Office of Structures
Manual for Hydrologic and Hydraulic Design

Chapter 14: Stream Morphology and Channel Crossings

OFFICE OF STRUCTURES

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Preface

Federal and state policies and practices that apply to the hydraulic design of structures are presented throughout the various chapters of the Manual for Hydrologic and Hydraulic Design. These policies and practices have been developed to meet the objectives of applicable federal and state laws and regulations regarding streams and floodplains while achieving the transportation objectives of a safe, efficient, and cost-effective structure that is compatible with the environment of the stream being crossed. This chapter presents guidance developed and implemented by the Office of Structures (OBD) specifically for Maryland streams.

These procedures outline the approach to be used in evaluating the morphology of a stream reach in the vicinity of a waterway crossing. Similar guidance on several provided procedures has not been found to be available in federal manuals or other publications accessible to the public. Most of the guidance in Chapter 14 is based on the results of studies and investigations conducted since the mid-1990s in Maryland.

The investigations from which these techniques were developed targeted wadeable gravel-bed streams that generally maintain a pool-riffle morphology and have channel slopes of 0.2% to 4%; many of the techniques, however, may be found to be applicable to streams of other morphologies. Likewise, while the guidance focuses on bridge and culvert crossings of streams, it is equally relevant to other investigations of stream stability. Occasionally, for example, the OBD conducts stream morphological studies to evaluate stream stability with regard to highway embankments, retaining walls, or adjacent non-highway infrastructure such as utility lines that may parallel or cross a highway or stream corridor.

This is a working draft of Chapter 14. The guidance will continue to be modified and expanded as additional information becomes available regarding the morphological behavior of Maryland streams and as improved methods are developed for assessing this behavior.

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Symbol	Definition	Units of Measurement
A	Cross-sectional flow area	ft^2
d	Mean depth	ft
d_{max}	Maximum flow depth	ft
D	Diameter of intermediate-sized axis of sediment particle	mm
D_{50L}	Median particle size of the bed load	mm
D_{50R}	Median particle size based on the pebble count of the riffle surface	mm
D_{84R}	Particle size which equals or exceeds the diameter of 84% of the particles based on the pebble count of the riffle surface	mm
D_{max}	Largest mobile particle size under bankfull conditions	mm
$D_{mode\text{-}L}$	Most frequent size interval for the coarse-grained bed load particles	mm
$D_{mode\text{-}R}$	Most frequent size interval for the coarse-grained riffle surface particles	mm
ER	Entrenchment ratio, W_{fpa} /W	
IR	Channel incision ratio, I_{vf} /d_{max} (no incision IR = 0)	
I_{vf}	Channel incision from valley flat	ft
j	Sieve size	mm
K	Sinuosity	
n	Manning roughness coefficient	
Q	Flow	ft^3/s
R_h	Hydraulic radius	ft
S	Specific weight of the sediment (considered to be 2.65 for quartz sediment)	
S_{dgr}	Slope (along riffle crests) of the degraded bed	ft/ft
S_{exist}	Existing riffle-crest slope	ft/ft
S_{entr}	Existing riffle-crest slope in stream reach with highest bank heights	ft/ft
S_{rec}	Existing riffle-crest slope in reach that has incised, over-widened, and is recovering sinuosity with low-flow channel drops over stable riffles	ft/ft
S_{num}	Slope required for sediment continuity	ft/ft
S_f	Estimated friction slope	ft/ft
V	Average channel velocity	ft/s
W	Channel width	ft
W_{fpa}	Width of flood-prone area	ft

X	Station along the stream thalweg where the degradation is being computed	ft
X_{DLBLP}	Station of the degraded local base level point along the thalweg	ft
Y	Average flow depth	ft
Z_{dbl}	Riffle-crest line elevation of the degraded streambed	ft
Z_{DLBLP}	Streambed elevation at station X_{DLBLP} that represents a known or approximated degraded local bed level point	ft
Z_{exist}	Existing riffle-crest elevation	ft
ΔZ	Change in riffle-crest elevation	ft
γ	Unit weight of water (62.4 pounds per cubic foot)	lb/ft^3
τ_b	Cross-sectional average boundary shear stress over the riffle	lb/ft^2
τ_{avg}	Average channel boundary stress	lb/ft^2
τ_{c-L}	Critical boundary shear stress for the largest particles in the bed load	lb/ft^2
τ_c^*	Dimensionless boundary shear stress required for critical conditions	

Glossary

The terms in this glossary are defined as they are used within this chapter. 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 semi-permanently by the level of the ocean (mean sea level).

base level point A point along the stream channel that represents an elevation below which the channel is unlikely to degrade during the life of the crossing.

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

bed control A channel bed feature, such as a bedrock outcrop or culvert inlet invert, that holds a constant elevation in the streambed and limits degradation caused by downstream channel disturbances.

bed load 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.

degraded local base level point (DLBLP) The base level point that provides provides a downstream boundary condition from which a degraded stream profile may be computed. Under ideal conditions, the DLBLP should be located in one of three places: (1) where the local base level is controlled by resistant bedrock; (2) at a culvert invert that is unlikely to be replaced; or (3) at a downstream water body with a controlled outlet.

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 ft per second).

downstream fining A decrease in the median particle size of bed sediments in a downstream direction. This decrease is generally due to processes of abrasion and selective deposition.

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.)

fining See *downstream fining*.

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.

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.

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

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 effects Residual impacts that past land disturbances continue to have on contemporary streams and their valleys. These persistent impacts may affect channel evolution by altering sediment supply and gradation, debris supply and transport, flow resistance, and bank and bed stability for decades or even centuries after the disturbance practices have been discontinued.

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

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.

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.

residual pool depth The depth of pools from the water surface to the stream bed measured during low but non-zero flow conditions.

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.

riffle crest A local maximum of the channel thalweg profile that corresponds to the upstream limit of the riffle.

scour The cumulative effect of the erosive action of water that causes an identifiable depression or cusp in a streambed, stream bank, 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 (*valley flat*) and the adjacent side slopes (*valley walls*) created primarily by the removal of the landmass by ground water (solution) and surface water (erosion).

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 than the active floodplain.

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

14.1 Introduction

Stream morphology, also referred to as *morphology* in this chapter, pertains to the form of the stream channel (the shape, depth, pattern, and location), the form of its valley, and how they change over time. Changes in channel form are caused by the response of the channel not only to channel network and watershed conditions but also to local conditions introduced by a waterway crossing (i.e., the embankments, the crossing structure, and the waterway approaching, beneath, and exiting the structure). Analysis of stream morphology for waterway crossings therefore needs to consider both the effects of the channel on the crossing and the effects of the crossing on the channel.

The interaction of a channel and a crossing can have substantial reciprocal effects. If the channel avulses or migrates laterally, for example, its movement can result in highly skewed flow that impinges on piers, abutment walls, or highway embankments, increasing the extent and severity of scour. Vertical degradation of the streambed can expose and, in some cases, undermine both pier and abutment foundations. Changes in channel form and location can also affect flood capacity and the potential for debris jam formation, particularly where sediment deposits form in culverts and bridge openings. Crossings influence all of these processes by affecting the distribution and magnitude of flow, the capacity of the channel to mobilize and transport sediment, and the transport of debris.

Awareness and understanding of the relationship between channel morphology and stream crossings can lead to crossing design approaches that accommodate changes, reduce the potential for damage, and avoid or minimize adverse impacts on the environment. Those design approaches may be complemented by stream restoration efforts that reduce channel instability and improve stream habitat. Thus, the purpose of morphology studies is to provide information that will lead to waterway crossings that reduce both the effect of stream instabilities on the crossing and the potential adverse impacts of the crossing on the stream and its environment. Specific stream study objectives for replacement structures or new crossings may include any or all of the following:

1. Evaluate the existing channel morphology and the interaction of the channel and the existing crossing.
2. Estimate the potential for long-term channel degradation or aggradation at the crossing structure.
3. Estimate the potential for channel lateral movement at the crossing.
4. Provide design recommendations for the project area that meet project objectives.
5. Identify possible morphological changes that may increase the potential for flooding of the roadway and adjacent land.
6. Identify potential mitigation and/or enhancement sites within the study area.

14.1.1 QUALIFICATIONS

The stream morphology studies are to be led by a hydraulic engineer with extensive training and field experience in hydrology, open channel hydraulics, and stream morphology as evidenced by completion of projects that contain comprehensive and detailed field evaluations and interpretations regarding the stream study objectives listed above. The lead hydraulic engineer must have the knowledge and experience to perform the following tasks and to supervise others in their completion:

- Conduct stream morphology studies
- Apply hydraulic engineering concepts and methods (including the design of hydraulic structures and the numerical modeling of hydraulic structures using the HEC-RAS program of the Corps of Engineers)
- Conduct sediment transport and river mechanics analyses

Persons conducting stream morphology studies should have the capability to make subtle and critical field observations, to collect necessary field data, and to present this information in a manner that will be useful in the design process. The qualifications of the stream morphology team should be submitted to the OBD for review and acceptance prior to the commencement of the studies.

14.1.2 ELEMENTS OF THE STREAM MORPHOLOGY STUDIES

Each evaluation of stream morphology will require a preliminary morphology study (Section 14.2) to identify evidence of channel instability and related scour or flooding problems at the existing crossing and to identify the potential for problems for the proposed crossing. Where problems are identified, the preliminary study should ascertain which specific detailed analyses are needed to quantify them. Those detailed analyses will constitute the detailed morphology study (Section 14.3). The findings and recommendations of the preliminary study are to be presented to the OBD for review after completion of the study. If a detailed study is subsequently completed, its findings are to be provided to the OBD in a formal engineering report. The OBD may request that additional reviews be scheduled based on the scope and complexity of the studies.

The preliminary morphology study should be initiated early in the project development process, concurrent with hydrology studies as described in Chapter 5 (Project Development) of this manual. The detailed morphology study is typically initiated soon after the preliminary morphology study but usually not until the results of the existing condition hydraulic modeling are available. A review of Chapter 5 is important for understanding the time frames within which these different studies are initiated. The scheduling of the morphology studies should allow sufficient time to effectively conduct them while completing them in time for the findings to be useful for the design of the waterway crossing. Note that if the methods of assessment provided in Chapter 14 are found to be inadequate at any time during the preliminary or detailed morphology studies, then the OBD should be contacted to discuss alternative assessment methods.

At least eight elements may need to be assessed in the morphology studies. The information obtained from assessment of these key elements serves as a basis for evaluating channel and crossing interactions, fish migration barriers, and other features of interest and concern as discussed below. The required elements include

1. Existing crossing
2. Long-term changes in channel bed elevation
3. Channel lateral movement
4. Sediment dynamics
5. Debris
6. Structure and bend scour
7. Environmental considerations
8. Historic and contemporary modifications to channels and valleys

1. Existing Crossing

The type, size and location of the existing structure, the channel geometry in the vicinity of the crossing, and associated channel embankments can affect flow velocity magnitude, direction, and distribution, sediment transport, and channel morphology not only at the channel crossing but also upstream and downstream. The flood flow magnitude, direction, and distribution affected by the existing crossing may result in scour and erosion problems at the crossing that endanger the structure foundations or embankments. Embankments and submersed components of the crossing structure may cause non-uniform flood flow distribution and/or flow contractions that result in high-velocity flow through the crossing structure and backwater upstream. Backwater from the crossing may reduce flood flow conveyance of upstream crossings, resulting in increases in flood elevations. Non-uniform flood flow distribution, which may also be caused by obstructions upstream of the crossing, may result in high-velocity flow and/or very low-velocity flow. High-velocity flow, particularly in highly contracted bridge openings, may intensify scour in one section of the crossing, while very low-velocity flow may result in deposition in another part of the crossing. Scour holes can undermine foundations or damage crossing embankments that may cause structural failure (Chapter 11). Scour holes and bars created by floods can also have a significant effect on both lateral movement and vertical stability of the project channel.

The existing crossing structure, its embankments, and the waterway beneath, upstream, and downstream of the structure should be examined as part of stream morphology (Chapter 14), hydraulic (Chapter 10), and scour (Chapter 11) studies. Observations of these areas will facilitate evaluation of the current and potential future effects both of the channel on the proposed structure and of the proposed crossing on channel morphology.

2. Long-Term Changes in Channel Bed Elevation

Two of the main forms of change in the channel bed level are degradation and aggradation. Degradation refers to erosion of the streambed that causes a general lowering of the bed along its profile. Aggradation refers to deposition of sediment on the streambed that causes a general rise in the bed along its profile. Degradation and aggradation that extensively change the main channel streambed and banks over a period of up to 100 years are usually a response to natural or manmade channel network disturbances. These disturbances may include changes in channel base level, local channel modifications, watershed-scale changes in hydrology, and watershed-scale changes in sediment storage and supply. Because long-term degradation and aggradation are generally caused by disturbances well beyond the vicinity of the crossing, they differ from other forms of channel response that occur at the crossing (e.g., local or contraction scour). Nevertheless, channel changes at a crossing can initiate long-term changes upstream and downstream of the crossing, and long-term changes in channel bed elevation may be influenced by the crossing configuration.

3. Channel Lateral Movement

The position of the stream channel in its valley and the channel planform pattern can change substantially over the life of a waterway crossing. Two of the main forms of change in channel location and planform pattern are *channel bend migration* (gradual movement of the channel across or down valley) and *channel avulsion* (rapid channel movement to a new location), together called *channel lateral movement*.

Lateral movement of the channel can affect many aspects of scour and the hydraulic capacity of a crossing. Past morphological studies conducted for OBD projects indicate that many

Maryland streams have been directly modified by straightening them to accommodate agriculture, railway and road embankments, or other forms of land development. The channels appear to be redeveloping sinuosity as a result of many factors; therefore, channels that appear straight at the time of the study may have a high potential for future lateral instability. At some locations, bank erosion, collapsing banks, and deep scour pools in bends may indicate active channel migration; at other locations, the channel may avulse, moving suddenly to a new location without obvious signs of channel instability. Therefore, the assessment of channel lateral movement needs to be included in the scour evaluation and stream stability studies, and it needs to be considered in the design of the bridge foundations.

4. Sediment Dynamics

Sediment dynamics, including mobilization, transport, and storage, are the primary drivers of channel morphological change, and they directly or indirectly affect each of the other seven key elements. Identification of the sources of specific size fractions is often a prerequisite for understanding channel morphology problems. The source of material from the largest size fractions is often located close to the site of deposition, whereas finer-grained material often has a source that is more widely distributed throughout the watershed. Determination of the sources of specific sediment size fractions and the flow conditions under which these fractions are mobilized or deposited is essential for determining the conditions under which a stream may become unstable or may create the potential for significant scour at the structure.

5. Debris

Accumulation of debris can lead to log jams and upstream flooding. In some cases, extensive debris can redirect flood flows at structures, leading to increased scour or even to the loss of the structure. Debris also affects channel morphology: it temporarily stabilizes the channel grade during channel incision, causes upstream backwater and deposition of sediment, and facilitates channel widening and lateral migration. The conditions for supply, transport, and accumulation in the stream reach under consideration should be evaluated.

6. Structure and Bend Scour

The depths of bend scour, measured in various channel bends during the stream morphology investigation, can be used as one indicator for the potential for future bend scour in the stream reach under consideration. This information may serve a number of purposes during project development, including stream restoration and enhancement and the evaluation of substructure foundation elements.

While the evaluation of scour at structures is conducted as a separate study (Chapter 11), the occurrence and potential causes of scour at the existing crossing is made as part of the preliminary study. Furthermore, identification and measurements of (1) the channel bed load and (2) surface and subsurface soils or rock on the flood plain and in the channel upstream of and at the crossing are key elements in the evaluation of the scour potential at the structure (see Appendix B). The integration of the results of morphology studies and the scour evaluation is necessary to complete the evaluation and/or design of waterway crossings and highway embankments.

7. Environmental Considerations

Stream ecosystems and riparian wetland ecosystems are highly dependent on channel morphology; impairment of aquatic ecosystems is often linked to channel and floodplain form and channel morphology. Channel degradation and channel aggradation, in particular, cause changes in channel form and hydrology that can be detrimental to aquatic habitat. Deposition of fine-grained sediment (sand and smaller sizes) in the channel bed, for example, can cause embeddedness of the coarse-grained channel substrate, possibly reducing available habitat; frequent mobilization of bed material affects aquatic organisms dependent on channel substrate characteristics and stability; steps in the channel bed and at culvert outlets can present migration barriers to aquatic organisms, particularly fish; and channel degradation reduces the frequency of inundation of the floodplain and may lower the valley groundwater systems, affecting stream valley wetlands and low-flow supply of water to the channel.

Although the intention of the morphological studies is not a biological assessment of channel habitat, identification of embedded channel substrate, highly mobile substrate, headcuts, or knick points that may be migration barriers at or near structures, and entrenched channel conditions should be noted in the stream morphology report(s) for possible use by natural resources or regulatory personnel. In particular, this information is useful to identify impacts of the existing crossing, and to design crossings that minimize impacts, and for future restoration efforts that may be considered in the vicinity of the crossing.

8. Historic and Contemporary Modifications to Channels and Valleys

Valley and channel modifications, both current and historic, contribute to instability of stream channels. Problems common to many Maryland streams arise from the response of the stream channels to the legacy of historic land-use practices. Maryland watersheds and channel networks have been modified for transportation, agriculture, industry, and commercial and residential land-development since at least the 17th century (Cook 1990; Costa 1975; Cravens 1925; Hopkins 1975; Jacobson and Coleman 1986; Scott, 1807). Resulting impacts to the valleys were relatively consistent and pervasive. At a minimum, valley bottoms were filled with recent (less than 300-year-old) sediments; floodplains were encroached upon by roads, utilities, buildings, railroads, and berms; and channels were relocated and ditched to improve the raising of livestock and production of crops.

14.2 Preliminary Morphology Study

The purpose of the preliminary morphology study is threefold: (1) to identify existing or potential channel morphology-related problems; (2) to determine whether these problems are significant enough to warrant a detailed morphology study; and (3) to develop recommendations for a scope of the detailed study if one will be recommended. The preliminary study generally consists of five components:

1. Background data collection and review.
2. Visual assessment.
    a. Field reconnaissance.
    b. Preliminary interpretation of observations.
3. Rapid channel measurements (if needed).
4. Analysis and development of recommendations.
    a. Revised interpretation of observations.
        i. Identification of existing and potential future morphology-related channel and crossing problems.
        ii. Determination of whether a detailed morphology study is needed to investigate the implications of identified problems.
    b. Development of recommendations for the scope of the detailed study (if needed).
5. Reporting.

The preliminary morphology study typically requires about three to ten workdays to complete, including one to three days of fieldwork. For safety purposes, fieldwork should be carried out by a two-person team; analysis and reporting will usually require only one person. The results of this study are presented in a letter report to the OBD. The preliminary morphology study should be completed at an early stage in project development so that its findings and recommendations can be used in evaluating the type, size, and location of the proposed crossing structure. The study results may also be useful in conducting environmental and/or planning studies. The coordination and interaction of all the disciplines involved in the project location and design stage is highly encouraged. Changes in location and design features of the structure or roadway embankment are much easier to accomplish at this preliminary stage than later in the process when the location/alignment or design has been accepted and approved.

14.2.1 BACKGROUND DATA COLLECTION

Existing Land Use and Existing and Ultimate Development Hydrology

Using mapping and/or GISHydro (UMD 2007), an estimate of the watershed area and the percentage of each type of land use should be developed to identify the basic watershed parameters. Data for a more detailed analysis of land use or flows is not necessary and is not usually available because the preliminary stream morphology study is typically conducted concurrently with a hydrologic study of the watershed.

