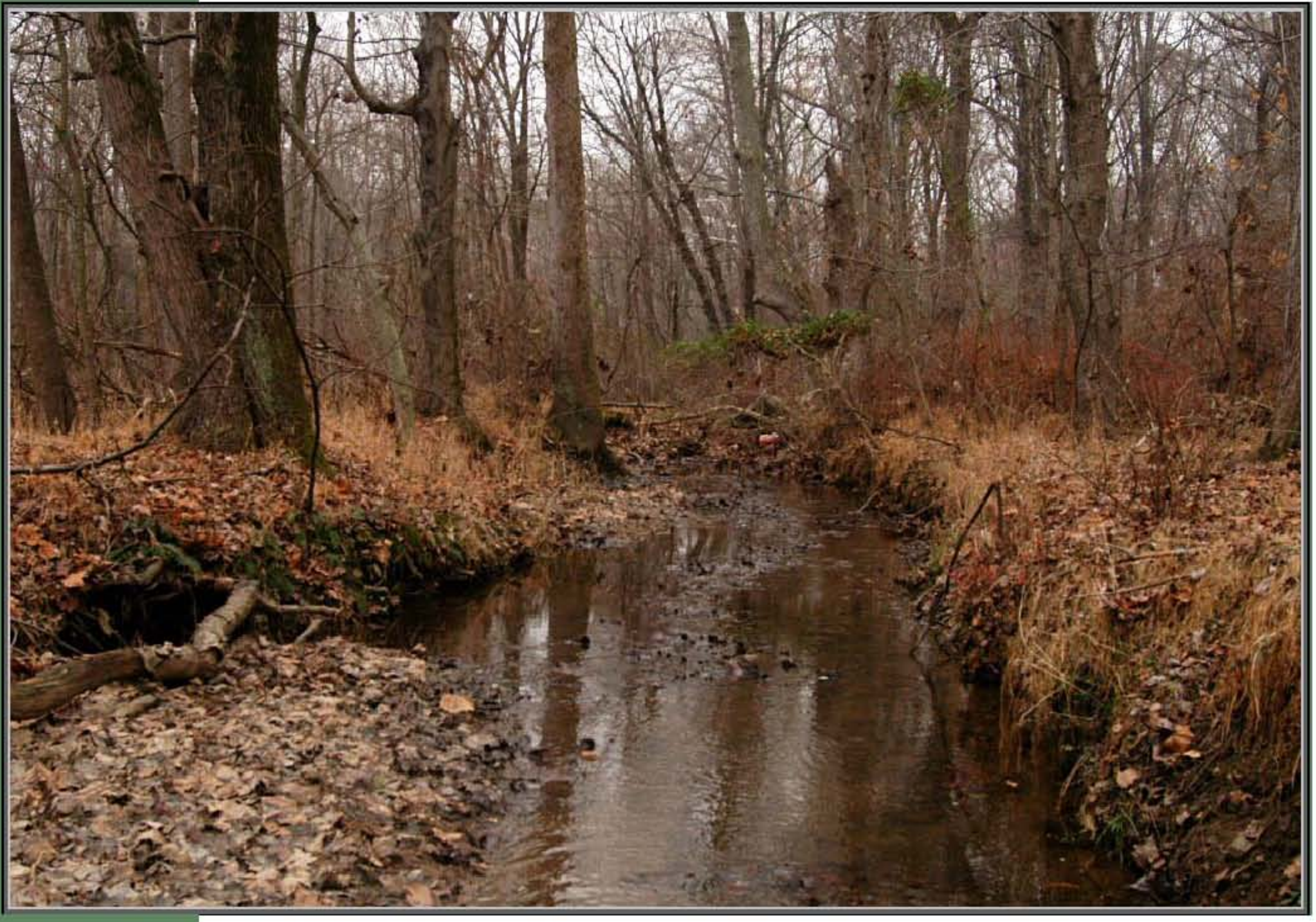
Appendix 14-D: Detailed Study Report Example

Note: Some of the field methods, analytical methods, and reporting guidelines in Chapter 14 have been modified since this example was submitted to OBD. Where differences occur, the manual guidance supersedes the example. The example is intended only to provide an indication of the length, detail, and general organization of a detailed study report.

Final Stream Geomorphic Report for Intercounty Connector Proposed Crossing BR-21 at the Brooke Manor Country Club Tributary of North Branch of Rock Creek



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Cover photo: Brooke Manor Country Club tributary of North Branch of Rock Creek, downstream view approaching the proposed crossing location. Photo taken in November 2004.

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Glossary

The terms in this glossary are defined as they are used within this report. Different or more general definitions can be found for some terms in other sources.

abutment The structure supporting the ends of a bridge and retaining the embankment soil. In scour analysis, the end of roadway embankments in addition to the supporting structure is referred to as the abutment.

aggradation The general increase in the elevation of the streambed or floodplain caused by sediment deposition.

alluvium Material, transported and then deposited by water, that has not been consolidated or cemented to form rock.

avulsion A sudden change in the course of a stream where the stream deserts its old channel for a new one.

backwater Flowing water that has had its velocity reduced or has become ponded behind an obstruction or constriction such as a dam or a bridge with a narrow opening.

bank The rising ground, bordering a stream channel, which restricts lateral movement of water at normal water levels. The left and right banks are defined from a downstream-facing orientation.

bankfull discharge The flow that just begins to flood the active floodplain. The active floodplain is the floodplain that is being created by the channel under the current watershed and climate conditions.

bar A ridge-like accumulation of sand, gravel, or other alluvial material formed in the channel. See also *point bar*.

base level control A point representing the lower limit of erosion of the land's surface by running water. Controlled locally and temporarily by the water level of stream mouths emptying into lakes, resistant bedrock, streambed protection, or more generally and semipermanently by the level of the ocean (mean sea level).

bed The ground on which any body of water lies, limited laterally by a bank.

bedload Stream-transported materials carried along the streambed by sliding, rolling, or saltation (bouncing or other discontinuous movement).

bedrock The solid rock underlying unconsolidated surface materials (as sediment or soil).

boundary shear stress The force per unit area exerted by the flow on the channel boundary in a direction parallel to the channel boundary (bed and banks).

channel A discernible waterway that continuously or periodically contains moving water within a defined bed and banks.

channelization The artificial straightening or dredging of a stream either to relocate it or to make it deeper, straighter, or shorter.

cobble Rounded and subrounded rock fragments between 64 and 256 millimeters in intermediate diameter.

colluvium Mixture of rock material that has reached its present position as a result of direct, gravity-induced mass movements down a slope to its base.

critical shear stress The minimum force per unit bed area that will mobilize the bed material.

culvert A concrete, corrugated steel, or plastic pipe, of varied size and shape, used to convey water, typically under a road. Is usually open at each end and not tied to a larger closed storm-drain network.

degradation (1) The general lowering of the streambed or floodplain surface elevation caused by erosion. (2) A reduction in quality with respect to in-stream, riparian, or stream corridor habitat.

discharge Volume of water flowing through a given stream at a given point and within a given time period, usually measured as volume per unit of time (e.g., cubic feet per second).

entrenchment (channel entrenchment) A measurement used to indicate the amount or degree of vertical containment of flood flows within a channel. This measurement of containment considers both vertical and lateral confinement of the channel. (Entrenchment ratio equals the width of the flood-prone area at an elevation twice the maximum bankfull depth, divided by the bankfull width.)

floodplain The relatively flat land bordering a stream or river channel that is formed by the deposition of sediment during floods. The active floodplain is that being formed by the current stream of the channel in the current climate. Note that this definition differs from that of a flood management floodplain that is defined as any land, flat or otherwise, that is inundated by a specific magnitude flood event such as a 100-year flood.

flat (valley flat) Extensive, nearly level surface of the valley bottom that typically coincides with the active floodplain for channels that are not entrenched. Where channels are entrenched, the valley flat is higher in elevation that the active floodplain.

fluvial Produced by the action of a stream.

geomorphological Pertaining to the study of the origin of landforms, the processes whereby they are formed, and the materials of which they consist.

grade control An erosion-resistant feature that may be natural or man made, such as a bedrock outcrop or culvert, that is part of the channel bed and that prevents the bed in that area from further degrading. The bed longitudinal profile of the upstream channel is highly affected by the stability of these features.

headcut A waterfall-like feature that forms in soil or rock as channel degradation progresses upstream.

hydrologic Pertaining to the science of water, its properties, and its movement (cycling) over and under land surfaces.

incised stream A stream that has incurred vertical streambed degradation to the extent that the height of the banks is greater than the depth identified for the bankfull stage.

lateral migration Movement of the entire channel in a cross valley direction. This typically occurs near bends where one bank erodes and the other accretes (builds) such that the channel moves across the valley. In some cases the overall dimensions of the bankfull channel may not change substantially with this translation movement.

landform A natural feature of a land surface.

legacy sediments Sediment originating from historic land disturbances that is deposited on floodplains or in channels.

local control point See *grade control*.

longitudinal profile A plot of the stream thalweg elevations versus distance along the channel (see *profile*).

meanders Regular and repeated bends of similar amplitude and wavelength along a stream channel.

nickpoint Area of abrupt change in bed elevation, resulting from erosion or the outcropping of a resistant bed.

offset channel reach A section of channel abruptly bent aside and out of line with straight sections immediately upstream and downstream.

pattern See *planform*.

plan view Representation of the site as seen from above.

planform or **planform pattern** The form of the channel from a plan view perspective.

point bar A bar found on the inside of bends.

pool Portion of the stream, often deeper than surrounding areas, with reduced current velocity during normal flow periods. During floods, flow velocities may be higher than in other parts of the channel.

profile Representation of a structure as seen from the side; a plot of the stream thalweg elevations versus distance along the channel (see *longitudinal profile*).

reach Any specified length of stream.

riffle A shallow extent of stream where the water flows more swiftly over completely- or partially-submerged rocks to produce surface disturbances under normal flow periods. A shallow extending across and along the streambed and causing broken water.

scour The cumulative effect of the erosive action of water that causes an identifiable depression or cusp in a streambed, streambank, or other channel or floodplain boundary. Flow in bends, around bridge piers and abutments, and in contractions often causes identifiable erosion features called scour holes that can be associated with the specific pattern and intensity of flow that formed them. Scour evaluations are conducted at bridges to ensure that bridge foundations are adequately protected from or are designed to prevent undermining by scour.

sediment Fragmented material that originates from the weathering of rocks and decomposition of organic material and is transported in suspension by water, air, or ice to be subsequently deposited at a new location.

thalweg A line connecting the lowest or deepest points along a streambed or valley bottom. The stream longitudinal profile is a plot of the elevation of the thalweg versus distance along the channel.

valley An elongated, relatively large, externally drained depression of the Earth’s surface that is primarily developed by stream erosion. In this report, the valley is the low-lying land and the adjacent side slopes (walls) created primarily by the removal of the landmass by ground water (solution) and surface water (erosion).

valley walls The side slopes adjacent to the valley bottom (see *valley*).

Executive Summary

A geomorphic assessment was completed for a proposed waterway crossing (**crossing BR-21**, formerly known as **crossing 1-9**) for the Intercounty Connector (ICC) roadway at an unnamed tributary (herein referred to as Brooke Manor Country Club tributary to distinguish it from other unnamed tributaries) of the North Branch of Rock Creek. Based on the geomorphic assessment, estimates of long-term channel degradation and channel lateral migration, necessary for scour computations, are provided. The study results are also valuable for determining the size, location, and type of structure.

The detailed geomorphic study included an analysis of the stream and valley profiles, channel planform history and lateral channel movement, representative channel cross section characteristics, and bed sediment mobility. The analysis was based on a channel survey and sediment sampling completed under this study, topographic mapping developed for the ICC project by Maryland State Highway Administration (MDSHA), and USGS topographic maps. Historic mapping was also examined to determine the location of mills or other historic changes to the stream valleys.

GENERAL FINDINGS

The existing stream channel was found to be degraded, unstable and undergoing significant change. Effects of past channel straightening and relocation efforts have contributed to past and current channel degradation. The stream is moving laterally away from its previously straightened alignment. Channel avulsion and migration, caused by debris jams and bank erosion in channel bends, appear to be the primary causes of channel lateral movement. Of particular importance are four bends that form an offset (i.e., abruptly bending out of line) channel reach that extends 100 feet upstream of the proposed crossing centerline. This dynamic section of channel, which has shifted 40 feet from its previously straightened alignment, will be located, at least in part, under the crossing structure.

Deterioration of protection for a sewer line crossing downstream of the proposed crossing location indicates past vertical degradation, although the stream shows no current signs of active rapid vertical degradation. The existing channel grade is dependent, however, on the vertical stability of the BMCC tributary's confluence with North Branch, located 900 feet downstream of the proposed crossing BR-21 centerline, and two boulder jams, located 650 and 400 feet downstream of the centerline, respectively. Although these vertical controls are currently stable, they appear to be highly vulnerable to failure, which would cause severe vertical degradation at the proposed crossing.

Both measured channel cross sections indicate significant channel incision. Based on the Rosgen (1996) classification system, the channel at Cross Section 1 (200 feet downstream of the proposed crossing centerline) is a B4c-type channel; the channel at Cross Section 2 (350 feet upstream of the proposed crossing centerline) is an F4-type channel. The table below (also given as Table 4) provides a summary of the channel cross section characteristics. Based on analysis of these data and a rough estimate of channel friction slope using riffle crest elevations, a flow with a return interval of about 2 years was determined to be required to overtop the highest banks and initiate flooding of the valley flat at Cross Section 1. (This result may be dissimilar to that computed using HEC-RAS for the BR-21 hydraulic model study because of differing computational methods and cross section information.)

DESIGN CONSIDERATIONS AND RECOMMENDATIONS

Based on analysis of these morphological processes, the following considerations and recommendations are provided to support the short- and long-term stability of the proposed crossing:

- **The BMCC tributary is highly vulnerable to significant future vertical degradation, although currently the BMCC tributary is not degrading rapidly.** The channel is capable of downcutting up to 8.5 feet as a result of long-term degradation (see Section 2.6) and an additional 4 feet in scour holes in main channel bends (see Sections 2.5). **Scour computations for piers and abutments should include 8.5 feet of long-term degradation and 4 feet of main channel bend scour, for a total of 12.5 feet**. While no evidence of bedrock exposure in the streambed was found near the proposed crossing, resistant bedrock beneath the current streambed materials would probably limit the total scour.

- **Long-term lateral movement of the channel will be significant**. The main channel is laterally unstable (Sections 2.4 and 2.7) and is capable of migrating or avulsing across a large section of the valley bottom (at the proposed crossing location, **up to 60 feet** from its current position) over the next 50 years (see Section 2.7). Although the channel was relocated and positioned near the valley wall, the lowest part of the valley lies to the southwest, and over the long term (50 years) the channel will tend to move in that direction. **Consideration should be given to positioning the crossing toward the central and lowest part of the valley rather than aligning the crossing with its current channel position along the valley wall**. If piers or abutments are placed in the valley bottom, they should be designed with two expectations: they will someday be in the main channel; and for scour computations, the angle of **flow attack to the structure will be large (60 to 90 degrees)**. **For design flood flows, abutments and piers should be parallel to the centerline of the low part of the valley**.

  The four sharp bends and offset section of channel currently located upstream and within 100 feet of the proposed crossing centerline will likely at least partially be located under the crossing structure (see Section 2.7). Left unaltered, these bends will migrate into piers or abutments that are located on the valley

Bankfull Flow Parameter Summary (Report Table 4)

Bankfull Flow Parameter	**Assessment Reach Cross Section 1**	**Cross Section 2**
Cross Section Area, A_{bkf} (ft^2)	7.7	7.7*
Width, W_{bkf} (ft^2)	13.0	12.9
Mean Depth, d_{bkfl} (ft)	0.59	0.60
W_{bkf} / d_{bkfl}	21.8	21.6
Maximum Flow Depth, d_{mbkf} (ft)	0.75	1.45
Hydraulic Radius, R_h (ft)	0.58	0.48
Channel Roughness Coefficient, Manning *n*	0.045	–
Width of Flood-Prone, W_{fpa} (feet)	22.5	17.2
Entrenchment Ratio, ER = W_{fpa} / W_{bkf}	1.73	1.33
Channel Incision from Valley Flat, I_{vf} (ft)	2.41	1.73
Channel Incision Ratio, IR = I_{vf} / d_{mbkf} (no incision IR = 0)	3.21	1.2
Sinuosity, K	1.23	1.0
Riffle Surface, $D_{50riffle}$ (mm)	35	–
Riffle Surface, $D_{84riffle}$ (mm)	75	–
Energy Slope, S_f (ft/ft)	0.011†	0.014‡
Flow, Q_{bkf} (ft^3/s)	18.5	18.5*
Average Channel Boundary Stress, τ_{avg} (lb/ft^2)	0.40§	–
Largest mobile particle size, D_{max} (mm)	37	–
Average Channel Velocity, V_{bkfl} (ft/s)	2.4	–
Critical Boundary Stress for Largest Mobile Particle Size, τ_c (lb/ft^2)	0.46	–
Rosgen Channel Type	B4c	F4

* Value assumed to be the same as assessment reach value.
† Value estimated from field measurement.
‡ Value computed.
§ Boundary stresses here represent total average boundary stress. Particle boundary stress may be substantially less, depending on backwater effects that may include resistance from the planform, bed forms, debris jams, and channel bank roughness.

bottom and cause scour holes at severe angles of attack (90 degrees) for flows near top-of-bank conditions. During design flood conditions for scour (100- and 500-year events), however, flood flows will tend to be aligned with the valley, and scour computations for piers and abutments should consider flood flow alignment creating an angle of attack of up to but no more than 60 degrees. Two short sections of channel that are currently aligned perpendicular to the valley direction are located within this 100-foot section. These sections will be severely eroded when vegetation dies as a result of (1) shading, which will weaken the bank strength, and (2) flood flows that will be directed perpendicular to their alignment by the crossing, which should be aligned primarily with the downstream valley direction. Consideration should be given to cutting off the offset reach and removing the bends to improve channel stability and to allow the crossing to be repositioned closer to the center of the valley. Grade control may be required to prevent headcutting upstream if the channel is shortened by cutting off the offset reach.

