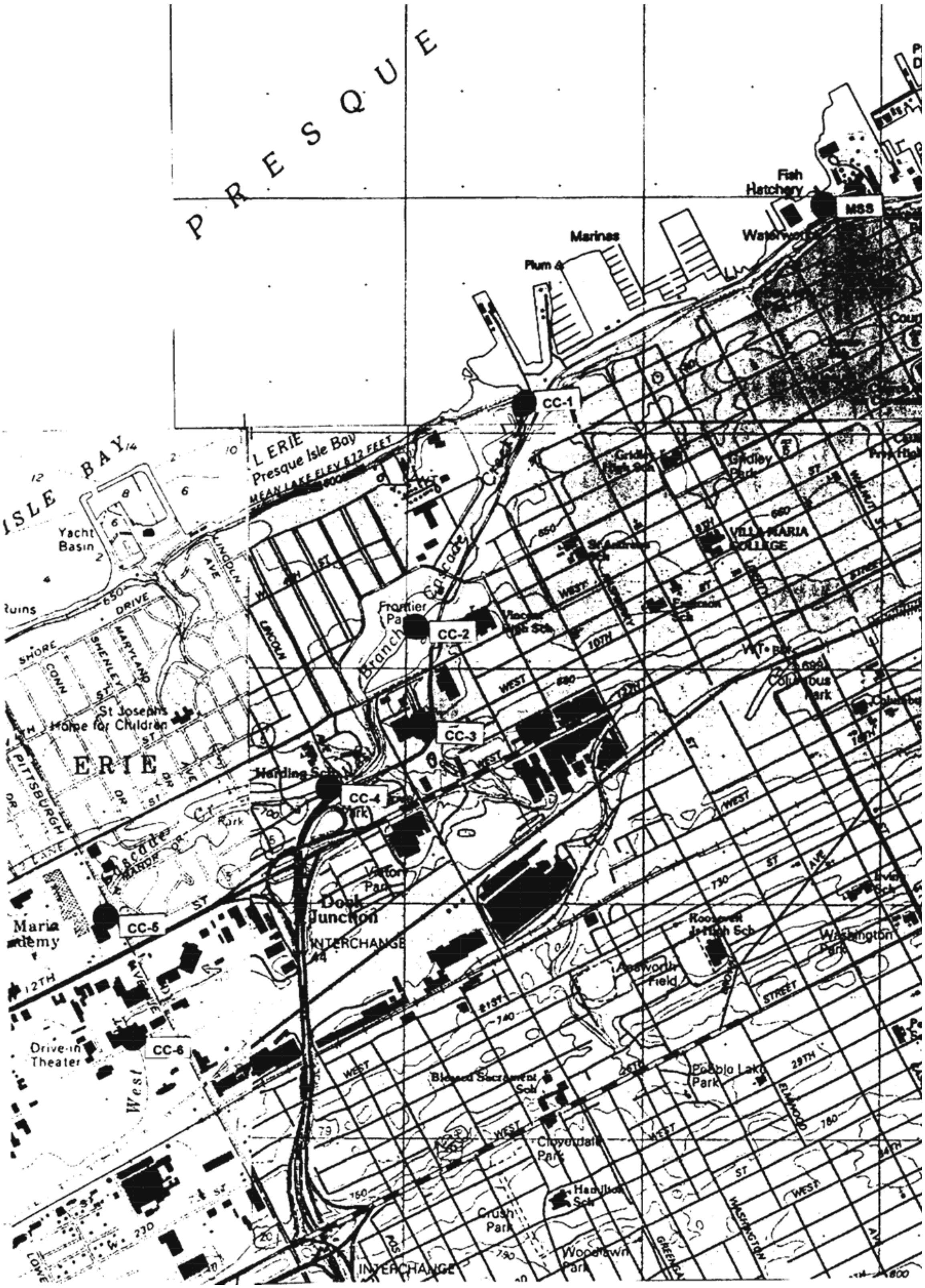

Figure 3. Cascade Creek study sites and the Myrtle Street sewer outfall. Maptech, 1997.

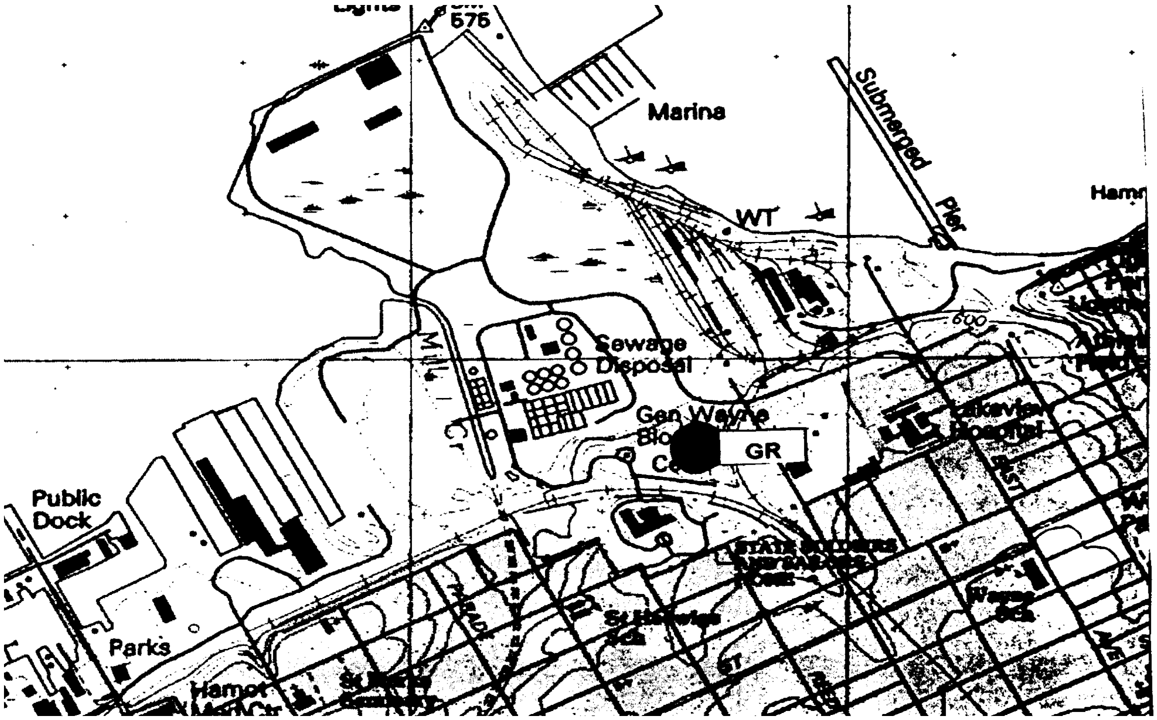

Figure 4. Garrison Run study site. Maptech, 1997.

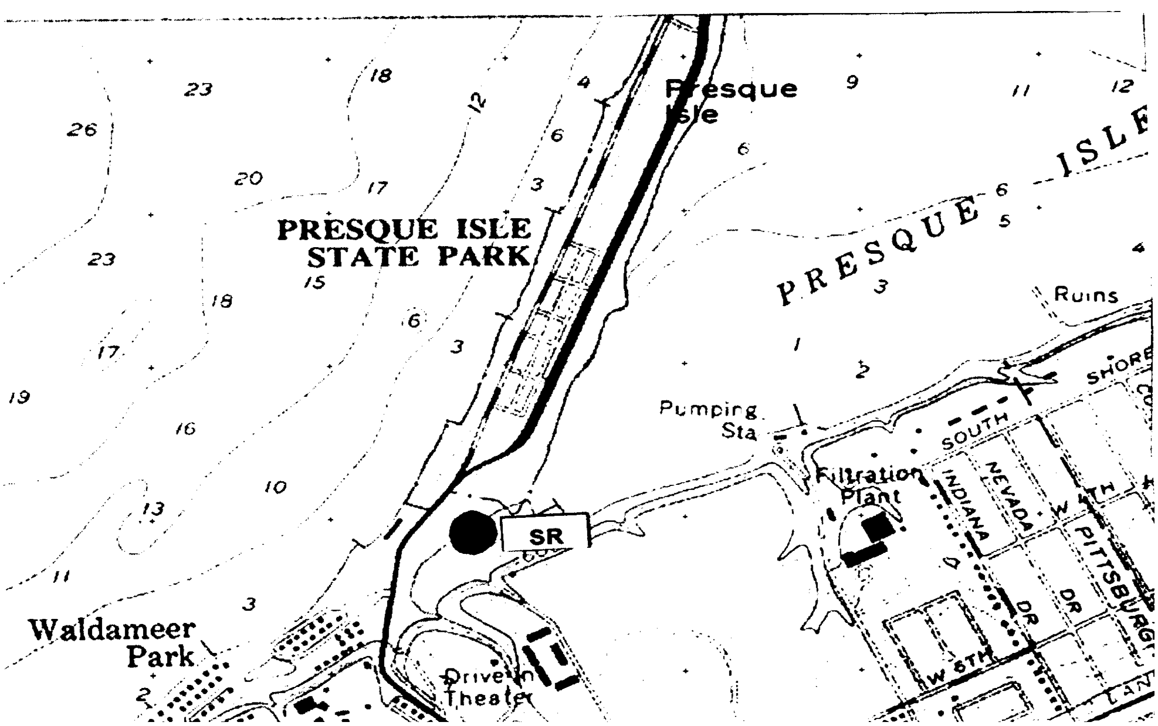

Figure 5. Scott Run study site. Maptech, 1997.

3.2 Field Activities

3.2.1 Surveys of Cross Sections

Within each 100 meter long study reach, a location was selected for a simple cross section survey. If there was a location which had an erosion problem or severe bank instability, it was selected. A steel re-bar stake was driven into the ground on each bank, and was marked with survey tape. The location of each stake was documented in a field notebook for future reference. A tripod and survey transit were set up on the higher of the two banks. A 100m tape was stretched across the channel and tied off on each stake. Vertical and horizontal measurements were taken across the channel and recorded. Then, the stakes were driven into the ground for future reference. Cross-section data is presented in Appendix F.