Bankfull Flow and Channel Geometry Estimates

Preliminary bankfull flow and channel geometry parameters should be estimated from regional curves developed by United States Fish and Wildlife Service (USFWS 2007) for the appropriate physiographic region and drainage area. The estimates of bankfull characteristics should be noted as shown in Table 14-1. These values will be used in the field to visually classify the channel (Rosgen 1996).

Physiographic Region and Geology of Site

Information on the geology of Maryland, including maps, brief descriptions, and publications, can be obtained from the Maryland Geological Survey (MGS 2007). Geotechnical investigations of the study area conducted for prior OBD projects may also contain information about local bedrock properties. The specific physiographic region or regions contributing flow and sediment to the stream should be identified for the morphology study. The person conducting the morphology study should become familiar with the characteristics of local bedrock and/or major deposits. Important characteristics of rock include its resistance to weathering and abrasion and the potential thickness of highly erodible/scourable material (e.g., saprolite). In addition, in watersheds underlain by carbonate bedrock, the potential effects of subsurface flow in solution cavities should be considered.

Historic and Contemporary Modifications to Channels and Valleys

Historical documents, maps, and photographs should be reviewed for information regarding land use changes and modification to streams and their valleys during the 18th, 19th, and 20th centuries. Old bridge plans, aerial photographs, topographic maps, county historical atlases/maps, and articles and periodicals are a few of the items that contain information that may reveal changes to valley bottom topography as well as to stream channels. These documents identify past channel locations, mills, mill races and milldams, old roads, railroads, trolley lines, forges, mines, quarries, channelization projects, utility lines, and other sites of interest. A review of these documents, combined with field evidence obtained during the visual assessment (Section 14.2.2), can provide a qualitative understanding of past modifications to the valley and channel that are continuing to influence the channel's evolution. Evidence of legacy effects that may be observed in the field is described in Appendix 14-A.

Table 14-1 Summary of Stream Parameters

Stream Parameter	Value
Physiographic Region	
Drainage Area (mi^2)	
Bankfull Width (ft)	
Bankfull Depth (ft)	
Cross Section Area (ft^2)	
Width/Depth Ratio	
Bankfull Velocity (ft/s)	
Bankfull Discharge (ft^3/s)	

Valley and Channel Planform Characteristics

Topographic mapping of the project stream and valley should be acquired. Coverage should include at least 5000 ft of the channel upstream and 5000 ft downstream of the crossing and at least 1000 ft of major tributaries upstream of any confluences with the main channel. The mapping should be reviewed and compared to identify evidence of past channel modifications and to identify sites that should be closely examined in the field. These sites should be marked on the maps and/or entered into a GPS receiver for use in the field.

- Examine representations of past channel locations, channel planforms, and valley characteristics. Identify channel segments that are straight and/or positioned near valley walls. Those segments are likely to have been straightened and/or relocated prior to the date of the base aerial photography used to develop the map.
- Compare representations of current and past channel locations, channel planforms, and valley characteristics. Identify modifications made to the channel and/or valley (e.g., channel straightening or relocation, bridge construction, dam removal) between mapping dates. Also identify locations where the channel may have avulsed or migrated during the same time period.
- Determine approximate latitude and longitude of points 1500 ft and 500 ft downstream of the crossing centerline and 500 ft and 1500 ft upstream of the crossing centerline. These points approximately coincide with reach limits that will need to be identified in the visual assessment.
- Examine recent maps to identify channel and valley features that may be used to establish the upstream and downstream limits of the study (e.g., confluences, culverts, dams, areas where valley widths or slopes increase or decrease). These features should be at least 1500 ft from the crossing centerline.

A variety of topographic mapping is available for most streams in Maryland:

- *USGS 7.5-Minute Quadrangle Maps:* USGS 7.5-minute quadrangle maps (1 in:2000 ft) should be obtained, and paper copies should be made available for use in field. If electronic versions of the maps are used or printed, confirm that the images are replicas of the original maps rather than copies created by digitizing. Digitization renders the blue lines as straight line segments that are much less accurate than the original drawings.

  The planform details provided on the original topographic maps are important for assessing changes in channel location and planform. The blue line representation of the streams provides the approximate location and channel planform at the time of the base aerial photography, which is typically from the period between 1950 and 1965. The date of base aerial photography for these maps is given on the maps. During the 1970s and 1980s, some modifications that had been made to the streams were added to the maps and shown as purple lines.
- *County Contour Maps:* County mapping typically can be obtained for the entire extent of the project. Several Maryland counties have developed 2-foot or 5-foot contour interval mapping (1 in:200 ft) in digital format. They are useful for determining the general position of the channel. Light Distancing and Ranging (LiDAR) data that may provide contour accuracy on the order of 1 ft may become available over the next decade for most Maryland counties. Where available, contour mapping based on LiDAR should be obtained for use in the field.

- *MDSHA Project Survey Maps:* MDSHA contour maps (1 in:100 ft) for the crossing being examined are typically not available until after the period of the preliminary assessment. Contour maps created for nearby projects, however, may include the crossing stream and valley in their coverage. These maps, developed with 2-foot contour intervals, should be obtained, if available. The details of stream planform characteristics are usually sufficient on MDSHA maps; the coverage, however, will rarely extend 5000 ft upstream and downstream of the crossing. Therefore, other forms of mapping must be used to supplement the coverage of the MDSHA maps.

14.2.2 VISUAL ASSESSMENT

The visual assessment consists of the collection and interpretation of field observations of specific channel and valley features: channel bed, channel banks, tributaries, confluences, existing stream crossings, and valley bottom. In some cases, the visual assessment may be augmented with rapid measurements as discussed in Section 14.2.3.

Summary of Field Procedures

Equipment and Mapping

The following equipment and mapping will be necessary for conducting the field component of the visual assessment:

- *GPS receiver* capable of horizontal error less than 50 ft and display of contour maps.
- *Topographic maps*: Printed copies of USGS 7.5-minute quadrangle maps, county 2-foot contour maps (or 5-foot if a higher resolution is not available), and MDSHA project survey maps. Loading electronic copies (USGS 7.5-minute quadrangles, if available) onto the GPS receiver is recommended.
- *Digital SLR camera* with an aspherical lens capable of 18 to 100 mm focal lengths and sufficient memory (1.5 Gb) and battery life to obtain 500 photos at a minimum resolution of 3872 x 2592 pixels.
- *Pocket rod* or *stadia rod* with a major scale interval of 1 ft and minor scale interval of 0.1 ft that can be easily viewed in photographs.
- *Field notebook* with all-weather paper and pen.
- *Ruler* with major scale interval of 1 cm and a minor scale interval of 1 mm that can be viewed easily in photographs of the channel substrate.
- *100-foot open reel tape measure.*
- *Hand level.*

Photographic Documentation

Field observations should be documented in the form of a high-quality, geo-referenced photographic record of the project stream and valley and their key features. Analysis of the stream's morphology will be based primarily on a review of this photographic record following completion of the field reconnaissance. The record consists of (1) digital photo-documentation of the channel, the existing crossing, specific key channel features, and any other important characteristics of the channel and valley bottom and (2) an Excel 2000-compatible spreadsheet that briefly describes each photograph as shown in the example of Table 14-2. The location of every photo should be recorded using a handheld GPS device. Before the first photo is taken, the camera and the GPS device should be set to number corresponding photos and points identically (i.e., Photo 1/GPS Point 1, Photo 2/GPS Point 2, etc.). The photo-documentation will consist of three sets of photos and corresponding field notes:

- *Continuous channel photos*: A series of photos should be taken to provide a continuous documentation of the channel in a generally upstream direction. Orient the photos primarily in the upstream direction; where necessary, obtain photographs in the downstream direction to capture important aspects of such features as bends or sediment deposits upstream of channel blockages. Depending on the length and characteristics of the examined channel reaches, this series may consist of approximately 60 to 300 photos.
- *Existing crossing photos:* In studies conducted for replacement of an existing structure, the photographic record will include a series of photos taken to document the existing crossing, its structure, and all evidence of problems at the structure and of its interactions with channel morphology.
- *Key feature photos*: Key features should be documented at a sufficient number of points to show consistency, trends, or anomalies in their characteristics (Schumm 1999). If these key channel and valley features are not adequately documented in the continuous channel photos, additional photos should be taken to document them. A pocket rod, tape measure, and/or ruler should be used for scale in each of the photographs taken to document bank heights, pool depths, channel widths, sediment sizes, or any other quantifiable characteristics.
- *Field notes*: Notes and observations may be recorded in the field and/or they may be based on a review of the photos following completion of field reconnaissance. Some features or characteristics may be difficult to distinguish in the photographs (e.g., changes in slope, headcuts in consolidated fine-grained materials) and should be recorded in the field notebook during the reconnaissance. Rapid measurements should also be recorded in either the GPS receiver or the field notebook. These field notes should be incorporated into the spreadsheet created to catalog and describe the photos (Table 14-2).

Organization of the Visual Assessment

The primary objectives of the visual assessment vary according to location relative to the crossing. Downstream of the crossing, the main objectives of the assessment are to evaluate the channel base level, the potential degradation that may propagate up to the crossing, and the potential effects of backwater that may cause sediment deposition or flooding at the crossing. In the immediate vicinity of the crossing, the main objective is to evaluate all existing and potential morphological changes that may occur near the crossing. Upstream of the crossing, the main objective is to evaluate the supply of sediment and debris that may be transported to the project reach. Thus, the channel region examined during the visual assessment may be delineated as three distinct reaches: the ***base level reach***, the ***project reach***, and the ***supply reach***.

The field reconnaissance component of the visual assessment of the three reaches should generally be completed in the following sequence over the course of one to two days:

1. *Preliminary* examination *of the project reach*: At the site, examine the project reach to identify signs of existing and potential future instability or flooding problems that may be influenced by conditions upstream or downstream. The project reach is loosely defined as the area within 500 ft downstream and upstream of the crossing. Photo-document the

Table 14-2 Example of Photographic Documentation Spreadsheet

	A	B	C	D	E	F	G
1	**Photo No.**	**GPS Point No.**	**Date/Time**	**Lat**	**Long**	**Direction of Photo**	**Comment**
2	1	1	13-JUN-07 10:01:02AM	N39 29.534	W76 15.553	DS	Channel base level point, entrance invert of box culvert built in 1996
3	2	2	13-JUN-07 10:01:42AM	N39 29.532	W76 15.552	US	Riprap-protected approach channel to culvert
4	3	3	13-JUN-07 10:02:48AM	N39 29.523	W76 15.552	US	Eroding bend upstream of culvert
5	4	4	13-JUN-07 10:04:21AM	N39 29.522	W76 15.551	US	Channel section with debris jam
6	5	5	13-JUN-07 10:05:59AM	N39 29.519	W76 15.551	US	Debris jam, approximately 1 ft drop in water surface
7	6	6	13-JUN-07 10:07:06AM	N39 29.514	W76 15.550	Vertical	Fine gravel deposit upstream of debris jam

crossing and classify the channel (Rosgen 1996) as described below in *Key Features and Observations*.

2. *Preliminary examination of the base level reach*: From the project reach, proceed downstream at least 1500 ft. During the walk downstream, formulate a general perception of the stream based on observations of the streambed, stream banks, and valley bottom. These observations may include the identification of points to investigate during the assessment of the base level reach. Look for a high-permanence base level point near the center of the valley to establish the downstream limit of the base level reach. (Refer to *Base Level Points* Table 14-4 for an explanation of how to evaluate features that may represent base level points.)
3. *Establishment of the downstream limit of the base level reach*: The downstream limit of the base level reach must be at least 1500 ft from the crossing location and should be far enough from the crossing to ensure that sources of instability that may migrate upstream to the crossing location will be included in the assessment. If a high-permanence base level point has not been located within 1500 feet of the crossing location, the limit of the base level reach should be extended farther downstream to the nearest point that can be identified as a high-permanence base level point.
4. *Visual assessment of base level reach*: From the downstream limit of the base level reach, proceed upstream. Photo-document the channel and key features as described below in *Key Features and Observations*. Locate and identify as many potential base level points as possible. Examine deep pools carefully and attempt to identify the pre-settlement/post-settlement interface. Thoroughly examine channel features that indicate current trends in bed elevation change and that may indicate potential for future trends in bed elevation change. Also look for blockages or topographic features that could cause backwater that may affect upstream flooding, sediment deposition, or aggradation at the crossing.

5. *Visual assessment of the project reach*: Continue photo-documenting the channel and key features. Document all floodplain and channel features that affect backwater flooding, distribution and skew of flow, sediment deposition, debris jam formation, or scour at the crossing. Examine the floodplain thoroughly for indications that the channel has migrated or avulsed in the past and/or has the potential for lateral movement in future. Examine and photo-document the streambed and banks of the main channel and tributary channels within a few hundred feet of their confluence, focusing on existing and potential future sediment and woody debris supply as well as the potential for the confluence to shift to a new location.
6. *Visual assessment of the supply reach*: Continue photo-documentation; identify and document current and potential future sources of coarse sediment and debris. Examine and photo-document the streambed and banks of the main channel and tributary channels within a few hundred feet of their confluence, focusing on existing and potential future sediment and woody debris supply.
7. *Establishment of the upstream limit of the supply reach*: After reaching a point at least 1500 ft upstream of the crossing location, continue photo-documentation. Proceed upstream until the main source of coarse-grained sediment and large woody debris can be identified. The upstream limit of the supply reach must be at least 1500 ft upstream of the crossing location, and the reach should be of sufficient length to characterize the sediment and debris supply from the main watershed and local sources.

Field reconnaissance should be conducted under low-flow conditions such that the water surface in pools is effectively level and the flow in riffles is shallow but at least partially covers them. These conditions allow examination and photo-documentation of the channel substrate, the stream banks, and the water surface gradient over the downstream face of bed features.

Key Features and Observations

Many factors affect stream stability, but the OBD considers the key features described below to be the most informative for diagnosing potential channel morphology problems at Maryland crossings. Some indicators of potential future instability may be very subtle, and in many cases features will need to be interpreted in conjunction with multiple other indicators. Therefore, experience in making these types of field observations is critical for the person conducting the study.

The continuous channel and existing crossing photo-documentation will record much of the information needed for analyzing the channel and its interaction with the existing crossing. As a supplement to these photos, many key features need only be documented at a sufficient number of points to show consistency, trends, or anomalies in their characteristics. The following descriptions of key channel features suggest observations that may be relevant in evaluating the channel and existing structures while in the field and while reviewing the photo-documentation following field reconnaissance. Tables describing potential indicators and considerations are provided to facilitate the interpretation of observations. Unless otherwise noted, the suggested procedures may not be necessary in every preliminary study; their relevance and significance should be determined by the lead engineer according to his/her experience.

Existing Crossing

Conditions at the existing bridge or culvert may indicate current and/or potential future problems with channel morphology, the stability of the structure and/or its embankments, and the stream environment. Tables 14-3a, 14-3b, and 14-3c describe indicators of potential problems at the crossing. In preliminary studies conducted for replacement of an existing structure, the existing crossing, all evidence of problems at the crossing, and evidence of channel and crossing interaction should be photo-documented according to the following procedures.

On the Embankment

- Photo-document the upstream channel and downstream channel from the roadway: Obtain one photo directly over the channel centerline looking upstream and a second photo directly over the downstream channel centerline looking downstream.
- Photo-document the vertical curve of the roadway: From the roadway near one side of the valley bottom, obtain one photo in the direction of the roadway centerline showing the lowest elevation area of the roadway where overtopping would first occur. Obtain another photo of the lowest elevation area of the roadway from the opposite side of the valley bottom.
- Photo-document the roadway approaching the structure: Standing over the centerline of the structure, obtain one photograph showing the centerline of each approach roadway.
- Photo-document any evidence of flow over the structure or roadway embankments. Evidence may include debris accumulated on bridge railings or guard rails, overtopping damage, or riprap repair of the approach embankment, roadway embankment, or shoulder.

Upstream of the Structure

- Photo-document the alignment of the upstream channel with the structure: Looking downstream from upstream of the structure, obtain at least one photo that shows the channel alignment with the structure.
- Photo-document any evidence of lateral movement of the channel approaching the structure. Determine whether this movement has resulted in increased skew of the channel with piers, abutment walls, and culvert entrances. Photo-document bars, debris, or other potential causes of the movement.
- For an existing culvert, extend a pocket rod up from the channel bed at the centerline of the culvert entrance. Photo-document the depth of flow in the culvert at the entrance invert.
- Photo-document accumulations of woody debris in the channel or on the crossing structure. Evaluate the cause of the jams and the potential for future jam formation at the crossing.
- Examine and photo-document tributary channels that confluence with the main stem channel near the entrance of the crossing structure. Examine the structure to determine whether flow, sediment load, or debris from the tributary may have affected scour or lateral movement of the channel at the structure. Photo-document evidence that the existing structure is causing backwater or affecting flood flow distribution, either of which may cause sedimentation, channel lateral migration, or scour at the confluence.
- Photo-document the construction date of the structure if it is indicated on the entrance.

Table 14-3a Observations at Embankments

Features	General Observations	Indications and Considerations
Evidence of recent roadway flooding	Debris on railings or guard rails	Accumulations of floating debris such as tree limbs and trunks on bridge railings and guard rails can indicate overtopping of the roadway. Accumulations of herbaceous plant stalks with other woody debris may indicate recent roadway flooding. Note that if a large flood has not recently occurred in the area, the roadway may frequently be overtopped.
Damage to roadway and embankment	Damaged or repaired roadway shoulders and pavement and downstream embankment	The lowest point in the roadway profile is where flood flows first overtop and flood the roadway and spill over the downstream side of the embankment. The susceptibility of the existing crossing to flooding is indicated by roadway damage, damage to the roadway shoulder and the downstream side of the embankment, or by repaired riprap sections of embankment. Specifically, erosion of the downstream face of the embankment typically indicates that the water surface drops substantially from the upstream side to the downstream side of the structure during overtopping flooding. The drop in water surface represents the energy loss through the bridge opening. Damage extending several feet down the downstream side of the embankment face may indicate the need for a larger structure to avoid severe flow contraction.
Scour around the embankment	Scour damage, riprap repair of the embankment	Lateral movement of the main channel over time may result in main channel bends that migrate into or impinge on the roadway embankment.
Embankment erosion along parallel tributaries	Erosion of the roadway embankment by tributary channels	Tributary channels that flow parallel to the crossing embankment may migrate into or impinge on the embankment. Typically, tributaries are relocated and confined as a consequence of the construction of the embankment and, unless they have been heavily armored, these tributaries commonly become unstable.