Long-term migration of the channel upstream of the crossing will trend toward the center of the valley and away from the valley wall where the channel is currently located (see Section 2.4, Proposed Crossing Reach, and Section 2.7). Although adding armoring to the channel near and under the crossing would initially stabilize that section, alignments of the dynamic stream segments with respect to the protected and therefore stationary channel reach under the crossing would deteriorate as channel sections upstream and downstream of the crossing migrated from their existing locations. Progressive failure of channel protection could ensue as flows impinged on channel lining. After the channel lining failed or the channel abandoned its initial protected location, channel flow could impinge at high skew angles on substructure components.

Relocation and restoration of a more sinuous channel in a location near the center of the valley would place the stream back to where it was probably positioned, prior to being relocated, and where it will tend to migrate in the future. The crossing could then be designed for and positioned in a more natural location to minimize potential migration of the channel into structure elements such as piers and abutments.

- **The supply of debris from the upstream channel and floodplain to the proposed crossing location is expected to be low** (see Section 2.4, Upstream Supply Reach). Although bank erosion and channel incision are causing a large number of bankline trees upstream to fall, the channel's relatively narrow width and channel bends prevent their transport to the proposed crossing location. The greatest threat of debris jam formation at the crossing comes from trees immediately upstream that may fall across the channel or on the floodplain and be transported the short distance to the crossing. The size of the proposed crossing opening should be sufficiently large to pass debris and meet all pertinent regulations (see guidance on design for debris in reference number 13).

1

Introduction

1.1 PURPOSE

A geomorphic assessment was completed to evaluate the stability of an unnamed tributary of the North Branch of Rock Creek at the proposed Intercounty Connector (ICC) roadway crossing BR-21 (formerly known as crossing 1-9). Although this tributary is not named on USGS 7.5 minute quadrangle map (Sandy Spring) of the region, Montgomery County refers to the stream as the Brooke Manor Country Club tributary in its hydrologic studies of the Rock Creek basin (URS Corporation, 2001). The abbreviation BMCC will be used to refer to this tributary throughout this report to avoid confusion with other unnamed tributaries.

Channel stability affects several aspects of waterway crossing performance, including the ability of the crossing to pass the design storm, the potential for scour around foundations or highway embankments, and the quality of aquatic and riparian habitat near the crossing. The purpose of this geomorphic study was to evaluate existing channel stability, to determine the potential for long-term channel degradation or aggradation, and to determine the potential for lateral movement of the channel near the proposed crossing. The results of this study provide a basis for design recommendations that incorporate the effects of long-term channel dynamics. These recommendations are intended to provide designers with information useful for determining the crossing type, size, and location. Further, the study report provides information necessary to design a crossing that accommodates, protects against, or avoids channel stability and foundation scour problems.

1.2 PROJECT DESCRIPTION

The proposed Intercounty Connector (ICC) project is intended to link existing and proposed development areas between the I-270 and I-95/US 1 corridors. The project will provide a state-of-the-art, limited access, east-west highway connecting central and eastern areas of Montgomery County to western Prince George's County.

This transportation project is being planned to address multiple needs. The ICC is a necessary addition to the existing transportation network which will support planned regional development where it has already occurred along the major corridors of I-270 and I-95/US 1. It will also help to relieve the heavy volume of non-local traffic on local roads which has contributed to an increase in congested and unsafe travel conditions.

The construction will involve several key components, one of which will be the construction of crossings over all streams along the proposed alignment. This report focuses on the potential crossing BR-21 over the BMCC tributary to the North Branch of Rock Creek approximately 850 feet upstream of their confluence, approximately 950 feet east of the proposed ICC North Branch crossing BR-20 (see Figures 1 and 2), and approximately one mile upstream of Lake Bernard Frank within North Branch Park. Figure 1 also indicates the boundaries for both streams' watersheds, which are located in the Washington metropolitan area of Montgomery County.

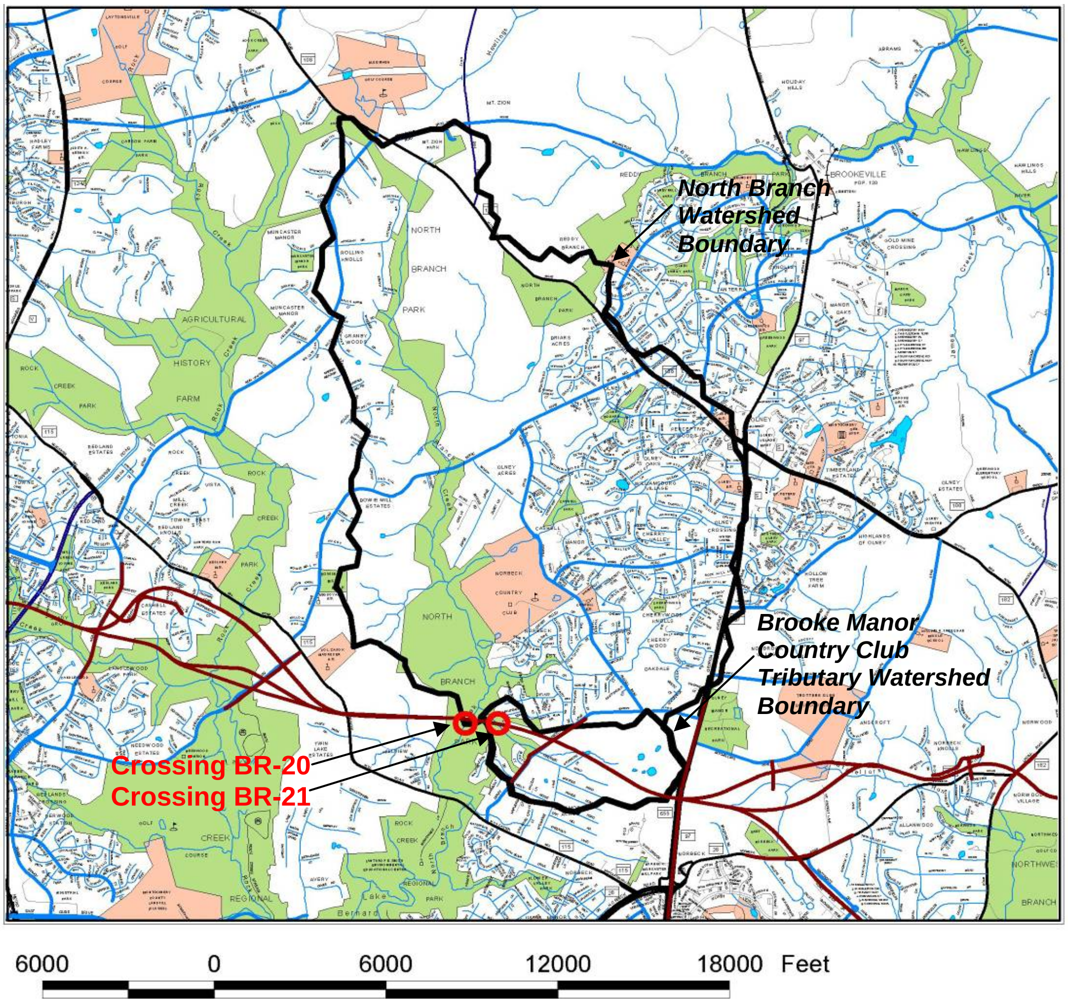


Figure 1 Crossing BR-21 vicinity map and watershed delineation.

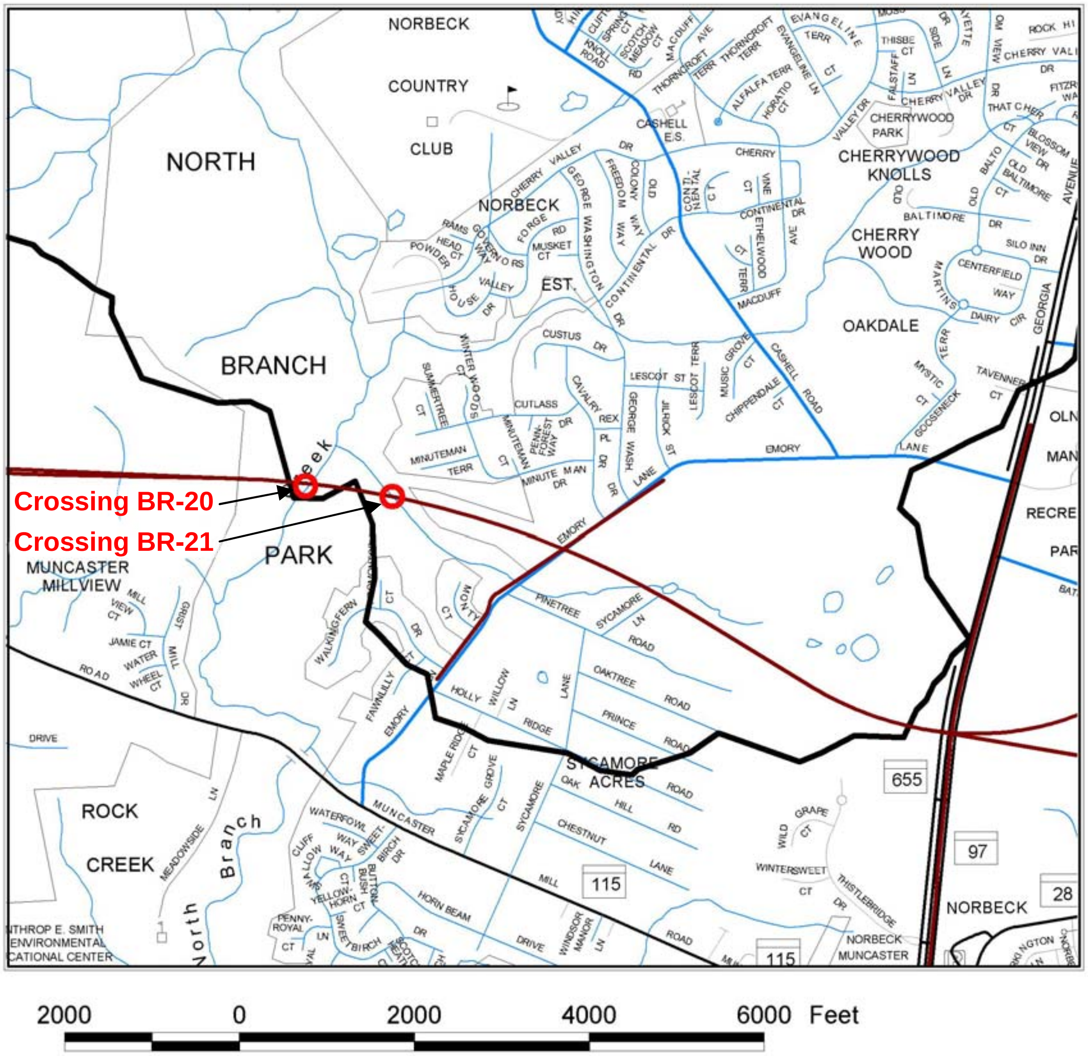


Figure 2 Crossing BR-21 location map.

1.3 STUDY OBJECTIVES

The specific objectives of this study included the following:

1. Evaluation of the stability of the existing channel near the location of the proposed crossing, and identification and determination of causes for instability.
2. Evaluation of the potential for channel aggradation, degradation and lateral migration at the crossing and during the service life of the crossing.
3. Provision of design information that promotes long-term crossing and channel stability.

These objectives were achieved through the following tasks:

1. Determination of historic changes to North Branch that may influence stream stability.

2. Acquisition and evaluation of the geomorphologic implications of available hydrologic and geologic information for the watershed.
3. Acquisition and analysis of specific site survey data to evaluate the channel profile, channel planform, bankfull conditions, and sediment mobility.
4. Development of design recommendations.

2

Existing Stream Reach Stability Analysis

A fluvial geomorphic assessment was conducted to evaluate the stability of the stream reach in the vicinity of proposed crossing BR-21. Figure 3 shows the general location of the crossing with respect to the stream valley. General hydrologic conditions of the North Branch watershed, locations of historic mills, and a summary of relevant geologic considerations for North Branch and its tributaries are provided in the report entitled *Preliminary Geomorphologic Study for the Assessment of Potential ICC Bridge Crossings in the Rock Creek and North Branch Watersheds* by Parola, Oberholtzer and Altland (2004). The geomorphic investigation in this report focuses on the reach in the vicinity of the crossing and includes a detailed survey of the stream reach and an evaluation of sediment mobility in the reach, an estimation of the bankfull flow conditions, and a general analysis of reach stability, including potential long-term migration and vertical degradation. General North Branch watershed information developed in the Parola et al. (2004) report will be summarized or referenced here. Specific hydraulic and hydrologic information was also extracted from MDSHA hydrologic and hydraulic studies for the crossing.

2.1 HYDROLOGY

A detailed hydrologic study entitled *SHA's Hydrologic Analysis Report for the Intercounty Connector Over Rock Creek and Mill Creek Tributaries* was performed by MDSHA (2004). The drainage area (Figure 1) at the BR-21 crossing is 0.7 square miles. Hydrologic analysis was conducted for both existing and ultimate development conditions. The rainfall data was derived from the Rainfall Frequency Atlas of the United States, Technical Paper No. 40. Table 1, below, provides estimates for storm events at four levels, with the 2-year storm being the least and the 100-year the greatest. For the details of this analysis refer to the above mentioned report by the SHA's Structure Hydrology and Hydraulic Unit of the Bridge Design Division.

Table 1 Results of Hydrologic Analysis for Brooke Manor Country Club Tributary Crossing BR-21

Return Period (years)	Fixed Region ± 1 Std Error Lower Limit (cfs)	Fixed Region ± 1 Std Error Upper Limit (cfs)	Fixed Region Regression Eqtn for Urban Watersheds (cfs)	TR-20 Results Existing (cfs)	TR-20 Results Ultimate (cfs)
2	110	230	170	190	200
10	370	630	500	430	450
50	760	1340	1050	840	860
100	970	1830	1400	1010	1020

As Table 1 indicates, the peak flows for ultimate development watershed conditions are not significantly different from those estimated for existing conditions; therefore, substantially different future hydrologic conditions caused by land-use changes is not anticipated.

2.2 PHYSIOGRAPHIC REGION AND SURFACE GEOLOGY

The watershed of the BMCC tributary is located within the Eastern Piedmont Plateau Province. In this particular part of the physiographic region, soils and sediments are derived from the parent rock material of the Upper Pelitic Schist of the Wissahickon Formation, which formed during the Late Precambrian period. The Upper Pelitic Schist is an albite-chlorite-muscovite-quartz schist with sporadic thin beds of laminated micaceous quartzite.

2.3 HISTORICAL LAND-USE AND CHANNEL MODIFICATIONS

Agricultural land-use practices, urbanization, milldams, sewer line construction and protection of utility line crossings, and channel modification have all affected the North Branch stream valley and channel and may affect the BMCC tributary. Several studies have shown that agricultural land-use practices have resulted in hydrologic and sediment regime changes prior to suburban land development in the Maryland Piedmont. These changes have caused widespread erosion of uplands and massive deposition of soils (legacy sediments) in the stream valleys (Cravens 1925, Costa 1975, Jacobson and Coleman 1986). Examination of streambanks in the Rock Creek and North Branch watersheds indicates that similar deposition occurred in these stream valleys (Parola et al. 2004). Although the stream valleys are forested, the current watershed land-use in upland areas is highly urbanized in several parts of the watershed, increasing the peak discharges in these streams.