3.2.2 EPA Rapid Bioassessment Protocol

Habitat and physicochemical parameters were assessed at each site using the EPA Rapid Bioassessment Protocol (RBP). The purpose of the RBP is to characterize and rank impairments to a water resource by identifying and evaluating sources and causes (Barbour, et al., 1999). The RBP habitat assessment is divided into two parts: 1) physical characteristics and water quality, and 2) a visual-based habitat assessment. The physical characterization combines such information as land use, stream origin and type, riparian and in-stream features with in-situ measurements for water quality parameters. This physical characterization is done in order to assess the stream's ability to support an aquatic ecosystem. This information, coupled with analytical testing, can provide information on chemical and physical stressors present at the site. The physical habitat and water quality data sheets used at each site are found Appendix A.

The visual-based habitat assessment includes ten parameters evaluated and scored on a range of 0-20 based on subjective judgment using guidance supplied by the protocol. Parameters differ depending on whether the stream has a high or low gradient. The ranges for each parameter are described as "optimal, sub-optimal, marginal, and poor." Reference sites (those that appear not to be stressed ecosystems) are valuable in comparing scores with study sites. Impairment of a study site is defined as being a relative difference in score when compared with appropriate reference sites.

Each parameter is weighted equally. The parameters included are as follows.

- <u>Epifaunal substrate or available cover</u>; evaluated for high and low gradient streams; overall evaluation of all structures present in the reach which could provide opportunity for fish and macroinvertebrates to feed and spawn; new fall, i.e., material recently deposited in the stream, is not a stable habitat and is not considered.
- <u>Embeddedness</u>; only measured in high gradient sites where there is substantial flow; results from large-scale sediment movement within a stream; poor habitat is the result of gravel, cobbles, etc. being nearly or completely surrounded and covered by silt and mud; (for low gradient streams, the pool substrate is characterized).

- Velocity/depth regime: (slow deep, slow shallow, fast deep, fast shallow); only assessed for high gradient streams; stable situation, all four regimes will be present; pool variability is used for low gradient streams.
- Sediment deposition; evaluated for high and low gradient streams; a measure of the amount of sediment moved and deposited through a reach; islands and point bars are indicators of large volumes of sediment moving through the system, indicating an unstable condition.
- Channel flow status; the amount of water in the channel is estimated for both stream gradients; a measure of the exposure of the stable substrate or available habitat; few stable habitats exist in streams where the shape of the channel is changed or diverted.
- Channel alteration; urban and agricultural streams altered for flood control or irrigation purposes; measured in both high and low gradient streams.
- Frequency of riffles; in high gradient streams, stream community depends on riffles to provide high-quality habitat and otherwise enhance the aquatic community through diversity; in low gradient streams, the meandering or sinuosity of the stream is measured; numerous bends can better accommodate floodwaters, absorbing energy from the flow, reducing erosion and sedimentation.
- Bank stability; for both gradients, raw banks and undercutting are signs that the banks are unstable and erosion could be a problem; severely eroded banks can be strong indicators of sedimentation problems downstream.
- Vegetative protection; strong effect on the stability of a bank; a variety of vegetation as well as strong root systems can increase the stability of a bank by holding the soil together.
- Riparian vegetative zone width; scored by measuring the width of the natural vegetative zone along the stream bank; provides a buffer for pollutants from roadways and other sources of runoff.

3.2.3 Photo-documentation

Photographs of erosion problems or any outfalls into the stream were taken at each site using a digital camera. The stretches of stream in between sites were also inspected and photographed for future reference. Together, these photographs provide a visual record of the status of the watershed.

3.2.4 *In-Situ* Measurements

On-site measurements of pH, dissolved oxygen (DO) and temperature were made at each site using Accumet portable pH and DO meters. Specific conductivity was measured with a Corning 311 portable conductivity meter and recorded in mS/cm. The surface velocity was taken at the thalweg of the stream with a hand-held velocity meter and recorded in ft/s, then converted to m/s.

3.2.5 Water and Sediment Sample Collection Procedures

Three water and sediment samples were collected within each sample reach, one upstream, one downstream, and one in the middle of the sample reach. A duplicate was collected at each site from one of the three sample locations, chosen randomly. Sample bottles were pre-washed using Alconox and rinsed with tap water. The bottles were then placed in a 0.1 N nitric acid bath for 24 hours and rinsed with deionized water and acetone. Bottles used in BOD analysis were not rinsed in acetone.

Water samples were collected in 1 L plastic bottles (TSS and NPOC analysis) and in 250 mL small-neck plastic bottles (turbidity analysis). One additional 1 L plastic bottle was used to collect a sample for BOD_5 testing. All water samples were collected with the bottle mouth facing downstream and were filled to the top so as to avoid air headspace in the bottle.

Sediment samples were collected using a small garden shovel to scoop the sediment from the stream bed. The sediment was then passed through a VWR Scientific #10 U.S Standard Testing Sieve of ASTM F-11 specification and transferred to the bottle with the shovel. The four samples collected at each site were placed in 250 mL wide-mouth plastic bottles for metals analysis. In addition, one sample was collected in a 250 mL wide-mouth glass bottle for oil & grease (HEM) analysis. The glass-bottle sample was a composite containing a mixture of sediment from the various spots along the sample reach. The sediment was mixed before it was transferred to the bottle.

3.3 Laboratory Procedures

3.3.1 Total Suspended Solids (TSS)

One-Liter samples were filtered using a vacuum pump. Suspended solids were recovered using Whatman 934-AH glass fiber filters and placed in a drying oven at 105° C overnight. The increase in weight was recorded as TSS.

3.3.2 Dissolved Organic Carbon (DOC)

Dissolved organic carbon was measured for four samples per site using the filtrate from the suspended solids samples. Dissolved organic carbon was measured in the sample by the non-purgeable organic carbon (NPOC) method using a Shimadzu 5050A Total Carbon Analyzer. Each sample was acidified with phosphoric acid to convert carbonate and bicarbonate ions to carbonic acid. The sample was then sparged with oxygen for 10 minutes, stripping carbonic acid (as carbon dioxide) from the sample (this may also remove volatile organics). Before and after each sample batch, a standard of known carbon content as well as a deionized water blank were analyzed for quality control purposes.

3.3.3 5 Day Biochemical Oxygen Demand (BOD_5)

The BOD_5 was determined at each site using the five-day test procedure as described by Standard Method 5210B (APHA et al., 1998). Initial and final DO concentrations were measured using a YSI 52 Dissolved Oxygen Meter. Samples were incubated in a Hach BOD Incubator 205 at 20° C in the dark for the test period. When necessary, samples were diluted 1:10 with dilution water prepared in accordance with Section 4.a. of the procedure. To insure quality control, a dilution water blank was run with each batch of diluted samples. A deionized water blank was run with all batches when the sample was not diluted.

3.3.4 Turbidity

Turbidity measurements were made on four samples per site. Readings were made using an Orbecco-Hellige Digital Direct-Reading Turbidimeter. Results were measured in nephalometric turbidity units (NTUs). The unit was zeroed and checked with a 40 NTU turbidity standard before every sample batch.

3.3.5 Acid Digestions for Metals Analysis

Acid digestions were performed on all plastic-bottle sediment samples. Samples (1-2 g wet wt) were digested with repeat additions of trace-metal grade nitric acid and 30% hydrogen peroxide according to EPA Method 3050B (EPA, 1990b). Hydrochloric acid (trace-metal grade) was added to the digestate and refluxed for 15 minutes. This is an optional step to increase the solubility of certain metals for later analysis (EPA 3050B, Section 2.3). The final digestate was diluted to 100mL using a volumetric flask. A duplicate and matrix spike (1.5mg/L) of every tenth sample was digested for quality control purposes.

3.3.6 Moisture content

Approximately 10-g of sediment was placed in an aluminum weighing pan and its actual weight recorded. The sample was then dried at 105° C overnight in a drying oven. The sample was then cooled in a desiccator for at least 1 hour and weighed. The change in weight was then calculated. Two replicates from each bottle were measured and the average dry weight fraction was determined.

3.3.7 Metals Analysis by Flame Atomic Absorption (FLAA)

Final digestate from acid digestions were analyzed for metal content using FLAA spectroscopy. The analysis was performed for five metals: cadmium, copper, lead, nickel, and zinc using a Perkin Elmer AAnalyst 100 Atomic Absorption Spectrometer. Calibration and setup followed the procedure in the instrument User's Guide. The machine was optimized for each metal using a standard made at the characteristic concentration of that particular metal (the concentration at which the instrument detects an absorbance of 0.20 units). Once calibrated, the instrument was checked using a standard of known concentration every ten samples to ensure accuracy. Metals standards were prepared using 1mg/mL Fisher Scientific stock solutions of each metal.

3.3.8 Oil & Grease

Oil & grease was determined using the Hexane Extractable Material (HEM) in accordance with EPA Method 9071B, and was performed on one glass-bottle composite sample per site. The dry weight fraction was used to calculate the oil and grease concentration in mg/kg of dry sediment. A duplicate and matrix spike was extracted on every tenth sample. A method blank and a laboratory control sample were also extracted. Spiking solution was prepared according to Section 7.7 of the Method. Spiked samples and laboratory control samples contained 20mL of the 4000mg/L spiking solution.

4. Results and Discussion

4.1 Physico-chemical Assessment

The results of the physical characterization and *in-situ* testing for the Mill Creek, Cascade Creek Sites, Scott Run (SR), Garrison Run(GR), and the Myrtle Street Sewer(MSS) are as follows. The reach area at each site ranged from 0.0002 to 0.0021 km^2 with an average of 0.00099 km^2. Stream depth varied from 0.08m to 0.35 m, and stream velocity at the thalweg ranged from negligible to 2.3 m/s.

The density of large woody debris (LWD) varied greatly within the Mill Creek sites, from near zero to a high value of 52 m^2 LWD/km^2 area. The average Mill Creek LWD density was 11.7 m^2/km^2. Only two of the six Cascade Creek sites contained LWD. CC-4 had a LWD density of 119.3 m^2/km^2, over double that of the highest value at any Mill Creek site. The LWD density at CC-2 was 14.2 m^2/km^2. The remaining sites contained no LWD.

Conductivity values ranged from 0.51-1.1 mS/cm in Mill Creek, averaging at 0.70 ms/cm. The conductivity values at the Cascade Creek sites were between 0.8 and 3.42 mS/cm, and the average was 1.41 mS/cm. The conductivity values at SR, GR, and MSS were 0.84, 1.1, 0.9 mS/cm, respectively.

DO measurements varied from 6.0 to 11.1 mg/L at the Mill Creek sites, and from 8.8 to 11.0 mg/L at the Cascade Creek sites, with averages of 8.76 and 9.89. The DO at SR, GR, and the MSS were 8.64, 7.53, and 8.55 mg/L.

