U.S. Fish & Wildlife Service

Moores Run, Baltimore City, Maryland Geomorphic Condition and Channel Stability Study

CBFO-S04-01

March 2004

MOORES RUN, BALTIMORE CITY, MARYLAND
GEOMORPHIC CONDITION AND CHANNEL STABILITY SURVEY

By: Christopher K. Eng, Tamara L. McCandless and Richard R. Starr

Stream Habitat Assessment and Restoration Program
U.S. Fish and Wildlife Service
Chesapeake Bay Field Office

CBFO-S04-01

Prepared in cooperation with:

City of Baltimore, Department of Public Works, Bureau of Water and Wastewater

Annapolis, MD
2004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The City of Baltimore (City) and the U.S. Fish and Wildlife Service, Chesapeake Bay Field Office (Service) entered into a cooperative agreement (Agreement 51410-1902-5047) to collect geomorphic condition and channel stability data on Moores Run in Baltimore, MD (Figure 1). Moores Run is part of a stream monitoring network under the City's National Pollutant Discharge Elimination System (NPDES) permit.

The City has monitored the reach since 2001. Several sets of survey data exist for Moores Run but due to inconsistencies in data gathering, the City has been unable to compare among the surveys with reliability. In October 2003, the Service completed a geomorphic condition and channel stability field survey for Moores Run. Under the project scope of work, the Service conducted a limited data analysis, including a comparison of the existing data sets with the data gathered by the Service, a bank erosion prediction, and Rosgen Level III stream stability and sediment supply analysis.

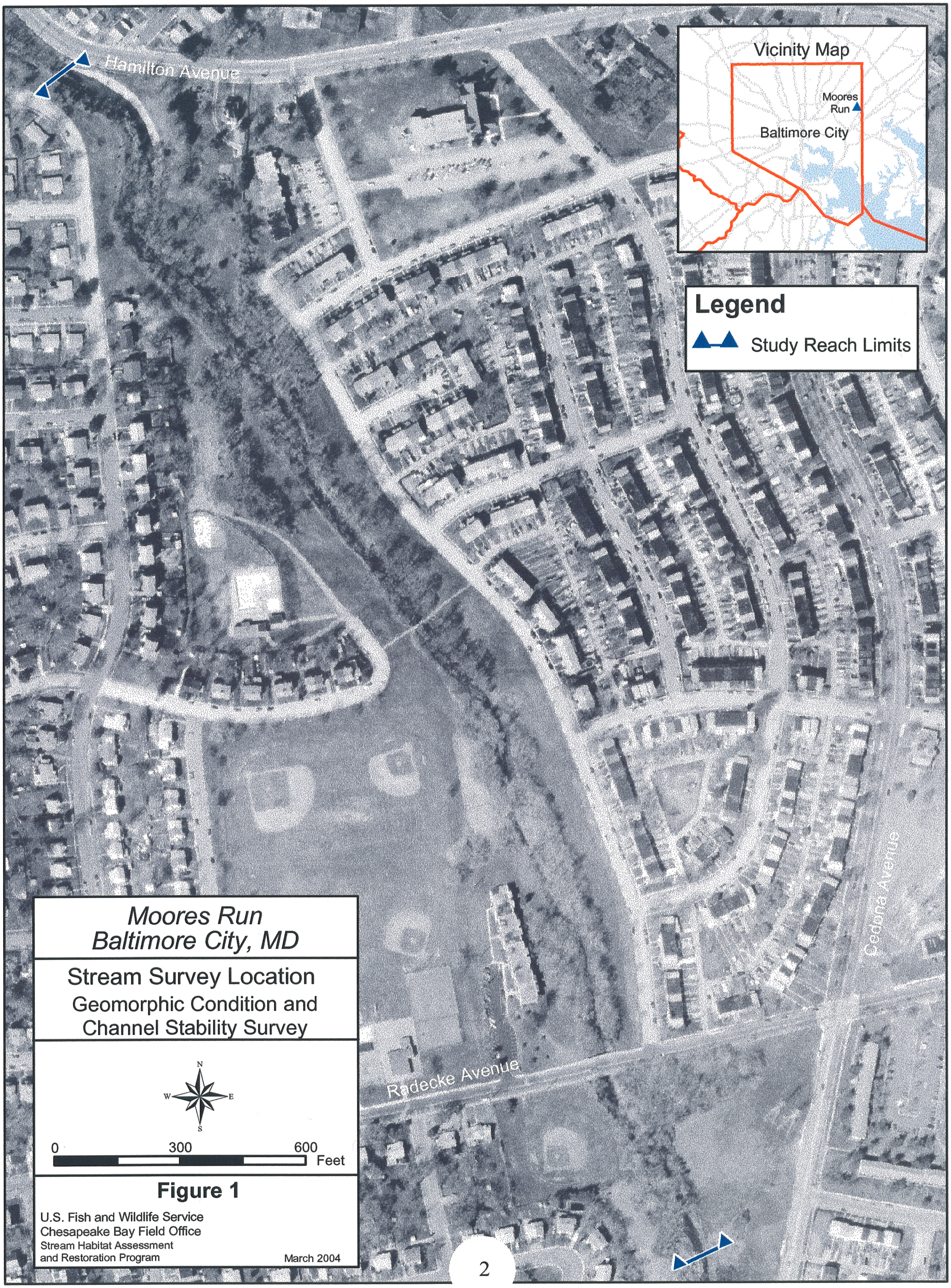
This report presents the results of the field data comparison, a summary of the field data collected by the Service, and the results of the bank erosion prediction and Rosgen Level III stream stability and sediment supply analysis. An overall and reach specific predicted stability discussion is also presented in this report.

II. MOORES RUN EXISTING CONDITIONS

The Moores Run assessment area starts at the triple-cell box culvert located near the intersection of Hamilton Avenue and Evanshire Avenue, and ends approximately 520 feet downstream of the Radecke Road crossing in Baltimore City, MD (Figure 1). The Service identified nine study reaches within the assessment area based on geomorphic characteristics and stability conditions (Figure 2, Table 1).

Table 1. Reach Number and Lengths.