Channelization of the North Branch, including channel straightening and channel cross section enlargement, appears to have occurred both prior to and after 1950. The unnaturally straight alignment and the armoring of the BMCC tributary streambed and banks with large boulders that appear to be remnant blast rubble indicate that the tributary channel was modified over all of its length between its confluence with North Branch and the Emory Lane crossing. Examination of the tributary near bends indicates that the stream

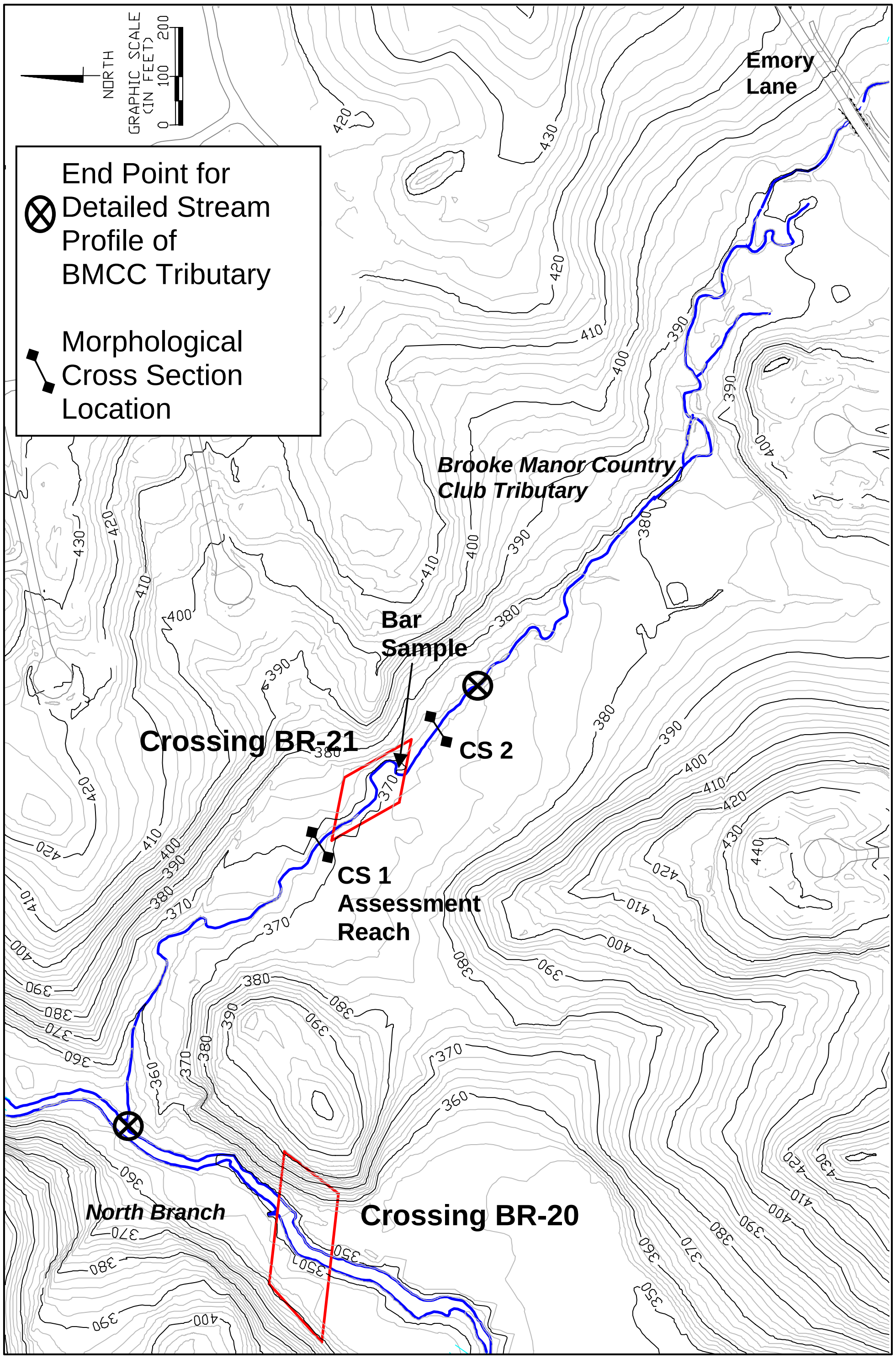


Figure 3 Crossing BR-21, topographic features, and geomorphic assessment sampling and data collection locations.

only relatively recently (in the last 50 years) has begun to migrate away from a straightened alignment. Evidence from the unusual profile of the stream valley and what appears to be rock rubble lining of the channel downstream of the proposed crossing indicates that the channel was moved to accommodate the sewer line or that a small dam may have been constructed on the BMCC tributary. In the late 1700s through at least the late 1800s, mills and their associated milldams were common on streams in Montgomery County (see summary in Parola et al. 2004). Figure 4 shows the location of two sets of mills on North Branch: a saw and grist mill upstream of the confluence of the BMCC tributary near Bowie Mill Road, which lies beyond the channel sections discussed in this report, and another saw and grist mill near Muncaster Mill Road.

2.4 SITE EXAMINATION, VISUAL ASSESSMENT, AND VALLEY PROFILE

A visual site inspection of Rock Creek, North Branch and several tributaries with watersheds greater than one square mile was conducted during 2003 and 2004. The findings of that watershed assessment are documented in the *Preliminary Geomorphologic Study for the Assessment of the Potential ICC Bridge Crossings, Rock Creek and North Branch Watersheds* (Parola et al. 2004), available from the SHA's Structure Hydrology and Hydraulics Unit of the Bridge Design Division. Photographs and specific findings from the watershed report that are relevant to the site conditions at the proposed ICC crossing BR-21 will be provided in this report.

Factors that contribute to or limit long-term bed degradation were identified based on site observations and an examination of bed and bank elevations of the North Branch and BMCC tributary valley profile. Repeated site visits were made in the section of the BMCC tributary between its confluence with the North Branch, located 900 feet downstream of proposed crossing BR-21, and the Emory Lane crossing, located 1760 feet upstream of proposed crossing BR-21. Site visits were also made in the section of North Branch between Muncaster Mill Road, located approximately 4500 feet downstream of proposed crossing BR-20, and an access point 2000 feet upstream of proposed crossing BR-20 near the west end of Cherry Valley Drive (see Figure 3 and the study area topographic map provided in the back pocket of this report). Figure 5 shows the valley bottom profile plot ("valley profile"). Note that distance along the *valley*, not the stream, was used to develop the plot of the valley profile.

The profile was produced with data from two MDSHA sources obtained for the ICC project: (1) aerial survey data (1" = 100' photogrametric mapping), and (2) ground survey data obtained for hydraulic model studies. These data, represented in Figure 5, are useful for examining average slopes along the valley, especially in the region where ground survey data were available. They may not indicate, however, rapid changes of less than one foot in the channel bed elevation. For example, sudden drops in the streambed of less than one foot that may occur over utility crossing protection or debris jams may not be detectable from this plot. Nonetheless, locations of steep valley sections or rapid changes in valley slope detectable in the Figure 5 valley profile indicate the presence of current or past hard points. These hard points, termed "bed level controls" in this report, may be natural (resistant bedrock), man-made, or a combination of both. The long-term sustainability of these controls is an important factor in determining the potential degradation of the streambed

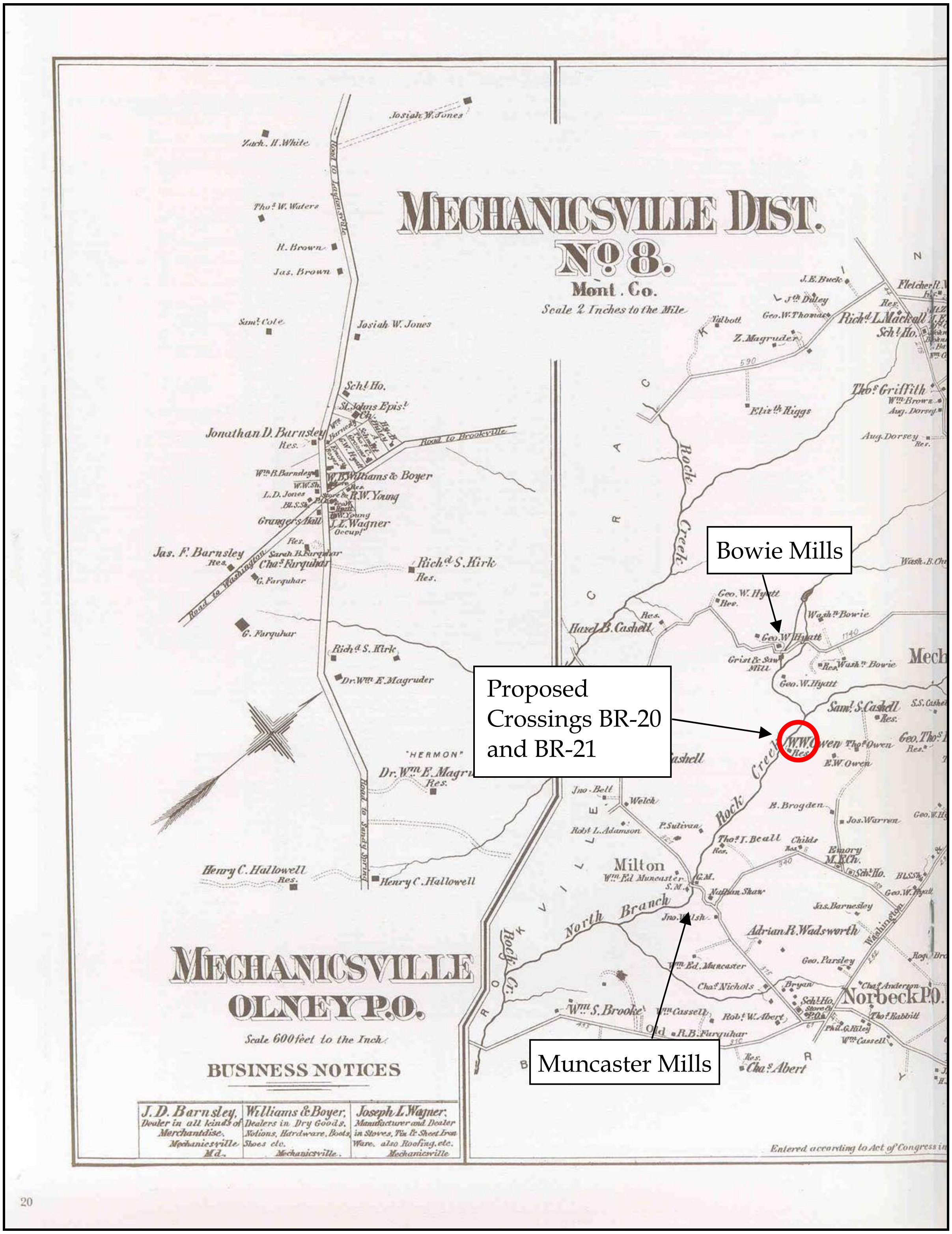


Figure 4 Historic map from Hopkins (1879).

upstream of the controls. The remains of utility crossing protection, milldams, and milldam channel or bank protection represent hard points in the bed that may currently control channel grade; the degradation of these hard points over time, however, may result in a corresponding degradation of the channel bed upstream.

Section 2.4 is separated into four parts in which general observations, including identification of hard points and other factors influencing long-term channel dynamics, made during site visits are described with respect to the valley profile:

- General Valley and Corridor Observations
- Downstream Base Level Control Reach
- Proposed Crossing Reach
- Upstream Sediment Supply Reach

Note that the proposed location of crossing BR-21 is at valley station 101+00 feet on the BMCC tributary; stations increase in the upstream direction.

General Valley and Corridor Observations

North Branch of Rock Creek

The approximate locations of Muncaster Mill Road and the proposed crossings BR-20 and BR-21 are shown in Figure 5 in addition to the approximate locations of the suspected remains of three milldams on North Branch and one dam-like structure on the BMCC tributary. The average valley slope of North Branch between the Muncaster milldam and proposed crossing BR-20 is approximately 0.32% in the examined reaches, except in locally steep segments located in narrow valley sections. The average channel slope measured along the valley is similar, although three distinct reach types are present: (1) steep heavily blast-rubble-armored reaches, which appear to have been part of milldams or roadway crossings; (2) mildly sloping reaches with degrading utility crossing bed and bank protection; and (3) mildly sloping sinuous sections with gravel armored riffles and debris jams. The existing North Branch channel is severely degraded (incised F4/6), with the exception of the rock armored sections (B4c Rosgen stream types), which currently appear to be more stable. Nearly all of the channel sections appear to have been modified (relocated, enlarged, and/or straightened) at least once or have been affected by channel modifications. The channel has downcut through legacy sediment (probably milldam backwater deposits) at and downstream of the proposed BR-20 crossing location and is significantly entrenched.

Utility crossing protection is present throughout the examined reaches; in some sections, however, the protection has not been undermined completely and these partially deteriorated protective structures control the channel grade. In sections that are more sinuous, the utility crossing protection, although present, appears to be degraded to an extent that it no longer controls the stream gradient; tree fall, debris jams, channel bends, and gravel riffles in over-widened sections combine to control stream gradient. In these reaches, channel degradation into gravel and cobble has provided the bed material for cobble armored riffles.

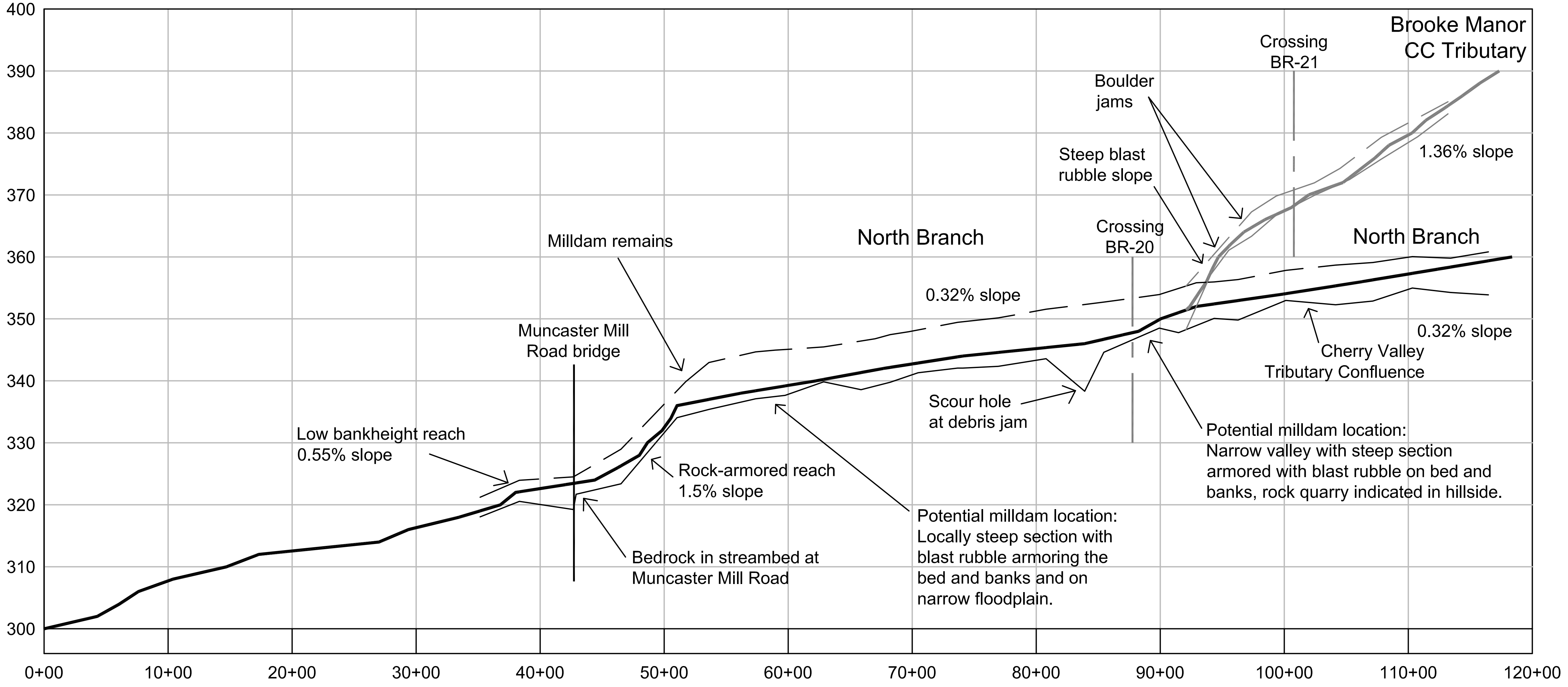


Figure 5. Stream and valley profile along North Branch and Brooke Manor Country Club Tributary.

SCALE: 1" = 1,000' horizontal
1" = 20' vertical

Note: Scaled for 11 x 17 paper size

Note : All slopes calculated using valley stations.

The fallen trees, debris jams, channel bends, and the coarse armored riffles appear to provide a channel slope of approximately 0.32%, about equal to those less sinuous locations where utility crossing protection dominates the control of the slope.

Brooke Manor Country Club Tributary

The tributary is set in an unusual valley that varies in width from less than 80 feet near the tributary's confluence with the North Branch to more than 250 feet approximately 1600 feet upstream of the confluence, as shown in Figure 3. The valley narrows again approximately 1000 feet upstream of the proposed crossing centerline. The valley flat (i.e., the flat part of the valley bottom) of the BMCC tributary and most of the steep hillsides are forested, although clearings occur along what appear to be access roadways for sewer lines or other utilities. Large boulders were observed in the floodplain of the narrow valley section between the proposed crossing and the confluence of the tributary and North Branch.

The section of channel that extends for approximately 900 feet from the proposed crossing centerline to the point where the valley narrows upstream has a very unnaturally straight alignment. Debris jams block channel sections and force them to migrate laterally at some locations, causing the channel to diverge from its straight alignment for short distances. Two sewer line access holes and a protected stream crossing were observed about 80 feet downstream of the proposed crossing centerline. Other sewer access holes were observed along an alignment parallel and south of the tributary and downstream of the proposed crossing.

Downstream Base Level Control Reach (Valley Station 92+00 feet to 97+70 feet)

Future bed elevation changes at the proposed crossing site are highly sensitive to changes in the bed level downstream. Therefore, a base level control reach approximately 500 feet long, extending from the confluence of the BMCC tributary with North Branch (valley station 92+00 feet) to a point 400 feet downstream (valley station 97+00 feet) of the proposed limits of the crossing centerline was established to identify bed level controls and signs of degradation in order to evaluate existing channel bed vertical stability and the potential for long-term bed degradation. A bolder jam located at valley station 97+00 is a local grade control and is the boundary between the steeply sloping, heavily rock-armored base level control reach and the milder sloping proposed crossing reach.

The downstream base level control for the bed of the BMCC tributary is the bed elevation at its confluence with North Branch. Grouted rock protection immediately upstream of the confluence of the BMCC tributary with North Branch has been undermined, and the channel has degraded approximately 1 foot below the level of bed protection. The Figure 5 valley profile shows a distinct convex "hump" between valley station 92+00, at the BMCC tributary confluence with North Branch, and valley station 105+00, approximately 400 feet upstream of proposed crossing BR-21. The unusual shape of the valley profile may be caused in part by the manipulation of the steep and narrow part of the valley during construction of the sewer line, or it may be a result of past milldam construction as indicated by the abundance of blast rubble on the floodplain and in the channel. In the hump, the channel is straight and steep (3% slope) from the confluence to a point 250 feet upstream where a boulder jam (valley station 94+50) controls the grade. The boulders are angular with sharp edges, indicating that they were placed and are probably a byproduct of sewer line construction or channel protection.