The pH values were relatively constant at all Mill Creek and Cascade Creek sites with an average value of 8.0. The values for SR, GR, and MSS were 8.0, 7.7, and 8.2, respectively.

TSS values were low at all Mill Creek sites and ranged from 0.002 to 0.046 g/L with the average of 0.016 g/L. The Cascade Creek sites had an average of 0.004 g/L of suspended solids. With a value of 0.054 g/L, SR had the highest value for TSS of all the sites. GR and MSS had values of 0.006, and 0.005 g/L, respectively.

Turbidity ranged from 1.4 to 11.1 NTU for Mill Creek sites with an mena value of 5.5 NTU. For the Cascade Creek sites the turbidity ranged from 1.3 to 6.7 NTU, with a mean value of 3.88 NTU. The turbidity for SR was 23.6 NTU, the highest value of all the sites. GR and MSS had values of 3.08 and 2.25 NTU. TSS and turbidity data appears in Appendix B.

4.2 Habitat Assessment Scores

The habitat assessment scores for all of the study sites are presented first for each parameter separately (individual score sheets for all sites appear in Appendix A). Then sites are ranked using combined scores for all factors. The maximum possible score is 20 for each parameter, and 200 overall per site. The actual scores ranged from a high of 156 to a low of 91. Only four sites fell below a score of 100, (2 reference sites, Scott Run (SR) and a site on Cascade Creek). Two reference sites scored above 140, while 3 Mill Creek sites exceeded that value. Overall results are reviewed in detail later in the report.

4.2.1 Epifaunal substrate/available cover

Sites MC-2 and MC-6 received the lowest scores for this parameter, while MC-8 and CC-6 fell into the "optimal" condition category, having more than 50% of substrate available for suitable habitat (Figure 6). A "poor" condition indicates that a lack of habitat exists with only about 20% being stable. The remainder of the sites fell mostly into the marginal category (score 6-10), however, three sites did fit into the "sub-optimal" category (score 11-15). The average score received at reference sites 1-3 was just over 11, while the average at reference sites 4-7 was slightly lower at nine. In comparison to the reference sites, most of the sites had a less suitable habitat for colonization.

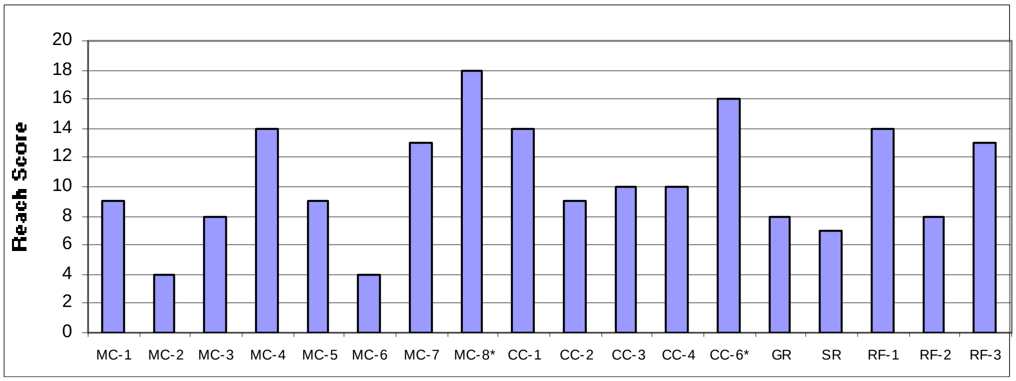

Figure 6. Scores for epifaunal substrate/available cover at each site. "*" denotes a low gradient site.

4.2.2 Embeddedness or Pool Substrate

Embeddedness was assessed at the high gradient sites, and pool substrate characterization was assessed at the low gradient sites (Figure 7). CC-6 received the only optimal score with a mixture of substrate material in the pools as well as root mat and submerged vegetation present. MC-8 was the other low gradient site and received a

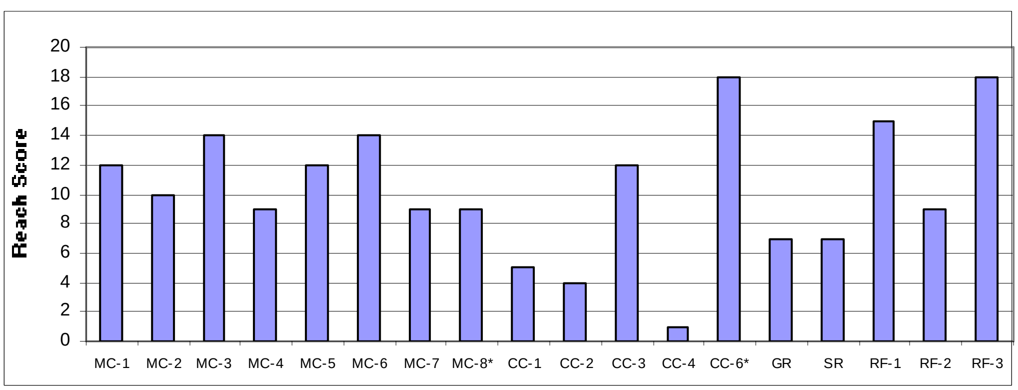

Figure 7. Scores for embeddedness or pool substrate characterization. "*" indicates low gradient.

score in the “marginal” condition category because of the presence of mostly mud, clay, sand, and the lack of submerged vegetation. CC-1, 2, and 4 contained the highest degree of embeddedness having gravel, cobble, and particles more than 75% surrounded by fine sediment. The Mill Creek sites were generally less embedded than the other sites, having four sites in the “sub-optimal” condition category (25-50% surrounded). CC-3 also fell into this category and the rest of the sites were in “marginal” condition (50-75% surrounded). All of the reference sites scored in the “sub-optimal” category. Reference sites 1-3 scored near the higher end of the category, and 4-7 at the lower end. In the embeddedness category, the Mill Creek sites habitats scored nearly as favorably as did the reference sites.

4.2.3 Sediment Deposition

A related parameter to embeddedness is sediment deposition. This parameter was assessed for both gradients (Figure 8). Scott Run, CC-1, and MC-7 all scored in the “poor” category having heavy sediment deposits and over 50% of the stream bottom changing on a regular basis. Garrison Run, CC-2, CC-4, MC-4, and MC-8 all scored in the “marginal” category with scores ranging from 6-10 (moderate deposition with 30-50% of the stream bottom affected by sediment). The remainder of the sites received scores in the “sub-optimal” range, including Reference Sites 1-3, which averaged 13. Reference Sites 4-7 averaged near 9, which placed them in a lower category. The “sub-optimal” category reflects some new increase in sediment formations with 5-30% of the bottom affected by sediment for high gradient and 20-50% affected for low gradient.

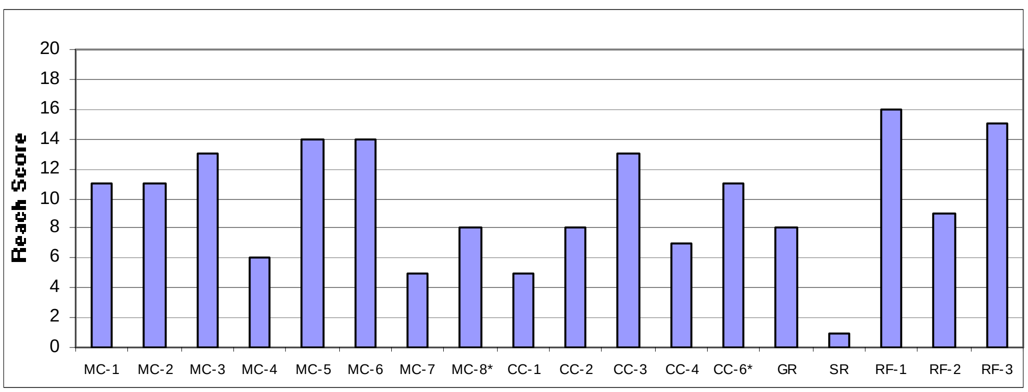

Figure 8. Scores for sediment deposition for all sites including low gradient. “*” indicates low gradient.

4.2.4 Velocity/Depth – Pool Variability

For high gradient sites, velocity/depth regimes were assessed while pool variability was examined in low gradient reaches (Figure 9). Three sites (MC-1, MC-2, CC-1) contained all four velocity/depth regimes and received scores in the “optimal” condition category. MC-5, CC-2, CC-3, and GR all received scores in the “sub-optimal” range, containing three of the four regimes. The rest of the sites fell into the “marginal” category having only two of the regimes present.

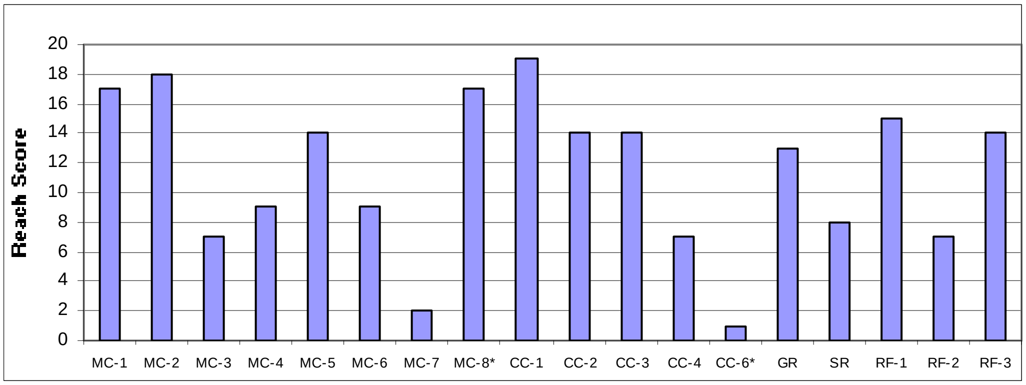

Figure 9. Habitat scores for velocity/depth regimes in high gradient sites, and for pool variability in low gradient sites. "*" indicates low gradient.

The two low gradient reaches, MC-8 and CC-6, had scores of 17 and 1, respectively. MC-8 was in the "optimal" condition category with a variety of types of pools. CC-6 received a "poor" score because of its lack of pools. The reference sites all scored in the "sub-optimal" range with averages of 14 for sites 1-3, and 11 for sites 4-7. A lower score was given to sites 4-7 because the missing regime was fast-shallow. More than half of the sites obtained scores similar or higher than those of the reference sites.