Table 14-3b Observations at Bridges

Features	General Observations	Indications and Considerations
Bars and poorly armored riffles in the channel upstream	Channel aggradation upstream of crossing	Aggradation of the channel may be caused by (1) a wave of sediment (typically gravel) that is gradually migrating downstream toward the bridge, (2) backwater from the bridge, or (3) backwater from a source downstream of the bridge. An upstream wave of sediment can be detected by examining the upstream channel. Backwater caused by the structure usually results in some form of scour at the bridge or evidence of flow contraction at the bridge. Aggrading conditions downstream, under, and upstream of the bridge indicate a backwater effect from a source downstream of the bridge. (*continued*)

Table 14-3b Observations at Bridges (*Cont'd*)

Features	General Observations	Indications and Considerations
Scour at piers	Scour holes around piers; exposed pier foundations; riprap or other scour countermeasures around piers; failing scour countermeasures	Scour holes around piers are an indication of high-velocity flow in the channel. Scour holes and sediment deposits downstream of scour holes can indicate the direction of flow that caused the hole to form and may indicate the degree of misalignment of the pier to the flow. Riprap and other countermeasures may indicate the repair of previous scour holes. Failure of scour countermeasures may indicate inadequate countermeasure design for scour protection; however, failure of countermeasures may also indicate morphological changes to the channel for which the countermeasure was not designed. For example, degradation or lateral migration of the main channel may result in failure of scour countermeasures or reduce the capacity of the countermeasure to resist scour.
Scour at abutments	Scour holes on the upstream side of the abutment; exposed abutment foundations; riprap or other scour countermeasures around abutments; failing scour countermeasures.	Scour holes at abutments may be an indication of high-velocity and high-curvature flow near the abutment. The high-velocity and high-curvature flow may be a result of (1) contraction of floodplain flows by the adjacent embankment, (2) impingement of flow on the embankment caused by skewed alignment of the channel and the abutment, or (3) migration of the channel into the abutment. The cause of the scour hole can be determined from the scour pattern and curvature and alignment of the approach channel.
Scour-widened main channel under the structure	Channel larger under structure than upstream or downstream of structure.	The channel may have been enlarged through scour caused by the contraction of flood flows at the crossing. Contraction of flood flows by the crossing results in upstream backwater and high velocity flow through the structure. The contracted flow may have also caused a deep pool under the structure that may extend downstream of crossing. The scour pool is often asymmetrical and may expose and erode bedrock and expose and undermine structure foundations. Scour may continue to enlarge the channel until it is constrained by the abutments at severely undersized structures.
Constructed over-widened channel under the structure	Channel wider under structure than upstream or downstream of the structure with a scour hole under the structure	The channel may have been widened locally under the structure as part of the crossing design or it may have enlarged through erosion caused by the contraction of flood flows at the crossing.
Constructed over-widened channel under the structure	Channel wider under structure than upstream or downstream of the structure. Deposition in the main channel and on the floodplain.	Sediment transported to the crossing is depositing in the constructed over-widened channel under the structure. Non-uniform deposition of the sediment frequently causes rapid lateral movement of the channel under the structure.
Bars downstream of piers and abutments	Coarse or fine-grained deposits in the wake zone	Typically indicates a skewed direction of the flow that causes deposition in the wake. May also represent large bed material or riprap scoured from around the pier or abutment. If the pier or abutment is in the main channel, the deposit may occur as a result of a supply of large sediment or a high sediment load. (*continued*)

Table 14-3b Observations at Bridges (*Cont'd*)

Features	General Observations	Indications and Considerations
Limited deposition on floodplains and in the main channel	Floodplain and main channel deposits limited to the area under and around the structure	Sediment deposition may represent ineffective flow areas (recirculation zones or other areas with very low-velocity flow) under some flood levels. Upstream or downstream obstructions—other crossings, abandoned embankments, high floodplain topography, or main channel bends—and the structure alignment with the flow may cause these low-velocity areas that result in sediment deposition. Deposition often occurs where the channel was locally widened or the floodplain was excavated to meet design flood requirements. The deposit may also be caused by an upstream tributary that supplies a high silt load. If the deposit forms in a flow area that is ineffective during some flood events, it may block the area, which otherwise may have been effective under design event conditions.
Extensive floodplain and main channel deposits	Floodplain and main channel deposits that extend upstream and downstream beyond the limits of the contraction and re-expansion areas of the bridge (see Chapter 10)	These extensive deposits usually indicate backwater conditions or a high upstream supply of sediment that is causing general ggradation of the channel bed and/or floodplain. Backwater may be caused by downstream structures, downstream debris jams, or confluence backwater. High sediment loads may be a result of a degrading section of the main channel or a tributary.
Downstream confluences	Deposition and debris lines higher than expected, frequent overtopping of roadway, and/or sediment deposition	Confluences with larger streams may cause backwater conditions that result in debris lines and sediment deposition at levels higher than they would be without backwater.
Confluence instability	Bank erosion or channel avulsion causes relocation of the confluence	Modification of the tributary, its valley, and its confluence prior to or during construction may have caused instability of the tributary. The location and orientation of the confluence may change over time, resulting in changes in the effect of the tributary on the crossing flood flow magnitude, direction, and distribution and scour and deposition patterns.
Tributary deposition	Local sediment deposits at the mouth of the tributary or on the downstream floodplain	Sediment deposits at the mouth of a tributary and on the floodplain downstream indicate the current effect of tributary sediment loads on deposition at the structure. The deposit may cause lateral movement of the main channel or change the distribution of flood flow at the crossing.
Tributary flow	Scour indicating flow from the tributary directed at a pier	The orientation of scour holes at the structure may indicate that a tributary, located in close proximity to the crossing, is influencing the direction, magnitude, and distribution of flow around piers or abutments. The potential for tributary flow to affect scour at the main channel bridge is greatest where the tributary flood hydrograph response timing is different from the main channel flood hydrograph response; therefore, the flow from the tributary may dominate flow at the crossing.

Table 14-3c Observations at Culverts

Features	General Observations	Indications and Considerations
Aggradation upstream of culvert	Upstream sediment deposition	Upstream backwater may have caused a reduction in sediment transport capacity upstream of culvert. May indicate that the culvert size is inadequate.
Suppressed culvert inlet	Culvert inlet invert below upstream channel invert.	Culvert should be examined to determine whether the channel has aggraded within the culvert or whether the culvert was intentionally constructed with its inlet invert below the upstream invert of the channel.
Debris on culvert inlet	Debris and upstream sediment deposits	Culvert is incapable of transporting the supplied debris load. If the debris blockage is chronic, then the upstream channel may have responded by aggrading and migrating laterally because of persistent backwater effects. Debris blockage may also affect roadway overtopping frequency, which may cause embankment damage.
Skew of channel to culvert inlet	Bank erosion, scour holes at the inlet, and misalignment of the channel and culvert	Culvert inlets misaligned with the flow may cause bank erosion, scour hole formation around wing walls, and reduced flow conveyance. Reduced conveyance may lead to sediment deposition upstream, upstream flooding, and increased frequency of roadway overtopping.
Downstream bank erosion	Erosion of bends downstream of culvert outlet	High velocity flow exiting the culvert can cause severe bank erosion in downstream bends.
Outlet scour pool	Scour hole with riffle downstream composed of ejected sediment	High velocity flow exiting the culvert can form a large scour hole downstream that may undermine the culvert outlet.
Perched outlet	Step in the low-flow water surface profile at the culvert outlet	The culvert outlet is considered "perched" if the outlet invert is elevated with respect to the low-flow channel water surface immediately downstream. Perched outlet conditions are a result of (1) downstream channel degradation that has migrated upstream to the culvert outlet and/or (2) high outlet-velocity flow that has caused outlet scour of a steeply sloping downstream channel. Often, channel degradation and high outlet-velocity flow combine to cause large scour holes and perched outlets. Degradation initiated by channel disturbances downstream of the culvert will be indicated by degradation of the channel well beyond the limits of the culvert outlet scour pool. On the other hand, scour caused solely by high outlet-velocity flow discharging from the culvert outlet tends to be limited to the extent of the scour hole and the deposited material eroded from it. On steep streams, long scour holes at outlets can effectively reduce the slope of the downstream channel, resulting in a perched outlet Fish passage may be impeded by a perched culvert outlet.
Suppressed culvert outlet	Culvert outlet invert below downstream channel invert.	Culvert may have been constructed with its outlet below the downstream invert of the channel. Culvert should be examined to determine whether the channel has aggraded within the culvert or whether the culvert invert was intentionally placed below the upstream streambed elevation. (*continued*)

Table 14-3c Observations at Culverts (*Cont'd*)

Features	General Observations	Indications and Considerations
Sediment deposit downstream of outlet pool	Aggradation downstream and deep pool within culvert	Channel aggradation in the channel downstream of the culvert may cause backwater into the culvert that can reduce its capacity to convey flood flow.
Wide and/or multiple-barrel/ cell culvert	Sediment deposition in one or all culvert barrels or cells	Channel may have been widened locally to transition into a wide box or multiple-cell/barrel culvert. Expanding the channel width may have resulted in deposition in several barrels/cells, reducing the design capacity of the culvert.
Modification to culvert to facilitate fish passage	Fish ladders, baffles, lowered inverts, low flow weirs, and other culvert modifications; constructed riffles, grade control structures, and other channel modifications	Various structures have been used to facilitate fish passage in culverts. Structures and channel modifications may have been constructed to reduce or eliminate the perched condition at the culvert outlet and to increase the low-flow channel depth in the culvert.

Under the Structure

- Photo-document conditions under or within the structure: Obtain at least one photo from the upstream end of the structure looking downstream and a second photo from the downstream end of the structure looking upstream. Multiple photos should be obtained from multiple-span structures.
- Photo-document any evidence of deposition under the structure, including channel bars, bars in the wake of piers and abutments, and sediment accumulation in culvert cells or pipes. Use a pocket rod for scale to indicate the depth of the deposit. Determine the cause of the sediment deposits.
- Photo-document any scour holes at the entrance, beneath the structure, and at the flow expansion area downstream. Use a pocket rod or stadia rod to determine the depth of scour. Determine the cause of each scour hole.
- Photo-document evidence of channel degradation at the existing crossing structure. Compare the position of the streambed or channel banks with the vertical position of the foundation footing. Look for and document soil stain lines, underpinning of the foundations, or repairs to the foundations under the structure.

Downstream of the Structure

- Photo-document the alignment of the downstream channel with the structure: Looking upstream from downstream of the structure, obtain at least one photo that shows the channel alignment with the structure.
- Photo-document the transition from the structure to the downstream channel and floodplain. Extend a pocket rod up from the low-flow water surface in the channel at the centerline of the culvert or channel. Photo-document the difference in elevation between the water surface and the exit invert of a culvert or channel bed protection for a bridge.

- Photo-document the maximum depth and downstream extent of downstream scour pools. Use a pocket rod for scale. Examine bed material that may have been ejected from scour pools. Determine if the material ejected is bedrock, cobble or placed riprap. Photo-document this material; include a ruler or pocket rod for scale.
- Examine and photo-document confluences immediately downstream of the structure. Evaluate the effect of the confluencing stream on backwater to the structure. Evaluate the effect of the structure on the confluencing stream.

Other Photos

- Photo-document all scour holes near the structure, including those that may occur on the valley flat away from the channel. Use a pocket rod to document their depth. Determine the cause of the scour. If possible, determine the general characteristics of the material that is in the base of the scour hole (e.g., bedrock, riprap, cobble, gravel). If a coarse sediment deposit has formed downstream of the scour hole, photo-document the material with attention the coarsest size fractions. Photo-document pieces of bedrock that may have been ejected from the scour hole.
- Photo-document riprap or other countermeasures (e.g., underpinned wing walls and other foundations, grout bags, channel paving, etc.) using a pocket rod to indicate scale. If possible, determine whether the riprap was an integral part of the crossing design or part of a patch repair of a previously erosion-damaged embankment or undermined foundation. Photo-document all indications of failure of the countermeasures.
- Examine and photo-document bars, sediment-blocked openings, and any other sediment deposits at existing crossings. Determine the apparent cause of bar formation and sedimentation (e.g., reduction in channel flood conveyance, lateral migration, bank erosion, or flow direction skewed to the structure or embankments). Use a pocket rod in these photographs.
- Photo-document all channel or floodplain obstructions near the structure that may cause backwater effects or alter the magnitude, direction, and distribution of flow, scour, or sediment deposition. Evaluate the potential for these obstructions to affect flood flow backwater, scour, bar formation, channel lateral movement, aggradation, and degradation.
- Examine the alignment of the structure to flood flows. Photo-document any indication that the structure is misaligned with flood flows.
- Photo-document all utility crossings and utility crossing protection near the structure. Include exposure of casings or pipes and steps in the water surface that may occur over the structure.
- Examine and photo-document all exposures of bedrock at the crossing in the channel bed, including pools, and in the channel banks. Attempt to break samples from the bed. Obtain a close-up photo of the broken bedrock for later identification; include a pocket rod or ruler to indicate scale. Examine and photo-document any fragments of bedrock that may have been scoured from deep pools.
- Examine and photo-document any instability in tributaries that parallel the embankments. Photo-document any scour, erosion, or repair of the embankments.
- Evaluate and photo-document any adverse environmental effects of the crossing on the channel.

Channel Classification at the Crossing

Classify the channel (Rosgen 1996) based on the depth of bankfull flow estimated from the regional curve data (Table 14-1) and a visual estimation of the floodprone width. The curves usually predict larger bankfull depths and widths than have been observed in OBD studies; therefore, field-based classifications may differ from those obtained using regional curve data. If consistent bankfull indicators are present, indicate the difference between the observed depth and that estimated from the regional curve. Use the field-based estimate of bankfull depth to classify the channel.

Base Level Points

Base level points are those points along the stream channel that represent elevations below which the channel is unlikely to degrade during the life of the crossing. In the base level reach and the project reach, identification of features that may represent base level points is critical for evaluating long-term degradation. Those points prevent channel degradation from migrating upstream to the crossing. In the supply reach, base level points are important in evaluating sediment dynamics. The thicknesses of the strata that lie above the base level points indicate the amount of coarse material that may be supplied to the channel and crossing from the bed and banks of the upstream reach. Table 14-4 describes in-channel features that commonly function as base level points. In all preliminary studies, every base level point in the three assessment reaches should be documented according to the following procedures.

- Examine and photo-document all features listed in Table 14-4. Look for these features near the valley wall and near the center of the valley; the features should represent several different locations across the valley. In many valleys, base level points near the center of the valley have lower elevations than those near valley walls. These variations should be considered when estimating long-term degradation. Some sections of channel that have been relocated to the base of valley walls, for example, are often perched on strata that are elevated compared to the strata in the center of the valley. Examination of stream reaches immediately upstream or downstream from the perched reach may reveal lower elevation features that would more accurately indicate the maximum potential degradation of the channel bed.
- Document and photograph the exposure of bedrock in all pools where it is observed. In the bed profile, pools represent local minima, where bedrock is frequently exposed. Because bedrock can be a limiting factor for channel degradation, its location and variation should be assessed wherever possible. Variation in pool depths can indicate the variation in bedrock surface elevation across the valley. Generally, the surface elevation of bedrock increases near the valley walls and pool depths frequently are substantially shallower along the valley walls as a result. In the most extreme cases, a bedrock riffle or run located along a valley wall may provide backwater for a deep pool upstream located closer to the center of the valley, indicating that the bedrock elevation upstream is lower than downstream. The variation in elevation, however, is probably caused by cross-valley variation in bedrock elevation rather than up-valley variation.
- Evaluate the permanence of each feature. Permanence should be considered to be relative to the service life of the crossing structure for which the morphology study is being conducted. Features that may degrade or be removed during the life of the crossing structure should not be considered to represent base level points.
- Remove and photograph fragments of bedrock that is weakly cemented, weathered, or fractured. Break the fragments of the rock and photograph the fractured area for documentation and future identification.

Table 14-4 In-Channel Features That Function as Base Level Points

Type	Control Feature	Permanence*	Comment
Exposed durable bedrock	Bed	High	Bedrock in streams along the fall-line is often very durable, whereas some seemingly durable rock in the Ridge and Valley region is often fractured, weathers rapidly, and degrades.
Exposed bedrock of unknown durability	Bed	Low to moderate	Depends on the weathering and stress conditions.
Exposed bedrock near base of hillside in a wide valley	Bed	Low to moderate	May include loss of control if stream is prone to movement toward center of valley where bedrock may be deeper.
Culvert inlet invert	Bed	Low to high	Potential for culvert to be replaced with a bridge.
Boulder jam and or colluvial riffles	Bed	Low to high	Depends on several factors, including resistance of boulders to weathering, potential for large flood events to destabilize boulders, or potential for the channel to move laterally around the large material.
Utility crossing protection	Bed	Low	Crossing may be abandoned and protection left to degrade.
Riprap-lined channel bed or bridge crossing	Bed	Low	Riprap may fail during large flood event.
Confluence with another stream	Bed and water surface	Low to moderate	Bed of main stem stream may degrade; water surface will fluctuate in the main stem stream and will affect the water surface boundary of the tributary. The stability of the main stem channel and its proximity to a reliable base level point must be considered.
Reservoir/outlet structure/spillway	Bed and water surface	Moderate to high	Potential for dam to be removed or spillway to be modified; operation of reservoir may involve fluctuation in reservoir levels for many purposes, including seasonal flood control. Dam may be removed and reservoir drained; therefore, the age and condition of facility should be considered.
Tidal waters	Bed and water surface	Moderate to high	Sea level expected to increase, causing aggradation conditions. Dredging of tidal area may cause a reduction in base level.
Depth of pre-settlement gravel bed	Input of gravel from the bed and banks	Moderate	Exposure of gravels in the bed and bank frequently causes rapid channel widening, increases in channel sinuosity, and decreases in channel slope. It can substantially change the supply and characteristics of bed materials downstream. Exposure of gravel in banks tends to increase bank failure and erosion rates and increases the tendency for channel widening and lateral migration. If the channel planform is confined by embankment fills or protected utility lines that limit planform evolution, the channel is likely to continue degrading through gravels to underlying bedrock.

* Permanence is evaluated in relation to the typical lifespan (~80 years) of Maryland crossing structures. High = more than 80 years; Moderate = 20 to 80 years; Low = less than 20 years.

Low-Flow High-Gradient Features

Under low-flow conditions, the water surface tends to be nearly flat over some regions of the channel (e.g., pools and low-gradient runs) and relatively steep in others. Those bed forms, bed protection, or structures over which water surface elevation changes substantially under low-flow conditions are termed *low-flow high-gradient features* in this manual. At this time, the OBD considers a substantial change to be about 0.3 ft or greater for streams with an average slope between 0.2% and 1.5%; for streams with an average slope greater than 1.5%, significant changes will be those exceeding about 0.2 ft per 1% of slope.

The water surface changes associated with low-flow high-gradient features and the permanence of those features may indicate the location and magnitude of currently active degradation or the potential for future long-term degradation: the cumulative change in water surface elevation over those features is approximately equivalent to the elevation change of the channel bed along a given section of channel. Common low-flow high-gradient features made of either natural materials or introduced materials and structures are described in Tables 14-5a and 14-5b, respectively. Note that some of the base level points may also be low-flow high-gradient features.

In all preliminary studies, every low-flow high-gradient feature should be photo-documented according to the following procedures. Particular attention should be given to determining which features (a) constitute the highest percentage of the total change in grade of the channel, (b) are likely to contribute to long-term degradation by being eroded or modified during the life of the crossing structure, and/or (c) are likely to control or limit bed degradation by remaining in place during the life of the crossing structure.

- Identify and photo-document all low-flow high-gradient features. A pocket rod should be included in the photos to show scale.
- For each low-flow high-gradient feature, determine the following:
    - ¤ Does the feature appear to be actively migrating upstream?
    - ¤ Which of the currently stationary features may be eroded during a large flood or may be modified (e.g., utility crossing protection), causing future degradation to be initiated downstream of the proposed crossing?
    - ¤ Which features may act as bed controls, limiting upstream migration of bed degradation?

Stream Banks

Bank morphology may indicate degree of channel incision, elevation of base level points, current and potential future locations of bank erosion and mass failure, and potential for changes in sediment supply from the bed and bank. Table 14-6 describes bank morphological indicators of channel instability.

- Photo-document the banks (include a pocket rod for scale) at several locations along the channel to indicate both consistency and variation in bank height.
- Photo-document the bank materials and strata and their variation at locations where the bank has recently been eroded. Look for indications of how these materials affect the erodibility and mass stability of the bank. Document areas where banks may be eroding rapidly, and assess the relative susceptibility of their strata to erosion.
- In the project and supply reaches, photo-document the banks and strata that indicate a high existing or potential future supply of coarse sediment (sand and gravel) that may affect bar formation and channel migration near the crossing. Place a ruler in the photo to indicate the size of gravel, if it is present.