Heavy armoring of the bed and banks, including several sections of floodplain, has prevented lateral migration of the channel in the steep reach. Currently, the armoring also prevents undermining of tree roots and the collapse of trees that would otherwise form debris jams in the channel. This steep reach appeared stable at the time of inspection; future vertical degradation of the stream channel bed, however, may cause the breakup of this armor layer and reduce its effectiveness in controlling the grade.

The upstream half (valley stations 94+50 to 97+00) of the base level control reach has a milder slope (1.5%) and a section of channel that contains two sharp bends with severe bank erosion. The section with the two bends appears to have migrated away from a previously straightened alignment. Two small debris jams were partially blocking the channel at the time of examination in this section. The boulder jam at the upstream limits (valley station 97+00) of this reach forms a local grade control point for the milder sloping proposed crossing reach.

Proposed Crossing Reach (Valley Station 97+00 feet to 105+00 feet)

From the centerline of the proposed crossing (valley station 101+00), the proposed crossing reach extends approximately 400 feet downstream (to valley station 97+00) and 400 feet upstream (to valley station 105+00). This reach forms the mild sloping (0.7% to 0.9%) portion of the "hump" (convex portion of the valley profile) described previously and has the lowest slope in the BMCC tributary. Upstream of the proposed crossing reach, the valley slope increases to 1.36% and remains consistent for more than 2000 feet.

Long-term vertical stability of the proposed crossing reach is mostly dependent on the stability of the downstream base level control reach, although degradation may occur because of channel entrenchment upstream of grade controls. Where the sewerline manholes and crossing were identified downstream of the proposed crossing, the large rock protecting the crossing has been undermined and is failing, which indicates that channel incision has occurred since the protection was installed.

The main concern in the proposed crossing reach is the potential lateral migration of the channel caused by debris jams and other obstructions such as channel bars and channel bends. A section of channel extending from 400 feet to 200 feet downstream of the proposed crossing centerline is dynamic, having several small debris jams and at least four major bends actively eroding their banks. From the centerline of the proposed crossing to the upstream limits of the proposed crossing reach, the channel has been relocated to the northeast valley wall. Valley contours indicate, however, that the ground surface elevation in the center of the valley is lower than that in the current location of the channel, which suggests that the valley center is the probable original location of the channel, and any lateral movement of the channel in this section will trend toward this lower elevation area. Another active section of channel extends 100 feet upstream from the proposed crossing centerline. This offset section, where a series of four sharp (low radius) bends has formed, has avulsed from a previously straightened channel alignment (see Figure 3).

Upstream of these four active bends, the channel is virtually straight for more than 400 feet. Tree fall and debris jams have initiated bank erosion that will likely continue to increase lateral instability upstream of the crossing. Gravel and debris from the upstream supply reach appear to be stored in the channel upstream of debris jams. At least one large debris jam located 150 feet upstream of the proposed crossing centerline has caused bars to form upstream and currently causes the complete capture of upstream gravels and much of the finer sediments in the upstream backwater-affected channel.

Upstream Sediment Supply Reach (Valley Station 105+00 feet to 118+50 feet)

The upstream supply reach extends from valley station 105+00 feet, 400 feet upstream of the proposed crossing centerline, to valley station 118+50 feet at Emory Lane. The main concern for this reach is the production of sediment and debris that it may supply to the relatively low-sloped reach at the proposed crossing location. In the absence of renewed vertical incision initiated in the bridge crossing reach, reduced channel slope, continued increases in the channel sinuosity, and a reduction in coarse sediment supply are indicated.

The slope of this reach is consistent at 1.36%. The stream appears to have been directly modified, as it is positioned along the north valley toe for much of its length. At several locations, the channel shows signs of lateral instability, including sections that have avulsed from straightened alignments and multiple channel sections. Scour around debris jams, bank erosion in channel bends, and treefall appear to be the primary causes of lateral channel movement. While channel incision and bank erosion are causing a large number of trees to fall into the channel upstream, channel bends and the channel's relatively narrow width prevent their transport to the proposed crossing location. Treefall in the vicinity of the crossing, however, could lead to debris jam formation at the crossing.

At present, the proposed crossing reach does not appear to be affected by a large supply of gravel from upstream; despite the active nature of the upstream channel, it appears to be storing coarse sediment behind debris jams or in bars. Should the Emory Lane crossing be reconstructed as part of the ICC project, the sediment load to the proposed crossing could increase. Culverts at Emory Lane are undersized and cause backwater during events that would transport bedload; consequently, these culverts appear to be limiting the sediment supply to downstream reaches.

2.5 DETAILED STREAM PROFILE

A detailed longitudinal survey was conducted to obtained specific information about the characteristics of the streambed profile that could be used to develop an estimate of potential long-term bed degradation in the vicinity of crossings BR-20 and BR-21 and to evaluate the impact of long-term degradation on overall channel stability. Figure 6 shows the streambed profile developed from the survey data. Stations shown in Figure 6 correspond to stations shown on the Figure 7 plan view.

North Branch Channel Profile

The detailed profile of Figure 6 shows that the confluence of the BMCC tributary occurs 75 feet upstream of a 4-foot-deep scour hole caused by a bend in the North Branch. The bend and pool in North Branch are located upstream of a steep rock-armored channel section (0.99% slope) that is vulnerable to long-term degradation. As described in the above sections, bed degradation at the confluence will result in bed degradation and potential destabilization of the BMCC tributary. Up to 4 feet of long-term degradation is predicted in the North Branch, as described in detail in the report entitled *Final Stream Geomorphic Report for Intercounty Connector Proposed Crossing BR-20 at the North Branch of Rock Creek* (Parola and Vesely, 2006). While no evidence of bedrock exposure in the streambed was found near crossing BR-20, resistant bedrock beneath the current streambed materials may limit vertical degradation and scour.

Upstream of the confluence, a bend on North Branch has migrated approximately 30 feet toward the tributary since it was straightened sometime before 1950. Field evidence indicates that this bend migration process will continue until the North Branch channel cuts off approximately 55 feet of the downstream length of the BMCC tributary. Prediction of the potential long-term degradation of the BMCC tributary, provided in subsequent sections, includes both the influence of the change in base level elevation at the confluence and the influence of the lateral movement of the tributary confluence and its effect on channel length.

Brooke Manor Country Club Tributary Detailed Channel Profile

The Figure 6 detailed streambed profile shows the same convex "hump" as the Figure 5 valley profile, though the Figure 6 channel slopes are slightly different from the valley slopes of Figure 5. The boulder jams in the steep downstream reaches of the tributary are clearly indicated in Figure 6 at locations of major changes in channel slope. Upstream of the boulder jams, which act as grade control points, the consistent channel slope indicates that gravel transport is forming the grade. Destabilization of these boulder jams would cause a wave of severe degradation that would propagate up to and through the proposed BR-21 crossing.

Scour Depth in Pools

In addition to the general profile characteristics, scour depth in channel bends was examined to determine potential scour depth in pools that may occur near crossing foundations in the BMCC tributary. Figure 8 shows pool depth for ten of the deepest pools in the BMCC tributary in the vicinity of the proposed BR-21 crossing. The histogram shows that pool depths greater than 3 feet are possible (measured from the riffle crest elevation). Although **pool depths of 3 to 4 feet should be anticipated**, the pools are not extensive.

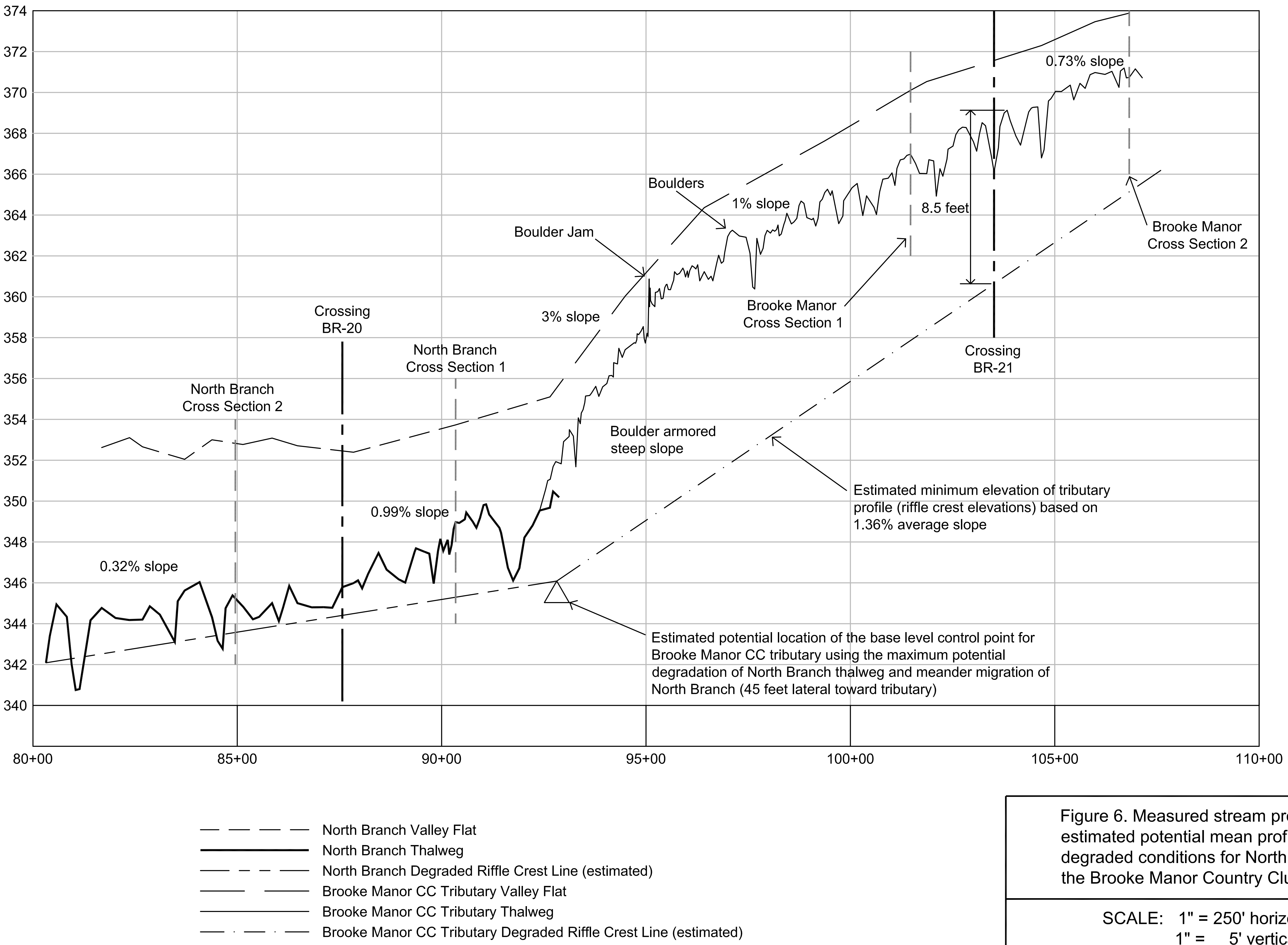


Figure 6. Measured stream profile and estimated potential mean profile under degraded conditions for North Branch and the Brooke Manor Country Club tributary.

SCALE: 1" = 250' horizontal
1" = 5' vertical

Note: Scaled for 11 x 17 paper size

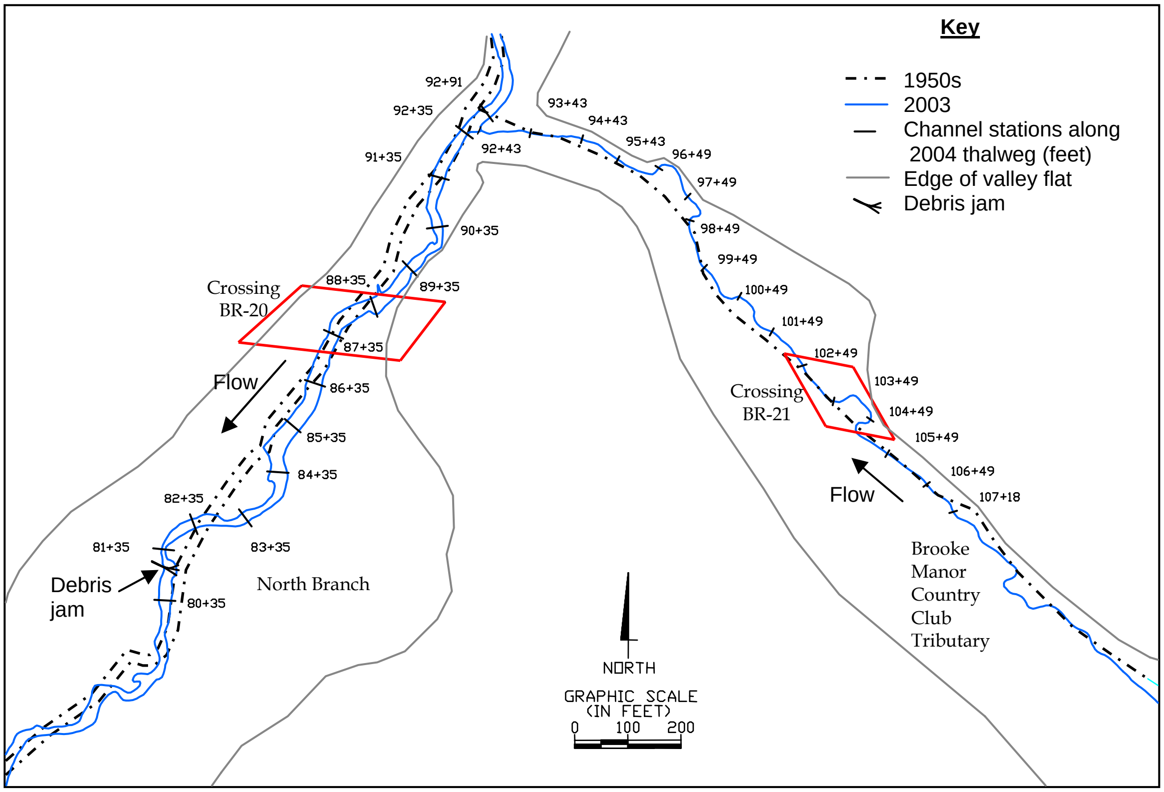
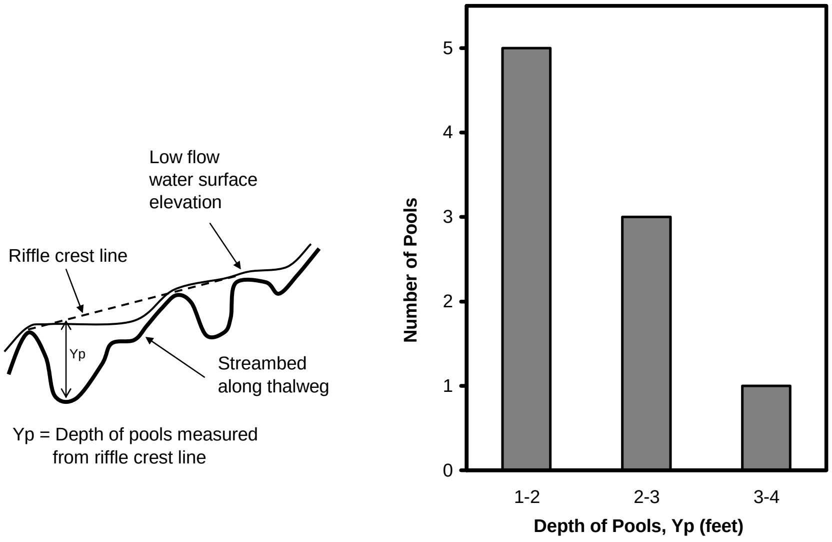


Figure 7 Alignment of North Branch and the Brooke Manor Country Club tributary in the 1950s and 2003.



(a) Pool Depth Measurement Method

(b) Pool Depth Histogram

Figure 8 The (a) method of measuring pool depths and (b) distribution of major pool depths in the vicinity of proposed crossing BR-21 over Brooke Manor Country Club tributary.