4.2.5 Channel Flow Status

Channel flow status is the degree to which the water reaches both banks of the reach. Only one site, MC-4, received a score in the "poor" condition category (Figure 10). MC-3, CC-1, CC-2, GR, and SR received scores in the "marginal" range. Reference sites 1-3 had an average score for this parameter of almost 7.5. The remainder of the sites all had scores above this value. MC-7 and CC-6 both fell into the "optimal" condition range with water nearly reaching both banks. The scores of the other sites were in the "marginal" category with similar scores to reference sites 4-7 with an average of 13.

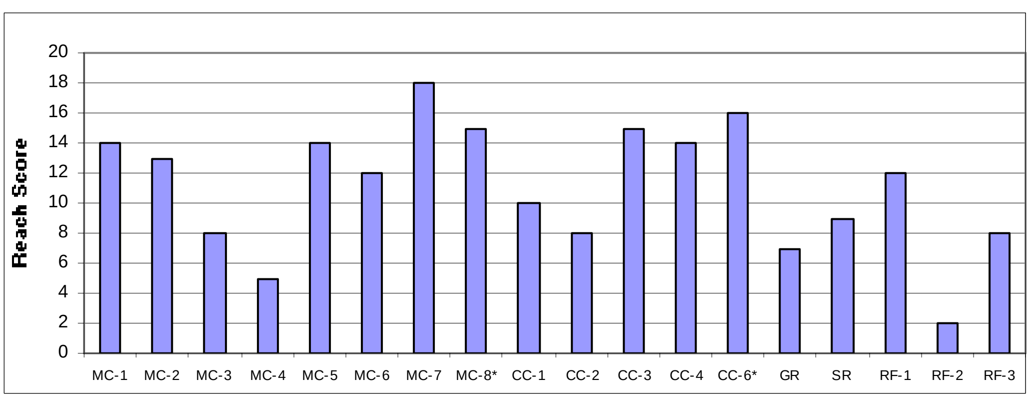

Figure 10. Channel flow status scores for all sites.

4.2.6 Channel Alteration

Estimating channel alteration assessed the degree to which the stream was impacted by human factors such as channelization and dredging. All sites except MC-2, had scores at least at the "sub-optimal" level (Figure 11).

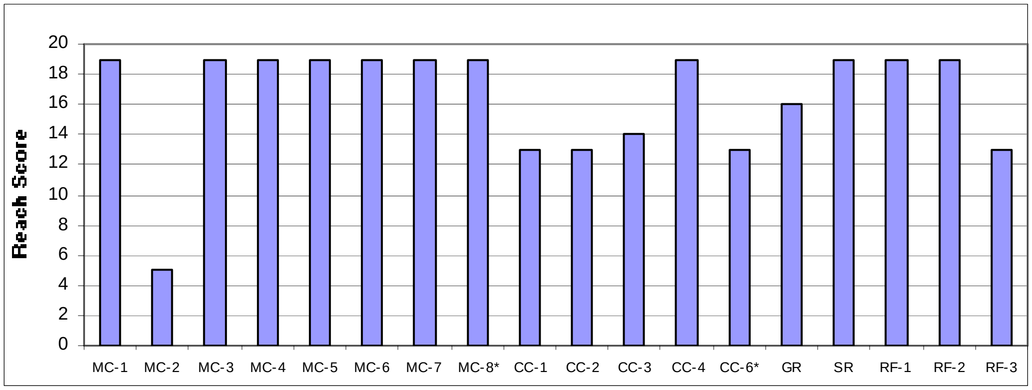

Figure 11 Channel alteration scores for all sites.

MC-2 received a low score because it was channelized with a concrete wall for a portion of the reach. All other Mill Creek sites scored higher than the average reference score of 17. These scores show that the reaches were contained streams with normal flow patterns. CC-4 was the only Cascade Creek site that scored in the "optimal" range. CC-1, 3, and 6 scored in the "sub-optimal" range with little channelization present due to bridges as well as some evidence of past channelization efforts. The rest of the sites were in the "marginal" range caused by 40-80% of the reach disrupted.

4.2.7 Riffle Frequency – Channel Sinuosity

The frequency of riffles was estimated on high gradient streams, and channel sinuosity on low gradient streams. Channel sinuosity is the ratio of the stream centerline length to the valley length. MC-8 scored in the "optimal" range for this parameter because meanders increased the ratio considerably (Figure 4.1-8). CC-6, having a virtually straight channel, scored in the "poor" range.

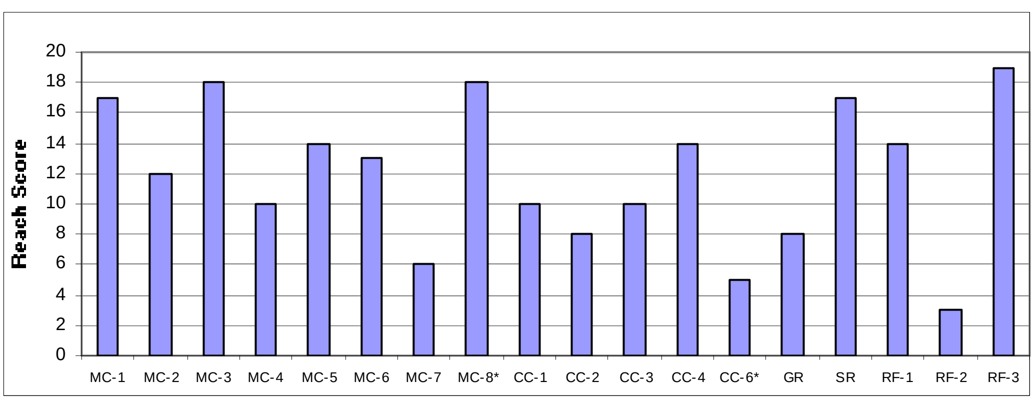

Figure 12. Reach scores from channel sinuosity or for the frequency of riffles.

MC-1, MC-3, and SR all received "optimum" condition scores having frequent occurrences of riffles. MC-7, CC-2, and GR scored in the "marginal" condition category with only occasional riffles. The majority of the sites scored in the "sub-optimal" category, receiving similar scores as the reference sites, which averaged about 13.

4.2.8 Bank Stability and Vegetative Protection

Bank stability, vegetative protection, and riparian zone width were assessed at all of the study sites, for each bank separately (right and left banks were determined by facing downstream). The scores for bank stability and vegetative protection are presented in Figure 13.

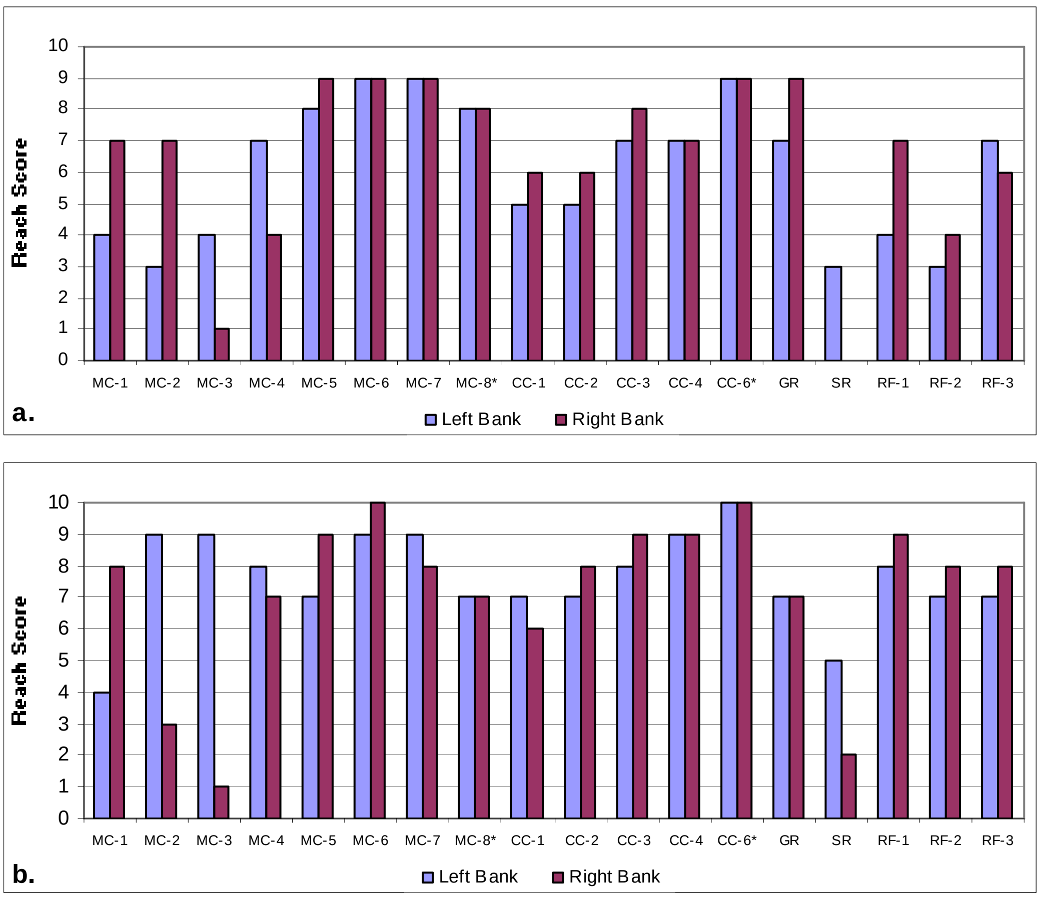

Figure 13. Assessment scores for (a) bank stability and (b)vegetative protection for all sites.

For bank stability (Figure 13a)Reference sites 1-3 had an average combined (left and right banks) score of 10.3. All of the Cascade Creek sites as well as most Mill Creek sites and Garrison Run exceeded this score. The bank stability scores for the remaining reference sites (4-7) had an average score below 9. Scott Run earned the lowest score with a 3 for the left bank and a zero for the right due to severe erosion problems. All reference sites received an average score of above 15 for vegetative protection (Figure

13b). The study sites showed similar results. Vegetative protection is a strong indicator of the stability of the stream banks. There appears to be a correlation between the bank stability scores and those for vegetative protection (Figure 14).