Reach Number	Reach Length (ft)	Reach Number	Reach Length (ft)
01	520	06	489
02	255	07	134
03	448	08	169
04	317	09	354
05	672	**Total**	**3,358**



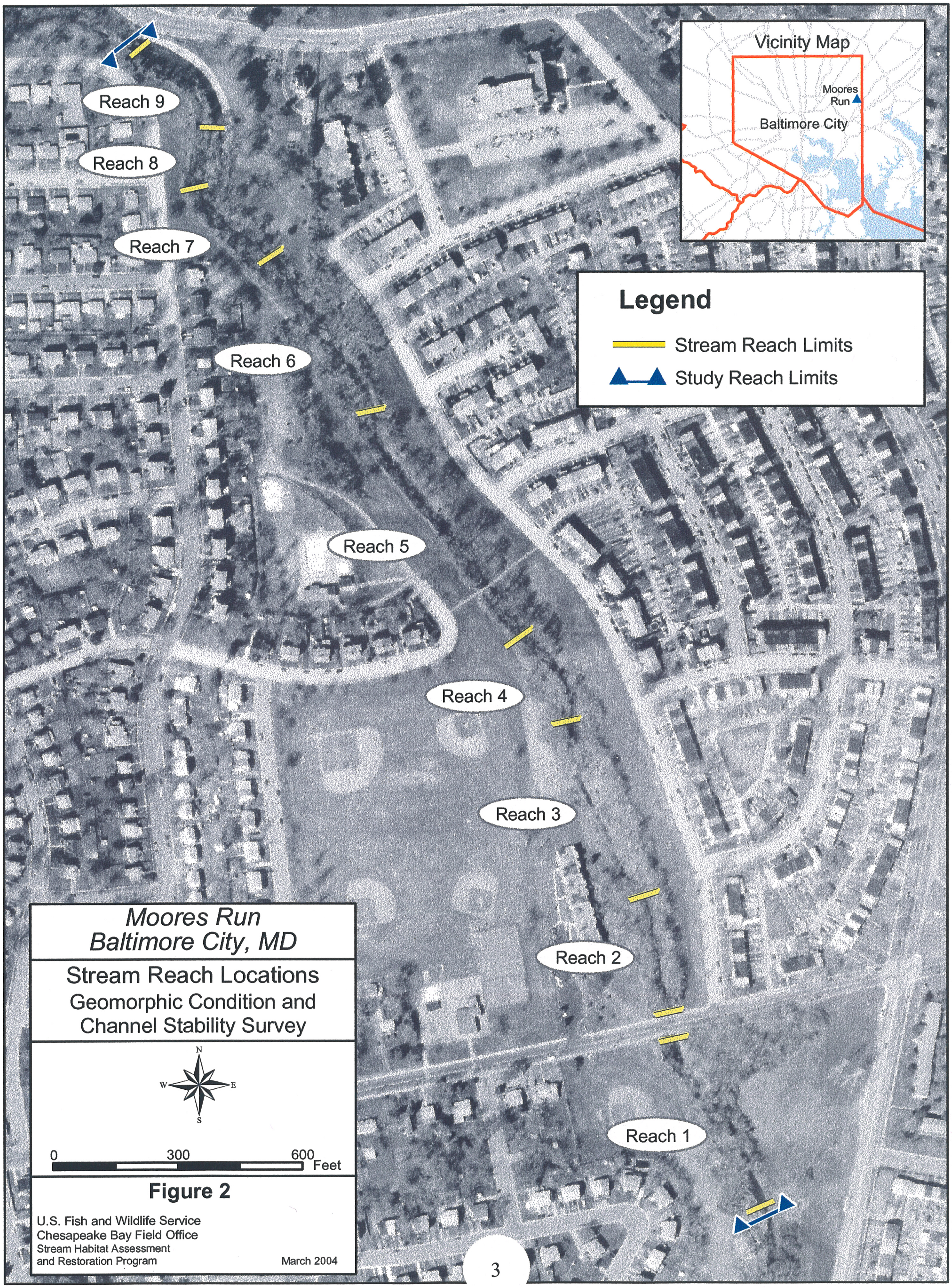
Moores Run
Baltimore City, MD

Stream Survey Location
Geomorphic Condition and Channel Stability Survey

Figure 1

U.S. Fish and Wildlife Service
Chesapeake Bay Field Office
Stream Habitat Assessment and Restoration Program

March 2004


Vicinity Map
Moores Run
Baltimore City
Legend
Stream Reach Limits
Study Reach Limits
Reach 9
Reach 8
Reach 7
Reach 6
Reach 5
Reach 4
Reach 3
Reach 2
Reach 1
Moores Run
Baltimore City, MD
Stream Reach Locations
Geomorphic Condition and
Channel Stability Survey
N
W
E
S
0
300
600
Feet
Figure 2
U.S. Fish and Wildlife Service
Chesapeake Bay Field Office
Stream Habitat Assessment
and Restoration Program
March 2004

A. Rosgen Stream Types

The Moores Run assessment area partitioned into four Rosgen Level I stream types (*i.e.,* B, C, D, and F) (Rosgen 1996). The F stream type represents 44 percent, the C stream type represents 28 percent, the D stream type represents 23 percent, and the B stream type represents 5 percent of the classified stream reaches (Table 2). Reaches 04 and 09 were transitional, predominately pools, which the Service did not classify. In the assessment area, the bed material is predominately cobble with combinations of cobble and boulders or bedrock. Reaches 01 and 04 have gravel with bedrock, and gravel/cobble substrate with bedrock, respectively. Reach 09 has a predominately sand and gravel substrate.

Reach 01, the farthest downstream reach, is a Rosgen C stream type that is slightly entrenched with a moderate width/depth ratio, shallow slope, and a gravel substrate with bedrock grade control. Reach 02 is also a Rosgen C stream type but with a moderately steep slope, and a cobble/boulder substrate. Reach 03 and 08 are Rosgen D (*i.e.*, braided) stream types, which are slightly entrenched with moderate width/depth ratios. Reach 03 has a moderately steep slope and cobble substrate and Reach 08 has a highly steep slope and a cobble substrate with bedrock control.

Reaches 05 and 06 are Rosgen F stream types, which are highly entrenched with moderate width/depth ratios, moderately steep slopes, and a cobble/boulder substrate. Reach 06 has bedrock control. Reach 07 is a Rosgen B stream type that is moderately entrenched with a moderate width/depth ratio, highly steep slope, and a cobble/boulder substrate.

Table 2. Rosgen stream type classification delineation values. One value for sinuosity was calculated for the entire Moores Run assessment area.