2.6 POTENTIAL LONG-TERM DEGRADATION AT THE CROSSING

The stability of the steeply sloping reach of the BMCC tributary within 500 feet of its confluence with North Branch is critical to vertical stability at the BR-21 crossing. Destabilization of this steep reach and, specifically, destabilization of two key boulder jams will cause a loss of downstream grade control and, consequently, severe degradation of the channel bed at the proposed crossing. Several processes may initiate degradation and lead to failure of these bed control features:

1. the base level of the confluence degrades because the North Branch channel degrades
2. the bend in North Branch migrates into the tributary, reducing the tributary length by approximately 55 feet and increasing the already steep downstream slope
3. one of the boulder jams in the BMCC tributary channel is destabilized by a high flow event or is undermined by piping of sediments from beneath or around the jam
4. treefall causes flow to divert around the boulder jams

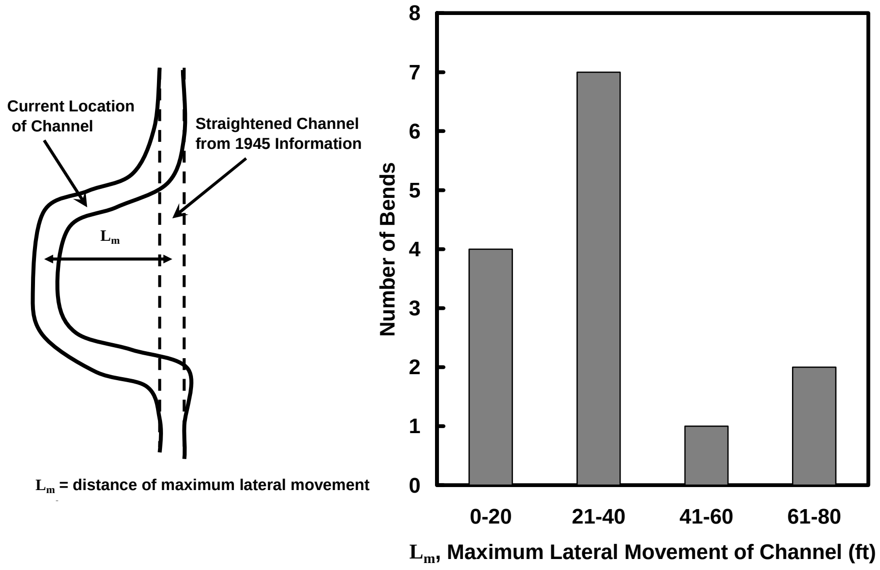
In Figure 6, both the maximum degradation line and the triangle representing the likely future location of the BMCC confluence are plotted based on the following considerations: (1) that the North Branch will degrade approximately 4 feet at the tributary confluence; (2) that the main stem of North Branch will migrate into the tributary, shortening its length by 55 feet; (3) that the average long-term slope of the tributary will be 1.36%, similar to the current slope of upstream sections, and (4) that degradation in the tributary is not limited by bedrock or other large material. **The resulting estimate of long-term channel degradation is 8.5 feet at the centerline of the proposed BR-21 crossing**.

2.7 CHANNEL LATERAL MOVEMENT

Horizontal channel movement in the BMCC tributary, including both lateral migration and avulsion, was examined to determine the expected lateral movement of the channel during the life of the proposed structure. Field examination of abandoned channel scars present in the floodplain verified that the channels of both North Branch and the BMCC tributary have been heavily modified by channel straightening and are moving away from those straightened alignments.

The maximum distance that each channel segment has moved from the straightened alignment of the 1950s was measured at several bends for the BMCC tributary. Figure 9 shows (a) the typical points on the channel planform where lateral movement was measured using the information from topographic maps and recent aerial mapping and (b) a histogram of the measured lateral distances for stream reaches of the BMCC tributary. Lateral movement in excess of 60 feet was measured using the information from topographic maps and recent aerial mapping. The lateral movement was estimated to be greater than 40 feet in three locations and more than 20 feet in 7 additional locations.

Immediately upstream of the proposed crossing centerline, the series of bends and the offset section of channel is currently migrating toward the west valley hillside and the



(a) Measurement of L_m (b) Frequency distribution of measured L_m

Figure 9 Lateral movement of the main channel of the Brooke Manor Country Club tributary from the straightened channel configuration recorded prior to 1950 was measured at 14 locations as shown in sketch (a), above. The histogram (b) shows that several of the bends migrated more than 40 feet from the straightened channel configuration.

probable location of structural elements such as piers or abutments. A portion of this channel section has avulsed more then 40 ft. Because the processes that caused the bend to avulse—treefall and bank erosion—are still active, lateral movements of similar magnitude should be expected over the next 50-year period. The potential also exists for the stream to cut off the large bend area (see Figure 3). Furthermore, lateral channel movement of up to 60 feet should be expected at any location near the proposed crossing because of the wide-valley setting and a significant cross-valley slope that would promote channel movement toward its probable original location in the center of the valley. The valley walls are the only significant topographic feature that would limit lateral movement.

The estimates of bend development and channel migration given here do not consider massive channel degradation of several feet that may occur because of destabilized downstream grade controls. Under massive degradation, scour depths in bends would be expected to be greater than those measured in the existing channel, while lateral migration could be less extensive than otherwise predicted.

2.8 STREAM CROSS SECTION CHARACTERISTICS AND BANKFULL FLOW ESTIMATES

Two stream cross sections were obtained (1) to document the stream conditions in the region of the proposed bridge; (2) to estimate bankfull flow conditions; (3) to classify the stream reaches; (4) to provide information for a sediment mobility analysis; and (5) to document the problem of flood flow orientation and bends in the vicinity of the bridge.

Stream Cross Section Characteristics

Cross Section 1 is located 200 feet downstream of the proposed crossing centerline in the channel section shown in the Figure 10 photo. This channel section represents a typical straightened reach in which bank erosion and channel migration have widened the original channel, leading to the formation within the over-widened channel of both a vegetated bench consisting mainly of fine-grained sediment and an active gravel channel. Surveyed Cross Section 1 elevation data, plotted in Figure 11, were obtained along the crest of the riffle shown in Figure 10. Note that the view in the photograph of Figure 10 is upstream, while the cross section plot in Figure 11 uses the downstream view convention typical of hydraulic analysis. The bankfull stage and top-of-bank stage lines are also plotted in Figure 11. Based on the Rosgen (1996) method of stream classification, the stream at Cross Section 1 was classified as a B4c.

Cross Section 2 is located 350 feet upstream of the proposed crossing centerline in the channel section shown in the Figure 12 photo. Surveyed elevation data for Cross Section 2 is plotted in Figure 13 with estimated bankfull stage and top-of-bank stage lines. This channel section, with high and steep banks, is typical of straightened sections upstream of proposed crossing BR-21 that have not migrated substantially away from the straightened alignment, although bank erosion is occurring on one or both sides of the channel. Based on the Rosgen (1996) method of stream classification, the stream was classified as an F4 at Cross Section 2.

Bankfull Flow Estimate and Sediment Mobility Analysis Assumptions

An estimate of bankfull flow is required for stability assessment at Cross Section 1. An estimate of the bankfull flow can be developed from bankfull indicators used to estimate stage, a resistance equation such as the Manning Equation, and an estimate of the friction slope and resistance coefficient (Manning *n*). Typically, an assumption of near uniform flow conditions, in which energy slope is approximately equal to water surface slope, is used to develop this estimate.

During three separate site visits in June, October and November of 2004, the BMCC tributary and North Branch confluence and the channel reach extending to the confluence were examined for evidence of high rates of sediment deposition that would indicate conditions of high upstream sediment transport, local deposition, and the size range of gravels frequently moved to the confluence. Evidence of high rates of gravel deposition was not found in the vicinity of the confluence. Indications of rapid deposition of gravel were found downstream of sharp (low radius) bends, near debris jams, or in reaches of severe bank erosion. Deposition of gravel, however, was not observed in straight reaches between these coarse sediment deposits downstream of the scour holes that appeared to be the primary source. Based on these observations, the largest mobile bed particles under bankfull conditions were considered to be near threshold conditions (i.e., low transport rate). An estimate of bankfull conditions was made at Cross Section 1. Sampling of bed material considered to be transported under bankfull conditions and data collection and analysis used to estimate bankfull flow conditions are provided in this section.

Figure 10 Reach used to assess sediment mobility and bankfull flow estimate. This channel section is typical of some reaches that have migrated away from the straightened alignment.

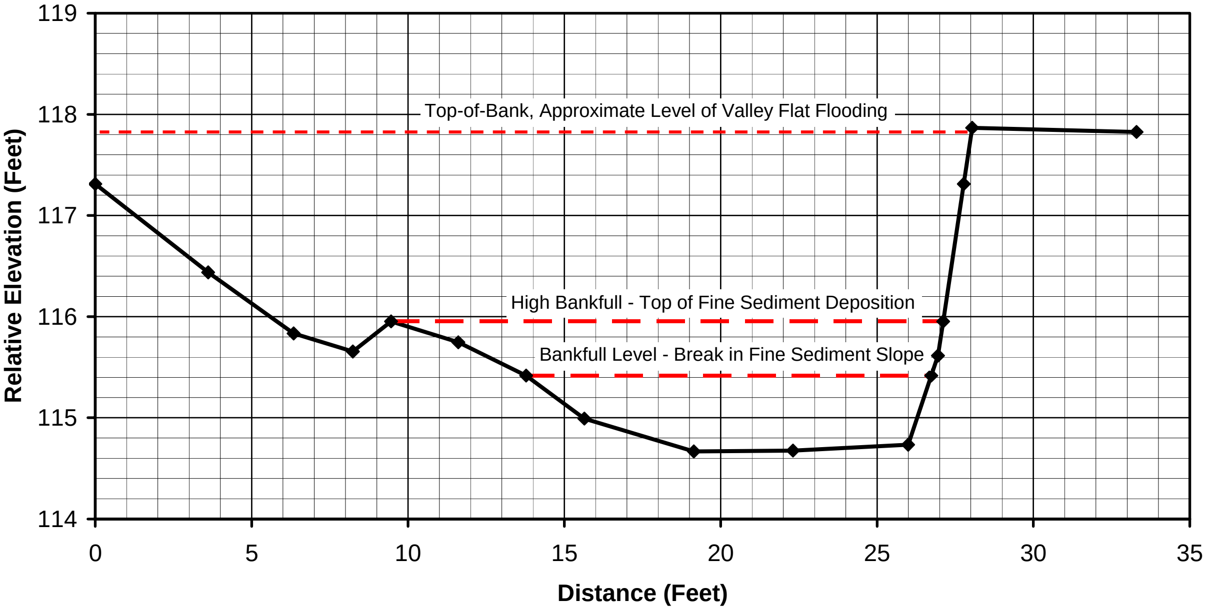


Figure 11 Cross Section 1 plot obtained from the channel section shown in Figure 10. Note that the view in the Figure 10 photo is upstream while the cross section view is downstream. For scaled version, see Attachments.

Figure 12 Typical conditions of the stream channel that is widening through bank erosion but has not migrated substantially from the straightened and channelized alignment. A debris jam downstream is causing deposition of fine grain sediment in the channel. View is downstream from Cross Section 2.

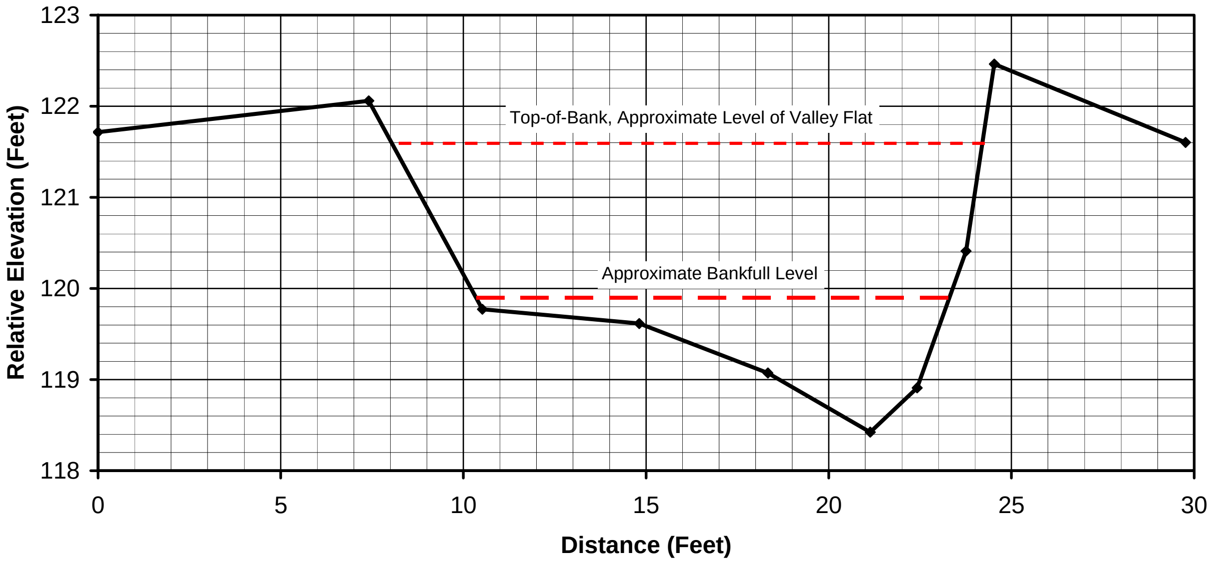


Figure 13 Channel Cross Section 2 is representative of straightened and gradually shifting and widening channels downstream of the proposed crossing. The Cross Section is located in the downstream end of the reach shown in Figure 12. For scaled version, see Attachments.

Bankfull Flow Indicators and Channel Characteristics

Bankfull flow indicators in the assessment area were limited to fine sediment deposits that formed benches within the over-widened channel reaches: the lower indicator corresponded to a break in the slope of the bench near the active channel bed; the higher indicator corresponded to the top of the fine sediment deposits. Because the streambed remained in a relatively straight planform over much of its length, well-developed and consistent indicators were not observed, other than in a few isolated locations such as that shown in Figure 10.

Bankfull Flow Energy Slope

The energy slope (friction slope), S_f, for the assessment reach was estimated for bankfull flow conditions as 1.1%, based on local riffle crest-to-crest elevation measurements. The channel was straight downstream and slightly steeper; therefore, energy dissipation was attributed primarily to the stream channel bed and bank friction. The flow that filled the entire entrenched channel was estimated using a riffle slope of 0.9% because the effects of downstream riffles at the higher flow depths appear to flatten the slope slightly.

Channel Roughness

Channel roughness was considered to be primarily caused by the roughness of the channel bed. Estimates of the Manning roughness coefficient, *n*, were based on the Limerinos (1970) relation, given here as

$$n = \mathrm{R}_\mathrm{h}^{1/6} \frac{0.0926}{1.16 + 2 \,\mathrm{Log} \dfrac{\mathrm{R}_\mathrm{h}}{\mathrm{D}_{84\mathrm{riffle}}}}$$

where R_h is the hydraulic radius (feet) and $D_{84riffle}$ (feet) is the particle size which equals or exceeds the diameter of 84% of the particles based on the pebble count of the riffle surface. As indicated by this relation, the *n* value changes with flow conditions. The Wolman pebble counting method (Bunte et al. 2001) was used to describe the surface particle size distribution over the active channel portion of the riffle surface. Particle sizes necessary for roughness estimates ($D_{84riffle}$) and for evaluation of the bed surface mobility ($D_{50riffle}$) were measured through the pebble count analysis.

Bankfull Flow Estimates and Boundary Shear Stress

The bankfull flow condition in Cross Section 1 was computed using the friction slope given above (1.1% for the bankfull conditions), an iterative solution of the Limerinos equation given above, the measured bankfull channel cross-sectional area and hydraulic radius, and the Manning Equation for flow resistance:

$$\mathrm{Q} = \frac{1.49}{n} \;\mathrm{A}\; \mathrm{R}_\mathrm{h}^{2/3}\, \mathrm{S}_\mathrm{f}^{1/2}$$

In this equation, Q is the flow in cubic feet per second (cfs), A is the cross-sectional flow area in square feet (ft^2), R_h is the hydraulic radius in feet (ft), and S_f is the estimated friction slope in feet/feet. Table 2 shows the characteristics of the channel at Cross Section 1 for three different flow levels: bankfull, high bankfull, and flooding of the valley flat. Based on the variation in field bankfull indicators, a range of bankfull flows from 18 cfs to 53 cfs was estimated. The average boundary shear stress for each flow condition was estimated as

$$\tau_b = \gamma R_h S_f$$

where τ_b is the cross section average boundary shear stress in pounds per square foot (psf) over the riffle.

Average boundary shear stresses, τ_b , for 18 cfs and 53 cfs were compared to the critical boundary shear stress required for threshold conditions of the largest particles in the bedload (see Section 2.9). The lower bankfull estimate (18 cfs) was closer to particle threshold conditions than the higher estimate was; therefore, 18 cfs was considered the most appropriate value for channel assessment purposes.

Top-Of-Bank Flow

The flow that fills the channel to the top of the bank and also floods the valley flat was computed for Cross Section 1 using the Manning flow resistance equation given above, the measured channel cross-sectional area and hydraulic radius for the channel filled to the top of the bank, the Manning *n* computed from the Limerinos Equation given above, and a friction slope assumed to be equal to 0.9%. Comparison of the 2-year return interval peak flows provided in Table 1 and the flow rates estimate provided in Table 2 indicates that a flow with a return interval of about 2 years is required to overtop the highest banks and initiate flooding of the valley flat at Cross Section 1.

Table 2 Cross Section and Reach Parameters for Bankfull and Top-of-Bank Flow

Parameter	Bankfull	High Bankfull	Flooding of Valley Flat
Cross Section Area (ft^2)	7.7	15.8	49.8
Top Width (ft)	13	17.7	27.8
Average Flow Depth (ft)	0.59	0.89	1.79
Hydraulic Radius (ft)	0.58	0.83	1.65
Manning *n*	0.045	0.041	0.036
Friction Slope	0.011	0.011	0.009
Flowrate (cubic feet per second, cfs)	18	53	272
Channel Average Boundary Shear Stress, τ_b (pounds per square foot, psf)	0.40*	0.57*	0.93*

* Boundary stresses here represent total average boundary stress. Particle boundary stress may be substantially less, depending on backwater effects that may include resistance from the planform, bed forms, debris jams, and channel bank roughness.

2.9 SEDIMENT SAMPLING, ANALYSIS, AND CRITICAL BOUNDARY STRESS

A bulk sediment sample (Bunte et al. 2001) was obtained from a bar approximately 100 feet upstream of the proposed crossing centerline on the inside of a bend (see Figure 3). The results of the sediment gradation analysis for the bulk bar sample and the pebble count are provided in Figure 14.