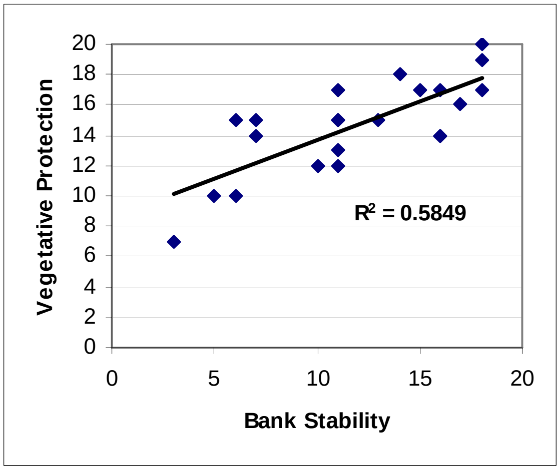

Figure 14. Relationship between the bank stability scores and the vegetative protection scores using combined right/left bank scores.

As indicated above, as the vegetative protection increases on the stream bank the bank tends to be more stable. This suggests that vegetation increases the stability of the bank by giving support through root systems and decreasing runoff and washouts.

4.2.9 Riparian Zone Width

Scores were assigned to sites based on the width of the riparian zone on each side of the stream (Figure 4.1-11). Natural riparian zones are essential to stream systems. Scores were determined based on the width of the riparian zone containing natural vegetation. "Optimal" scores are for zones above 18 meters, "sub-optimal", 12-18, "marginal", 6-12, and "poor" is less than six meters. Reference sites 1-3 had an

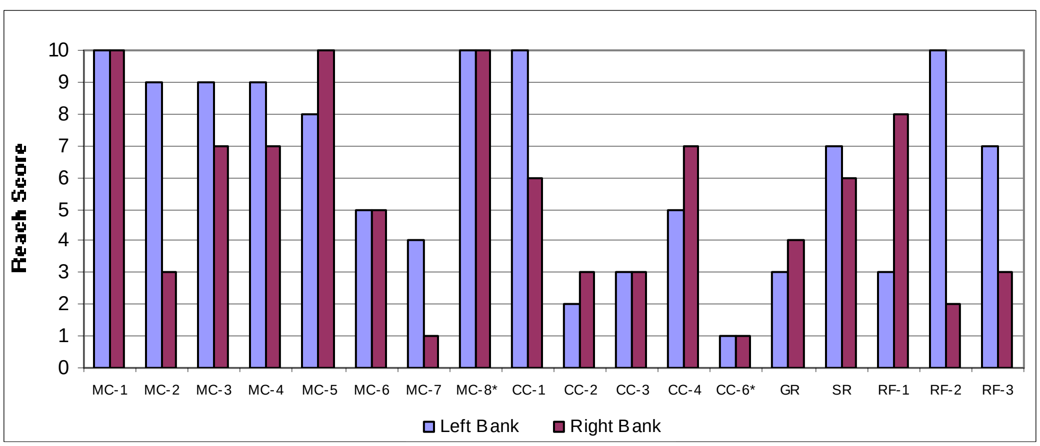

Figure 15. Riparian zone scores for all study sites.

average combined score of 11, and reference sites 4-7 had an average of 10.5. Cascade Creek sites received lower scores overall than Mill Creek and Scott Run sites. Cascade Creek flows in a more urbanized and developed watershed. Garrison Run scored below the reference sites but was still in the marginal category.

4.2.10 Combined Habitat Assessment Scores for All Sites

The mean total score for all sites was 120 (n=22, sd 18.7). The mean score for Mill Creek sites was 128 (n=8, sd 17.9). The mean score for Cascade Creek sites was 115 (n=5, sd 11.7), while the mean for the Reference Sites was 121 (n=7, sd 21.4). The score for Garrison Run was 104 and the score for Scott Run was 91. Using the Student's T-test assuming unequal variance, the Mill Creek, Cascade Creek, and Reference Sites were examined for significant differences. The only pairing which produced a significant result was Cascade compared to Mill Creek (P = 0.06). Neither set of stream sites was significantly different from the set of reference sites.

The total scores for all sites were ranked by descending value(Table 2). Two of the study sites earned the highest scores of all sites, but it is apparent that in the ranked list there is an intermingling of sites from the various watersheds studied, and reference sites are not uniformly better that the study sites. Similarly, there is no obvious trend in scores as one moves up or down stream on either Mill Creek or Cascade Creek (Figure 16).

Table 2. Site rankings by total habitat score.

Rank	Site	Total Habitat Score
1	MC-8	154
2	MC-5	147
3	RF-1	144
4	RF-4	142
4	MC-1	142
5	RF-3	138
6	MC-6	132
7	CC-3	126
8	CC-6	120
9	RF-7	119
10	MC-3	118
11	RF-6	117
12	CC-1	116
12	CC-4	116
13	MC-4	114
14	MC-7	112
15	MC-2	107
16	GR	104
17	RF-5	97
18	CC-2	95
19	RF-2	91
19	SR	91

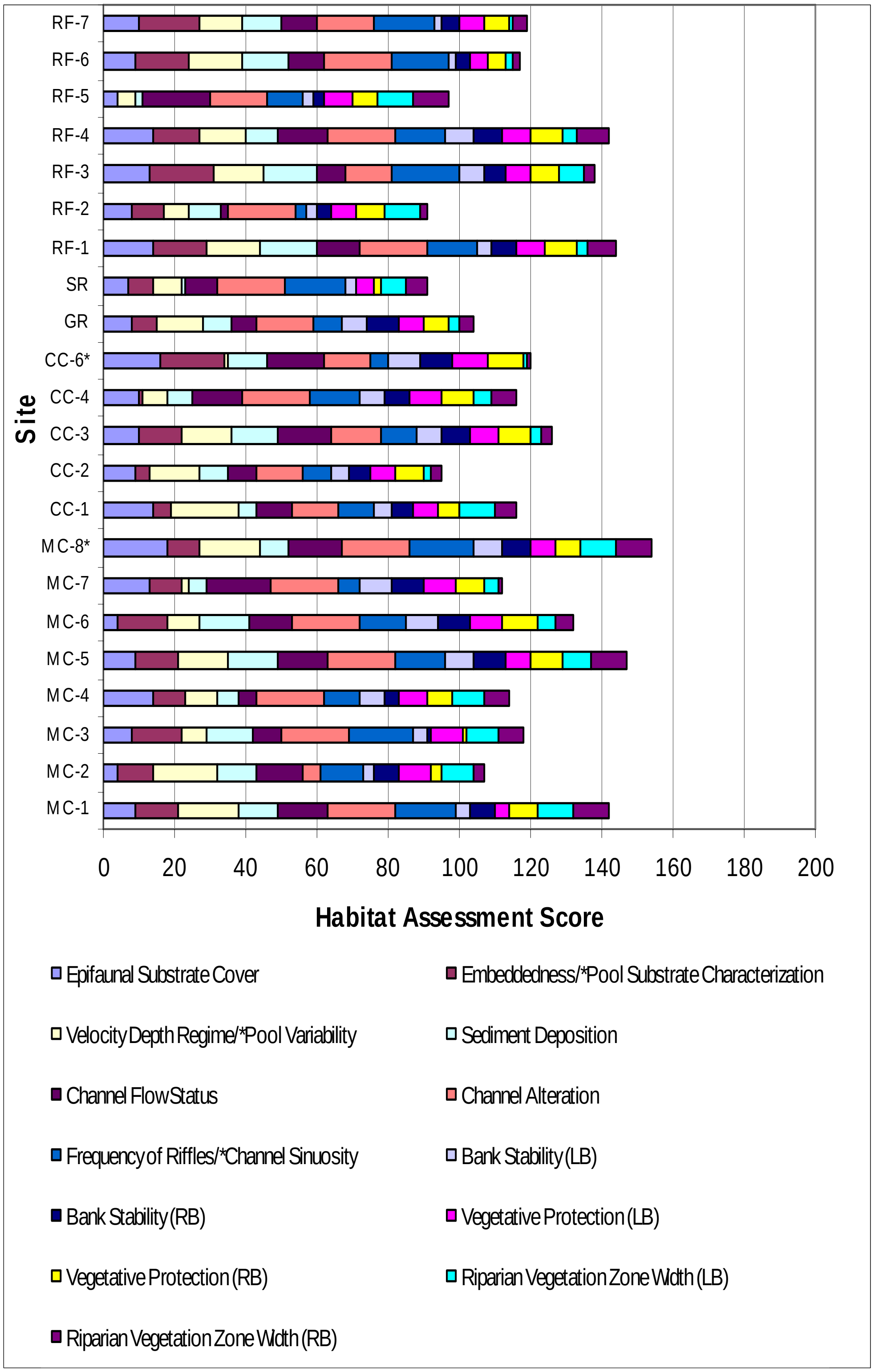

Figure 16. Consolidated scores for all parameters for all sites.

4.3 BOD_5 and NPOC

4.3.1 Organic Pollution (BOD_5)

The BOD_5 results presented in Figure 17 are the mean values (n=4) for the samples collected and analyzed from each site. A BOD_5 value of about 10 mg/L or less is considered typical for unpolluted natural waters (USGS, 2001). Seven of the study sites had a BOD_5 value in this range as did 5 of the reference sites. A value from 5-20 mg/L is considered to have some organic pollution. Two of the study sites, CC-4 and GR, exceeded 20 mg/L and would be considered polluted with organic matter.