Table 14-5a Low-Flow High-Gradient Features and Channel Bed Stability Indicators Composed of Natural Materials

Feature	General Observations	Indications and Considerations
Riffle	Shallow low flow over sloping section of streambed	May be an indicator of bed stability. Riffle material substantially coarser than other areas of the channel without a local input of coarse material may indicate channel armoring and a tendency for channel degradation. Riffles that have the same gradation as bars may indicate an aggrading condition.
Riffle/bars	Low flow over diagonal bars/riffles, no distinction in sediment size between riffles and bars	May indicate channels with high gravel load and/or depositional environment.
Bedrock riffles or steps	Exposure of bedrock in riffles	May be an indication that the stream has degraded. Highly resistant steps may be natural along the Piedmont fall line. Rock that is weathered, highly susceptible to weathering, thinly bedded, or severely fractured may indicate past and current rapid degradation. Bedrock exposure does not necessarily guarantee bed stability. Note that bedrock may be exposed where the stream is near a valley hillside and the top of the bedrock may be substantially lower in the center of the valley.
Boulder steps	Accumulation of broken bedrock from the streambed or colluvial deposit	May indicate a long-term grade control if boulders are resistant to weathering. Boulder steps that have been in place for a long time are typically rounded from many years of abrasion. Sharp edges and accumulations of degraded rock downstream may indicate breakdown of boulders or the upstream migration of a headcut temporarily stalled at coarse material.
Large woody debris steps	Woody debris fallen into the channel and retaining sediment	Typically indicates bank failure that may be a result of channel incision (trees falling from both banks in the same section) or channel lateral migration (trees falling from outside of bends). Eventually, wood in the channel will decompose. Consider whether the re-supply rate of large woody debris will be sufficient to replace decomposing debris forming the grade control.
Headcuts in sediment	A step or steep area in the streambed typically formed in sediment with a low resistance to erosion	Indicates degradation of the channel bed as headcut migrates upstream.
Headcut in cohesive bed material	Cohesive bed material exposed in patches in a riffle	May indicate channel is perched on milldam, backwater, or floodplain materials and is incising. All riffles with exposed clay patches or steps should be noted as low-flow high-gradient features even if the water surface elevation change over the feature is less than what is considered to be substantial.
Headcut in cohesive bed material overlying gravel	A step or steep area in the streambed formed in clay or silty clay and exposing underlying gravel	May indicate channel is perched on milldam, backwater, or floodplain materials and is incising into low-level gravels. Exposure of underlying gravel can substantially change the supply and characteristics of bed materials downstream. Exposure of gravel in banks tends to increase bank failure and erosion rates and increases the tendency for channel widening and lateral migration.

Table 14-5b Low-Flow High-Gradient Features and Channel Bed Stability Indicators Composed of Introduced Materials

Feature	General Observations	Indications and Considerations
Riprap protection	A steep drop in water surface elevation over a rock-protected section of stream channel	Degradation has occurred downstream and riprap is temporarily holding the grade.
Culvert outlet and/or outlet protection	Culvert "perched" above downstream channel bed and water surface	Channel degradation has lowered the bed level of the downstream channel and worked up to the culvert outlet; the outflow from the culvert has eroded the streambed downstream and flattened the local slope (mostly a problem on channel sections having slopes greater than 1%).
Utility line casing, crossing protection, or pipe	Steep drop in water surface over utility crossing	Channel degradation has lowered the bed level of the downstream channel and migrated up to the utility crossing.

Table 14-6 Bank Morphological Indictors of Channel Instability

General Observations	Indications and Considerations
Bank height (from valley flat) exceeds bankfull depth	Channel has incised with respect to the valley flat. The degree of incision should be estimated as the ratio of bank height to bankfull depth. Bank heights should be estimated at or near riffle crests and should represent the distance from the bank toe to the adjacent valley flat. Precise measurements are unnecessary in the visual assessment; a simple visual estimate or photograph with a pocket rod for scale at a few locations can be used for estimating the ratio of bank height to bankfull depth. (Note that the bankfull level may be much lower than that predicted by the regional curve.) The degree of incision should be estimated as ▪ *Slightly incised* if the incision ratio is less than 1.5 ▪ *Incised* if the incision ratio is between 1.5 and 2.5 ▪ *Highly incised* if the incision ratio is greater than 2.5
Bank height increases in the downstream direction	Although bank height may naturally increase in the downstream direction where flow changes at confluences, rapid changes in bank height often correspond to locations where bed degradation is migrating upstream. Where headcuts are not present, the variation in bank height may indicate the bed degradation is occurring along a steep section of channel that may not be apparent otherwise.
Bank mass failures and bank-line trees undermined and/or collapsing into channel on both banks	Channel is widening. Widening can occur as channels incise and bank heights increase. Exposure and rapid erosion of basal gravels in stream banks frequently leads to mass failure of overlying fine-grained bank materials and bank-line trees. Widening can also occur because the channel is aggrading with coarse-grained material.
Bank mass failures and bank-line trees undermined and/or collapsing into channel on one bank	Channel is migrating laterally. Many factors contribute to lateral migration of the channel. Three common causes are low radius of curvature of a channel bend, formation of coarse sediment deposit on one side of a channel or inside of a bend, and deflection of flow from debris blockages. *(continued)*

Table 14-6 Bank Morphological Indictors of Channel Instability (*Cont'd*)

General Observations	Indications and Considerations
Riprap failed	Riprap has moved because of bank slumping, erosion of the toe material, or vertical degradation of the channel. The failed riprap should be examined to determine the cause of failure.
Exposure of a lower level bank layer with different characteristics	Rapid exposure of a layer of cobble, gravel, or organically rich layer in a reach of streambed may indicate that the channel reach has degraded.
Thick horizontal bed of laminated fine-grained sediments	Bank composed of sediments deposited in a backwater condition. Thick beds of laminated (thinly layered) sediments may indicate a pond or lake deposit that often formed upstream of milldams or other small dams constructed after European settlement. These sediments, often termed *post-settlement alluvium* or *legacy sediments*, typically lack substantial organic materials such as leaf packs, small branches, and logs. However, cut or hewn logs, fence posts, and other colonial artifacts may be present in this layer. Banks composed entirely of fine-grained material indicate that the pre-settlement floodplain and gravels are buried and that the channel may incise to the underlying pre-settlement bed level.
Gray or black organically rich layer of sediment	This layer often represents the floodplain materials prior to European settlement. In the Mid-Atlantic region, the layer is commonly overlain by a thick layer of post-settlement alluvium and underlain by a gravel and cobble layer.
Gravel, cobble, and boulder layer	This layer typically overlays bedrock in all regions except the Coastal Plain. Exposure of this layer beneath steep and high banks composed of finer-grained material often causes rapid mass failure of channel banks and a shift from degradation to rapid channel widening and/or channel lateral migration. Release of gravels from this layer may increase the tendency for bars to form.
Highly mixed materials without layering	Near hillsides, the bank may be composed of colluvium (mixed material from landslides, creep, and other forms of hillside mass movement). The material may also be a fill such as that surrounding an underground utility line. Exposure of the material may cause rapid lateral migration and potentially the exposure of the underground utility line.
Saprolite	Exposure of saprolite (highly weathered bedrock) often indicates that the channel has incised to a level below the pre-settlement bed level or has migrated laterally into a hillside. Exposure of saprolite in one bank indicates that the channel may have been relocated and is eroding the hillside. Near the hillside, saprolite may be exposed in the channel bed. The channel is likely to migrate toward the center of the valley.
Bedrock, fractured bedrock	Bedrock exposed along hillsides may indicate that the channel has been relocated to the edge of the valley. If, however, the channel is located away from the valley hillsides and bedrock is on both banks (and, potentially, the channel bed), then the channel has incised into the bedrock. Fractures in the bedrock, thin bedding planes of the bedrock, and/or shale may indicate that the bedrock is degrading rapidly. A deposit of sharp-edged or platy boulders may likewise indicate that the bedrock is degrading rapidly. The stream is likely to migrate laterally away from the bedrock hillside toward the center of the valley.

- Develop a general impression of the effectiveness of bank-line vegetation in protecting the banks. Photograph banks that indicate that the channel has incised to the point where roots are no longer capable of preventing bank collapse. Photograph banks in locations where the bank height changes rapidly, indicating a sudden change in bed elevation or a change in floodplain topography. Look for indications of upstream migration of channel degradation that may cause a large number of trees to be supplied to the channel.
- Look for and document organic-rich strata that overlay gravel strata. Where these layers represent the interface between pre- and post-settlement alluvium, the gravel layer will be a potential base level point.
- Document locations where the most severe bank erosion is occurring, and attempt to determine why the erosion is occurring at those specific locations: high flow intensity, exposure of strata susceptible to erosion or mass failure, or a combination of factors.

Pools

Pools generally provide the greatest vertical exposure of bank strata and materials. The characteristics of materials in bed strata and bank strata and the variation of these materials from pool to pool are indicators of current trends and potential future changes in channel lateral and vertical stability. Indicators of channel instability provided in Table 14-6 apply equally to the banks of pools. Table 14-7 provides indicators and considerations specific to pools. In all preliminary studies, pools should be documented according to the following procedures.

- Remove samples of material from bank strata below the water surface. If bank strata are obscured, examine them by touch and remove samples by hand. Determine whether the samples represent layers that may limit or enhance channel degradation. Whenever practical, material from the banks of the deepest pools should be obtained for identification and documentation.
- Document the depth of the organic layer and gravel layer in the pools. Photograph the material removed from the bank. Pools are the most likely location to identify and document the interface between pre-settlement and post-settlement alluvium, usually represented by a layer of organic-rich soil, which often contains a leaf pack, seeds, branches, and logs, overlying a layer of gravel. These strata may be submersed below the water surface of the pool.
- In each pool, extend a pocket rod up from the deepest point. Photo-document the pool, including the bed material and the portion of the pocket rod protruding above the water surface.
- Downstream of the deepest pools, examine and photograph sediment deposits, especially heavily armored riffles. Photograph and document bedrock fragments, clumps of cohesive material, or large gravel or cobble that can be identified as material ejected from these scour holes. Examine the condition of the ejected fragments for signs of weathering. Fragments of bedrock, pieces of cobble and large gravel, and clumps of cohesive soil are typically present in sediment deposits downstream of deeply scoured pools. These large particles are eroded from alluvial or rock strata exposed during a flood.

Table 14-7 Pools and Channel Bed Stability Indicators and Considerations

Feature	General Observations	Indications and Considerations
Bedrock exposed in deepest section of pool	Pool has scoured to bedrock	Bed materials overlying bedrock were ejected from the pool and should be visible downstream. Bedrock surface elevation may represent a limit for degradation if rock is resistant to weathering and is not heavily fractured. Pieces of fractured bedrock down-stream of the scour hole or scour into the rock within the pool may indicate that the rock is susceptible to erosion or weathering.
Cobble- and boulder-armored riffles downstream of pools	Cobbles and boulders ejected from pools may form armored riffles downstream	These large bed materials may indicate the presence of a layer of cobble and boulder beneath the entire streambed that may inhibit bed degradation. In the case of exposed bedrock, the ejection of bedrock pieces may indicate fractured or weathered bedrock that is highly susceptible to erosion if exposed.
Cohesive strata in pool bed	Bed scoured into con-solidated silt/clay	Stream is perched on floodplain sediment or dam deposit. Poten-tial exists for channel to incise through silt/clay to underlying gravels.
Pool depth variation along profile	Pool depth increasing upstream	May indicate the migration of an upstream wave of degradation or a downstream wave of aggradation. Examination of the bed material gradation characteristics in bars and riffles should be made to determine whether the bed elevation change is due to aggradation or degradation.
Expanding point bar in pool with eroding outer bend; bar sediments composed of high and loose gravel or sand	Sediment is accumulat-ing on point bar	May indicate an aggrading channel condition. The size of bed material in riffles should be compared to those on the bar. If they are similar in size, then aggradation is likely.
Loose gravel in pools	Pools are filling with gravel	Flow intensity in the pool is insufficient to transport the size or the load of sediment being supplied from upstream.

Bars, Riffles, and Surface Particle-Size Characteristics

Bars are a clear indication of in-channel sediment storage and may indicate a tendency for channel aggradation; however, bars may also form in channels that are degrading. The frequency of bars along the channel, the extent of the bars across the channel, and the height of bars with respect to the bankfull elevation indicate the volume of sediment storage in the channel. A lack of channel bars generally indicates that the channel is capable of transporting all of the supplied bedload sediment.

Where armored riffles control the grade of the channel, mobilization of the riffles may result in channel instability. Comparison of the riffle surface size distribution to the characteristics of the supplied bed load can indicate the frequency of riffle armor layer mobilization. In channels that are transporting a high sediment load and are aggrading, the gravel size distribution of the riffles tends to be only slightly coarser than that found on the surface of bars. Conversely, in channels that are heavily armored and transporting the supplied load and in channels that are de-grading, the surface size distribution of the riffle tends to be substantially coarser than that of the surface of bars.

Bar and riffle material indicators for channel stability are given in Table 14-8.

Table 14-8 Bar and Riffle Indicators for Channel Stability

Natural Materials	General Observations	Indications and Considerations
Riffle	Algae-coated cobbles and boulders with clean gravel	Stable riffle under recent flow conditions capable of transporting gravel load.
Riffle or bar	Large angular material	Local source of material, fractured bedrock, or rip-rap.
Bar	Decrease in sediment size in the downstream direction (downstream fining)	Backwater or reduction in channel slope.
Bar	Point bars extend into diagonal bars	High sediment load and/or rapid channel deposition and storage typical of aggrading channels.
Riffle and bar	Gradation characteristics of riffle similar to bar	Unstable riffles; high sediment load or aggrading channel.
Riffle and bar	Riffle material substantially larger than bar material	Stable riffles or degrading channel.

Frequency, Extent, and Height of Bars

- Photo-document channel bars at sufficient intervals along the channel to show observed consistency, trends or anomalies in their characteristics. If bars are frequent and extensive, the continuous channel photos may be sufficient to document most of the bars. Include photos showing the orientation of the bars to channel bends or other channel features that influence their geometry and position in the channel. Document the height and extent of the bars with respect to the top of the banks and bankfull flow indicators. Include a pocket rod in some photographs to indicate scale.
- Determine the extent of bars, and determine whether they indicate local or extensive storage of sediment. Where possible, sources of sediment contributing to bar formation should be identified. Local as well as watershed-wide sources should be considered. Document the source of channel bar material if the bar is located within close proximity to the sediment source.
- Determine the apparent cause of bar formation in the project reach, and identify associated existing or potential future problems (e.g., reduction in channel flood conveyance, lateral migration, bank erosion, or skewed flow direction to structure or embankments).
- Determine whether bars in the supply reach indicate that a large wave of sediment may migrate into the project reach and cause a future sedimentation deposition problem at the crossing.

Bar and Riffle Surface Material

- Photo-document riffle surface material particle sizes in the upper third of riffles near the center of the bankfull flow channel. If possible, the materials should be in a part of bed that is not submersed. If a representative un-submersed area cannot be located, then scoop a sample of the surface layer from the submersed riffle and photograph the coarsest particles in the sample. Obtain the photos at sufficient intervals along the channel to show observed consistency, trends, or anomalies in their size distributions. Include a ruler in the photographs for scale.

- Photo-document bar surface material particle sizes at sufficient increments along the channel to show consistency, trends, and anomalies in their size distributions. Photograph the surface material in the downstream third of the bars at a point in the bar where the bar surface level is approximately half the bankfull depth. Include a ruler in the photographs for scale.
- Compare the sediment size of the riffle armor layer to the size of the bar material at several locations along the channel. Determine whether this comparison indicates infrequent or frequent mobilization of the riffle surface.
- Examine the variation of riffle material size along the channel. Determine whether the riffle armor layer size decreases along the channel, indicating a trend of downstream fining.
- Examine the variation of bar material size along the channel. Determine whether the bar material size decreases along the channel, indicating a trend of downstream fining.

Debris

Debris can affect the crossing in two ways: it forms jams at the crossing that may increase scour, flooding, and lateral forces on the structure; and it may instigate changes in channel morphology, including lateral and vertical movement of the channel. Therefore, debris assessment should focus on (1) the potential supply of debris to the crossing and the potential accumulation of debris on the existing or proposed crossing structure and (2) the existing and potential effects of debris on channel morphology. The supply of debris to the crossing is dependent not only on the supply from the watershed and from the channel banks and floodplain immediately upstream of the crossing but also on the capacity of the channel to transport debris. Evaluation of the supply of debris should include consideration of the length and number of trees or limbs that could be transported to the crossing.

In the base level reach

- Photo-document bank-line trees that have fallen or may fall into the channel and cause debris jams. Evaluate the potential for future debris jam formation in the base level reach that may influence backwater flooding and aggradation at the channel crossing upstream.

In the project reach

- Photo-document accumulation of debris on the existing structure or at the location of the proposed structure. Evaluate the cause and the potential for future jam formation at the crossing.
- Photo-document trees in close proximity to the existing or proposed crossing that have fallen or may fall into the channel. Evaluate the potential for the trees to fall and cause jams that may result in channel widening, migration, or avulsion in the project reach.

In the project reach and the supply reach

- Photo-document and measure the length of the largest pieces of woody debris that appear to have been transported beyond the location where they were introduced. Photo-document the width of the channel at the same locations. Determine the length of the largest piece of woody debris that appears to be transported by the channel.

- Photo-document and measure the length of large trees that have fallen into the channel and may be prevented from being conveyed downstream by flow. Evaluate the current and potential future supply and transport of woody debris to the project reach from the supply reach. Consider the current bank conditions and effect of potential upstream migration and/or degradation of the channel on the source and supply of channel debris.

See Chapter 10, Appendix C of this manual for additional guidance on the evaluation of potential supply and transport of debris to the crossing.

Channel Confluences and Tributaries

Confluences are typically locations of rapid channel change because they have been common locations for historic channel modifications and because the main channel downstream of the confluence is responding to flows, sediment loads, and debris from two watersheds. Streams that confluence with the project stream may supply sediment loads that overwhelm the channel and/or woody debris that causes jams. The supply of sediment and debris may affect both the lateral and vertical stability of the confluence and the project stream.

Tributaries may also be indicators of degradation or aggradation of the main channel. Main channel degradation causes tributaries to degrade. The degradation in the tributary tends to migrate more slowly than in the main channel, however, because the tributary's contributing drainage area is smaller and the flows required to cause headcut migration may be less frequent. Therefore, tributaries with headcuts within a few hundred feet of the main channel are a typical sign of past degradation in the main channel. On the other hand, tributaries that are submerged in backwater and show signs of aggradation near the confluence are signs that the main channel may have aggraded.

Confluences of the project stream with similarly-sized or larger channels downstream of the crossing can influence the capacity of the crossing to convey flood flows and can influence the morphology of the project stream at the crossing. Backwater from the confluence may extend upstream into the project reach, reducing flood flow capacity at the crossing. The backwater may also reduce sediment transport capacity in the crossing, causing aggradation and further reducing flood flow capacity. Lateral movement of the confluence that results in a significant change in the length of the project stream may cause a wave of degradation or aggradation to migrate upstream to the crossing. Similarly, bed degradation or aggradation at the confluence will likely cause a similar response in the bed elevation of the project channel. The bed elevation change in the project channel may, over time, migrate upstream or downstream of the confluence. Therefore, an examination of the potential for channel bed changes downstream of the confluence must be included in the assessment unless two conditions are met: a bed grade control can be located between the confluence and the crossing; and the backwater effect of the confluence does not extend to the crossing.

In all preliminary studies, confluences and tributaries should be documented according to the following procedures.

Confluence with Tributary Channel

- Examine the bed and banks of tributaries within at least 100 ft of all major confluences with the project stream or those that indicate a high sediment or debris load at the confluence. Photo-document evidence of headcuts or backwater conditions.

Evaluate how the tributaries may be responding (i.e., aggrading or degrading) to changes in the project stream.