The average channel boundary shear stress required for critical movement of the largest bed material over the assessment riffle was estimated using the relation developed for site-specific conditions by Andrews (1994). Critical conditions for movement of a specific sediment size, also called threshold conditions here, represent the flow conditions that cause weak movement of a specific-sized sediment. The weak movement results in a very low sediment transport rate for the specific sediment size. The Andrews (1994) relation, modified for use with the data collected in this study, is

$$\tau_c^* = 0.0384\left(\frac{D_{max}}{D_{50riffle}}\right)^{-0.887}$$

where τ_c^* is the dimensionless boundary shear stress required for critical conditions, D_{max} represents the maximum sized bed material transported in feet (ft), and $D_{50riffle}$ represents the characteristics of the bed surface in feet (ft). In this assessment, D_{max} was considered to be the size of the largest particle in the bar sample. Examination of the largest particles on the surface of several bars within the detailed channel profile limits confirmed that the largest particle in the bulk sample was representative of large particles on other bars.

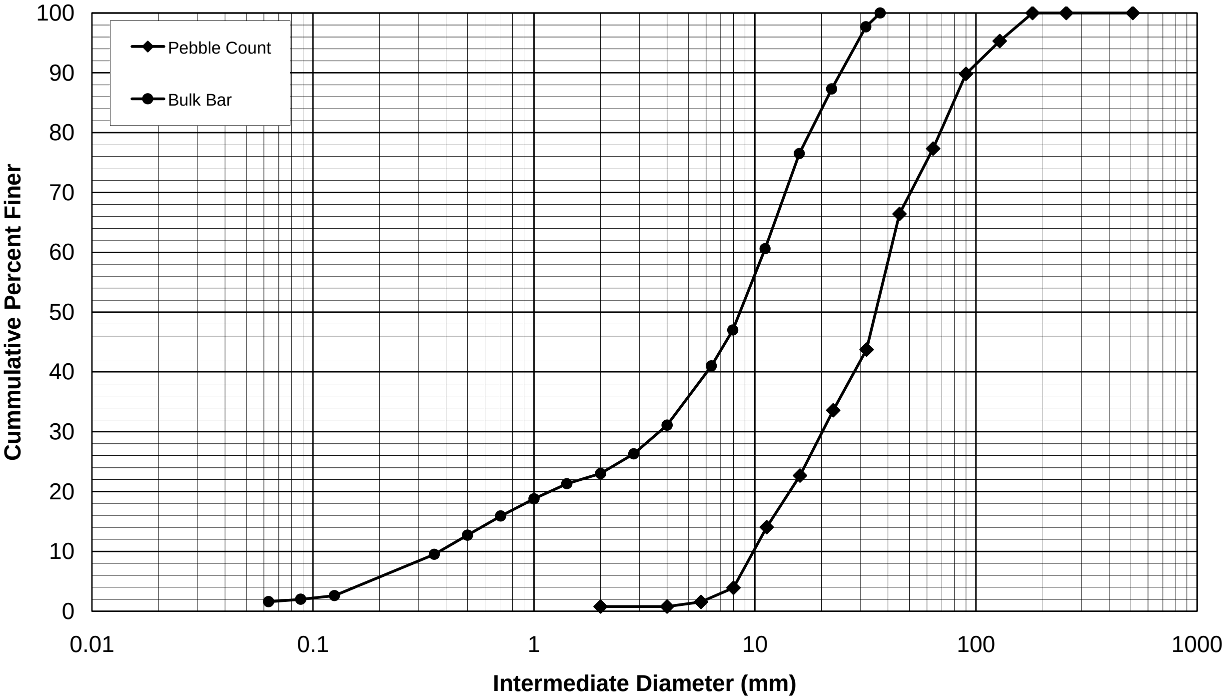


Figure 14 Bulk bar sample gradation curve with riffle surface pebble count obtained near Cross Section 1.

The critical boundary shear stress for the largest particles in the bedload, τ_c , was computed as

$$\tau_c = \tau_c^* (S - 1) \gamma D_{max}$$

where S is the specific weight of the sediment (considered to be 2.65 for quartz sediment) and γ is the unit weight of water (62.4 pounds per cubic foot). Table 3 shows the estimates of critical boundary stress using the Andrews (1994) relations.

Comparison of the average boundary stress provided in Table 2 and the computed critical boundary stress in Table 3 for Cross Sections 1 shows very good agreement for the approximate bankfull conditions and critical stress conditions for the largest particles in the bar. Comparison of critical boundary shear stresses in Table 3 and the average channel boundary stress, shown in Table 2, at flows that overtop the bank (top-of-bank flows that initiate flooding of the valley flat) indicates high stress conditions for Cross Section 1. This boundary stress is significantly higher than would be expected with natural bed materials. Significant changes to stream channel boundaries should be anticipated for flows that overtop the high banks and flood the valley bottom.

Table 3 Sediment Characteristics and Estimated Critical Boundary Shear Stress Required for Weak Transport of Largest Particles in the Bedload

Parameter	**Estimate**
$D_{50riffle}$ (riffle pebble count)	35 mm
D_{50bar} (bar sample)	8.7 mm
D_{max} (bar sample)	37 mm
Andrews (1994) τ_c^*	0.037 psf
Andrews (1994) τ_c	0.46 psf

2.10 SUMMARY OF BANKFULL FLOW PARAMETERS AND CLASSIFICATION

Table 4 provides a summary of parameters for the estimated bankfull flow conditions at Cross Sections 1 and 2. Based on the Rosgen (1996) stream classification system, the channel at Cross Section 1 is clearly a B4c-type channel. The c designation indicates a relatively low (less than 2%) channel slope for a B-type channel. The channel at Cross Section 2 is clearly an F4-type channel. Both cross sections indicate significant channel incision. The channel is incised by 2.4 feet at Cross Section 1 and 1.7 feet at Cross Section 2.

Table 4 Bankfull Flow Parameter Summary

Bankfull Flow Parameter	**Assessment Reach Cross Section 1**	**Cross Section 2**
Cross Section Area, A_{bkf} (ft^2)	7.7	7.7*
Width, W_{bkf} (ft^2)	13.0	12.9
Mean Depth, d_{bkfl} (ft)	0.59	0.60
W_{bkf} / d_{bkfl}	21.8	21.6
Maximum Flow Depth, d_{mbkf} (ft)	0.75	1.45
Hydraulic Radius, R_h (ft)	0.58	0.48
Channel Roughness Coefficient, Manning n	0.045	–
Width of Flood-Prone, W_{fpa} (feet)	22.5	17.2
Entrenchment Ratio, ER = W_{fpa} / W_{bkf}	1.73	1.33
Channel Incision from Valley Flat, I_{vf} (ft)	2.41	1.73
Channel Incision Ratio, IR = I_{vf} / d_{mbkf} (no incision IR = 0)	3.21	1.2
Sinuosity, K	1.23	1.0
Riffle Surface, $D_{50riffle}$ (mm)	35	–
Riffle Surface, $D_{84riffle}$ (mm)	75	–
Energy Slope, S_f (ft/ft)	0.011†	0.014‡
Flow, Q_{bkf} (ft^3/s)	18.5	18.5*
Average Channel Boundary Stress, τ_{avg} (lb/ft^2)	0.40§	–
Largest mobile particle size, D_{max} (mm)	37	–
Average Channel Velocity, V_{bkfl} (ft/s)	2.4	–
Critical Boundary Stress for Largest Mobile Particle Size, τ_c (lb/ft^2)	0.46	–
Rosgen Channel Type	B4c	F4

* Value assumed to be the same as assessment reach value.

† Value estimated from field measurement.

‡ Value computed.

§ Boundary stresses here represent total average boundary stress. Particle boundary stress may be substantially less, depending on backwater effects that may include resistance from the planform, bed forms, debris jams, and channel bank roughness.

3

Crossing Design Considerations and Recommendations

The results of the detailed morphological study documented in this report show that the BMCC tributary to North Branch is laterally active and is vulnerable to severe vertical degradation. Based on these results, a series of considerations and recommendations that incorporate the effects of long-term channel dynamics are provided to promote the short- and long-term stability of the proposed crossing and the channel.

3.1 SUMMARY OF GEOMORPHOLOGIC PROCESSES AFFECTING CHANNEL STABILITY IN THE VICINITY OF THE PROPOSED CROSSING

Channel Characteristics

The existing BMCC tributary channel is degraded over much of its length and is evolving from an incised and straightened alignment (see Sections 2.3 and 2.4). Although the cause of straightening was not determined, agricultural drainage practices and sewer line construction are suspected. The examined section of the tributary consists of a 500-foot steeply sloping section (1.5% to 3%) upstream of the confluence and two less steeply sloping sections (0.73% in the vicinity of the crossing and 1.36% upstream of the crossing). The steepest section is heavily armored and includes two large boulder jams. The channel armor and boulders appear to be byproducts of the excavation for the adjacent sewer line. Debris jams, formed on fallen trees that have grown along the channel banks, partially block the channel in a few locations. Bank erosion appears severe in bends of a few short sinuous reaches. In reaches near the proposed BR-21 crossing location, the stream was classified as a B4c and an F4 (see Sections 2.8–2.10).

Channel Morphology

Vertical stability of the North Branch streambed, the elevation and location of the confluence of the BMCC tributary with North Branch, and several of the intermediate

bed level grade controls are the primary factors influencing the stability of the BMCC tributary at the proposed BR-21 crossing location (see Section 2.4, Downstream Base Level Control Reach, and Sections 2.5 and 2.6). The base level control for the BMCC tributary is dependent on the stability of its confluence with North Branch and on the two boulder jams that control the grade in the steep section upstream of the confluence. Changes in the bed elevation and position of the confluence of the BMCC tributary with North Branch or destabilization of the key boulder jams on the steeply sloping section upstream of the confluence could destabilize the entire profile of the BMCC tributary. Degradation in North Branch may lead to as much as 4 feet of degradation at the confluence. In addition, the migration of a bend in North Branch into the tributary will shorten the tributary by approximately 55 feet. The vertical degradation of the confluence and the shortening of the tributary will increase the slope of the already steeply sloping section of the tributary, causing a headcut to propagate up the tributary. In addition to headcut migration initiated at the confluence, channel migration, a large magnitude flood event, or piping around or under the jams could destabilize the boulders.

The entire length of the BMCC tributary, including a very active section immediately upstream of the proposed crossing centerline, will be vulnerable to rapid and chronic lateral instability (see Sections 2.4 and 2.7). Comparison of 1950s channel locations with those obtained from recent aerial photography indicated that segments of the BMCC tributary are very active, some moving more than 60 feet from their 1950s straightened alignment. Debris jams and consequential bank erosion appear to be the main processes by which the channel forms bends and migrates or avulses from its straightened alignment. Prior to 1950, the channel upstream of the crossing was positioned along the northeast valley wall, away from the center of the valley. Sections of the BMCC tributary channel upstream of the proposed crossing will migrate or avulse from their current position along the valley hillside toward the lower elevation center of the valley over the next 50-year time period. Downstream of the crossing the channel, although relatively straight, is located near the center and lowest part of the valley or is constrained by hillside slopes.

The series of sharp (low radius) bends that have formed in the 100-foot channel section immediately upstream of the proposed crossing centerline will remain active (see Section 2.4, Proposed Crossing Reach, and Section 2.7). Severe bank erosion in these bends and undermining of mature trees on banks indicate that the stream will continue to migrate from its current position through scour and bank erosion in the bends and erosion around debris jams. The future movement of the sub-section of channel that has migrated away from its previously straightened channel alignment by approximately 40 feet is difficult to predict. Several possibilities exist, however, because this offset channel sub-section is against the valley hillside: bend movement down-valley, channel movement toward the center of the valley, or a cutoff of this offset section are likely.

Currently, the supply of coarse gravel to the proposed crossing location appears low (see Section 2.4, Upstream Sediment Supply Reach, and Section 2.8). Gravel bars were found downstream of what appeared to be their source of gravel: scour holes around bends and at debris jams and downstream of eroding banks. The supply appears discontinuous because debris jams upstream appear to capture the loads in their backwater.

3.2 DESIGN CONSIDERATIONS AND RECOMMENDATIONS

Based on analysis of these morphological processes, the following considerations and recommendations are provided to support the short- and long-term stability of the proposed crossing:

- **The BMCC tributary is highly vulnerable to significant future vertical degradation, although currently the BMCC tributary is not degrading rapidly.** The channel is capable of downcutting up to 8.5 feet as a result of long-term degradation (see Section 2.6) and an additional 4 feet in scour holes in main channel bends (see Sections 2.5). **Scour computations for piers and abutments should include 8.5 feet of long-term degradation and 4 feet of main channel bend scour, for a total of 12.5 feet.** While no evidence of bedrock exposure in the streambed was found near the proposed crossing, resistant bedrock beneath the current streambed materials would probably limit the total scour.
- **Long-term lateral movement of the channel will be significant**. The main channel is laterally unstable (Sections 2.4 and 2.7) and is capable of migrating or avulsing across a large section of the valley bottom (at the proposed crossing location, **up to 60 feet** from its current position) over the next 50 years (see Section 2.7). Although the channel was relocated and positioned near the valley wall, the lowest part of the valley lies to the southwest, and over the long term (50 years) the channel will tend to move in that direction. **Consideration should be given to positioning the crossing toward the central and lowest part of the valley rather than aligning the crossing with its current channel position along the valley wall**. If piers or abutments are placed in the valley bottom, they should be designed with two expectations: they will someday be in the main channel; and for scour computations, the angle of **flow attack to the structure will be large (60 to 90 degrees)**. **For design flood flows, abutments and piers should be parallel to the centerline of the low part of the valley**.

  The four sharp bends and offset section of channel currently located upstream and within 100 feet of the proposed crossing centerline will likely at least partially be located under the crossing structure (see Section 2.7). Left unaltered, these bends will migrate into piers or abutments that are located on the valley bottom and cause scour holes at severe angles of attack (90 degrees) for flows near top-of-bank conditions. During design flood conditions for scour (100- and 500-year events), however, flood flows will tend to be aligned with the valley, and scour computations for piers and abutments should consider flood flow alignment creating an angle of attack of up to but no more than 60 degrees. Two short sections of channel that are currently aligned perpendicular to the valley direction are located within this 100-foot section. These sections will be severely eroded when vegetation dies as a result of (1) shading, which will weaken the bank strength, and (2) flood flows that will be directed perpendicular to their alignment by the crossing, which should be aligned primarily with the downstream valley direction. Consideration should be given to cutting off the offset reach and removing the bends to improve channel stability and to allow the crossing to be repositioned closer to the center of the valley. Grade control may be required to prevent headcutting upstream if the channel is shortened by cutting off the offset reach.

Long-term migration of the channel upstream of the crossing will trend toward the center of the valley and away from the valley wall where the channel is currently located (see Section 2.4, Proposed Crossing Reach, and Section 2.7). Although adding armoring to the channel near and under the crossing would initially stabilize that section, alignments of the dynamic stream segments with respect to the protected and therefore stationary channel reach under the crossing would deteriorate as channel sections upstream and downstream of the crossing migrated from their existing locations. Progressive failure of channel protection could ensue as flows impinged on channel lining. After the channel lining failed or the channel abandoned its initial protected location, channel flow could impinge at high skew angles on substructure components.

Relocation and restoration of a more sinuous channel in a location near the center of the valley would place the stream back to where it was probably positioned, prior to being relocated, and where it will tend to migrate in the future. The crossing could then be designed for and positioned in a more natural location to minimize potential migration of the channel into structure elements such as piers and abutments.

- **The supply of debris from the upstream channel and floodplain to the proposed crossing location is expected to be low** (see Section 2.4, Upstream Supply Reach). Although bank erosion and channel incision are causing a large number of bankline trees upstream to fall, the channel’s relatively narrow width and channel bends prevent their transport to the proposed crossing location. The greatest threat of debris jam formation at the crossing comes from trees immediately upstream that may fall across the channel or on the floodplain and be transported the short distance to the crossing. The size of the proposed crossing opening should be sufficiently large to pass debris and meet all pertinent regulations (see guidance on design for debris in reference number 13).

Additional design considerations include the following:

- A sewer line runs generally parallel to the stream in the vicinity of the proposed crossing. If construction of the proposed crossing requires land disturbance near the channel or modification of the channel, relocation of the sewer line may be necessary.

- The proposed crossing structure will block sunlight and rainfall over much of the underlying channel and floodplain. Mortality of the vegetation beneath the structure will cause the surface of the floodplain to become more susceptible to erosion regardless of any construction techniques employed to prevent damage to vegetation. **Bends and cross-valley channel segments will be particularly vulnerable to erosion without the root reinforcement of healthy riparian vegetation.**

References

1. Andrews, E. D., 1984. Bed-Material Entrainment and Hydraulic Geometry of Gravel-Bed Rivers in Colorado. Geological Society of America Bulletin 95:371–378.
2. Andrews, E.D., 1994. Marginal Bed Load Transport in a Gravel Bed Stream, Sagehen Creek, California. Water Resource Research 30(7):2241–2250.
3. Andrews, E.D. and J.M. Nankervis, 1995. Effective Discharge and the Design of Channel Maintenance Flows for Gravel-Bed Rivers. American Geophysical Union, Natural and Anthropogenic Influences in Fluvial Geomorphology, Geophysical Monograph 89:151–164.
4. Bunte, K. and S.R. Abt, 2001. Sampling Surface and Subsurface Particle Size Distributions in Wadable Gravel and Cobble Bed Streams for Analyses in Sediment Transport, Hydraulics and Streambed Monitoring. General Technical Report RMRS-GTR-74. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 428 pp.
5. Coleman, D.J., 1982. An Examination of Bankfull Discharge Frequency in Relation to Floodplain Formation. Ph.D. Dissertation, The Johns Hopkins University, Baltimore, MD.
6. Cook, E.M.V., 1990. A History of Early Water Mills in Montgomery County, Maryland. Eleanor M.V. Cook, Silver Spring, MD, 147 pp.
7. Costa, J.E., 1975. Effects of Agriculture on Erosion and Sedimentation in the Piedmont Province of Maryland. Geologic Society of America Bulletin 86:1281–1286.
8. Craven, A.O., 1925. Soil Exhaustion as a Factor in the Agricultural History of Virginia and Maryland, 1606–1860. University of Illinois Studies in the Social Sciences 13(1), 179 pp.
9. Happ, S.C., G. Rittenhouse, and G.C. Dobson, 1940. Some Principles of Accelerated Stream and Valley Sedimentation. US Department of Agriculture Technical Bulletin 695, 134 pp.
10. Hopkins, G.M., 1975 [1879]. Atlas of Montgomery County, Maryland, 1879. Montgomery County Historical Society, Rockville, MD.
11. Jacobson, R.B. and D.J. Coleman, 1986. Stratigraphy and Recent Evolution of Recent Maryland Floodplains, American Journal of Science 286:617–637.
12. Limerinos, J.T., 1970. Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels. Water-Supply Paper 1898-B, U.S. Geological Survey, 47 pp.
13. MDSHA (Maryland State Highway Administration), Office of Bridge Development, Bridge Design Division, 2006. Manual for Hydrologic and Hydraulic Design. MDSHA, Baltimore, MD.