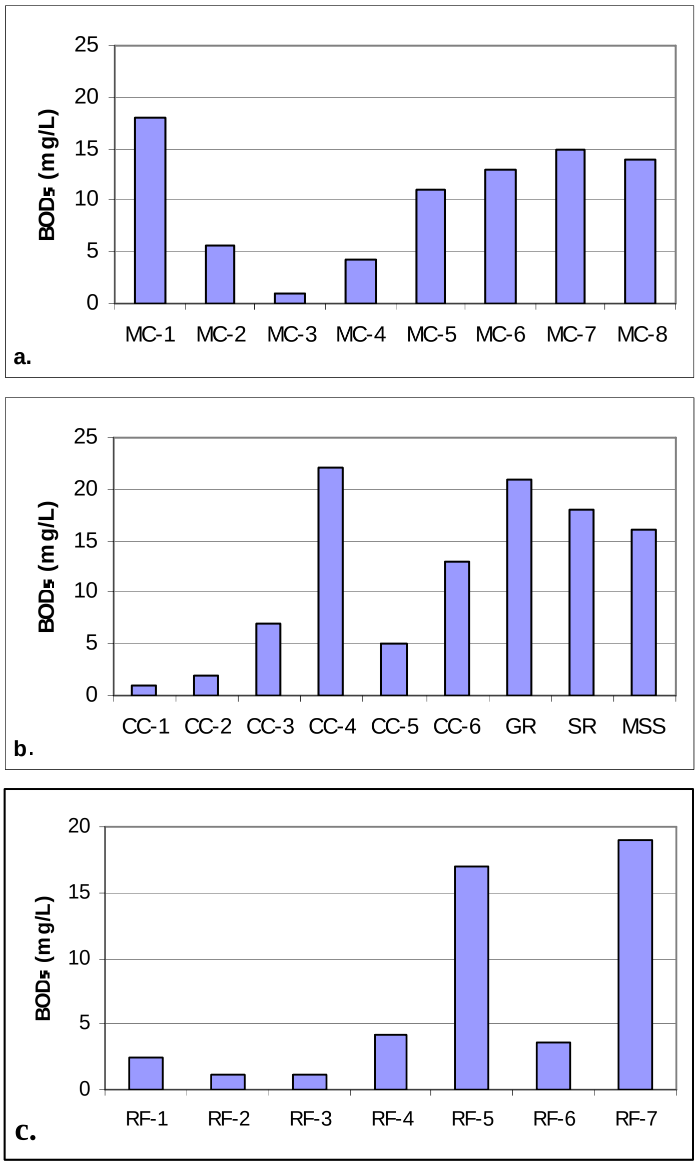

Figure 17. Mean BOD values for sites on (a) Mill Creek; (b) Cascade Creek, Garrison Run, Scott Run, and the Myrtle Street storm sewer outfall; (c) reference sites.

4.3.2 Dissolved Organic Carbon (DOC)

Not all organic carbon dissolved in water is biodegradable and thus a threat to oxygen levels in a stream. While the BOD_5 test relies upon microorganisms to feed on organic carbon in a sample over a five-day period and consume oxygen in the process, the NPOC test is a combustion procedure and will detect non-biodegradable carbon in the same sample. The NPOC test does cause a loss of volatile organics. Also, the results are reported in different units: BOD_5 is reported in terms of oxygen while DOC is reported in terms of carbon.

Mill Creek sites had dissolved organic carbon (reported as NPOC) concentrations ranging from 2.4-6.6 mg/l with a mean concentration of 4.9 mg/L. The mean for Cascade Creek sites was 3.7 mg/L with concentrations ranging from 1.5-9.1 mg/L. SR, GR, and MSS all had higher concentrations than the other study sites at 18, 21, and 16 mg/L, respectively. For these study sites, there appeared to be a reasonable correlation (R^2 = 0.54) between BOD_5 and DOC (Figure 18) . If the 3 data points which appear to consist mainly of non-degradable carbon are omitted, the correlation naturally improves (R^2 = 0.64).

For reference sites, DOC concentrations varied widely, perhaps reflecting the variety of settings in which these disparately located sites occurred. RF 1 and 3 had DOC concentrations of 15.6 and 13.6 mg/L, respectively. RF 4, 5, and 6 averaged just 5.6 mg/L, while DOC concentrations at RF-2 and RF-7 were 49 and 215 mg/L, respectively (this was noteworthy since there were low BOD_5 values at these sites).

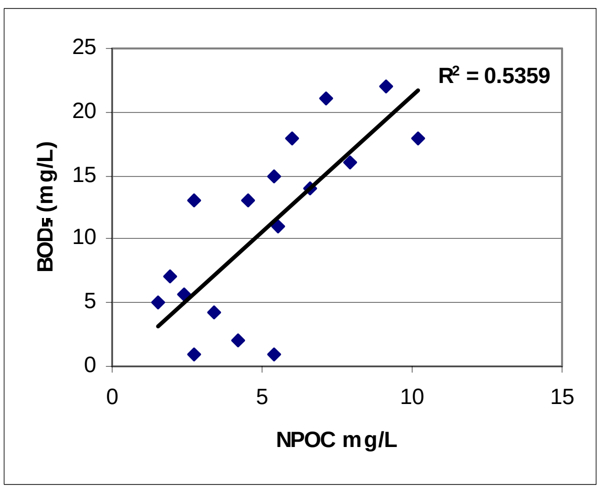

Figure 18. Relationship between BOD_5 and NPOC for PIB watershed sites.

4.4 Sediment-Associated Heavy Metals

For the purpose of this study, the sediment criteria risk levels determined by the State of New York (NYDEC,1999) since the USEPA has not yet adopted guidance for contaminated sediments. NYDEC (1999) used the results from two studies to determine low-effect (LEL) and severe effect levels (SEL). The LEL is the lower of either the Persaud et al. (1992) LEL or the Long and Morgan (1990) Effect-Range Low. Similarly, the lower value of the two studies was used to determine the SEL. The LEL implies a contaminant level such that the majority of benthic organisms would be able to conduct a complete life cycle. As stated by Persaud et al. (1992), the SEL suggest the likelihood of pronounced disturbance of the sediment dwelling community. The NYDEC considers an area where the LEL is exceeded to be contaminated (NYDEC, 1999).

All metals results are presented based on mean values for all samples analyzed at a given site, and reported as mg metal per kg dry sediment.

4.4.1 Cadmium

The LEL for cadmium in sediment is 0.6 mg/kg and the SEL is 9 mg/kg. Cadmium concentrations were low at all of the study sites on Mill Creek and Cascade Creek. Questionable results were obtained for the reference sites and will not be reported until confirmatory results are achieved.

4.4.2 Copper

Sediment at all sites was found to be moderately contaminated with copper, exceeding the LEL of 16 mg/L. The SEL for copper in sediment is 110 mg/kg, which was exceeded at one location (CC-5).

The copper concentrations on Mill Creek (Figure 19a) were below the SEL. With the exception of MC-1 and MC-2, the concentrations at the Mill Creek sites resembled the concentrations found at the reference sites (Figure 19c). MC-1 and MC-2 had sediment copper concentrations as much as double that of the reference sites. Scott Run had a copper concentration slightly over the LEL, while the concentration at GR approached the SEL. CC-5 was the only site in the study to exceed the SEL for copper, and thus was considered to be severely contaminated with copper. The rest of the Cascade Creek sites, as well as MSS, had copper concentrations that fell above the LEL but below the SEL.

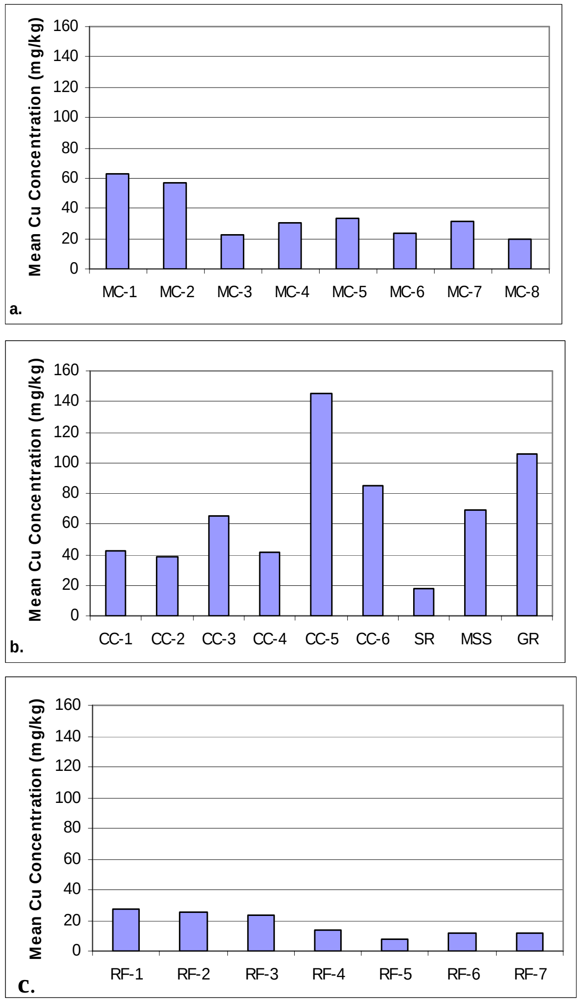

Figure 19. Mean copper concentrations at (a) Mill Creek sites; (b) Cascade Creek, Scott Run, Myrtle St. Sewer, Garrison Run sites; (c) reference sites.

4.4.3 Lead

The LEL and SEL for lead in sediment are 31 and 110 mg/kg, respectively. The sites along Mill Creek, on average, were lower than the rest of the study sites (Figure 20). There were four locations on Mill Creek site which had a lead concentration higher than the LEL of 31 mg/kg. The other Mill Creek sites had lead concentrations similar to the reference sites. RF-3 had the highest lead concentration of the reference sites at 81.4 mg/kg. The Cascade Creek sites were all above the LEL. CC-5 and CC-6 stand out as having the highest concentrations along Cascade Creek. CC-5 exceeded the SEL with a concentration of 130 mg/kg and CC-6 had a concentration of 101 mg/kg. GR and MSS were also severely impacted by lead contamination with levels above the SEL at 125 and 154 mg/kg, respectively. The mean sediment concentration of lead at Scott Run was below the LEL.

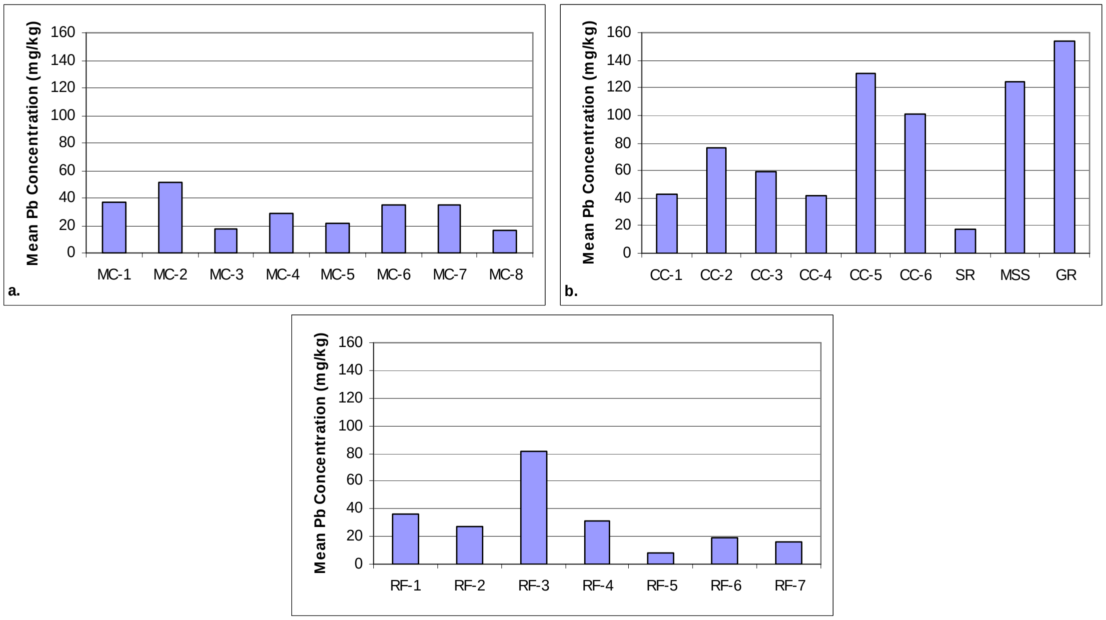

Figure 20. Mean lead concentrations at (a) Mill Creek sites and (b) Cascade Creek, Scott Run, Myrtle St. Sewer, and Garrison Run; and (c) reference sites.