Reach	Classification Cross Section	Stream Type	Entrenchment Ratio	Width/ Depth Ratio	Sinuosity	Reach Slope (ft/ft)	Substrate
01	Service XS G	C	2.83	22.0	1.07	0.0038	Gravel with Bedrock
02	Baltimore XS 32	C	3.24	20.0		0.0103	Cobble with Boulder
03	Service XS A	D	4.82	19.3		0.0159	Cobble
05	Service XS C	F	1.17	23.1		0.0122	Cobble with Boulder
06	Service XS D	F	1.11	21.4		0.0159	Cobble with Bedrock
07	Service XS E	B	1.73	18.8		0.0386	Cobble with Boulder
08	Similar to Reach 03	D	N/A	N/A		0.0241	Cobble with Bedrock

B. Moores Run Stability

The Service conducted a stream stability assessment of Moores Run to identify areas of instability, predict sediment supply and develop an understanding of the stream processes that influence the stability of Moores Run. The Service, using the stability and sediment prediction method described in Rosgen (2003), assessed quantitative and qualitative stream data to predict stability ratings for vertical and lateral stream stability for the nine study reaches (Figure 2). The stream data assessed by the Service includes width/depth ratio, near bank stress, bank erodibility, incision, entrenchment, shear stress, stream successional stage, depositional pattern, meander pattern, and confinement. The Service then used the vertical and lateral stability ratings, as well as the Pfankuch channel stability rating and enlargement potential, to predict the sediment supply for Moores Run, by study reach. The Service was also able to predict, based on the data collected, quantitative amounts of sediment entering Moores Run from stream bank erosion. Resurvey of the stream, on an annual basis, is required to validate predictions of sediment supply and total stream bank erosion. Validation of predictions is necessary for managers to make informed planning and implementation decisions.

Analysis of the data allowed the Service to predict and describe the relationship between stream processes and stability conditions in Moores Run. The following provides a description by study reach and for the entire Moores Run assessment area (Figure 2). Photographs for each reach are provided in Appendix A.

Reach 01 has a predicted vertical stability rating of stable because of the bedrock control, but is laterally unstable. The lateral instability is caused by a high width/depth ratio, lack of bank vegetation, high vertical banks prone to erosion, and high near bank shear stresses. A section of the reach, near the downstream limits in the right flood plain, is beginning to braid, which is a further indication of lateral instability. An outfall, directly upstream of the braiding area, will increase the potential for the braided channel to develop.

Reaches 02, 04, and 07 have a predicted vertical and lateral stability rating of stable. Large cobble and boulder substrate, bedrock grade controls, access to floodplain, bank vegetation, bank protection, low near bank shear stresses, and lower reach slope contributes to the reaches' stability. However, not all of these factors are present in each reach; but adequate combinations of these factors are present to establish a stable channel. Although the overall predicted lateral and vertical stability for these reaches is stable, there are localized areas of erosion, such as in Reach 04 along the left bank, downstream of the large outfall. The accelerated flows from the outfall and the lack of bank vegetation are contributing to this erosion. In addition, conditions upstream may have a significant impact on the future stability of these reaches. For example, instability in Reaches 03 and 08 may contribute significant increases in sediment loads to Reach 02 and Reach 07, respectively because Reach 03 has a very high potential for sediment supply and Reach 08 has a moderately high potential for sediment supply. As a result, Reaches 02 and 07 may become laterally and vertically unstable as near bank shear stresses, width/depth ratios, and depositional patterns adjust to the new sediment load.

Reach 03 and 08 are braided reaches with two channels. The Service separately assessed the stability of each channel. The left channel in Reach 03 was most likely the original channel and the right channel formed because of a large debris jam that diverted flows. Over time, the left channel received less flow and now is aggrading and no longer receive base. Conversely, the right channel received more flow and is now laterally and vertically unstable. Even if stream processes remove the debris jam, it is unlikely that the left channel will receive any significant flows because of the aggradation and the lower base level and steeper slope of the right channel. In time, the Service predicts that the right channel will receive all flow as it continues to downcut and widen in its attempt to create a floodplain and reduce energy by increasing sinuosity.

The right channel of Reach 08 was the original channel and the left channel most likely formed because of a debris jam composed of concrete construction debris. The City put the concrete debris in the deep pool of Reach 09. The high-energy flows coming out of the triple-cell outfall, where Moores Run daylights, moved the concrete downstream to Reach 08, formed the debris jam and caused the braiding. Prior to the reach braiding, there may have been active bank erosion on the right bank because the City armored the bank with concrete. However, this bank is laterally unstable because of active toe erosion that is undermining the concrete armoring. The lateral stability of the left channel is currently stable; however, there is significant localized erosion occurring on the left bank at the beginning of the reach. Accelerated flow velocities coming from the triple-cell outfall and the concrete bank protection, in Reach 09, contribute to the erosion. As this area continues to erode, there is an increasing potential for the erosion to extend downstream, despite the presence of bank protection from large boulders and bank vegetation. Bedrock grade control maintains vertical stability for both channels.

Although the Reach 05 has a high entrenchment and bank height ratio, it has a predicted vertical and lateral stability rating of stable. The reach contains large cobble, and has a low floodplain bench with mature vegetation. These factors lead to energy dissipation and contribute to the reach's stability. Reach 06 has a predicted vertical stability rating of stable because of the bedrock controls, but is moderately unstable laterally. A high width/depth ratio and lack of a floodplain are the main reasons for the lateral instability. The lateral adjustments are an indication that the channel is attempting to create a floodplain and sinuosity so it can dissipate energy. In addition, two transverse riffles are increasing local near bank shear stress which is promoting localized erosion. Reach 09 has a predicted lateral stability rating of unstable because of the accelerated flow velocities from the triple-cell outfall. This stability rating is limited to the right bank because the left bank is armored with concrete. Additional factors contributing to the instability of the right bank is the lack of a floodplain, lack of bank vegetation, and high vertical banks.

Overall, Moores Run is predicted 50 percent laterally unstable and 23 percent vertically unstable. The enlargement potential applies to 62 percent of the reaches. Sediment supply potential is high or very high for 20 percent of the reaches with an overall estimate of 857 tons per year of sediment coming from bank erosion. These stability conditions are likely to remain the same or even deteriorate, over time, for Reaches 01, 03, 04, 06, 08, and 09 as they continue to adjust in an attempt to create floodplains and increase sinuosity to reduce stream energy. The adjustment of these reaches may adversely affect the remaining stable reaches by increasing the sediment load they must transport.

Increases in the flow regime will have a significant impact on Moores Run stability. The erosion rates at localized areas of lateral erosion will increase and threaten areas, which are prone to erosion, such as in the braided reaches. The extent of erosion may also extend into currently stable banks that are not heavily armored or vegetated. Toe erosion along the right bank, in Reach 08, will likely accelerate the undermining of the concrete wall. Other impacts may include increased sediment loads, nutrient loads, poor water quality, habitat degradation, and property loss.