- For all tributaries that confluence with the project stream, examine the project channel for evidence that any of the tributaries are producing a high sediment load that is forming a fan or bar at or downstream of the confluence. Photo-document the depositional features and the sediment. Use a pocket rod for scale in the deposits and a ruler for scale in the photographs of the sediment.
- At confluences where an alluvial fan is identified, examine the banks of the project channel in the region of the confluence to determine whether the project channel is migrating into the fan. The channel banks along a fan may contain coarse materials that, when eroded, could supply a sufficient quantity of gravel to affect downstream channel stability.
- Examine the project stream for changes in channel width, bank heights, and bed sediment gradation characteristics, upstream and downstream of all confluences. Photo-document changes and confluence. Evaluate the cause of changes in these parameters.
- Examine bars and debris in tributaries that confluence within the project and supply reaches. Photo-document the sediment (include ruler) in bars and debris in the tributary channel. Evaluate the supply of sediment and debris from the tributaries.
- Photo-document unvegetated cut banks of degrading or laterally migrating tributaries that confluence within the project and supply reaches. Evaluate the potential for a large amount of gravel or debris to be supplied by the tributary if the tributary were to continue to degrade or move laterally.
- Examine the confluences for signs of recent changes in their locations and any potential channel responses related to the change for confluences within the project and supply reaches. Photo-document evidence of changes in the locations of the confluences.
- Examine the project channel and tributary planforms near confluences within the project and supply reaches to determine the potential for either to migrate or avulse, resulting in a sudden change in the location of the confluence. Photo-document this condition and evaluate the potential consequences of the change such as a shortening of tributary channel length, a change in base level elevation for the tributary, or a change in the orientation of the main channel to the crossing structure.

Downstream Confluences with Similarly-Sized or Larger Channels

- Examine the similarly-sized or larger stream in the vicinity of its confluence with the project stream. Determine whether the base level reach should be extended to include the larger stream.
- Examine the confluence for signs of backwater effects. Photo-document evidence of the effects (e.g., changes in the valley slope, debris lines that increase in height in the downstream direction, bankfull depth indicators that increase in elevation in the downstream direction). Evaluate the potential for the confluence to cause backwater flooding of the crossing.
- Photo-document evidence of the potential for lateral movement of the confluence that may shorten or lengthen the downstream extent of the project channel. Evaluate the potential for lateral movement of the confluence to cause degradation or aggradation in the project channel.

- Photo-document evidence that the streambed at the confluence has degraded or aggraded. Backwater upstream of the confluence under low-flow conditions indicates aggradation at the confluence. Degradation in the project stream upstream of the confluence indicates degradation at the confluence. Determine the potential for future vertical movement of the channel bed at the confluence.

Other Structures and Flow Obstructions

Railroad bridges, abandoned roadway bridge abutments, floodplain fills, and other topographic features and channel obstructions can affect flow velocity magnitude, direction and distribution, sediment transport, and channel morphology at the crossing. Backwater from a downstream obstruction reduces flood conveyance, resulting in increases in flood elevation. Backwater also reduces flow velocities at the crossing. Reduced flow velocities may result in sedimentation in the form of bars that further decrease flood flow capacity or initiate lateral migration of the channel. Obstructions upstream of the crossing can cause a highly non-uniform flood flow distribution across the valley bottom and/or in the main channel. Non-uniform flood flow distribution results in high-velocity flow and/or very low-velocity flow. High-velocity flow may intensify scour in one section of the crossing, while very low-velocity flow may result in deposition in another part of the crossing. The scour holes and bars created by floods can then have a significant effect on both lateral movement and vertical stability of the project channel.

In all preliminary studies, structures and other flow obstructions that may affect the proposed structure should be documented according to the following procedures.

- Examine and photo-document bars, sediment-blocked openings, and scour holes at all structure. Use a pocket rod in these photographs. Identify the cause of deposition or scour, including any upstream or downstream obstructions.
- Examine the valley bottom and channel to identify all flood flow obstructions that may cause backwater (base level and project reaches) or change the flow distribution (project and supply reaches) at the each structure. Photo-document the obstructions.
- Evaluate the potential for these obstructions to affect flood flow backwater, scour, bar formation, channel lateral movement, aggradation, and degradation at the proposed structure.

Terraces, the Active Floodplain, and Other Valley Bottom Features

The valley bottom should be examined during the visual assessment to determine whether (1) the channel is incised such that valley flat is functioning primarily as a terrace rather than as an active floodplain, (2) fills such as embankments have confined the valley, (3) abandoned channels or newly forming floodplain swales indicate a potential for channel avulsion, and (4) the cross-valley gradient indicates a potential for long-term lateral movement of the channel. Each of these features should be documented in the project reach; in the other two assessment reaches, documentation should be sufficient to indicate trends, consistencies, and anomalies.

- Examine the valley flat adjacent to the channel and compare the bank heights along the valley flat. Photo-document evidence of whether the valley flat is an active floodplain or a terrace.
- Identify and photo-document fills that confine the valley, such as highway or railroad embankments. Identify and photo-document the morphological effects of the fills on the channel and floodplain. Evaluate the potential future effects of the confinement on the crossing.

- Identify and photo-document quarries and other historic features that may confine flood flows or provide a local source of sediment that is inconsistent with the sediment loads being supplied from upstream. Determine whether the feature may affect channel morphology at the crossing.
- Identify and photo-document abandoned channels, floodplain swales, and cross-valley gradients that may provide a path for channel avulsion or encourage channel lateral migration.

Channel-Valley Orientation and Channel Planform

Channel-valley orientation and channel planform and their past changes indicate the potential for future lateral movement of the channel. In general, channels are responding to historic and contemporary modifications (see Appendix 14-A) that include relocation of the channel within the valley and straightening of the channel planform. Channel responses to these modifications may include a general movement of the channel across the valley and an increase in channel sinuosity. Therefore, the assessment of potential lateral movement of the channel should include a determination of relevant past modifications to the channel, an evaluation of cross-valley movement and planform changes such as the development and migration of channel bends, and an evaluation of channel and valley features that may encourage future channel movement.

Evaluation of the potential for lateral channel movement requires both a review of available mapping and a field examination of existing channels and evidence of past channel locations. Evaluation of potential lateral movement should concentrate on the project reach and direct implications to the crossing. In the supply and base level reaches, however, identification of lateral movement and its causes should also be considered because lateral movement in the project reach may be similar to what is observed in the other reaches.

- Compare the channel’s orientation in the valley and its planform characteristics to the blue line representation of the channel on the USGS 7.5-minute quandrangles.
- Identify and photo-document channel segments in the field where the current channel location within the valley or the planform characteristics are different from those indicated by the blue line representation on the USGS topographic maps. These segments will typically show signs of active channel movement, such as bank erosion, sediment deposition in bars, or skewed alignments with crossing structures or embankments.
- Attempt to locate and photo-document field evidence of past channel positions that correspond to blue line representations.
- In a few of the locations where lateral movement has been identified, photo-document evidence that indicates whether the movement occurred as an avulsion or as migration.
- Evaluate the effect of lateral movement on the existing crossing structure and/or the potential for lateral movement to affect the design of a proposed crossing structure. This evaluation should include consideration of how channel features such as tree fall and debris, valley bottom features, and bars may affect channel lateral movement.

14.2.3 RAPID CHANNEL MEASUREMENTS

In some cases, rapid measurements of some channel features (Table 14-9) may be necessary to make a reliable determination about the necessity of a detailed study. Measurements may be

Table 14-9 Summary of Rapid Channel Measurements

Method	Location	Purpose
1. Pebble count	Riffle at representative cross section location	To determine bed sediment gradation
2. Bulk bar sample	Supply or project reach upstream of the crossing	To provide an estimate of the bedload characteristics for scour analysis
3. Soil and bed load materials for scour studies	Project reach	To provide data for scour analysis
4. Cumulative Degradation	Base level and project reaches	To develop an estimate of potential long-term degradation
5. Pool depths	All three assessment reaches	To develop an estimate of potential long-term degradation

taken at the discretion of the lead engineer, after obtaining the OBD's concurrence, for the purpose of collecting (1) data necessary for deciding whether a detailed study will be needed, or (2) sediment data for scour studies.

Pebble Count

At least one Wolman pebble count (Bunte and Abt 2001) should be conducted to characterize the gradation of the streambed. The pebble count should be conducted over the active channel bed of one armored riffle in the project reach and, wherever possible, should include at least 400 particles with diameters greater than 2 mm. In streams with small riffle surface areas and large sediment size, the number of pebbles measured may be fewer than 400 but should be at least 100. The sampling should be conducted using a grid spacing method (Bunte and Abt 2001). The size categories in Table 14-10 *must* be used to measure and record the size interval of each particle. Note that this table is slightly different than other similar tables.

Bulk Bar Sample

A bulk bar sample (Rosgen 2006) should be obtained in the project reach from a bar that represents the bed load. Determine whether large pieces of broken bedrock or cobble/boulders are from a nearby source or whether they are representative of the load upstream and downstream of that source. Obtain the bar sample from the downstream third of the selected bar at a level equal to half of the local bankfull depth. Where bars do not represent the bankfull sediment load or where they are not present, a bulk subsurface sediment sample of the riffle selected for the pebble count can be obtained and used as a surrogate. Sieve analysis of the bulk sample *must* be completed using the sieves specified in Table 14-11.

Soil and Bed Load Materials for Scour Studies

Information regarding surface soils and bedload characteristics may be needed for scour studies. Procedures for the collection and evaluation of these materials are described in Appendix B of this chapter.

Table 14-10 Riffle Pebble Count Data Sheet

Material Type	Texture	Size (mm)	Count (卌)
Bedrock	Consolidated	—	
Silt/clay	Consolidated	D ≤ 0.063	
	Unconsolidated	D ≤ 0.063	
Sand	Very fine to very coarse	0.063 < D ≤ 2	
Gravel	Very fine	2 < D ≤ 2.8	
		2.8 < D ≤ 4.0	
	Fine	4 < D ≤ 5.6	
		5.6 < D ≤ 8	
	Medium	8 < D ≤ 11.2	
		11.2 < D ≤ 16	
	Coarse	16 < D ≤ 22.4	
		22.4 < D ≤ 31.5	
	Very coarse	31.5 < D ≤ 45	
		45 < D ≤ 63	
Cobble	Small	63 < D ≤ 90	
		90 < D ≤ 128	
	Large	128 < D ≤ 180	
		180 < D ≤ 256	
Boulder	Small	256 < D ≤ 362	
		362 < D ≤ 512	
	Medium	512 < D ≤ 724	
		724 < D ≤ 1024	
	Large	1024 < D ≤ 1450	
		1450 < D ≤ 2048	
	Very large	2048 < D ≤ 2900	
		2900 < D ≤ 4096	

Table 14-11 Complete Sieve Series for Sediment Particle Size Analysis

Sieve ASTM No.	Sieve Size (in)	Sieve Size (mm)
230		0.063
120		0.125
60		0.25
35		0.5
18		1.0
10		2.0
7		2.8
5		4.0
3-1/2		5.6
	5/16	8.0
	7/16	11.2
	5/8	16.0
	7/8	22.4
	1-1/4	31.5
	1-3/4	45
	2-1/2	63
	3-1/2	90

Potential for Long-Term Degradation

The potential for long-term channel degradation can be evaluated by means of a combination of two rapid measurement techniques: the cumulative degradation method and the pool base level method. These techniques are designed to be less rigorous than those provided for the detailed study (Section 14.3.2): they are less time-intensive, and they do not require surveying equipment other than a hand level and stadia or pocket rod. As a result, the measurements they produce may be imprecise and should only be used to develop a gross estimate of potential long-term degradation.

The cumulative degradation method is most useful where a well-defined bed or water surface base level point can be located downstream of the crossing. This method identifies potential vertical change in the channel profile by measuring the changes in water surface elevation over low-flow high-gradient features. Degradation or modification of features is assumed to accumulate over the profile between the crossing location and an identified downstream bed or water surface control.

The pool base level method identifies potential degradation by measuring the depth to identified base level points in pools. Unlike the cumulative degradation method, the pool base level method does not require a bed level or water surface control; it relies mainly on the measurement and analysis of pool bank and bed strata and/or the existence of armor layers. Its reliability depends on the consistency of gravel, cobble, and boulder strata or of bedrock depth in pools. This method is particularly relevant to streams in which legacy sediment deposition has caused the entire valley to aggrade and the channel is now degrading through the fine-grained sediments.

Cumulative Degradation Method

From the nearest high-permanence base level point (see Table 14-4) that controls the channel bed or water surface downstream of the crossing to the crossing location, any water surface elevation change over a low-flow high-gradient feature of at least 0.2 ft should be measured with a hand level and a pocket rod. Each of the measurements should be photo-documented and recorded in the GPS receiver and/or the field notebook.

The photo-documented measurement data should be entered into a table or spreadsheet similar to that created to describe the continuous photo series. An example is shown in Table 14-12. The first, second, and third columns of the table are used to record photo numbers and GPS point numbers and coordinates. The fourth column is used to record the type of low-flow high-gradient features, beginning with the downstream-most feature. The downstream-most feature should be a base level point that controls the bed or water surface. In the fifth column, the measured change in the low-flow water surface elevation over each feature is recorded. In Table 14-12, the sixth column shows the expected degradation associated with each of the example features; those features that are expected to erode or fail over the life of the crossing structure will contribute to long-term degradation, and their associated water surface drops will be carried over to this column from the fifth column.

In the hypothetical scenario of Table 14-12, the durable rock outcrop provides a base level point that controls the bed and is not expected to degrade appreciably over the 80-year service life of the crossing structure. The utility crossings and the debris jam are expected to degrade

Table 14-12 Example* of Preliminary Data Collected and Summarized for Low-Flow High-Gradient Features

Photo No.	GPS Point No.	Latitude	Longitude	High-Gradient Feature	Estimated Water Surface Drop over Feature (ft)	Potential Local Long-Term Degradation (ft)
85	85	N39 23.122	W76 28.111	Durable rock step in center of valley	1.1	0.0
87	87	N39 23.129	W76 28.113	Utility protection	1.0	1.0
90	90	N39 23.141	W76 28.114	Riffle	0.7	0.0
93	93	N39 23.149	W76 28.120	Debris jam	0.8	0.8
97	97	N39 23.160	W76 28.125	Riffle	0.3	0.0
100	100	N39 23.169	W76 28.129	Utility protection	1.5	1.5
				Total		**3.3 ± 0.6**†

* Values provided in this table are for example only and should not be used as standard values.
† Estimated accuracy of hand-level measurements assumes an error of ±0.1 ft per measurement.

completely over the life of the structure. While degradation of approximately 1.0 ft and 0.8 ft are expected to propagate through the riffles, the assumption reflected in the table is that the slope of each riffle will remain approximately the same at this particular site. Thus, the potential long-term degradation at the crossing is estimated to be roughly 3.3 ft. If the riffles were also expected to degrade, then a total of about 4.3 ft could be used as a gross estimate of potential long-term channel degradation.

Pool Base-Level Method

The potential for long-term degradation at the crossing can also be evaluated by measuring the depth to base level points in pools. The pools' water surface levels under low-flow conditions are an estimate of the downstream riffle-crest elevation. The depth of each pool's base level feature measured from the pool's water surface is roughly equal to the potential degradation of the current riffle-crest elevation. Therefore, measurement of the depths of the low-flow water surface in pools to a base level point provides an estimate of potential channel degradation.

Base level points should be evaluated with respect to pool location along and across the valley. Pools along valley walls are likely to be shallow, limited by bedrock or colluvial material, and have banks that may contain colluvial material rather than alluvium. Pools not influenced by valley walls are likely to be deeper and will tend to have banks that contain consistent gravel and cobble strata. Therefore, estimates of long-term degradation should be developed from pools where minimal influence of valley walls is indicated.

Depth measurements of base level features should be made in several pools. Multiple base level points (Table 14-4) should be identified in each pool to provide a range of potential long-term degradation. Measurements should include the depth to the pool's deepest point and to bank strata that could be potential channel base level points, especially any resistant rock layers, the interface between rock and gravel, and the top of the gravel layer. Each of the measurements should be photo-documented. Table 14-13 shows an example of the data that should be collected for each pool that is used to develop the estimates of long-term degradation.

Three estimates of potential long-term degradation may be obtained from pools. One estimate of long-term degradation is based on the depth of an extensive and consistent gravel layer. In the example of Table 14-13, the top surface of a gravel layer is consistently located at a depth of 3.4 to 3.6 ft, except in the pool located along the valley wall (GPS Point 105), in which the

Table 14-13 Example* of Preliminary Data Collected for Pools

Photo No.	GPS Point No.	Latitude	Longitude	Depth to Gravel Stratum (ft)	Depth to Bedrock or Bed Armor (ft)	Depth to Deepest Point in Pool (ft)	Comment
102	102	N39 23.131	W76 28.116	3.5	—	3.7	No bedrock
105	105	N39 23.143	W76 28.117	—	1.5	1.5	Pool along valley wall and contains cobble
110	110	N39 23.151	W76 28.123	3.6	—	4.5	No bedrock
113	113	N39 23.162	W76 28.128	3.4	—	4.4	Pool near center of valley
118	118	N39 23.171	W76 28.130	3.5	—	4.0	No bedrock

* Values provided in this table are for example only and should not be used as standard values.

gravel layer is not present. Prior channel assessments by OBD indicate that when these extensive basal gravel layers become exposed in the bed and banks, rapid bank collapse and tree fall occur, resulting in processes that tend to prevent further degradation. Therefore, one estimate of long-term degradation is 3.4 to 3.6 ft.

A second estimate of long-term degradation is based on the depth to bedrock or other material such as an extensive layer of boulders or cobble that may armor the bed; in this example, however, bedrock and cobble are only present in one pool along the valley wall. Also, the depth of the pool is less than that recorded for all other pools in the table, indicating that the bedrock level along the valley wall may be elevated compared to other locations in the valley. The depth to bedrock should not be considered as an estimate of long-term degradation in this case.

A third estimate of long-term degradation is based on the depth of the deepest pool. Other than the bedrock and cobble observed in the pool along the valley wall, a consistent layer that would armor the streambed is not indicated by the pool observations in Table 14-13. If the processes initiated during the exposure of the gravel as described above do not stop degradation, then the potential exists for the channel to degrade to at least the deepest pool level observed, 4.5 ft.

Based on the evaluation of pool base level points in the example of Table 14-13, the range of estimated channel degradation would be reported as 3.4 to 4.5 ft. The fact that an armor layer or bedrock was not present in the deepest pools would also be reported.

14.2.4 ANALYSIS AND DEVELOPMENT OF RECOMMENDATIONS

Existing and potential future morphology-related problems should be identified and evaluated based on the data obtained from the visual assessment and any channel measurements that were needed. The data should also form the basis for determining whether a detailed morphology study is needed to investigate the implications of identified problems. Detailed stream morphology studies may be unnecessary at crossings where (1) the potential for significant morphological change of the project stream over the service life of the crossing structure is not indicated, (2) site constraints such as land development restrict options for replacement structures, or (3) the flow is dominated by tidal fluctuations. At crossings where long-term changes in the channel bed elevation and planform are indicated, however, a detailed study will usually be necessary. If a detailed study will be recommended, its objectives should be identified.

Development of the Detailed Study Scope

The analysis that will be required to satisfy the objectives of the detailed study should guide the development of the scope, which describes the methods to be used and the upstream and downstream limits of the study. The complexity of the methods used in the detailed study should be proportional to the complexity of the work to be undertaken for construction of the crossing structure. Off-right-of-way work or other work that would require landowner permission and/or a significant increase in cost will generally only be considered by OBD when the project plan includes channel relocation. The scope should be designed to adequately address the identified stream stability problems and provide the data necessary to develop reliable and effective solutions. Considerations for development of the scope are suggested in Section 14.3.1.