4.4.4 Nickel

The LEL and SEL for nickel in sediment are 16 and 50 mg/kg. All of the study sites contained sediment concentrations of nickel above the LEL (Figure 21). Therefore, all sites were considered to have been at least moderately contaminated. The Mill Creek sites had uniform nickel concentrations, averaging about 26 mg/kg. Except

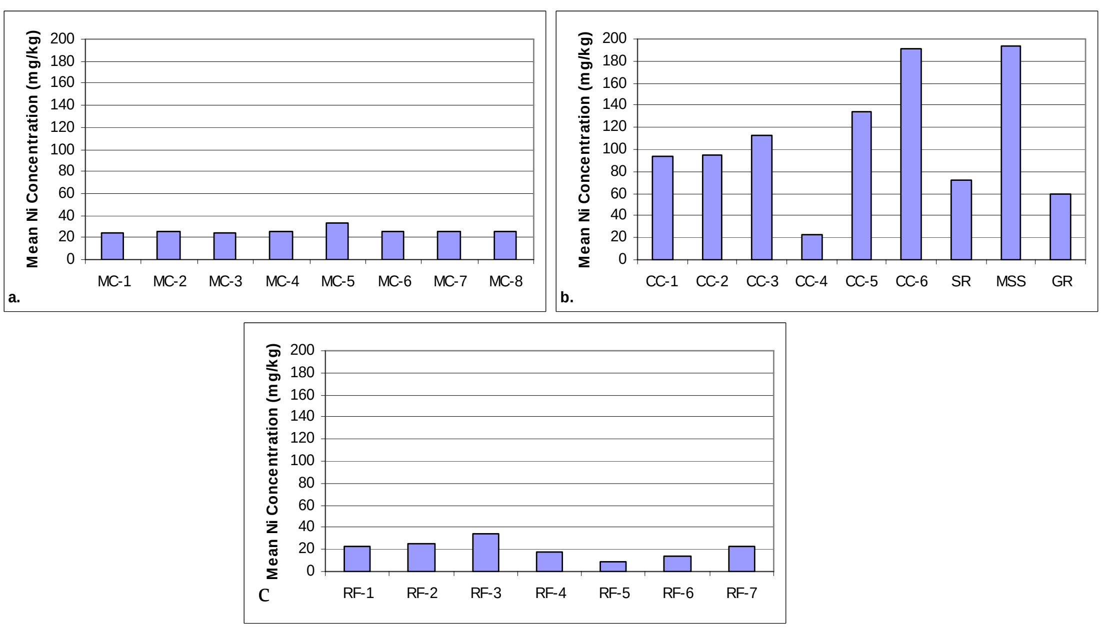

Figure 21. Mean nickel concentrations at (a) Mill Creek sites and (b) Cascade Creek, Scott Run, Myrtle St. Sewer, and Garrison Run, and (c) reference sites.

for CC-4, all of the Cascade Creek sites exceeded the SEL. CC-6 (at 191 mg/kg), was almost four times higher than the SEL. MSS had an even higher nickel concentration at 194 mg/kg. Reference sites exhibited uniformly low nickel concentrations.

4.4.5 Zinc

The LEL for zinc in sediment is 120 mg/kg, and the SEL is 270 mg/kg (NYDEC, 1999). Figure 22 presents the mean zinc concentrations from each site sampled. Using the NYDEC guidance, all of the Mill Creek sites were contaminated with zinc since all sites exceeded the LEL. MC-7, with a value of 283 mg/kg, exceeded the SEL of 270 mg/kg and therefore was considered to be severely impacted.

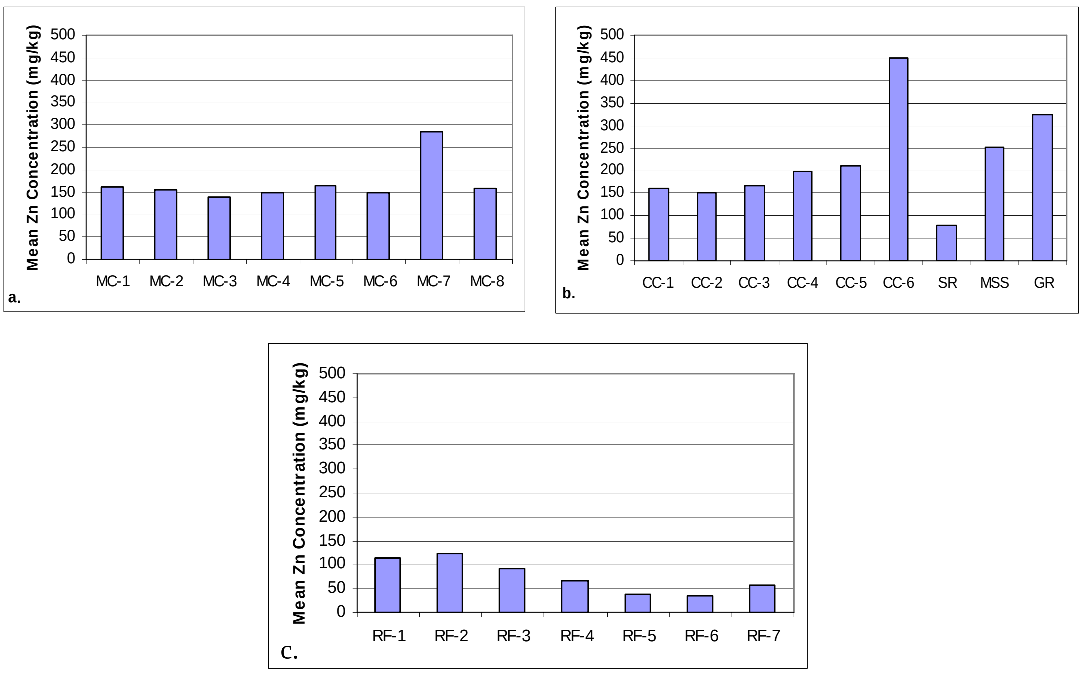

Figure 22. Mean zinc concentrations at (a) Mill Creek sites and (b) Cascade Creek, Scott Run, Myrtle St. Sewer, and Garrison Run; and (c) reference sites.

All Cascade Creek sites exceeded the LEL and were considered to be moderately contaminated. CC-6, with a value of 450 mg/kg, exceeded the SEL and its sediment was considered to be severely impacted. SR was the only study site to have a concentration below the LEL. MSS concentration was just below the SEL but GR exceeded the SEL with a value of 325 mg/kg.

Zinc concentrations at the reference sites were all below the LEL of 120 mg/kg with the exception of RF-2, which had a concentration of 124 mg/kg.

4.4.6 Consolidated Heavy Metals Findings

All data from heavy metal testing appears in Appendix D. To aid in an overall assessment of the extent of metal contamination at the study sites, the sediment metals concentrations were summed and ranked (Table 3). Using this approach, all of the reference sites, Scott Run, and certain of the Mill Creek sites are ranked as among the least contaminated sites. Conversely, the Cascade Creek sites, Myrtle Street Sewer, Garrison Run, and one Mill Creek site (MC-7) constitute the most contaminated sites.

Table 3. Site ranking according to total metal concentration.

Rank	Site	Total Metal Concentration (mg/kg)
1	RF-5	62
2	RF-6	80
3	RF-7	107
4	RF-4	128
5	SR	187
6	RF-1	200
7	MC-3	203
7	RF-2	203
8	MC-8	218
9	RF-3	229
10	MC-4	232
11	MC-6	233
12	MC-5	253
13	MC-1	285
14	MC-2	288
15	CC-4	304
16	CC-1	338
17	CC-2	361
18	MC-7	375
19	CC-3	404
20	CC-5	619
21	MSS	639
22	GR	643
23	CC-6	826

Note: cadmium results were not included in the above totals.

Mill Creek sites had similar concentrations overall as the reference sites. Reference sites 4-7 had an average total metal concentration of 94 mg/kg, lower than all study sites. A possible explanation for this is the rural area of the streams. These sites are far removed from any major roadways and other urbanization. The higher metal concentrations at the Cascade Creek sites may be linked to the characteristics of the watershed. The upper portion of the Mill Creek watershed, while somewhat urban is nonetheless relatively undeveloped and still retains a high portion of natural ground cover. Cascade Creek runs through a more industrialized urban area, with a high fraction of impervious cover, and a history of metal manufacturing, metal finishing, and metal plating industry. Also, Cascade Creek sites had less riparian zone than the Mill Creek sites. This may explain to some degree why it is more contaminated with heavy metals. It has been documented the riparian zones can protect the streams from urban runoff, especially from roadways and in industrialized areas, which can contain heavy metals. While not statistically significant, the relationship between total metal concentration and riparian zone width (as reflected in the RBP score) suggests a trend (Figure 23). As shown in the figure, as the size of the riparian zone decreases, the more likely a site is to be contaminated with heavy metals. This suggests that urbanization, loss of vegetation, and loss of riparian buffers may be factors in the contamination of streams with heavy metals.