III. CITY OF BALTIMORE FIELD DATA SETS

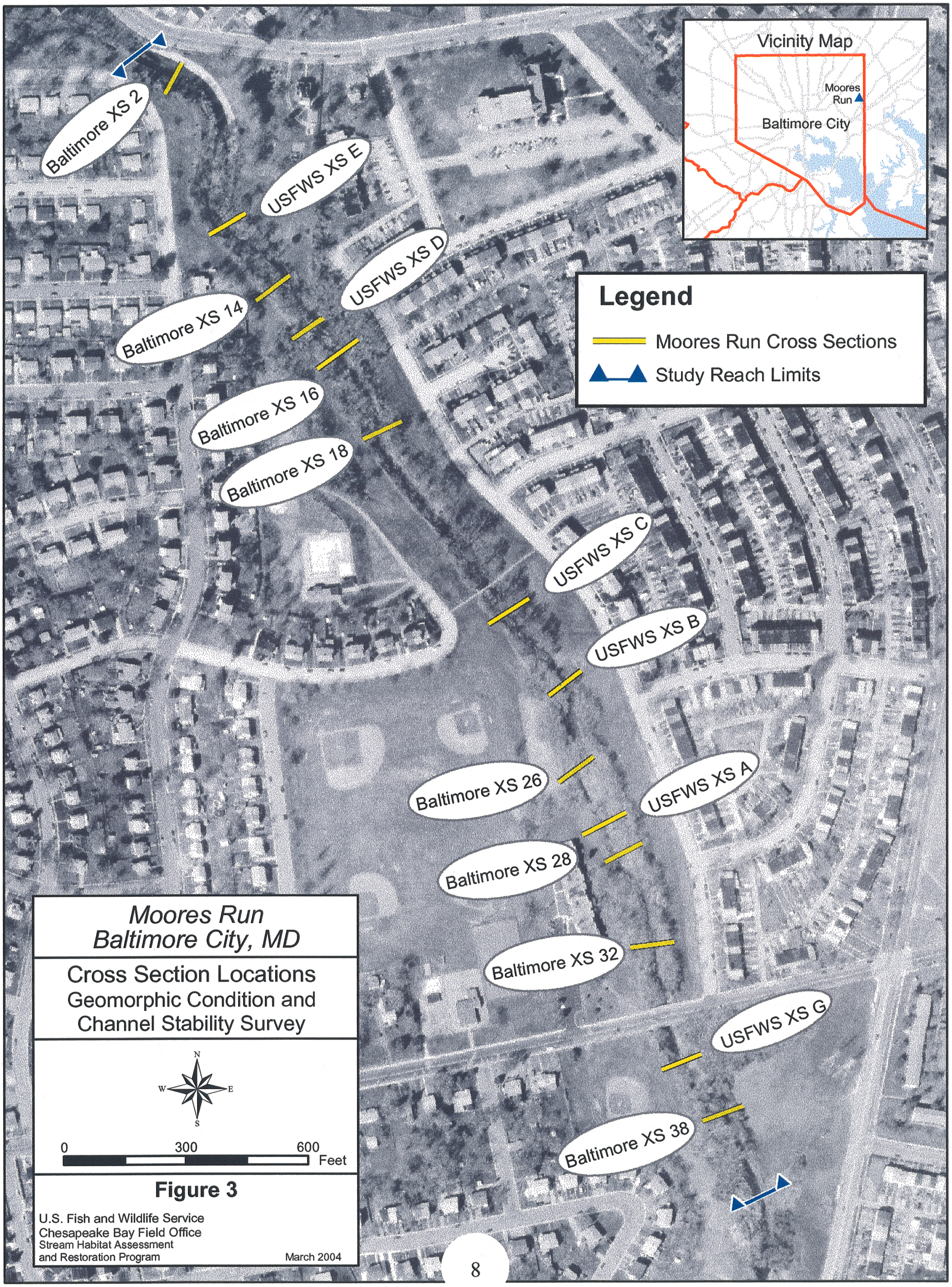
The City initially surveyed Moores Run in 2001, contracted Dewberry and Davis to resurvey it in 2002, and resurveyed it again themselves in 2003. In 2001, the City surveyed several monumented cross sections and a longitudinal profile. In 2002, Dewberry and Davis resurveyed 4 monumented cross sections, resurveyed the longitudinal profile, and conducted bank erodibility hazardous index assessments for a select number of stream banks. In 2003, the City resurveyed 4 monumented cross sections and the longitudinal profile. As part of the scope of work, the City requested the Service to resurvey six existing monumented cross sections (cross sections Baltimore XS 2, 14, 16, 18, 28, and 38 as shown on Figure 3) and the longitudinal profile for the purpose of documenting channel adjustment, if possible. For the comparison, the City provided three field data sets (*i.e.,* 2001 Baltimore City, 2002 Dewberry and Davis, and 2003 Baltimore City) for the six monumented cross sections, and two field data sets (*i.e.,* 2001 Baltimore City and 2003 Baltimore City) for the longitudinal profiles.

A. Cross Section Comparison

The Service compared the six monumented cross sections over the period of 2001 to 2003 (Table 3). Unresolved issues regarding the previous data sets prevented a straightforward comparison with most of the cross section surveys. In some cases the data was missing, the monuments were not identified in the field notes, or the surveys did not provide sufficient detail for comparison. This prevented a percent change analysis for the cross sectional area.

For cross section 2, Reach 09, the Baltimore 2003 data overlaid with the Service survey using the right monument (Appendix B). However, due to the depth of the pool in this reach, the data sets do not provide an accurate representation of the stream bottom. For cross section 14, aligning the left monuments, none of the data sets aligned with the right monument. Only the Baltimore 2001 data set provided a reasonable overlay. The pool is deeper in the 2003 survey, with an increase in cross sectional area of 28 percent, and an increase in mean depth of 0.79 feet.

Only one data set was provided for cross section 16, and it does not overlay with the Service survey (Appendix B). Cross section 18 provided the best results, overlays matched for two of the last three surveys (Appendix B). The data sets overlaid at both monuments with the exception of the Baltimore 2001 data sets, which did not match up to the right monument. Comparing the Service 2003 data set with the Dewberry and Davis and Baltimore 2003 data sets to the shows a decrease in the cross sectional area of one and ten percent, respectively. There is also a decrease in mean depth of 0.26 feet for the Dewberry and Davis data set and a decrease of 0.27 feet for the Baltimore 2003 data set.



Moores Run
Baltimore City, MD

Cross Section Locations
Geomorphic Condition and
Channel Stability Survey

Figure 3

U.S. Fish and Wildlife Service
Chesapeake Bay Field Office
Stream Habitat Assessment
and Restoration Program

March 2004

All data sets for cross section 28 tie into the left monument (Appendix B), but do not tie into the right monument, making comparisons unreliable. Aligning the right monuments, all data sets for cross section 38 do not tie into the left monument, with the exception of the Baltimore 2001 data set. The run is slightly deeper in 2003, with a six percent increase in cross sectional area, and a 0.21 feet increase in mean depth. The Service also aligned the Dewberry and Davis cross section using the left top of bank, because it provided a better overlay than the monuments. However, the overlay for the 2002 data set was not adequate to conduct a percent change comparison.