A brief re-examination of the site may need to be conducted to develop recommendations for the scope. Note, however, that the development of scope recommendations to be included in the preliminary report should focus on establishing the downstream and upstream limits of the study. Specific locations for data collection do no yet need to be selected or marked in the field.

14.2.5 PRELIMINARY MORPHOLOGY REPORT

A letter report should be developed to communicate the results of the preliminary morphology study. An example of a preliminary morphology letter report is provided in Appendix C. The purpose of the letter report is to provide information that either (1) explains why a detailed study is unnecessary or (2) justifies the need for a detailed study and describes its scope. The preliminary report should consist of a letter and three attachments. The general organization and content of the letter and attachments are outlined below. The letter should be written in narrative form; the attachments, however, should be outlined. Attachment A should provide the background information and any explanations of potential causes of crossing structure or channel instability. Attachment B should provide photos selected to illustrate problems identified in the report, a complete set of the documentation photos, and their associated spreadsheet (Table 14-2). Attachment C should provide channel measurement data (if obtained). A draft of the report should be submitted to the OBD in either a portable document format (PDF) or a standard word processor format compatible with MS Word 2000. The final report may be submitted as a PDF; however, the document must also be submitted in a standard word processor format compatible with MS Word 2000. Spreadsheets should be compatible with MS Excel 2000. A printed copy of the entire final report should also be provided, except as noted for Attachment B.

Preliminary Stream Morphology Letter Report

I. Introduction
   A. Identify the associated road designation, stream name, and purpose of constructing a new crossing or replacing an existing one.
   B. Identify the project location: the part of the county, the watershed, and the physiographic region in which the project is located.
   C. State the purpose and scope of the preliminary study.

II. Summary of Significant Findings

   Briefly summarize the most significant findings reported in Attachment A. Provide cross-references to the sections of Attachment A that contain more detailed descriptions and data.

III. Recommendations
   A. Detailed study: explain why a detailed morphology study is or is not recommended.
   B. Objectives and scope: If a detailed study is recommended, identify its objectives and describe the proposed scope of the study.
   C. Design recommendations and considerations (e.g., countermeasures) if detailed study is not needed.

Attachment A: Background and Analysis

I. Background Information (see Section 14.2.1)
   A. Existing land use and existing and ultimate development hydrology (based on OBD hydrology study)
      1. Give the watershed area.
      2. Itemize land use. (Obtain GISHydro stats sheet from OBD.)
   B. Estimate bankfull flow and channel geometry based on USFWS curves (see Table 14-1).

C. Describe historic and contemporary modifications to channels and valleys indicated by documents, maps, and photographs examined prior to the visual assessment. Include mapping that indicates channel modifications.

II. Visual Assessment

A. Findings

Describe the general findings of the visual assessment. The findings may relate to any or all of the following elements:

1. Effect of historic and recent modifications to the channel
2. Channel characteristics at the crossing
3. Rosgen channel classification in the project reach
4. Vertical bed changes
5. Lateral channel movement
6. Sediment dynamics
7. Supply and characteristics of debris
8. Backwater flooding
9. Scour and deposition at the crossing
10. Bankfull flow parameter summary
11. Effect of the existing structure on channel morphology and the potential for crossing-channel interaction to be detrimental to the structure and/or the environment.
12. Existing and potential effects of channel morphology and debris on the crossing
13. Environmental considerations

B. Key Features and Observations

Describe the key channel features as appropriate to describe the project stream and valley conditions. These descriptions may be presented as lists, tables, narratives, or any other form that communicates the general field observations on which the findings were based. While the same features should be described for each of the three assessment reaches, the focus of the description will differ for each reach. For the base level reach, emphasize base level changes and channel degradation. For the project reach, emphasize the potential instability of the channel at the crossing location and on problems with an existing structure. In the supply reach, the supply of debris and sediment to the crossing location should be emphasized. Address each of the following key features and observations:

1. Existing crossing (see Tables 14-3a, 14-3b, and 14-3c).
2. Qualitative classification of the channel type.
3. Base level points (see Table 14-4).
4. Low-flow high-gradient features and channel bed instability indicators composed of natural and introduced materials (see Tables 14-5a and 14-5b).
5. Stream bank height and materials and indicators of instability (see Table 14-6).
6. Pools and channel bed instability indicators and considerations (see Table 14-7).
7. Bar and riffle material indicators for channel instability (see Table 14-8).
8. Debris: supply, transport, and jams in the channel and at the existing or proposed crossing.
9. Tributaries and tributary confluences.

10. Structures and other flow obstructions.
11. Terraces, the active floodplain, and other valley bottom features.
12. Channel-valley orientation and channel planform.

III. Channel Measurements (if obtained)

A. Pebble count at riffle
   1. Provide pebble count data in Attachment C (Table 14-10).
   2. Plot cumulative size distribution and size histogram as indicated in Figures 14-7 and 14-8 (Section 14.3.3), respectively, including D_{50R}.

B. Bulk bar sample
   1. Provide results of sieve analysis in Attachment C (Table 14-11).
   2. Plot cumulative size distribution and size histogram as indicated in Figures 14-7 and 14-8 (Section 14.3.3), respectively, including D_{50L}.

C. Floodplain soil and channel bed material samples (see Appendix B).

D. Potential for long-term degradation
   1. Briefly describe method or methods used to evaluate long-term degradation.
   2. Provide measurement and analysis data in table format (Table 14-12 and/or Table 14-13).
   3. Briefly discuss analysis results.

IV. References

Attachment B: Photographs

I. Figures: Several photos should be selected and printed to illustrate problems identified and discussed in the letter report.

II. Geo-referenced Photographic Record

A. Provide a complete set of the digital photographs taken for the preliminary morphology study. These files should be provided in a standard image format (e.g., JPG or TIF). OBD does *not* need printed copies of this complete set.

B. Compile a spreadsheet that briefly describes each photograph (Table 14-2). The spreadsheet should be printed and should also be provided in an Excel 2000-compatible format.

Attachment C: Channel Measurement Data

I. Pebble Count Data

II. Bulk Bar Sample Data

III. Floodplain Soil and Channel Bed Material Sample Data

14.3 Detailed Morphology Study

The purpose of the detailed morphology study is threefold: (1) to develop a comprehensive understanding of the channel instability problems and the significance of these problems to the project area, (2) to the extent practical, quantify the instability, and (3) to develop recommendations for the design of the crossing structure, potential channel modifications, and countermeasures. The results of this study are presented in a formal engineering report to the OBD. The detailed study generally consists of four components:

1. Verification of the visual assessment and development of the scope
   a. Review of preliminary morphology report and photo-documentation
   b. Field reconnaissance
2. Data collection
3. Analysis
4. Reporting

The detailed study typically takes about three to eight workweeks to complete, including three to five days of fieldwork. As in the preliminary study, fieldwork should be carried out by a team of two people, while analysis and reporting will usually require only one person. The field components of the detailed study will require contour mapping (see Section 14.2.1) as well as a copy of the preliminary report, including the photo-documentation and accompanying spreadsheet with comments and field notes. Data and results from the existing conditions hydraulic model (see Chapters 5 and 10) should be available from OBD during the initial stages of the detailed morphology study and may be incorporated into the analysis for the detailed study.

The detailed study should be initiated as soon as possible after the preliminary study is completed and should be conducted in parallel with the proposed condition modeling; persons conducting the detailed morphological study should work closely with those conducting the hydraulic modeling of proposed conditions. Prior to the development of the proposed conditions model, stream stability problems should be identified, and alternative solutions should be made available. These results often influence decisions about the crossing type, size, and location as well as potential channel modifications. Likewise, hydraulic modeling of proposed conditions usually influences the solutions to channel instability problems. The coordination and interaction of all the disciplines involved in the project location and design stage is highly encouraged. Changes in location and design features are much easier to accomplish at this preliminary stage than later in the process when the design has become accepted and approved.

14.3.1 PRELIMINARY STUDY REVIEW AND SITE RE-EXAMINATION

The findings and the photo-documentation provided in the preliminary report should be reviewed and a re-examination of the site should be conducted prior to beginning the detailed study. The purpose of this review and re-examination is to (1) familiarize the field team with the project channel; (2) verify the problems identified in the preliminary study; (3) confirm that the channel conditions have not been affected by storm events or other factors introduced since the completion of the preliminary visual assessment; (4) confirm that the proposed scope will adequately address the identified stream stability problems and will provide sediment data needed for scour analysis if it was not collected in the preliminary study; and (5) verify the proposed extent and select specific locations for data collection.

Development of the Detailed Study Scope

The analysis required to satisfy the objectives of the detailed study should guide the development of the scope, which describes the methods to be used and the upstream and downstream limits of the study. The complexity of the methods used in the detailed study should be proportional to the complexity of the work to be undertaken for construction of the crossing structure. Off-right-of-way work or other work that would require landowner permission and/or a significant increase in cost will generally only be considered by OBD when the project plan includes channel relocation. Depending on the objectives of the study, the scope may need to incorporate the locations of the upstream and downstream limits of the channel profile survey, the sediment assessment reach, and regions showing evidence of recent lateral movement.

Extent of the Channel Profile Survey

A channel longitudinal survey should be obtained in the detailed study to identify and describe all significant features and changes in the streambed, stream bank, and low-flow water surface profile that may have an effect on degradation at the crossing or that may be affected by changes at the crossing. The survey should extend downstream at least 500 ft; if a *degraded local base level point* (DLBLP; see *Base Level Points*, below) does not fall within that region, the survey should be extended farther downstream to the nearest downstream point that can be identified as a DLBLP. The survey should extend to a point at least 500 ft upstream of the crossing and a sufficient distance to include profile features that may be associated with sedimentation, scour, or channel alignment in an existing crossing, or a significant channel feature upstream of the crossing that may affect or be affected by the proposed crossing. The profile will also serve to document the pre-project channel bed from which future bed changes can be evaluated, and therefore it should extend to a point where channel changes associated with the introduction of the proposed crossing are unlikely. In cases where these parameters would require that the extent of the survey exceed 2000 ft, an alternative survey option should be developed and included in the recommendations for OBD's consideration. This alternative option may include fewer survey points (e.g., only riffle crests, the deepest points in pools, and base level points), but it should still provide for a detailed survey of at least 500 ft downstream and 500 ft upstream of the crossing.

The locations of base level points, tributaries, confluences, low-slope regions where an estimate of minimum degraded channel slope can be obtained, and structures and other flow obstructions may need to be considered when determining the extent of the channel profile survey.

- *Base Level Points* If possible, several base level points that can be surveyed in the detailed study should be identified. At least one of the base level points downstream of the crossing should be identified as a degraded local base level point and should be located as close as possible to the crossing. The DLBLP provides a downstream boundary condition from which a degraded stream profile will be computed. Under ideal conditions, the DLBLP should be located in one of three places: (1) where the local base level is controlled by resistant bedrock; (2) at a culvert invert that is unlikely to be replaced; or (3) at a downstream water body with a controlled outlet. In most cases, however, none of these three conditions exist in the vicinity of the crossing, and a local base level must be approximated either as the depth of bedrock in a pool or as the level of cobble that may be overlying bedrock.

A culvert inlet provides a base level point; it may be used as the DLBLP if it is expected to remain in place for the life of the proposed crossing structure. However, culvert inlets may be replaced or lowered in the future, especially to provide for fish passage. If the culvert outlet invert is perched above the low-flow water surface, then the profile should be extended downstream to a different DLBLP. The base level points listed in Table 14-4 may be used to define the DLBLP.

- *Tributaries and Confluences* The proximity of tributary channels and confluences should be considered in the development of the limits of the profile survey. Upstream tributaries should be included in the study if they are found to provide a high supply of sediment to the project channel. Tributaries that confluence in the project reach will need to be included in the detailed study. If the project stream confluences downstream with a much larger channel that indicates potential for degradation, the detailed study should extend downstream beyond the confluence.
- *Low-Slope Regions* The minimum degraded channel slope (S_{dgr}) will be needed in the detailed study to approximate the degraded channel profile. An estimate of the minimum degraded channel slope may be obtained from the lowest-sloped regions of the channel bed (see Table 14-14). As channel degradation progresses upstream, the channel slope is reduced. At some point, the channel slope reaches a minimum value for reasons that may include the exposure of underlying resistant material, an increase in the supply of coarse bed material available for transport, an increase in the supply of woody debris from bank failure, or an increase in channel length caused by channel lateral migration. These low-slope regions are often found where channel entrenchment is greatest and where mildly sloping riffles have formed in the most sinuous reaches. Those channel sections that have widened and regained their sinuosity and those sections with the deepest entrenchment and lowest slopes should be examined carefully to evaluate their potential use as reaches where S_{dgr} could be estimated from field measurements.
- *Structures and Other Flow Obstructions* The effects of structures and other flow obstructions (described in Section 14.2.2) should be considered in the development of the limits of the profile survey.

Table 14-14 Field Methods for Obtaining Estimates of S_{dgr}

Variable	Slope Description	Method for Obtaining Slope
S_{exist}	Existing riffle-crest slope	Detailed profile of site
S_{entr}	Existing riffle-crest slope in stream reach with highest bank heights	Detailed stream profile survey or additional survey to locate reach with the highest banks that is still representative of the upstream reach conditions
S_{rec}	Existing riffle-crest slope in reach that has incised, over-widened, and is recovering sinuosity with low-flow channel drops over stable riffles	Detailed stream profile survey or additional survey to locate site with recovering sinuosity
S_{num}	Slope required for sediment continuity or mobility	Analysis based on sediment load computation or critical shear stress of bed material

Sediment Assessment Reach

In the project reach or the supply reach, a section of channel where the sediment load and mobility can be evaluated should be identified. This section of channel is referred to as the *sediment assessment reach*. The selected reach should be longer than two riffle-pool sequences and, where possible, should be a reach where bankfull indicators are unambiguous, the channel is straight, and backwater effects are minimal. Data collected in the sediment assessment reach should include a profile survey, cross section measurements, pebble counts, and bed load sampling. The OBD recommends that sediment assessment reaches be located on the project stream and within or in close proximity to the project or supply reach; use of reference reaches from other watersheds should be avoided.

Lateral Channel Movement

Where the channel is not confined by valley walls and/or embankments, a study of the potential lateral movement may need to be included in the scope of the detailed study.

Soil and Bed Load Materials for Scour Studies

Information regarding surface soils and bed load characteristics may be needed for scour studies. Procedures for the collection and evaluation of these materials are described in Appendix B of this chapter.

Selection of Locations for Data Collection

During the re-examination of the project stream, sites for collection of other data that will be needed in the analysis should be selected and marked. These may include locations where bankfull indicators are unambiguous or where channel cross sections or pebble counts may be needed. The need for subsurface investigation of soils in the crossing should also be considered when developing the scope. At most sites, however, private land ownership and/or forested conditions may preclude the use of these methods. Early requests that allow time to obtain access permission provide the best opportunity for use of subsurface sampling methods.

14.3.2 DATA COLLECTION

Valley Longitudinal Profile

Using the most accurate topographic data available, a longitudinal profile of the valley flat should be created to identify valley features that may indicate local grade controls or sections of channel that may be degrading. Data from which the plot can be developed include county topographic maps, topographic maps developed by MDSHA for specific projects, and LiDAR data that is being obtained for the entire state of Maryland. The valley profile plot should be based on valley stationing rather than stream stationing. The valley profile should extend at least 1000 ft beyond the downstream limit of the base level reach and 1000 ft beyond the upstream limit of the supply reach. The length of the profile should be 5000 to 10,000 ft.

If mapping with resolution of 1-foot or 2-foot contours is available, the valley profile may include points that represent the low-flow water surface elevation and the top of the stream banks. These features, as well as channel thalweg points, can also be obtained from the cross sections surveyed for hydraulic model studies. All channel and valley features that are suspected of influencing the channel profile should be plotted on the valley profile. These features may include existing and historic roadway and railway crossings, existing dams, historic mill dam locations, tributaries, exposed bedrock, utility crossing protection, debris jams, and low-gradient reaches. Base level points and the DLBLP should also be plotted on the valley profile.

Channel Profile Survey

A channel longitudinal survey should be obtained according to the parameters established by the scope of the detailed study. The survey should include a sufficient number of survey points to identify features such as all low-flow high-gradient features along the channel, the deepest region and points in each pool, the crest of each riffle, all bedrock steps, bedrock in pools, cobble riffles, and debris jams. The sediment assessment reach should also be surveyed, even if it is located up-stream or downstream of the limits of the channel profile survey. The water surface elevation should be measured along the edge of water, especially where flat or mildly sloping topography allows the survey points to be easily obtained. Where banks are near-vertical or undercut, how-ever, the water surface elevation at the edge of water may not be accessible for surveying. In those locations, the water surface elevation should instead be measured over the thalweg, except in high-velocity riffles where the water surface is fluctuating rapidly. At least one water surface elevation point should be obtained at the crest of the riffle to delineate the breakpoint between the upstream pool and downstream riffle. The base level points identified in the verification of the visual assessment should be surveyed as part of the stream longitudinal profile. If fine-grained depositional benches are present that may represent bankfull features, these deposits should be surveyed along the channel as well.

Channel Cross Sections

The objectives for obtaining the cross section data are fourfold: (1) to document the stream conditions in the region of the proposed crossing; (2) to estimate bankfull flow conditions; (3) to classify the stream reaches; and (4) to provide channel geometry data for a sediment mobility analysis. If depositional features such as channel benches are present, an estimate of bankfull flow can be obtained from these features. Appropriate field measurements should be made to ob-tain an estimate of bankfull conditions. Normally, a minimum of two stream cross sections are required to accomplish the objectives. Additional cross sections may be required (1) to determine where bankfull flow may be most reliably estimated and the mobility of riffle and bedload sedi-ment can be evaluated; (2) to evaluate poor channel alignment to the bridge opening; (3) to evaluate channel blockages; or (4) to evaluate floodplain constrictions and blockages that may cause deposition within the bridge opening. Common types of cross sections include the follow-ing, though a single cross section may combine elements from two or more of these:

Channel Representative Cross Section at Crossing: A representative cross section should be obtained in the vicinity of the existing bridge or near the proposed crossing centerline. If possible, the cross section should be measured in the upper third of a riffle. The cross section should extend across the valley a sufficient distance to determine the local chan-nel entrenchment (about 3 times the channel width). An attempt should be made to in-clude bankfull indicators if they are present. Factors such as floodprone width and bank height and angles should be identifiable in the cross section. At least two reinforcing rods should be driven to mark the location of this surveyed cross section.

Channel Classification Cross Section and Reach: At least one cross section should be ob-tained in a riffle in the vicinity of the existing or proposed crossing structure such that the channel can be classified according to the Rosgen (2006) classification method. If possible, the cross section should be measured in the upper third of the riffle. The classification cross section should extend onto the valley floor at least to the extent that the channel can be classified and the channel incision from the valley flat can be determined.

Bankfull Flow Estimate and Sediment Mobility Cross Section: A cross section should be obtained in the sediment assessment reach identified in the verification of the visual assessment. At least two reinforcing rods should be driven to mark the location of this surveyed cross section. The cross section used to identify bankfull conditions should be representative of the crossing flow and sediment load conditions. As a general rule, the bankfull cross section should be obtained in a stream segment where confluences with other streams cumulatively change the contributing drainage area by less than approximately 10%. Regardless of the contributing drainage area, highly urbanized tributaries or highly unstable tributaries that contribute large-sized sediment or loads that obviously change the morphological conditions should also be used as upstream or downstream limits on where the cross section may be taken.