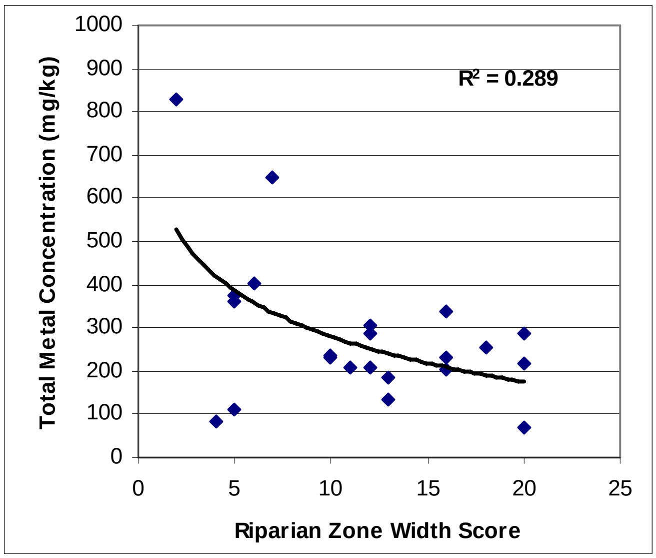

Figure 23. Relationship between total metal concentration and riparian zone width RBP score.

Another approach to assessing heavy metal toxicity from a mixture of metals is to compute the ratio of the concentration of each metal at a site to the LEL for that metal, and to sum the LEL equivalents. The summed LEL equivalents can then be ranked so as to give an indication of the potential ecological health risk to aquatic organisms at each site from the full array of metals present.

Such an approach produced the ranking shown in Table 4. Differences when compared with total metal concentrations are minor. Scott Run appears more in the middle of the ranking using LEL equivalents, and is thus more contaminated than might otherwise be thought. Using either approach, the trend is consistent: reference and Mill Creek sites are less contaminated with heavy metals than are Cascade Creek, Garrison Run, and the Myrtle Street sewer outfall.

Table 4. Ranking of sites based on summed LEL equivalents for heavy metals.

Rank	Site	Summed LEL Equivalents
1	RF-5	1.6
2	RF-6	2.5
3	RF-7	3.2
4	RF-4	3.5
5	MC-8	4.6
6	MC-3	4.7
7	RF-2	5.1
7	RF-1	5.2
8	MC-6	5.4
9	MC-4	5.6
10	MC-5	6.3
11	SR	6.9
12	RF-3	6.9
13	MC-7	7.0
14	CC-4	7.0
15	MC-1	8.0
16	MC-2	8.1
17	CC-1	11.2
18	CC-2	12.1
19	CC-3	14.4
20	GR	18.0
21	MSS	22.6
22	CC-5	23.4
23	CC-6	24.3

4.5 Oil & Grease

The US Environmental Protection Agency set standards for oil and grease in sediment at 1000 mg/kg for non-polluted, 1000-2000 mg/kg for moderately polluted, and highly polluted at levels greater than 2000 mg/kg (EPA, 1977). Most of the study sites exceeded the highly polluted level (Figure 24). Oil & Grease was measured using the hexane extractable material method and is reported as HEM in mg/kg.

The Mill Creek sites on average, were slightly more contaminated with oil and grease than the Cascade Creek sites. Only CC-5 exceeded 10,000 mg/kg, while MC-1, MC-3 as well as MSS exceeded this value.

The reference sites 1-3 have lower concentrations than sites 4-7, but all sites exceeded the highly polluted criteria level. RF-2 had the highest oil and grease concentration at just above 20,000 mg/kg. Oil & grease pollution appears to be ubiquitous, since concentrations at sites removed from urban areas are not much lower. Assuming that the solvent-washed sand was free of oil and grease, the average gain in weight for the flasks of the blank samples was 0.38 g. All values have been adjusted according to this change in weight.

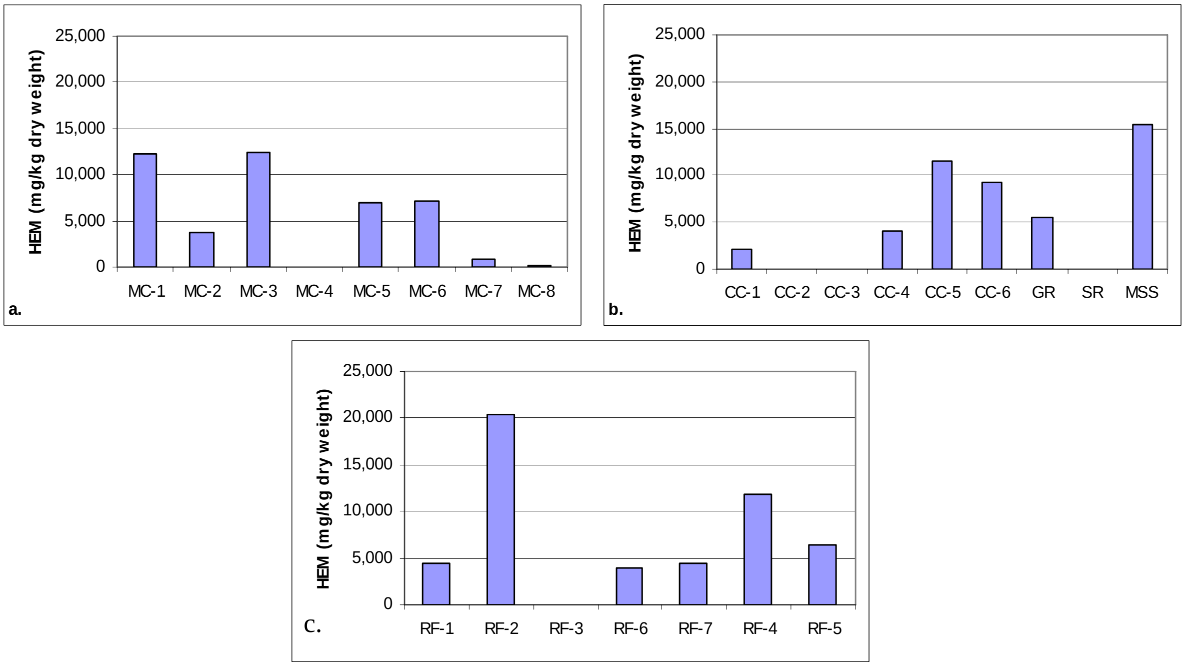

Figure 24. Oil and grease concentrations at (a) Mill Creek sites and (b) Cascade Creek, Scott Run, Myrtle St. Sewer, and Garrison Run; and (c) reference sites.

5. Summary

Physical habitat degradation is present at all sites to some degree. Overall, Cascade Creek sites received lower habitat scores than the Mill Creek sites. Low scores at most sites can be attributed to anthropogenic activities in the immediate riparian vicinity. Cascade Creek is located in a more urbanized and developed watershed than Mill Creek. Mill Creek habitats were only slightly impaired when scores were compared to those of the reference sites. Two Mill Creek sites had scores which exceeded those of the reference sites. The habitat assessment results showed a relationship between the loss of vegetation and the instability of the bank. These results suggest that restoration of stream banks with natural vegetation may not only improve the aesthetics of the area, but also may decrease erosion and stabilize the banks.

Sediment quality was impaired to some degree at all study sites. Each site was at least moderately contaminated. Sediments in Cascade Creek and Garrison Run were more contaminated with heavy metals than the Mill Creek sites, where sediment was on average more contaminated with oil and grease. Cascade Creek's proximity to major roadways and industry may be linked to sediment degradation at those study sites. The loss of a riparian habitat seems to be a factor in this contamination.

The findings in this study suggest that a trend may exist between the riparian zone width and total heavy metal concentration in the sediment. As the riparian zone decreased in width, total metal concentration increased. Restoring vegetation to stream banks, restoring the native vegetation to the riparian zone, and limiting construction within the zone could be helpful in buffering the streams from pollution.

6. Literature Cited

APHA, AWWA, WEF, 1998. Standard Methods for the Examination of Water and Wastewater, 20th Edition . American Public Health Association, Washington, DC.

Barbour, M.T., J. Gerritsen, B.D. Snyder, and J.B. Stribling. 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C.

Callender, E., and K. C. Rice. 2000. "The Urban Environmental Gradient: Anthropogenic Influences on the Spatial and Temporal Distributions of Lead and Zinc in Sediments. Environmental Science and Technology. 34(2): 232-238.

EPA, 1977. Guidelines for the Pollutional Classification of Great Lakes Harbor Sediments. Region V, April.

EPA. 1990a. Managing Contaminated Sediments. USEPA, Sediment Oversight Technical Committee. EPA 506/6-90/002.

EPA, 1990b. Test methods for evaluating solid waste: physical/chemical methods. 3rd Edition. SW-846.U.S. Environmental Protection Agency, Washington, DC.

EPA, 1996a. Nonpoint Source Pollution: The Nation's Largest Water Quality Problem. Fact Sheet on Nonpoint Source Pollution. EPA841-F-96-004A.

EPA, 1996b. Managing Urban Runoff. Fact Sheet on Nonpoint Source Pollution. EPA841-F-96-004G.

GLNPO, 2000. Presque Isle Bay Area of Concern. Great Lakes National Program Office, EPA Region V, Chicago.

Fischenich, J. C., R. B. Stoir, and T. Stanko. 2001. Assessing Urban Watersheds: The Case of Big Creek, GA. The Journal for Surface Water Quality Professionals. Forester Communications, Inc.

Long, E. R. and L. G. Morgan, 1990. The Potential for Biological Effects of Sediment-Sorbed Contaminants Tested in the National States and Trends Program. National Oceanic Atmospheric Administration (NOAA) Technical Memorandum No. 5, OMA52, NOAA National Ocean Service, Seattle, Washington.

Nerbonne, B. A., and B. Vondracek. 2001. Effects of Local Land Use on Physical Habitat, Benthic Macroinvertabrates, and Fish in the Whitewater River, MN. Environmental Management. 28: 87-99.

NYDEC, 1999. Technical Guidelines for Contaminated Sediments. New York State Department of Environmental Conservation.

Novotny, V., and H. Olem. 1994. Water Quality: Prevention, Identification, and Mangement of Diffuse Pollution. International Thomson Publishing, Inc.

Persaud, D., R. Jaagumagi, and A. Hayton, 1992. Guidelines for the Protection and Management of Aquatic Sediment Quality in Ontario. Ontario Ministry of the Environment, Queen's Printer for Ontario.

Potomac-Hudson, 1991. Presque Isle Bay Ecosystem Study: Background Report. Potomac-Hudson Engineering, Inc.

USGS., 2001. Selected Findings and Current Perspectives on Urban and Agricultural Water Quality by the National Water-Quality Assessment Program. United States Geological Survey News Release.

Zhou, C.Y. et al. 1997. Soil, Lead and other Metal Levels in Industrial, Residential and Nature Reserve Areas in Singapore. Environmental Monitoring and Assessment. 44:605-615.

7. Appendices