Table 3. Moores Run cross section data set comparison with Service 2003 data.

Cross Section	Survey Data Sets		
	2001 (Baltimore)	2002 (Dewberry and Davis)	2003 (Baltimore)
02	Not surveyed	Overlay problem	Ok
14	Overlay problem	Not surveyed	Not surveyed
16	Overlay problem	Not surveyed	Not surveyed
18	Overlay problem	Ok	Ok
28	Overlay problem	Overlay problem	Overlay problem
38	Ok	Overlay problem	Overlay problem

B. Longitudinal Profile Comparison

Because the previous data sets were not tied into a common benchmark, the Service overlaid the longitudinal profiles by aligning the invert of the triple cell culvert or concrete apron, at the upstream limit of the assessment area and converted all elevations to Baltimore City datum (Appendix B). The Baltimore 2001 longitudinal profile was the best overlay compared to the Service longitudinal profile. However, only minor portions (*i.e.*, 18 percent) of this survey are vertically aligned.

While the Service measured Baltimore City monuments or benchmarks located throughout the study reaches, the previous surveys did not measure the same benchmarks or it was unclear which benchmarks were measured. As a result, the Service cannot make stationing or elevation corrections to the previous surveys, in order to conduct a longitudinal profile analysis.

IV. SERVICE FIELD DATA SUMMARY

The Service collected the following geomorphic condition and channel stability field data:

- Gage Analysis
- Geomorphic Mapping
- Cross Section Survey
- Bank Erosion Hazard Index Assessment
- Bank Profiles
- Pfankuch Channel Stability Assessment
- Longitudinal Profile Survey

- Riffle Pebble Counts

The Service 2003 field data and plots are compiled and organized by study reach in Appendix C and also provided electronically. Upon completion of this report, the Service will provide a description of the survey tasks in the Moores Run Field Protocols document.

A. Bankfull Discharge Determination

Moores Run has a U.S. Geological Survey (USGS) gage station, established in July 1996 (drainage area of 3.52 square miles), near the downstream limits of the assessment area (Station Number 01585230). The Service used the USGS gage station data, Service measured cross section, and longitudinal profile survey data to determine the bankfull discharge. Previous work in a highly urbanized area, the District of Columbia (USFWS-CBFO July 2003 draft), provided additional information.

The Service identified geomorphic indicators that could potentially represent the bankfull discharge throughout the Moores Run assessment area and found two consistent and clearly defined indicators. In some locations, the indicators were less defined or absent because of active erosion or where the stream was entrenched (e.g., Reaches 05 and 06); and completely non-existent where banks were armored (e.g., Reaches 08 and 09). The lower indicator was a slope break feature generally associated with a vegetated low bench within the active channel. This feature did not represent the bankfull discharge and most likely formed in response to flashy flow regime and low base flows in Moores Run. The Service has surveyed and observed this low bench feature in several other urban streams. The higher geomorphic indicator representing the bankfull discharge was typically associated with a significant slope break or floodplain feature above the lower bench feature. The longitudinal profile data further supported the conclusions made by the Service regarding these geomorphic features.

The Service used Baltimore City cross section 32, located approximately 197 feet (ft) upstream of the Radecke Avenue bridge, to estimate bankfull discharge. The Service selected this cross section because of its proximity to the USGS gage station, clear geomorphic indicators, stable channel conditions, and distance from bridge to avoid backwater effects. Applying the difference between the water surface elevation and the bankfull indicator to the gage location corresponded to a gage height of 4.88 ft. The USGS discharge-rating table indicated a discharge of 594 cubic feet per second (cfs) for this stage. The USGS log-Pearson flood frequency curve indicated a recurrence interval of less than 1.01 years for this bankfull discharge.

Using the longitudinal profile through the gage station and reading the bankfull elevation at the staff plate resulted in gage height of 5.00 feet and corresponding discharge of 645 cfs. The recurrence interval is also less than 1.01 years. The difference between the two results is approximately 8.5 percent.

In the Maryland Piedmont, bankfull flood events typically occur between a 1.26 and 1.75-year recurrence interval frequency (McCandless and Everett 2002) associated with predominately-rural watersheds. The Service has found recurrence intervals for the urban streams in the District of Columbia between 3 to 6 months. The gage station period of record is less than ten years and there are no measured discharge events greater than 320 cfs, preventing further validation of measured velocities using the USGS gage information. However, with the consistency of both the bankfull geomorphic indicators through the reach and the cross-sectional dimensions measured throughout, the Service is comfortable with the range of discharge for bankfull provided above.

B. Geomorphic Mapping

Using aerial photographs overlaid by mylar, the Service illustrated geomorphic conditions of the stream at the time of the survey (Appendix C). The Service used the maps to evaluate geomorphic conditions (*i.e.,* channel conditions and stability, adjacent land uses and land cover, and anthropogenic structures) and partition the assessment area into nine study reaches.

C. Cross Sections

The Service surveyed eight existing monumented cross sections, and established six new monumented cross sections (Figure 3). For the newly established cross sections, the Service installed rebar or two-inch steel pipe monuments. Each monumented cross section has a monument location map included in the reach field data (Appendix C). Global positioning system (GPS) coordinates for Baltimore City and Service benchmarks and cross section monuments are provided in Appendix D.

The Service entered the cross section field data into a Microsoft Excel template, plotted the cross section, and calculated the bankfull cross sectional dimensions (*i.e.,* area, width, mean depth, maximum depth, wetted perimeter, and hydraulic radius) (Table 4). The cross section plots are provided in Appendix C.

The bankfull dimensions for the monumented cross sections at the riffles ranged from 100 to 115 square feet (ft^2), the run cross sectional area ranged from 105 to 136 ft^2, and the pool cross sectional area ranged from 125 to 211 ft^2.

Table 4. Monumented Cross Section Data. All data are presented for the bankfull discharge.