Cross Sections Describing Poor Channel Alignment or Causes of Deposition: One method for describing the blockages, constrictions, or poor alignment of the channel or floodplain to the bridge or culvert waterway opening is to obtain three cross sections: one in the most restricted or offset section of channel or floodplain in the approach to the structure, one in the structure opening, and one in the most restricted or off-set section downstream of the structure. All potential blockages and constrictions such as floodplain fills, high local floodplain topography, or structures such as abandoned bridge abutments should be represented in these cross sections.

Typically, effective representation of cross section features requires at least 20 survey points (Figure 14-1). The number of cross section points should be sufficient to describe the following features:

- the valley flat
- terraces
- top of bank
- berms
- water surface elevation at the time of survey
- channel thalweg
- bankfull elevation

Measurements of the water surface elevation should be obtained along the edge of water whenever possible, as described above for the channel profile survey.

A photograph of each cross section similar to the one shown in Figure 14-2 should be obtained while a tape or string line is stretched level across the channel at the location of the cross section. The photograph should be obtained in the downstream direction. Photos taken facing upstream, the left bank, and the right bank of the cross section are often helpful as well.

Bed Sediments

Sediment sampling should be conducted to assess the surface characteristics of riffles or other armored features of the streambed and to assess the sediment load. The Wolman pebble count method (Bunte and Abt 2001) on the active channel bed is recommended for assessing the sediment size distribution over riffle surfaces. Bar samples (Rosgen 2006), subsurface bed

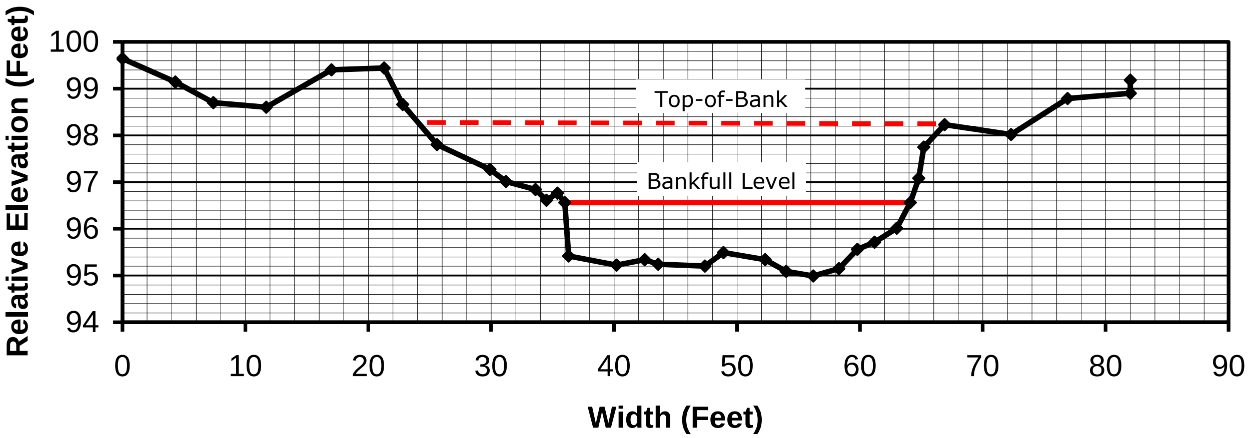


Figure 14-1 Sediment assessment reach cross section view downstream.

Figure 14-2 Downstream view of sediment assessment reach cross section.

samples (Bunte and Abt 2001), or pit traps (Bunte and Abt 2001) are recommended to evaluate the sediment bed load characteristics. A pebble count of at least 200 particles should be collected in the riffle where the classification cross section was obtained. A pebble count of at least 400 particles should be collected in the riffle of the sediment assessment reach. In streams with small riffle surface areas and large sediment size, the number of pebbles measured may be fewer than 400 but should be at least 100. The sampling should be conducted using a grid spacing method (Bunte and Abt 2001). The size categories in Table 14-10 (Section 14.2.3) *must* be used to measure and record the size interval of each particle. Note that this table is slightly different than other similar tables. Where bed aggradation is suspected, at least three pebble counts (200 particles each) should be conducted along the channel profile to document the change in surface particle-size distribution.

Where possible, bed material mobilized over several flow events should be obtained from the site. Event sampling using hand-held sediment samplers (e.g., Helly-Smith) is the best available method for obtaining bed load samples and relating those samples to hydraulic conditions of the channel. Effective event sampling, however, is rarely feasible under the time and cost constraints of OBD projects. Therefore, the preferred method of obtaining samples that indicate the sediment transport rate and sediment size distribution is the installation and monitoring of pit traps (i.e., 5-gallon buckets lined with sandbags and placed in the channel bed). The traps provide an integral sample collected over the entire hydrograph of the flow event. Pressure transducers and/or staff gages that record peak stage can be installed to obtain information about flow hydraulics during the period that the load was captured in the traps. Subsurface material excavated from the installation of the pit traps can also be used as another estimate of the bed load and can be compared to the material obtained in the pit trap.

While pit traps should be used whenever practicable, their use presents two problems that frequently require that bulk samples from bars and/or subsurface samples from riffles be obtained as a substitute for actual bed load samples. First, the load of specific size fraction transported during specific hydraulic conditions cannot be determined directly from this method of sampling. Under high bed load transport conditions, the traps may be filled during only a portion of the flow event. Installation of a series of buckets can alleviate some of this problem. Second, practical considerations, including vandalism, may prevent the collection of bed load samples using pit traps at some locations. (Note: A more detailed explanation of pit trap use is under development and will be added to this chapter at a later date.)

The method described by Rosgen (2006) for collecting and analyzing bulk bar samples is a commonly used method for approximating the size distribution of the sediment load. In this method, a bulk sediment sample is obtained from the downstream third of a point bar at a level equal to half of the local bankfull depth. The size distribution of the bar sample will be obtained, and the largest two particles in the sample should be selected and weighed; all three axes of both of these particles should be measured and recorded.

To supplement Rosgen's method for estimating the largest size fraction transported under bankfull conditions, 30 of the largest particles from the surface of the bar that is below the bankfull elevation should also be collected. The intermediate and smallest axes of these particles should be measured and recorded.

Where bars are not present, bulk subsurface sediment samples of a riffle can be obtained and used as a surrogate for the bedload. Subsurface samples obtained in the Maryland Piedmont streams, however, indicate that the subsurface material often contains large pieces of broken bedrock or very coarse cobble from nearby sources, including the streambed and/or colluvium. These materials may not be representative of the load from the rest of the watershed. Although the same problem may occur in bars, the occurrence of large pieces of broken bedrock there appears to be much lower. When sampling either the subsurface or bar material, careful observations should be made to determine whether the large pieces of broken bedrock or cobble/boulders are from a nearby source or whether they are representative of the load upstream and downstream of that source. An evaluation of the source of the largest bed material should be made to determine its impact on channel stability.

Bankfull Flow Indicators and Channel Characteristics

The bankfull level should be determined through an examination of bankfull indicators along the channel profile (Harrelson et al. 1994). Well-developed and consistent indicators of bankfull flow levels are often not observed other than in a few isolated locations. Often, a fine sediment deposit that has formed a bench within an incised and over-widened channel is the only indicator of bankfull level.

Subsurface Sampling: Site Borings, Geoprobe® Samples, and Trenches

The Office of Structures is currently investigating the use of site borings, Geoprobe® samples, and trenches to evaluate subsurface strata and bedrock surface elevations. While guidance has not yet been developed for the application of these techniques in stream morphology studies, subsurface samples may help to clarify observations made in the morphology studies. They should be considered, especially in cases of large projects involving significant channel modification or restoration work.

Bank Geometry, Bank Materials, and Stratification

Streambank geometry (i.e., bank height and angle) should be measured, and bank material composition and stratification should be described both at representative locations and at other locations that may be diagnostic of channel instability or indicative of base level points. One location in each reach is usually sufficient; in the project reach, these measurements may be taken at the location of the cross section if the banks are exposed. The elevation of the cobble-gravel interface with finer-grained sediments and the level of leaf packs, buried wood, and organic-rich layers should be documented. Banks along deep pools, particularly those in the central part of the valley, should be described.

Table 14-15 should be used to describe bank conditions in the project channel. Bank height should be measured from the bank toe. Strata should be numbered starting from the top of the bank to the bottom. Materials within each stratum should be described using the material codes listed in the note at the bottom of the table. Multiple material codes should be used to describe mixed materials with the first code representing the most abundant material. Documentation of banks can be accomplished using a pocket rod and photographs from which Table 14-15 can be completed; however, bank materials and strata should be examined carefully in the field and notes should be taken to describe the bank conditions.

Lateral Channel Movement and Planform Changes

Past channel movement can be measured by comparing blue line representations of streams from the 1950s to recent aerial photographs or topographic maps, or it may be measured in the field. Field measurements also serve to verify whether recent mapping accurately represents the current channel-valley orientation and planform.

Attempt to locate field evidence of past channel positions that correspond to blue line representations. The geo-referenced photo-documentation collected in the preliminary study should facilitate the identification of these locations (see *Channel-Valley Orientation and Channel Planform* in Section 14.2.2). Measure the distance from the left or right bank of the past channel position to the respective bank in the channel's present location (see Table 14-16). Note that multiple abandoned channels may be identified in the field; only those abandoned channel segments that are in the locations indicated on the contour map should be measured.

Table 14-15 Example of Collected Stream Bank Field Data

Valley Station (ft)	Photo No.	Bank Height (ft)	Bank Angle H:V*	Rooting Depth (ft)	Stratum Number	Stratum Thickness (ft)	Stratum Material†	Comments
20+00	20,21,22	6.2	1.5	1	1	4	6-7-5	
"	"	"	"		2	0.5	8-6-5	Leaf pack and branches
"	"	"	"		3	1.5	4-3	
"	"	"	"		4	0.2	1	
20+30	23,24	5.7	2.1	1.2	1	3.8	6-7	
"	"	"	"		2	1.9	4	
21+30	25,26,27	6.0	–1.1	1.5	1	4.1	6-7-5	Buried log
"	"	"	"		2	0.8	4-3	
"	"	"	"		3	1.1	1	
(*etc.*)								

* Use a negative bank slope to describe undercut banks.

† Use the following codes to describe strata material in order of highest abundance: 1 – bedrock, 2–boulder, 3–cobble, 4–gravel, 5–sand, 6–silt, 7–clay, and 8–organic.

Table 14-16 Example of Data Collected for Channel Movement

Blue Line Stream Location			Current Stream Location						
Photo No.	GPS Point No.	Lat/Long	Photo No.	GPS Point No.	Lat/Long	Mvmt. Distance (ft)	Bank Measured	Movement Process*	Comment
102	102	N39 23.131 W76 28.116	103	103	N39 23.139 W76 28.124	60	Left bank	Avul-sion	Channel debris jam caused avulsion
105	105	N39 23.125 W76 28.118	106	106	N39 23.128 W76 28.119	20	Left bank	Migra-tion	Bars in channel
110	110	N39 23.128 W76 28.113	111	111	N39 23.131 W76 28.112	25	Right bank	Migra-tion	Debris blockage
113	113	N39 23.121 W76 28.112	114	114	N39 23.125 W76 28.114	30	Right bank	Modi-fication	Channel relocated for utility line

* Migration, avulsion, or modification.

14.3.3 ANALYSIS

Analysis of Long-Term Changes in the Stream Bed Elevation

Channel Degradation

The conceptual framework for the method described below for estimating a degraded stream profile is based on a simple channel evolution model and four associated assumptions. First, degradation is considered to be initiated by a downstream change in the channel network or base level. Second, degradation migrates upstream as a single segment or multiple high-gradient segments of channel and continues through the crossing unless bedrock, a metal or concrete culvert invert, or other resistant material is present that may limit the extent or depth of degradation. Third, as a result of increased entrenchment and the effect of the entrenchment on containment of flood flows and related increased bed stresses, the bed may continue to degrade after headcuts have propagated through the reach and further reduced the slope. Finally, the channel may reach a minimum slope as supplied or underlying streambed materials such as gravel and cobble are exposed and the channel widens, increases sinuosity, and begins to aggrade.

The analysis should be conducted with an awareness that channels typically go through several episodes of degradation associated with the degradation of local grade controls. For example, a wave of degradation may migrate upstream, exposing riprap protection of a sewer line. Although the upstream channel may go through all four phases of the conceptual model described above, the degradation may be re-initiated as the riprap fails over the sewer line crossing. Similar behavior may occur as a channel incises into elevated bedrock along the hillside of a valley. Then, as the channel migrates toward the middle of the valley and away from the elevated bedrock over time, a second phase of channel incision may be initiated. Realization of these potential conditions is necessary for making reliable estimates of the degraded stream profile.

Channel Aggradation

Channel aggradation occurs because the capacity of the channel to transport sediment is reduced or because the characteristics of the supplied sediment change with time or along the channel profile. Many factors can locally influence a channel's ability to transport sediment; some of the most common are (1) a reduction in the channel slope downstream, (2) backwater effects from downstream constrictions or blockages, (3) changes in channel geometry, including channel entrenchment, incision, and width-to-depth ratio, and (4) ineffective flow areas at the crossing caused by flow curvature, flow separation, and recirculation. Changes in sediment load characteristics often occur near depositional areas as a result of bank or bed erosion and/or contributions from tributaries. At this time, a practical method based on a simple conceptual model is available for channel degradation but not for channel aggradation. In cases where the channel is found to be aggrading, the OBD should be consulted as soon as possible to discuss how to proceed.

Riffle-Crest Reference Line for Long-Term Channel Changes

Long-term changes in the bed elevation will be referenced from the existing channel riffle-crest line. Long-term changes in bed elevation are defined as the change in the riffle-crest line elevation at any point along the streambed over the 60-to-100-year life of the crossing. This period, which may be shorter for existing crossings, is useful when considering the durability of bedrock or the growth of trees and their potential effects on the morphology of the channel at the crossing.

Estimation of the Degraded Stream Profile and Long-Term Channel Degradation

The degraded stream profile is an estimate of the lowest elevation to which the channel bed could potentially degrade over the life of the crossing in the absence of local scour that may be caused by the crossing such as local and contraction scour at bridges. The degraded stream profile can be developed from field data and/or from a computational model. While computational models may reduce the level of uncertainty of the estimation sufficiently to warrant their extra expense, their usefulness is also limited by the spatial variability of bed and bank material properties and the effects of treefall. The use of field data without a computational model will usually suffice for development of a simple first-order estimate of the degraded riffle-crest elevation.

The degraded stream profile is derived from two main parameters: the DLBLP, which represents the downstream boundary of the degraded stream profile; and the degraded riffle-crest slope, S_{dgr}. Although bed elevations in pools represent the local minimum elevation of the stream profile, they are a local scour feature and will be considered separately.

Once the DLBLP is located along the valley profile and the elevation of the DLBLP is estimated, the *minimum degraded riffle-crest slope,* S_{dgr}, is approximated (see below, *Estimation of the Minimum Degraded Riffle-Crest Slope*). A first-order approximation for the function representing the degraded riffle-crest line can be expressed as

$$Z_{dbl} = Z_{DLBLP} + S_{dgr} * (X - X_{DLBLP}) \qquad (14\text{-}1)$$

where

Z_{dbl} = the riffle-crest line elevation of the degraded streambed (ft)
Z_{DLBLP} = the streambed elevation at station X_{DLBLP} that represents a known or approximated degraded local bed level point (ft)
S_{dgr} = the slope (along riffle crests) of the degraded bed (ft/ft)
X_{DLBLP} = the station of the degraded local base level point along the thalweg (ft)
X = the station along the stream thalweg where the degradation is being computed (ft)

The variables of Equation 14-1 are illustrated in Figure 14-3, which shows the hypothetical profile of a typical pool-riffle stream bed, the degraded base level point (DLBLP), and the degraded stream riffle-crest line projected upstream from the DLBLP using the minimum bed slope.

The estimated potential long-term degradation, ΔZ, is computed as

$$\Delta Z = Z_{exist} - Z_{dbl} \qquad (14\text{-}2)$$

where

ΔZ = long-term degradation (ft)
Z_{exist} = the existing riffle-crest line elevation (ft)
Z_{dbl} = the riffle-crest line elevation of the degraded streambed (ft)

Note that the difference in estimated potential vertical degradation is defined here as ΔZ and does not include the depth of pools that typical form in bends, in flow constrictions, or around obstructions. The depth of pools is discussed in a subsequent section.

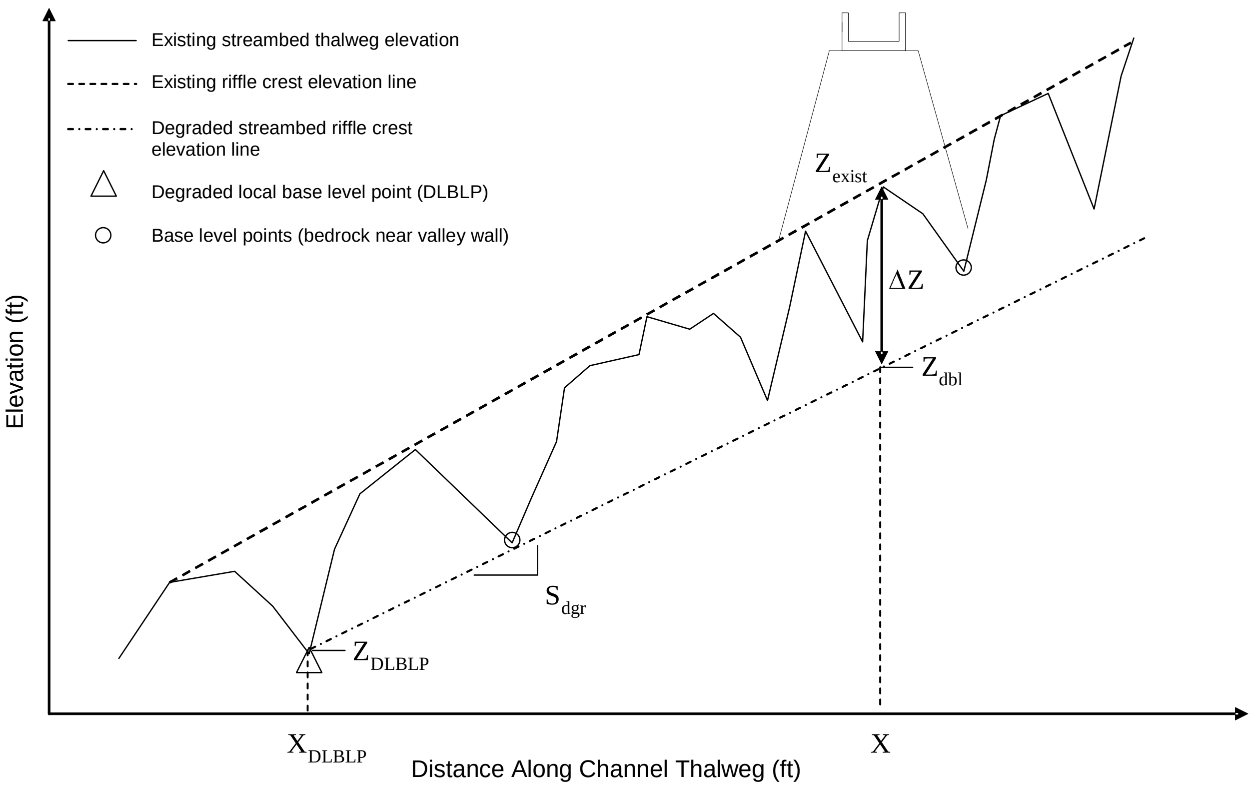


Figure 14-3 Degradation line illustrating Equation 14-1.

Two of the most important assumptions implied in this simple model of Equation 14-1 are (1) that a point along the stream profile can be located that represents the elevation and location of a reliable local degraded base level point (DLBLP) and (2) that a constant minimum slope can be determined that represents the degraded riffle-crest line.