14. MDSHA (Maryland State Highway Administration), Office of Bridge Development, Bridge Design Division, 2004. Hydrologic Analysis Report for the Intercounty Connector Over Rock Creek and Mill Creek Tributaries.
15. MGS (Maryland Geological Survey), 2005. Maryland Geological Survey. *Available at* http://www.mgs.md.gov/. *Accessed in* June 2005.
16. Parola, A.C., W.L. Oberholtzer, and D.A. Altland, 2004. Preliminary Geomorphologic Study for the Assessment of the Potential ICC Bridge Crossings, Rock Creek and North Branch Watersheds.
17. Parola, A.C. and W.S. Vesely, 2006. Final Stream Geomorphic Report for Intercounty Connector Proposed Crossing BR-20 at the North Branch of Rock Creek. Riverine Systems, LLC, Louisville, KY, 40 pp.
18. Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology Books, Pagosa Springs, CO.
19. Wilcock, P.R., 1988. Method for Estimating the Critical Shear Stress of Individual Fractions in Mixed-Size Sediment. Water Resources Research 24(7):1127-1135.
20. Scott, J., 1807. A Geographical Description of the States of Maryland and Delaware Also of the Counties, Towns, Rivers, Bays, and Islands: with a List of the Hundreds in Each County. Kimber and Conrad, Philadelphia, PA, 191 pp.
21. URS Corporation, 2001. Rock Creek Watershed Study: A report to the Montgomery County Department of Environmental Protection, Montgomery County, MD.

Attachments

A. GEOMORPHIC FIELD DATA AND PLOTS AT PROPOSED CROSSING

A-1 Brooke Manor Country Club Tributary Longitudinal Profile Data
A-2 Brooke Manor Country Club Tributary Longitudinal Profile Plot
A-3 Brooke Manor Country Club Tributary Cross Section 1 Data
A-4 Brooke Manor Country Club Tributary Cross Section 1 Plot
A-5 Brooke Manor Country Club Tributary Cross Section 2 Data
A-6 Brooke Manor Country Club Tributary Cross Section 2 Plot

B. SEDIMENT GRADATION AND MOBILITY ANALYSIS

B-1 Particle Size Distribution Report
B-2 Modified Wolman (1954) Pebble Count, Cross Section 1
B-3 Brooke Manor Country Club Tributary Cross Section 1 Grain Size Distributions Plot
B-4 Sediment Mobility Analysis, Andrews Methodology

C. MAPS

C-1 Study Area Topographic Map (in back pocket)

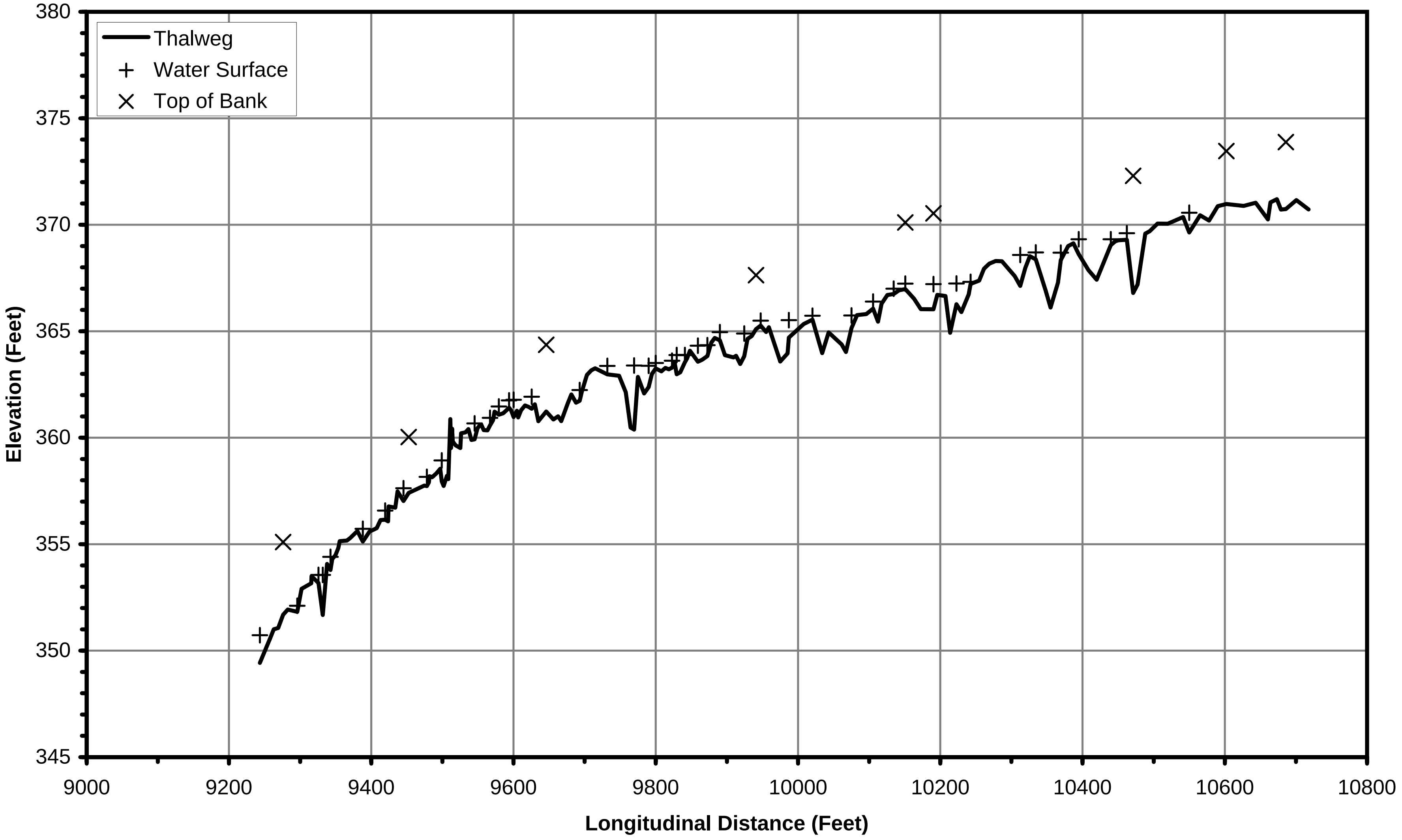
Brooke Manor Country Club Longitudinal Profile
Survey Date: 9-Jun-04
Survey by: Riverine Systems LLC

Station (feet)	Thalweg Elevation (feet)	Water Elevation (feet)	Top of Bank (feet)	Notes
9243.38	349.43	350.73		N Branch Confluence
9257.89	350.58			
9263.05	351.01			
9269.19	351.06			
9276.17	351.69		355.10	
9282.73	351.93			
9296.01	351.83	352.11		
9301.97	352.91			
9315.71	353.17			
9316.00	353.50			
9325.86	353.18	353.56		
9331.95	351.68	353.56		
9337.83	354.07			
9342.73	353.79	354.40		
9345.15	354.31			
9349.60	354.47			
9353.68	354.82			
9355.61	355.14			
9365.88	355.17			
9370.37	355.29			
9380.53	355.62			
9388.09	355.12	355.73		
9397.59	355.59			
9407.66	355.75			
9413.04	356.13			
9419.51	356.15	356.57		
9423.75	356.07			
9424.31	356.77			
9433.73	356.71			
9437.00	357.48			
9445.35	357.03	357.63		
9452.59	357.41		360.03	
9474.71	357.75			
9478.14	357.73	358.16		
9481.11	357.90			
9481.91	358.19			
9485.49	358.15			
9491.52	358.32			
9496.96	358.54			
9499.20	357.95	358.94		
9501.87	357.74			
9506.35	358.21			
9508.38	358.06			
9511.22	360.87			
9512.11	359.51			
9513.79	360.43			
9514.62	359.82			
9518.54	359.65			
9525.19	359.52			
9526.37	360.21			
9532.46	360.25			
9536.53	360.41			
9540.81	359.90			
9545.32	359.93	360.68		
9549.40	360.45			
9552.69	360.59			
9554.80	360.61			
9558.09	360.36			
9563.34	360.35			
9567.02	360.58	360.93		
9571.18	360.82			
9573.40	361.22			

Station (feet)	Thalweg Elevation (feet)	Water Elevation (feet)	Top of Bank (feet)	Notes
9579.33	361.08	361.47		
9585.45	361.14			
9589.22	361.26			
9593.80	361.41	361.75		
9596.77	361.27			
9600.12	360.97	361.78		
9604.71	361.26			
9606.59	360.95			
9610.68	361.29			
9616.24	361.52			
9621.07	361.45			
9625.65	361.36	361.92		
9630.08	361.57			
9635.04	360.78			
9646.00	361.23		364.36	
9656.06	360.85			
9662.68	361.01			
9667.03	360.78			
9676.13	361.61			
9681.27	362.03			
9687.92	361.64			
9693.08	361.73	362.24		
9696.11	362.16			
9703.25	362.94			
9709.31	363.16			
9714.76	363.26			
9731.86	362.98	363.37		
9748.43	362.91			
9757.87	362.13			
9764.59	360.48			
9769.52	360.38	363.39		
9774.88	362.86			
9783.60	362.08			
9790.01	362.37	363.38		
9794.59	363.00			
9800.00	363.25	363.51		
9808.02	363.12			
9813.35	363.27			
9818.35	363.21			
9822.92	363.29	363.62		
9826.50	363.51			
9829.44	362.98	363.88		
9834.44	363.07			
9840.95	363.54	363.88		
9843.96	363.72			
9848.11	364.09			
9859.18	363.57	364.32		
9865.37	363.66			
9872.58	363.84	364.35		
9877.99	364.47			
9882.90	364.68			
9890.08	364.57	364.95		
9897.19	363.87			
9909.35	363.77			
9912.91	363.85			
9918.78	363.46			
9924.47	363.83	364.89		
9929.08	364.64			
9934.90	364.77			
9940.93	365.10		367.63	
9947.51	365.26	365.50		
9955.07	364.96			
9958.97	365.19			
9974.99	363.58			
9985.33	363.96			
9987.08	364.70	365.52		
10007.83	365.34			
10020.28	365.55	365.73		

Station (feet)	Thalweg Elevation (feet)	Water Elevation (feet)	Top of Bank (feet)	Notes
10033.96	363.97			
10043.08	364.94			
10061.28	364.38			
10067.29	364.03			
10075.20	365.14	365.74		
10083.00	365.75			
10095.99	365.81			
10105.52	366.06	366.39		
10112.52	365.45			
10117.46	366.29			
10125.60	366.70			
10134.41	366.75	367.00		
10142.00	366.92			
10150.74	366.98	367.23	370.11	Cross Section 1
10163.04	366.53			
10172.74	366.04			
10190.49	366.03	367.21	370.53	
10195.72	366.71			
10207.29	366.65			
10213.80	364.93			
10222.76	366.27	367.24		
10229.72	365.90			
10239.90	366.73			
10242.60	367.22	367.32		
10254.63	367.38			
10261.51	367.94			
10268.85	368.17			
10277.76	368.30			
10286.63	368.29			
10304.56	367.59			
10312.45	367.13	368.58		
10319.45	367.97			
10325.96	368.52			
10334.25	368.37	368.70		
10348.51	366.87			
10355.01	366.11			
10365.56	367.29			
10369.44	368.34	368.69		
10379.75	369.00			
10387.16	369.13			
10394.56	368.62	369.32		
10408.35	367.87			
10419.75	367.42			
10434.47	368.62			
10439.73	369.05	369.32		
10446.23	369.23			
10450.39	369.27			
10462.21	369.29	369.61		
10471.09	366.80		372.30	
10477.28	367.19			
10482.06	368.22			
10488.15	369.59			
10494.16	369.69			
10505.35	370.06			
10519.73	370.05			
10541.53	370.36			
10549.98	369.64	370.57		
10565.31	370.45			
10577.87	370.20			
10590.09	370.87			
10602.13	370.97		373.46	
10626.52	370.88			
10643.40	371.03			
10660.57	370.25			
10664.14	371.05			
10673.20	371.20			
10678.84	370.72			
10685.77	370.74		373.88	Cross Section 2
10700.61	371.16			
10717.82	370.72			

Brooke Manor Country Club Tributary Longitudinal Profile
ICC Crossing BR-21



Brooke Manor Country Club Tributary Cross-Section Data

Location: Station 101+51
Survey Date: 9-Jun-04
Surveyed by: Riverine Systems LLC

Station (feet)	Elevation (feet)	Notes
0.00	369.59	VALLEY FLAT
3.61	368.72	BANK
6.34	368.11	BENCH
8.24	367.93	BENCH
9.46	368.23	BENCH
11.61	368.03	BENCH
13.78	367.70	BANKFULL
15.64	367.27	TOE
19.14	366.95	BDA
22.31	366.96	BDA
25.99	367.01	TOE
26.73	367.70	BANKFULL
26.95	367.89	BANK
27.11	368.23	BANK
27.77	369.59	BANK
28.04	370.15	TOB
33.29	370.11	VALLEY FLAT

Bankfull Computations

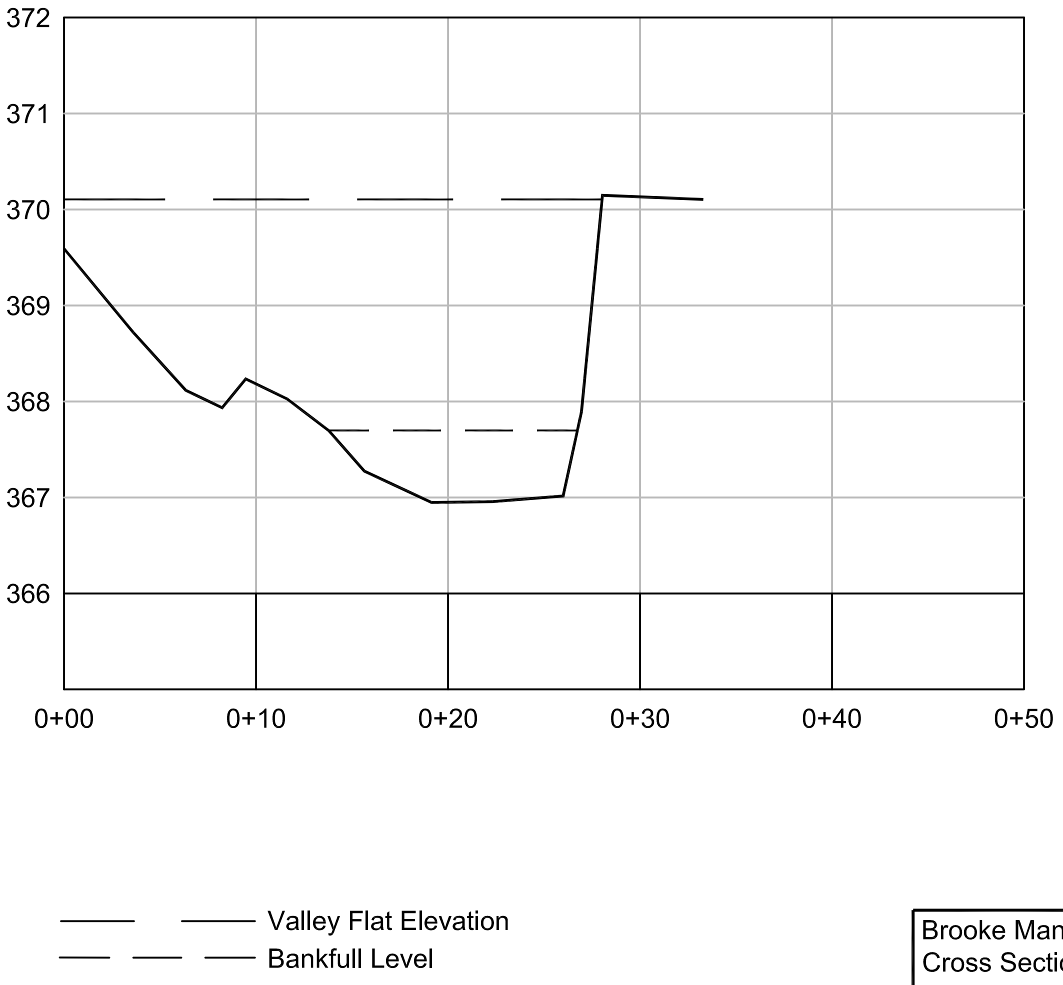
subwidth (feet)	mean d (feet)	subarea (sqr. feet)	subWP (feet)
1.86	0.21	0.40	1.91
3.50	0.59	2.05	3.51
3.17	0.75	2.36	3.17
3.68	0.71	2.62	3.68
0.74	0.34	0.25	1.01