Reach	Cross section Number	Cross section Feature	Area (ft^2)	Width (ft)	Mean Depth (ft)	Maximum Depth (ft)	Wetted Perimeter (ft)	Hydraulic Radius
01	Baltimore XS 38	Run	105	41.0	2.56	3.69	42.9	2.44
	Service XS G	Riffle	101	46.5	2.17	4.48	51.7	1.95
02	Baltimore XS 32	Riffle	103	45.1	2.29	3.87	46.4	2.23
03	Baltimore XS 26	Riffle	101	54.5	1.86	3.34	57.4	1.76
	Service XS A	Riffle	100	44.0	2.28	3.81	50.1	2.00

Table 4. Monumented Cross Section Data. All data are presented for the bankfull discharge.								
Reach	**Cross section**		**Area (ft^2)**	**Width (ft)**	**Mean Depth (ft)**	**Maximum Depth (ft)**	**Wetted Perimeter (ft)**	**Hydraulic Radius**
	Number	**Feature**						
03	Baltimore XS 28	Riffle	101	54.1	1.87	4.10	61.7	1.64
04	Service XS B	Pool	211	60.2	3.50	6.24	65.3	3.23
05	Baltimore XS 18	Riffle	114	41.6	2.73	5.09	49.9	2.28
	Service XS C	Riffle	108	50.0	2.17	3.11	51.8	2.09
06	Baltimore XS 16	Run	136	44.7	3.04	4.12	49.5	2.75
	Service XS D	Riffle	115	49.5	2.32	4.00	55.3	2.07
	Baltimore XS 14	Pool	125	44.1	2.84	5.13	53.2	2.35
07	Service XS E	Riffle	108	45.0	2.40	4.68	47.6	2.27
09	Baltimore XS 02	Pool	The Service was unable to safely survey across the deep pool, so the cross sectional area is not reflective of the actual cross sectional area. In addition, the bankfull indicators were not present or very poor because of the concrete wall and active erosion. The purpose of this cross section is to monitor lateral change.					

D. Bank Erosion Hazard Index and Near Bank Shear Stress

To predict sediment contributions from bank erosion, the Service rated the Bank Erosion Hazard Index (BEHI) and near bank shear stress (NBS) on all stream banks prone to erosion in the study reaches. The Service uses the ratings and a bank erosion curve to obtain erosion rates. The final predictions of bank erosion quantities are a result of multiplying the erosion rates times the bank lengths times the bank heights. For validation purposes, the Service also conducted BEHI and NBS assessments at monumented cross sections, representing the combination of BEHI and NBS combinations. Repeated surveys of these cross sections will show lateral adjustments, from which actual bank erosion rates can be determined and predicted bank erosion rates can be validated. Reach and cross section BEHIs and cross section bank profile data are provided in Appendix C.

1. Reach BEHI and NBS

To determine the reach BEHI and NBS ratings, the Service assessed 5,130 feet of stream bank of the total 7,950 feet of bank (Figure 4). The Service did not assess banks with significant


Vicinity Map
Moores Run
Baltimore City
Legend
BEHI Locations
Study Reach Limits
Concrete Banks
Aggrading Banks
BANK #28
BANK #27
BANK #26
BANK #25
BANK #24
BANK #23
BANK #22
BANK #21
BANK #20
BANK #19
BANK #18
BANK #17
BANK #16
BANK #15
BANK #14
BANK #13
BANK #12
BANK #11
BANK #10
BANK #9F
BANK #9E
BANK #9D
BANK #9B
BANK #9A
BANK #9C
BANK #8
BANK #7
BANK #6
BANK #5
BANK #4
BANK #3
BANK #2
BANK #1
Moores Run
Baltimore City, MD
Reach BEHI Locations
Geomorphic Condition and
Channel Stability Survey
N
W
E
S
0
300
600
Feet
Figure 4
U.S. Fish and Wildlife Service
Chesapeake Bay Field Office
Stream Habitat Assessment
and Restoration Program
March 2004

deposition. Detailed reach BEHI criteria and scores are provided in Appendix E. A summary of the reach BEHIs and NBS ratings are provided in Table 5.

The BEHI ratings range from very low to extreme. The very low and low ratings represent 43 percent of the banks while the moderate rating represents 10 percent of the banks. The high and very high ratings represent 7 percent, and the extreme rating represents 4 percent of the banks. NBS ratings range from low to extreme. The low rating represents 30 percent while the moderate rating represents 22 percent of the banks. The high rating represents 9 percent of the banks, and the extreme rating represent 4 percent of the banks.

Table 5. Study Reach BEHI and NBS.

Reach	BEHI Bank		BEHI Rating	NBS Rating
	Number	Length (ft)		
01	01	120	Low	Moderate
	02	151	Very Low	Moderate
	03	74	High	Low
	04	268	Extreme	High
02	05	260	Low	Moderate
	06	250	Low	Low
03	07	54	High	Moderate
	08	110	Low	High
	09A	80	Very High	Moderate
	09B	21	Moderate	Low
	09C	75	Very Low	Moderate
	09D	125	Very Low	Low
	09E	20	Moderate	Low
	09F	35	Low	Low
04	10	392	Very Low	Low
	11	52	Moderate	Moderate
	12	88	Very High	Moderate
	13	102	Very Low	Low
05	13	153	Very Low	Low
	14	75	Very High	Moderate
	15	88	Moderate	Low
	16	135	Low	Moderate
	17	113	Low	Low
	18	350	Low	Low
	19	285	Low	Low
	20	35	Very High	High
	21	63	Moderate	Moderate
06	22	70	Extreme	High
	23	397	Moderate	Moderate
	24	155	Low	Low

Table 5. Study Reach BEHI and NBS.				
Reach	**BEHI Bank**		**BEHI Rating**	**NBS Rating**
	Number	**Length (ft)**		
07	23	180	Moderate	Moderate
	25	221	Low	Low
08 (Left Channel)	26	213	Low	High
09	27	165	Very Low	Extreme
	28	155	Very High	Extreme

2. Representative Cross Section BEHI, NBS, and Bank Profiles

The Service assessed BEHI and NBS conditions on one or both banks at monumented representative cross sections, directly inline with the cross section (Table 6). The Service installed toe pins at cross sections, wherever possible, to reduce resurvey efforts. The monumented representative cross section BEHI and NBS conditions represent 83 percent of the reach BEHI and NBS conditions. The cross section BEHI scores and bank profile plots are provided in Appendix C for each study reach.

Table 6. Cross Section BEHI and NBS.				
Reach	**Cross Section**		**BEHI Rating**	**NBS Rating**
	Number	**Bank**		
01	Baltimore XS 38	Left	Moderate	Low
	Service XS G	Right	Extreme	High
02	Baltimore XS 32	Left	Low	Moderate
03	Baltimore XS 26	Left	Low	Low
	Baltimore XS 26	Right	Moderate	Low
	Baltimore XS 28	Right	Low	High
	Service XS A	Right	Moderate	Low
04	Service XS B	Left	Very High	Moderate
05	Baltimore XS 18	Left	Low	Low
	Baltimore XS 18	Right	Moderate	Moderate
	Service XS C	Left	Moderate	Low
	Service XS C	Right	High	Low
06	Baltimore XS 16	Left	Very High	Low
	Baltimore XS 16	Right	Low	Low
	Service XS D	Left	High	Moderate
	Baltimore XS 14	Left	High	Moderate

3. Bank Erosion Estimates

The Service used reach BEHI and NBS ratings, bank dimensions, for each assessed bank in the study reach, and bank erodibility curves to calculate a predicted reach average erosion rate

(Table 7). The Service used a bank erodibility curve developed by Wildland Hydrology for the Western United States (*i.e.,* Yellowstone National Park, Rosgen 2003) because Maryland has no bank erodibility curves. Baltimore City can validate these predictions by conducting annual cross section or bank profile surveys, and BEHI and NBS assessments.

Reaches 01 is predicted to produce the highest and Reach 02 the lowest total tons of sediment from bank erosion. Reaches 09 is predicted to have the highest and Reach 02 the lowest rate of bank erosion.

Table 7. Predicted Bank Erosion.

Reach	Bank Erosion		Reach	Bank Erosion	
	Total (tons/yr)	Rate (tons/yr/ft)		Total (tons/yr)	Rate (tons/yr/ft)
01	306	0.71	06	95	0.19
02	7	0.03	07	30	0.23
03	36	0.08	08	18	0.11
04	27	0.08	09	273	0.77
05	64	0.10	**Total**	**856**	

E. Longitudinal Profile

The Service measured the longitudinal profile, surveying 3,414 feet of stream (Appendix F). The longitudinal profile length is slightly longer than the totals for study reach lengths, because it includes the stream length under the Radecke Avenue bridge. The Service converted the survey to City of Baltimore datum and established a reference point at the downstream limit of the study reach (coordinates and monument map provided in Appendix D).

The Service entered the longitudinal profile field data into a Microsoft Excel spreadsheet and plotted the survey and benchmarks. In addition, the Service delineated the study reaches, and identified road crossings and other infrastructure on the plots. The slopes range from 0.00383 to 0.0386 ft/ft (Table 8). The lowest gradient is in Reach 01, downstream of Radecke Avenue bridge, and the steepest slope is in Reach 07 near the end of Moores Run Drive. Overall, the Moores Run assessment area has an average slope of 0.0148.

Table 8. Study Reach Slopes.

Reach	Slope (ft/ft)	Reach	Slope (ft/ft)
01	0.00383	06	0.0159
02	0.0103	07	0.0386
03	0.0159	08	0.0241
04	0.00551	09	0.00659
05	0.0122		

F. Pebble Counts

Because of the potential human health risks associated with poor water quality, the Service did not conduct a reach average pebble count. Based on field observations, the Service characterized the representative substrate condition for each of the nine reaches. During the field survey, the Service noted that Reaches 01 and 04 have a gravel substrate, Reach 03 and 06 have a cobble substrate, Reaches 02, 05, and 07 have a bimodal distribution of cobble and boulders, and Reach 09 has a sand and gravel substrate, with concrete rumble. In addition, Reaches 01, 04, 06, and 08 have bedrock.

The Service characterized two riffles substrates using pebble counts in study reaches 02 and 06. The Service entered the riffle pebble count field data into a Microsoft Excel template, plotted particle size distribution, and calculated the particle size for specific distributions (*i.e.*, D_{16}, D_{35}, D_{50}, D_{84}, and D_{95}). The particle sizes for the relevant distributions are provided in Table 9 and the plots from the two study reaches are provided in Appendix C.

Table 9. Riffle Pebble Count.

Reach	Cross-section	Particle Size Distribution (mm)				
		D16	D35	D50	D84	D95
02	Baltimore XS 32	10.84	52.83	89.18	229.19	362.39
06	USFWS XS D	52.83	128.00	217.19	689.10	990.75

G. Rosgen Level III Stream Stability and Sediment Supply Assessment

The Service conducted a Rosgen Level III stream stability and sediment supply assessment (Level III assessment) (Rosgen 2003), to predict lateral and vertical stability, channel enlargement potential, Pfankuch channel stability, and sediment supply. A summary of the Rosgen Level III assessment data is provided in Appendix G.

The predicted lateral stability, vertical stability, and channel enlargement potential ratings are based on several stability criteria derived from the cross section, bank erodibility, depositional pattern, planform characteristics, and successional stream type stage. Each of the stability criteria receive a rating based on the actual value or character of the stream. For example, a width/depth ratio value of 1.0 would have a stability rating of stable, while a width/depth ratio value of 1.3 would have a rating of moderately unstable. Furthermore, depositional features of side bars by themselves would have a rating of moderately unstable, while depositional features of side bars with mid-channel bars would have a rating of highly unstable.

Often the stability ratings of individual criteria do not agree in a given assessment reach. For example, an assessment reach may have a width/depth ratio stability rating of stable, but have a dominate BEHI and NBS rating of highly unstable. To determine the overall lateral or vertical stability rating for a given reach, the individual criteria are ranked in order of importance, with quantitative data (*e.g.*, width/depth ratio, entrenchment, near bank shear stress, bank erodibility, and confinement) having precedence over qualitative data (*e.g.*, depositional pattern and meander pattern). For each reach, the Service reviewed the collective results of the individual criteria ratings and selected an overall predicted lateral and vertical stability ratings and enlargement potential rating for the existing conditions. Then the Service combined the lateral and vertical stability ratings, enlargement potential rating, and Pfankuch channel stability rating to determine the reach's predicted sediment supply.

The Service did not assess study/reference confinement ratio due to the lack of reference meander width ratio information for the Maryland Piedmont streams. The Service did not collect bar samples because of the large substrate (*e.i.*, boulder and large cobble substrate) and sand substrate and consequently, did not assess critical dimensionless shear stress and critical shear stress. Lastly, the Service did not model sediment capacity. Despite the absence of these criteria, the Service had sufficient data to support the overall predicted stability ratings.

1. Lateral Stability Potential

The Rosgen Level III assessment predicts lateral stability potentials by evaluating width/depth ratios, depositional patterns, meander patterns, dominant BEHI/NBS, and confinement. The lateral stability assessment for the study reaches had four ratings (*i.e.*, stable, moderately unstable, unstable, and highly unstable) (Table 11). The stable rating represents 50 percent, and the moderately unstable rating represents 17 percent of the assessment area. The unstable rating represents 24 percent, and the highly unstable rating represents 9 percent of the assessment area.

Table 10. Lateral Stability Potential.