Bankfull Geometry

Area	7.7	sqr. feet
Width	13.0	feet
Mean D	0.59	feet
W/D	21.9	
Rh	0.58	feet
FP Width	22.4	feet
ER	1.7	
d50	35	mm
Slope	0.011	ft/ft
Type	B4c	

Bankfull Hydraulics

Slope	0.011	ft/ft
D84	77	mm
n-value	0.045	
Qbkf	18.5	cfs
Tau	0.40	lb/sqr. ft
Froude	0.56	



Brooke Manor Country Club Tributray
Cross Section 1
1" = 2' vertical
Scale:
1' = 10' horizontal

Brooke Manor Country Club Tributary Cross-Section Data

Location: Station 106+86
Survey Date: 9-Jun-04
Surveyed by: Riverine Systems LLC

Station (feet)	Elevation (feet)	Notes
0.00	373.99	VALLEY FLAT
7.41	374.34	TOB
10.39	372.15	BANKFULL
10.52	372.05	BAR
14.81	371.90	BAR
18.33	371.35	BED/WSE
21.14	370.70	BED
22.42	371.19	TOE
23.27	372.15	BANKFULL
23.76	372.69	BANK
24.53	374.74	TOB
29.77	373.88	VALLEY FLAT

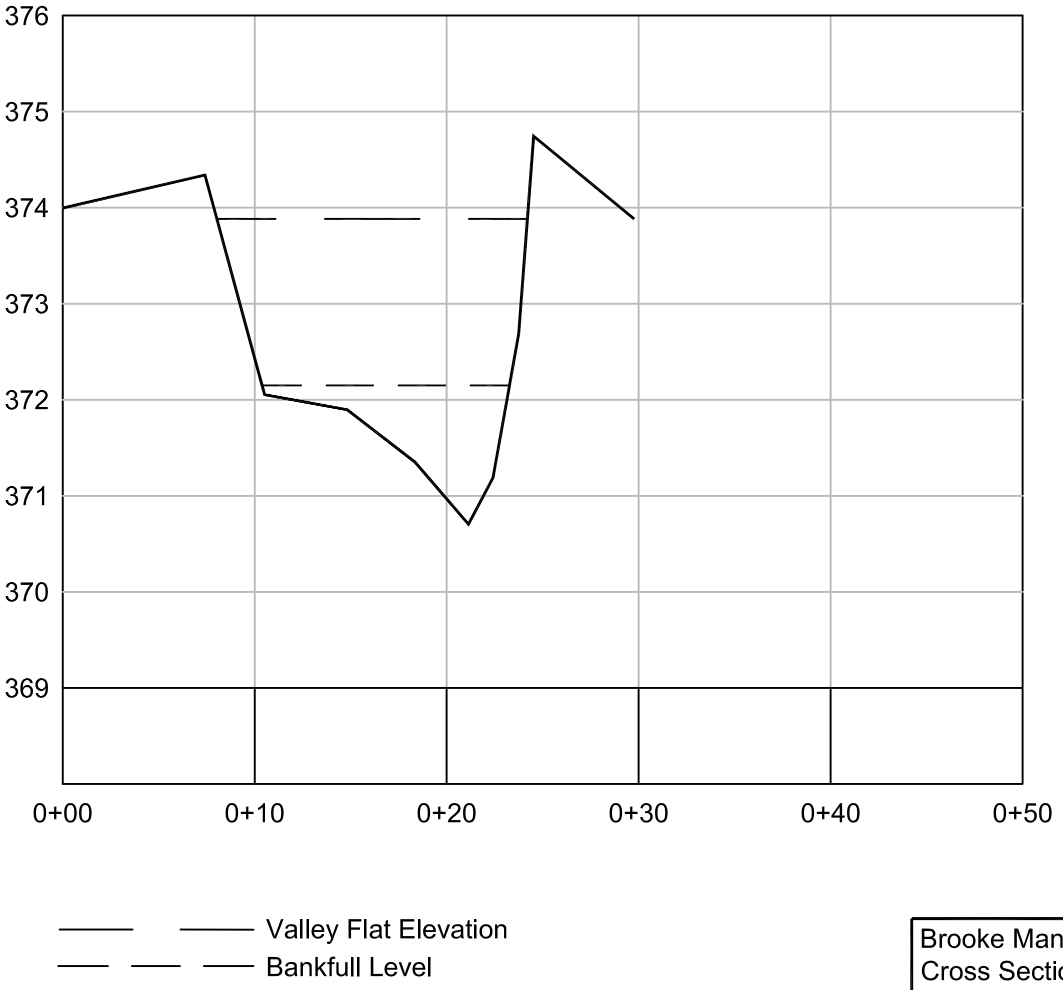
Bankfull Computations

subwidth (feet)	mean d (feet)	subarea (sqr. feet)	subWP (feet)
0.13	0.05	0.01	0.16
4.29	0.17	0.75	4.30
3.52	0.52	1.84	3.56
2.80	1.12	3.14	2.88
1.28	1.20	1.54	1.37
0.85	0.48	0.41	1.28

Bankfull Geometry

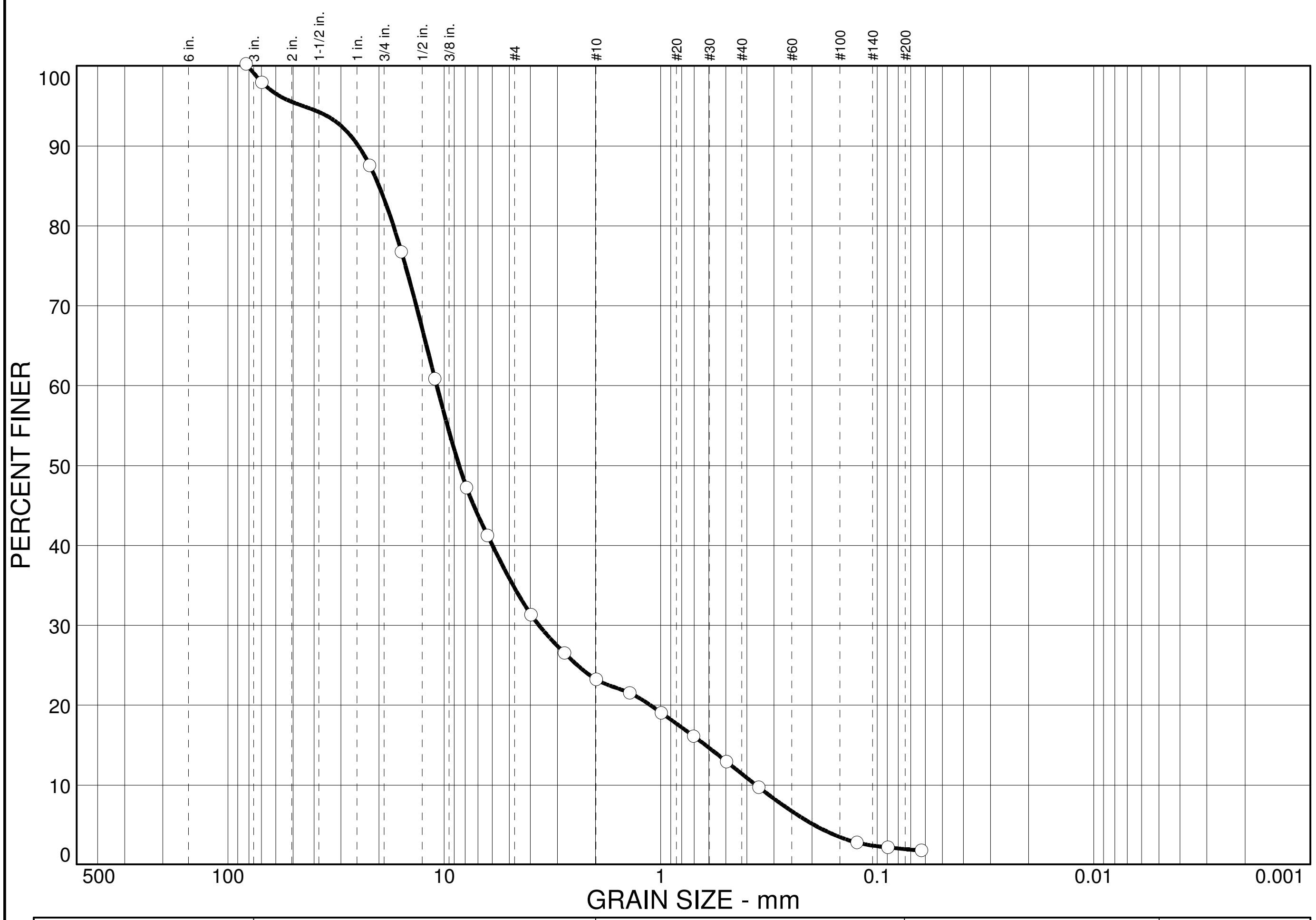
Area*	7.7	sqr. feet
Width	12.9	feet
Mean D	0.60	feet
W/D	21.6	
Rh	0.57	feet
FP Width	15.7	feet
ER	1.2	
d50	gravel	mm
Slope	N/A	ft/ft
Type	B4c	

* - Set to area of cross section 1



Brooke Manor Country Club Tributray
Cross Section 2
1" = 2' vertical
Scale:
1' = 10' horizontal

Particle Size Distribution Report



% COBBLES	% GRAVEL	% SAND	% SILT	% CLAY
1.2	75.8	21.2	1.8	

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
1 3/4 in.	100.0		
1 1/4 in.	97.7		
7/8 in.	87.3		
5/8 in.	76.5		
7/16 in.	60.6		
5/16 in.	47.0		
1/4 in.	41.0		
#5	31.1		
#7	26.3		
#10	23.0		
#14	21.3		
#18	18.8		
#25	15.9		
#35	12.7		
#45	9.5		
#120	2.6		
#170	2.0		
#230	1.6		

* (no specification provided)

Soil Description

LARGEST ROCK:
L=2.3075" W=1.4525"
T=1.1475" WT=0.10 lbs.

Atterberg Limits

PL= LL= PI=

Coefficients

D_{85}= 20.3 D_{60}= 11.0 D_{50}= 8.65
D_{30}= 3.73 D_{15}= 0.642 D_{10}= 0.375
C_u= 29.25 C_c= 3.39

Classification

USCS= AASHTO=

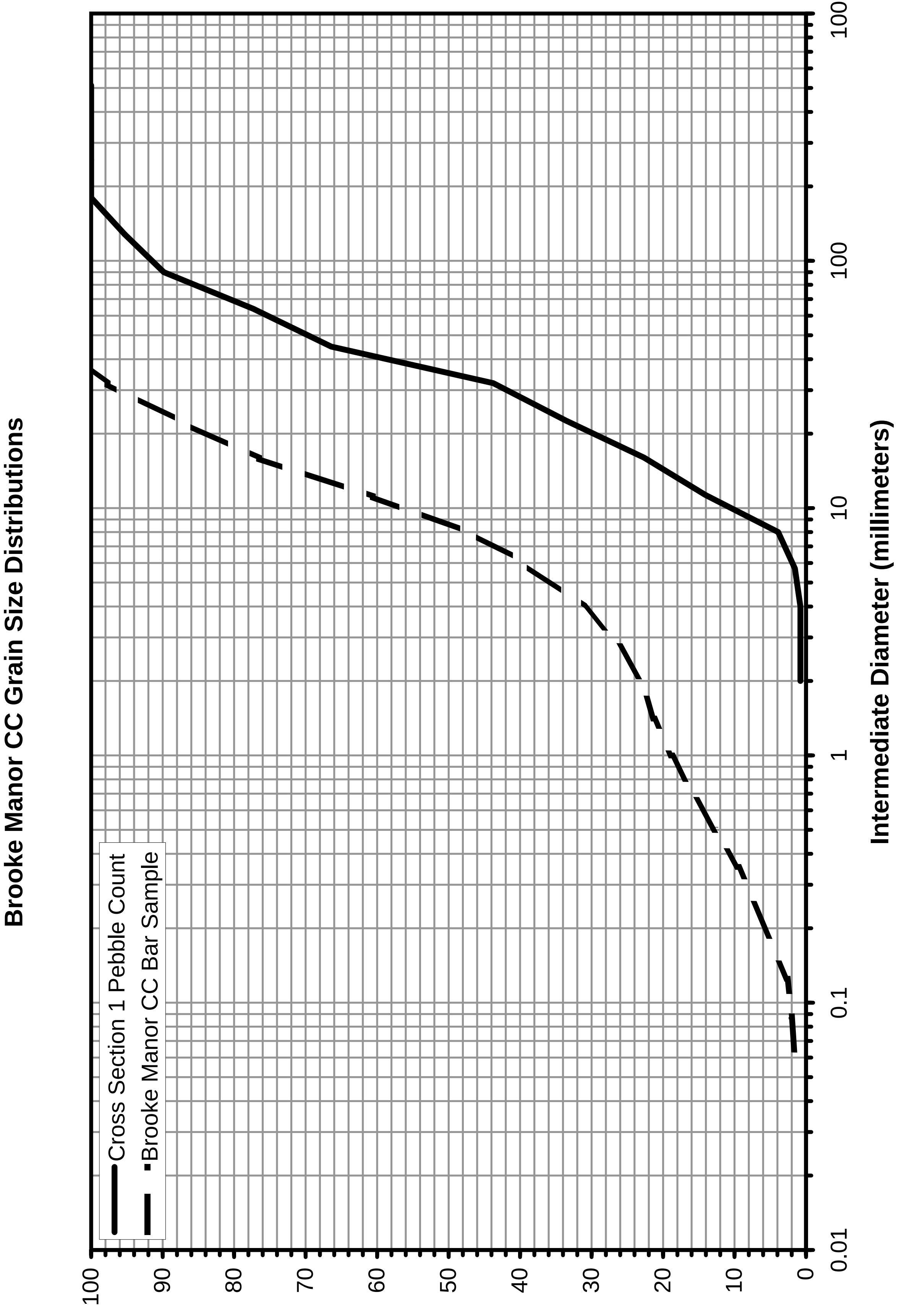
Remarks

Sample No.: AW 84 **Source of Sample:** **Date:** 7/15/04
Location: BAR SAMPLE **Elev./Depth:** SCOUR

MARYLAND DOT

Client: SHA
Project:
Project No: AT 376 A21 **Figure**

Modified Wolman (1954) pebble count		Range of particle size (mm)	Plot (i.e. finer than)	Particle count	Percentage finer than	Cumulative percentage
Project	MD ICC, BR-21	$D_i \leq 2.0$	2.0	1	0.8	0.8
		$2.0 < D_i \leq 4.0$	4.0		0.0	0.8
Location	Brooke Manor CC Tributary	$4.0 < D_i \leq 5.7$	5.7	1	0.8	1.6
		$5.7 < D_i \leq 8.0$	8.0	3	2.3	3.9
Sample site	Cross-Section 1 Riffle Surface	$5.7 < D_i \leq 11.3$	11.3	13	10.2	14.1
		$11.3 < D_i \leq 16.0$	16.0	11	8.6	22.7
Date	6-Oct-04	$16.0 < D_i \leq 22.6$	22.6	14	10.9	33.6
		$22.6 < D_i \leq 32.0$	32.0	13	10.2	43.8
Operator(s)	WSV, MAC	$32.0 < D_i \leq 45.0$	45.0	29	22.7	66.4
		$45.0 < D_i \leq 64.0$	64.0	14	10.9	77.3
Comments:	Sample truncated at 2mm. All data finer than threshold are excluded from this analysis, after Kondolf (1997)	$64.0 < D_i \leq 90.0$	90.0	16	12.5	89.8
		$90.0 < D_i \leq 128.0$	128.0	7	5.5	95.3
		$128.0 < D_i \leq 180.0$	180.0	6	4.7	100.0
		$180.0 < D_i \leq 256.0$	256.0		0.0	100.0
		$D_i > 256$	512		0.0	100.0
		Total		128		


Brooke Manor CC Grain Size Distributions
Cross Section 1 Pebble Count
Brooke Manor CC Bar Sample
Cummulative Percent Finer Than
100
90
80
70
60
50
40
30
20
10
0
Intermediate Diameter (millimeters)
0.01
0.1
1
10
100
1000

Sediment Mobility Analysis

Andrews Methodology

Project:	Brooke Manor Country Club Tributary
Reach:	ICC Crossing BR-21
Study Site:	Cross Section 1
D_{50}(riffle):	35 mm
D_{50}(bar):	8.65 mm
Mobile Size (D_{max}):	36.9 mm
Slope:	0.011 ft/ft

Andrews 1994 Methodology

τ_c^* (1994)	τ_c (1994)
0.037	0.46 lb/ft^2

Depth (1994)
0.67 feet

Andrews 1994 Methodology:

$\tau_c^* = 0.0384 \times [(D_{max} / D_{50}(\text{riffle})]^{-0.887}$
$\tau_c = \tau_c^* \times 1.65 \times 62.4 \times D_{max}$
Depth = $(\tau_c^* \times 1.65 \times D_{max})$ / Slope

End Point of Detailed Stream Profile

110+00 ⊕ Valley Station

Study Area Topographic Map
North Branch ICC Crossing BR-20
Brooke Manor CC Tributary ICC Crossing BR-21

Scale: 1" = 200' (Scaled for 24 x 36 Paper Size)