Reach	Lateral Stability	Reach	Lateral Stability
01	Unstable	06	Moderately Unstable
02	Stable	07	Stable
03 (Left Channel)	Stable	08 (Left Channel)	Stable
03 (Right Channel)	Unstable	08 (Right Channel)	Moderately Unstable
04	Stable	09	Highly Unstable
05	Stable		

2. Vertical Stability Potential

The Rosgen Level III assessment predicts vertical stability potentials by evaluating critical dimensionless shear stress, critical stress, degree of incision, sediment capacity model, width/depth ratios, stream type stage, depositional patterns, meander pattern, entrenchment, and confinement. The vertical stability assessment resulted in three ratings (*i.e.*, stable, aggrading, and degrading). The stable rating represents 78 percent of the assessment area. The left channel of Reach 03 is aggrading and represents 11 percent of the assessment area. The right channel of Reach 03 is degrading and represents 11 percent of the assessment area. (Table 12).

Table 11. Vertical Stability Potential.

Reach	Vertical Stability	Reach	Vertical Stability
01	Stable	06	Stable
02	Stable	07	Stable

Table 11. Vertical Stability Potential.			
Reach	**Vertical Stability**	**Reach**	**Vertical Stability**
03 (Left Channel)	Aggrading	08 (Left Channel)	Stable
03 (Right Channel)	Degrading	08 (Right Channel)	Stable
04	Stable	09	Stable
05	Stable		

There are two instances where special reach conditions lead the Service to select a different stability rating than one indicated by the stability assessment. The assessment criteria supported a degrading vertical stability rating for Reaches 05 and 06 because these reaches are incised and storm flows are vertically contained within the channel. However, Reach 05 contains a large cobble substrate and has a low floodplain bench, which dissipates energy, and results in a stable vertical stability prediction. Reach 06 contains bedrock which prevents vertical degradation, and results in a stable vertical stability prediction.

3. Enlargement Potential

The Rosgen Level III assessment predicts enlargement potentials by evaluating lateral stability, vertical stability, and Rosgen stream type successional stage. The enlargement potential assessment had four ratings (*i.e.,* stable, slight increase, moderate increase, and extensive) (Table 13). The stable rating represents 38 percent, and the slight increase rating represents 12 percent of the assessment area. The moderate increase rating represents 41 percent, and the extensive rating represents 9 percent of the assessment area.

Table 12. Enlargement Potential.			
Reach	**Enlargement Prediction**	**Reach**	**Enlargement Prediction**
01	Moderate Increase	06	Slight Increase
02	Stable	07	Stable
03 (Left Channel)	Stable	08 (Left Channel)	Stable
03 (Right Channel)	Moderate Increase	08 (Right Channel)	Stable
04	Stable	09	Extensive
05	Moderate Increase		

There was one instance where special reach conditions lead the Service to select a different stability rating than one indicated by the stability assessment. The assessment criteria support a moderate channel enlargement for Reach 06, because of the reach is incised and has a moderate lateral instability. However, the reach contains bedrock which prevents vertical degradation, and results in a lower predicted enlargement potential of slight increase.

4. Pfankuch Channel Stability Assessment

The Pfankuch Channel Stability Assessment method provides an overall channel stability rating (Pfankuch 1975). Pfankuch originally developed the method to evaluate the ability of mountain stream channels to move bed and bank materials and to provide information on the stream's ability to adjust and recover from the changes in flow and sediment production. It evaluates such parameters as mass wasting, vegetative banks, debris jams, channel capacity, cutting, deposition, consolidation of particles, and aquatic vegetation. Assessors evaluate of the parameters based on observations, their experience.

David Rosgen modified Pfankuch's method based on the Rosgen stream classification system (Rosgen 2003). Rosgen's assessment method does not use the Pfankuch stability score as a stand-alone, overall stream stability rating and it is not compared against the other stability ratings. Rather it is used in the Rosgen Level III sediment supply prediction.

The modified Pfankuch Channel Stability Assessment ratings for the study reaches are presented in Table 10. The Pfankuch assessment field data is provided in Appendix C. For Reaches 08 and 09, the Service limited the Pfankuch assessment to the non-concrete portion of the reach. The Moores Run assessment area rates as stable for 67 percent of the assessment area, and moderately unstable for 33 percent of the assessment area

Table 13. Pfankuch Channel Stability.

Reach	Pfankuch Rating	Reach	Pfankuch Rating
01	Stable	06	Stable
02	Stable	07	Moderately unstable
03	Moderately unstable	08	Moderately unstable
04	Stable	09	Moderately unstable
05	Stable		

5. Sediment Supply

The Rosgen Level III assessment predicts the sediment supply based on the results of the lateral and vertical stability, channel enlargement potential, and Pfankuch channel stability rating. The results are given a numeric value. The individual values are added together to get a total score for the reach. A higher score indicates a larger potential for sediment contribution from the study reach.

The sediment supply assessment resulted in four ratings (*i.e.*, low, moderate, high, and very high) (Table 14). The low rating represents 50 percent, and the moderate rating represents 30 percent of the assessment area. The high rating represents 9 percent, and the very high rating represents 11 percent of the assessment area.

Table 14. Sediment Supply Potential.			
Reach	**Sediment Prediction**	**Reach**	**Sediment Prediction**
01	Moderate	06	Moderate
02	Low	07	Low
03 (Left Channel)	Low	08 (Left Channel)	Low
03 (Right Channel)	Very High	08 (Right Channel)	Moderate
04	Low	09	High
05	Low		

V. RECOMMENDATIONS

The Service has three recommendations based on the findings of our survey and analysis.

1. Install additional monumented cross sections at unrepresented BEHI and NBS conditions, to represent 100 percent of the reach BEHI and NBS conditions (Table 15).

Table 15. Unrepresented BEHI and NBS Conditions.	
BEHI Rating	**NBS Rating**
Very Low	Low
Very Low	Moderate
Very Low	Extreme
Very High	High
Very High	Extreme

2. Discontinue cross section surveys at monumented cross sections, which do not represent existing reach BEHI and NBS conditions (Table 16).

Table 16. Discontinue Cross sections Recommendation.	
Cross Section	**Cross Section**
Baltimore XS 16	Baltimore XS 02
Service XS D	

3. Install a monumented cross section at the upstream limit of Reach 08, to monitor the erosion along the left bank.

LITERATURE CITED

1. McCandless, T.L. and R.A. Everett. 2002 Maryland stream survey: Bankfull discharge and channel characteristics in the Piedmont hydrologic region. U.S. Fish and Wildlife Service, Annapolis, MD. CBFO-S02-02. 41 pp.
2. Pfankuch, D.J. 1975. Stream reach inventory and channel stability evaluation. U.S. Forest Service, Missoula, MT.
3. Rosgen, D.L. 1996. Applied River Morphology. Wildland Hydrology. Pagosa Springs, CO.
4. Wildland Hydrology. 2003. River Assessment and Monitoring Field Manual. Pagosa Springs, CO.