Estimation of the Minimum Degraded Riffle-Crest Slope, S_{dgr}

One method for estimating the slope of the degraded riffle-crest slope, S_{dgr}, is the use of field data. Table 14-17 describes slopes that can be obtained from field data: the existing bed slope, S_{exist}, entrenched channel slope, S_{entr}, and the slope of a sinuous section of channel that is recovering after incision, S_{rec}. The three slopes represent sections of channel at three different stages of channel evolution. The first is prior to the most recent channel incision. The second is after the incision and widening but before channel sinuosity increases. The third is after the channel has begun the planform recovery process. These slopes should be computed from channel reaches that are void of locally steep sections that may be vertically unstable.

This slope can be obtained from riffle-crest-to-crest field measurements, preferably from profiles that extend over several pool and riffle sequences. Note that use of the minimum degradation slope will maximize the estimated value of long-term degradation.

Slope Change at Confluences

Tributary confluences often exist between the DLBLP and the location of the crossing structure. If flow and/or the sediment load from the tributary have a significant effect on the channel

Table 14-17 Estimates of S_{dgr}

Variable	Effect on Predicting Degradation
S_{exist}	Represents the existing stream profile and is typically steeper than the profile after channel incision has propagated through the reach and may result in a smaller estimate of degradation than S_{entr} and S_{exist} would produce.
S_{entr}	Represents a reach in which the channel bed has degraded and the channel cross section area has increased. Bed slopes in the incised reaches are typically less than those prior to incision. Use of this slope results in the largest estimate of bed degradation.
S_{rec}	Represents a reach of channel that has regained some sinuosity. The value of S_{rec} tends to be between than S_{entr} and S_{exist}.
S_{num}	A wide variation of slopes can be obtained, depending on the estimates of sediment load and assumptions about changes in channel geometry.

profile, then a change in the S_{dgr} will be required to compute the degraded riffle-crest slope upstream of the confluence. The need for such a change in the slope should be determined from the analysis of the valley profile and/or the detailed stream profile: a change in the main channel slope at the tributary indicates that a change in slope at the tributary will be required in the estimation of the degraded riffle-crest line. In this case, the estimation of the degradation line will require two computations. First, a degradation line is computed from the DLBLP to the confluence. The projected elevation of the degradation line at the confluence becomes the DLBLP for the channel upstream of the confluence. A second degradation line is then computed from this confluence DLBLP and a second S_{dgr}.

Crossings on Tributaries

If the crossing requiring evaluation is on a tributary channel that lacks a DLBLP between the crossing and the channel's confluence with a main stem stream, assessment of the potential main stem channel degradation will be required. The main stem assessment may be unnecessary if a DLBLP can be located between the crossing and the confluence. Otherwise, a degraded riffle-crest line should be developed for the main stem to determine the potential degradation that may occur at the confluence. Then a separate analysis should be conducted for the tributary using the degraded tributary elevation as the DLBLP for the tributary and the S_{dgr} based on an analysis of the tributary profile.

Degradation of tributaries can also be caused by planform changes in the main stem channel. Lateral migration of the main stem channel in the direction of a tributary can substantially change the location of the confluence and shorten the length of the tributary. The reduction in length will cause a change in the slope near the confluence that may initiate a wave of upstream degradation in the tributary. Similar and perhaps much more rapid changes may occur as a result of main channel avulsion toward and into the tributary channel. Analysis of the potential movement of the confluence and its effect on the vertical stability should be conducted.

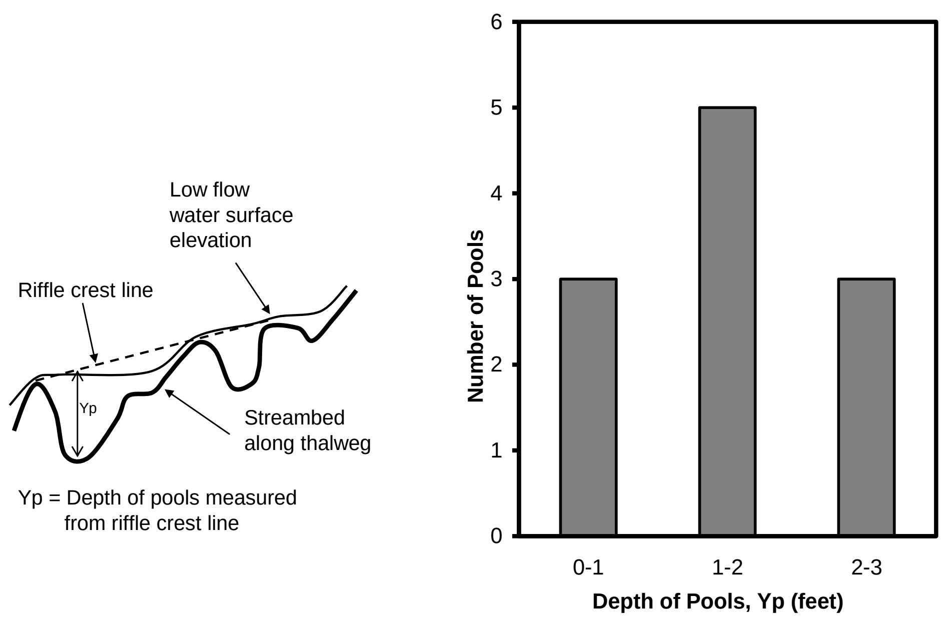
Estimation of Pool Depths

To this point, an analysis of the channel degradation was limited to changes in the elevation of the riffle-crest line. The deepest points along the channel profile are represented by the lowest point in pools. One method for assessing the potential future depth of pools is to examine the depth of all pools surveyed in the detailed stream profile. Figure 14-4(a) illustrates the method of measurement of the deepest pools within the surveyed reach. A pool depth histogram (Figure 14-4(b)) can be developed from the measured pool depths. A pool depth can be selected from the histogram to determine the likely lowest elevation of the channel profile that would occur at the crossing in the absence of other forms of local scour. In addition, any unusually deep pools measured during the visual assessment that are located beyond the limits of the profile survey should be considered. If these pools are substantially deeper than those measured in the profile survey, the pools should be re-examined to determine the cause of the deeper pool depths. If conditions that caused the deep pool to form also occur at the crossing, then consideration should be given to using the greatest observed pool depth to approximate the potential minimum elevation of the streambed at the crossing. This method of pool depth analysis assumes that both the bed material and the hydraulic conditions that formed the pools will be similar in the future.

Lateral Channel Movement and Planform Changes

The area on the floodplain that the stream channel may reasonably occupy at some future time during the service life of the crossing structure is referred to herein as the *channel lateral movement zone* (CLMZ). The boundaries of the CLMZ should envelop the extent of likely channel migration and pathways for channel avulsion, as illustrated in Figure 14-5. These boundaries can be estimated through examination of field data (Table 14-16), USGS 7.5-minute topographic maps from the 1950s, and recent documentation of stream locations in the form of aerial photographs, county topographic maps, and/or MDSHA topographic maps developed for the existing conditions of the project vicinity. The following factors should be considered in developing these boundaries:

1. Past channel movement. Blue lines from the 1950s topographic maps should be superimposed on the recent aerial photographs or topographic maps to determine the



(a) Pool Depth Measurement Method (b) Pool Depth Histogram

Figure 14-4 The (a) method of measuring pool depths and (b) distribution of major pool depths in the vicinity of proposed crossing BR-34 over Paint Branch.

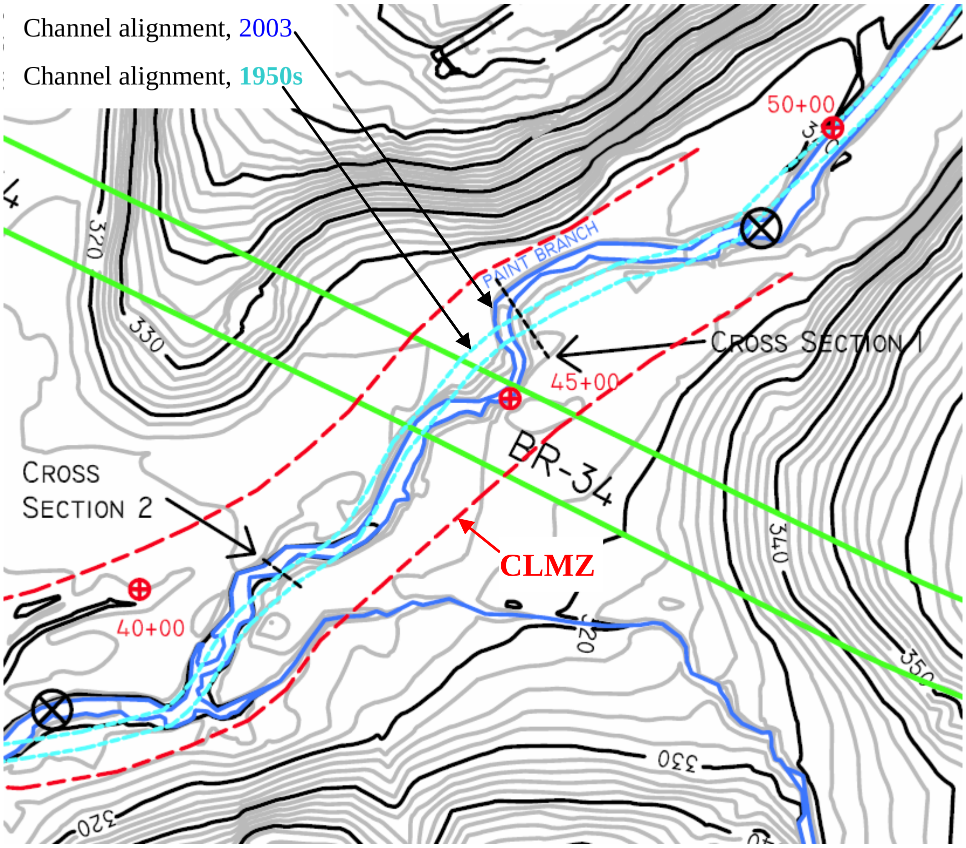


Figure 14-5 Example delineation of CLMZ.

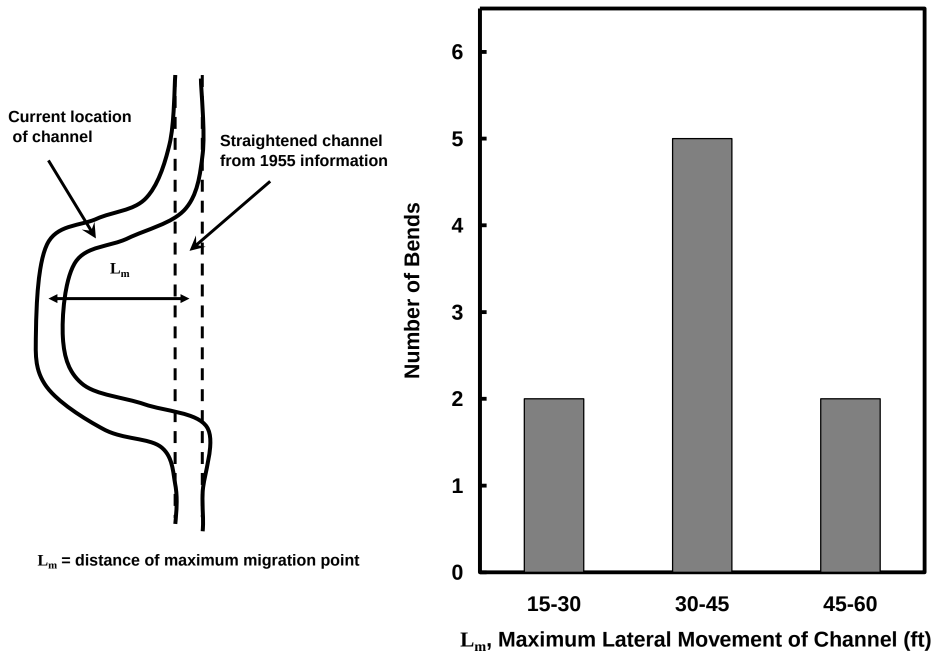
location, direction, and magnitude of channel movement that occurred between the1950s and the present. Figure 14-6(a) shows the typical points along the channel planform where lateral movement can be measured. A lateral movement frequency histogram can be developed from the measurements to assess the frequency and magnitude of channel lateral movement in the interim between the years documented by the mapping. The histogram should be used to infer the potential for similar movement to occur over a similar time period.

2. Potential pathways for channel avulsions. Valley topography should be examined to identify potential areas where the channel may avulse; these are indicated by depressions, abandoned channel sections, and developing channel segments.
3. Gradients influencing lateral migration. Cross-valley gradients can act as boundaries for channel movement by either impeding migration (upslope grade) or facilitating migration (downslope grade).

(Note: A more detailed explanation of procedures for delineating the CLMZ is under development and will be added to this chapter at a later date.)

Stream Cross Section Characteristics and Flow Estimates

An estimation of hydraulic parameters for bankfull and top-of-bank flow conditions should be computed for two cross sections: the bankfull flow estimate and sediment mobility cross section and the channel classification cross section (Section 14.3.2).



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

Figure 14-6 (a) Typical locations for measurement of lateral movement of the main channel from the straightened channel configuration recorded during the 1950s. (b) Histogram developed to examine the distribution of measured distances.

Bankfull Flow Estimate

At a minimum of one cross section, an estimate of the bankfull flow should be developed from the best available on-site bankfull indicators. The bankfull flow conditions can be obtained from the Manning resistance equation (Henderson 1966):

$$Q = \frac{1.49}{n} \; A \; R_h^{2/3} \; S_f^{1/2} \tag{14-3}$$

where Q is the flow in cubic ft per second (ft^3/s), *n* is the Manning roughness coefficient, A is the cross-sectional flow area in square ft (ft^2), R_h is the hydraulic radius in ft, and S_f is the estimated friction slope in ft/ft. Both area and hydraulic radius can be obtained from an analysis of the channel cross section. The friction slope, S_f, can be approximated from the low-flow water surface slope measured along the channel profile. Two low-flow water surface slopes measured from the channel profile survey can be used to approximate the friction slope: (1) the local riffle-crest-to-crest water surface slope, and (2) the local riffle water surface slope. The local riffle-crest-to-crest slope will provide a lower estimate of friction slope and, as a consequence, a lower corresponding flow than the local riffle slope will. Where downstream bends or obstructions are likely to cause backwater through the entire extent of the riffle during bankfull flow, the riffle-crest-to-crest slope is the better estimate of the two. Where bankfull flow over the riffle is unlikely to be affected by downstream backwater effects, the local riffle slope should be used to estimate the bankfull flow.

Where the resistance of the channel at bankfull flow conditions can be attributed primarily to the channel bed, estimates of the channel Manning roughness coefficient *n* can be obtained using the Limerinos (1970) relation:

$$n = R_h^{1/6} \frac{0.0926}{1.16 + 2 \, \text{Log} \dfrac{R_h}{D_{84R}}} \qquad (14\text{-}4)$$

where R_h is the hydraulic radius (ft) and D_{84R} (ft) is the particle size which equals or exceeds the diameter of 84% of the particles based on the pebble count of the riffle surface. D_{84R} is obtained from the cumulative gradation curve (shown in Figure 14-7). As indicated by the Limerinos relation, the value of *n* changes with flow conditions. Estimates of flow will be gross and should only be expected to be accurate to within 50% below to 100% above the estimated values because of the uncertainty and variability of hydraulic parameters caused by such factors as the channel planform, the non-uniformity of the streambed topography, and debris.

Average Channel Boundary Shear Stress

The average boundary shear stress (Henderson 1966) at the cross section should be estimated as

$$\tau_b = \gamma \, R_h \, S_f \qquad (14\text{-}5)$$

where τ_b is the cross-sectional average boundary shear stress in pounds per square foot (lb/ft^2) over the riffle and γ is the unit weight of water (62.4 pounds per cubic foot). Boundary stress here represents average boundary stress along the entire wetted perimeter of the channel. 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.

Top-of-Bank Flow Estimate

To date, geomorphologic studies of Maryland streams conducted for the OBD indicate that many Maryland streams are deeply incised in their valley flats. This means that the channels have degraded from the conditions in which the valley flats were created. Consequently, the top-of-bank stage of the channel is higher than the bankfull stage. The condition at which flow just fills the channel to the top of the banks is termed the *top-of-bank condition*. The flow, flow velocity, and boundary stress at the top-of-bank stage should be estimated using Equations 14-3, 14-4, and 14-5 or they should be determined from an in-channel HEC-RAS model.

Flow Conditions Summary and Analysis

A hydrologic analysis report by SHA's Structure Hydrology and Hydraulic Unit of the Bridge Design Division is typically completed prior to the initiation of the detailed stream morphology study. The hydrologic analysis report (see Chapter 5) provides an analysis of land use and watershed hydrology. A summary table, as shown in Table 14-18, should be obtained from the hydrologic study.

A summary of bankfull and top-of-bank flow conditions should be developed and incorporated into Table 14-19. The flow recurrence interval for the existing and ultimate development flows should be compared to bankfull and top-of-bank flows. The approximate recurrence interval of the top-of-bank flow should be determined by comparing computed flow values for top-of-bank conditions with flows of various frequencies conducted under the hydrologic analysis. In

Table 14-18 Results of Hydrologic Analysis at a Specific Crossing

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	150	310	230	290	300
10	490	830	660	630	650
50	980	1720	1350	1160	1180
100	1230	2330	1780	1400	1420

Table 14-19 Cross Section and Reach Parameters for Bankfull and Top-of-Bank Flow

Parameter	Bankfull Cross Section 1	Top-of-Bank Cross Section 1
Cross Section Area, A (ft^2)		
Top Width, W (ft)		
Average Flow Depth, Y (ft)		
Hydraulic Radius, R_h (ft)		
Manning *n*		
Friction Slope, ft/ft		
Flow Rate, Q (ft^3/s)		
Flow Velocity, V (ft/s)		
Channel Average Boundary Shear Stress*, τ_b (lb/ft^2)		

* Boundary stress here represents 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.

addition, the bankfull flow should be compared to flows of various frequencies conducted under the hydrologic analysis. To date, bankfull flow has been found to be much less than the estimated flow for a 1.5-year recurrence interval in OBD morphology studies.

Rosgen Channel Classification

Using the cross section survey measurements and the estimated hydraulic parameters, the channel should be classified using the Rosgen (1996) channel classification method. Note that cross section elevations, channel profile elevations, and valley profile elevations should all be referenced to the same datum.

Characteristics of Bed Material and Load

The main objectives of the sediment analysis portion of the detailed stream morphology study are to (1) characterize the surface composition of riffles, (2) characterize the sediment that is frequently transported, and (3) compute the critical boundary stresses required to mobilize the bed load. An analysis of the bed material in armored riffles indicates the flow conditions that mobilize the bed and often destabilize the bed and banks. Analysis of the bed material characteristics, the bed load characteristics, and the ability of the flow to mobilize and transport sediment at bankfull and top-of-bank conditions should be conducted to assess the stability of the channel.

Observations of Maryland streams in the Piedmont and Ridge and Valley regions indicate that many riffles remain stable under bankfull conditions, while a load composed of finer-grained gravels and sand appears to be transported over the coarsest material in the riffles. Consequently, the gradation characteristics of very stable riffles are substantially different from those of the load determined from bar samples or pit traps. In very unstable streams and aggrading streams, such as some of those in the Maryland Coastal Plain, much less difference appears to exist between the gradation characteristics of riffle surface material and frequently mobilized bed load material. The degree to which the critical stress required to mobilize sediment that composes the riffle armor are exceeded and the frequency at which they are exceeded are important for evaluating both the stability of these riffles and the stability of the stream profile. These analyses of sediment mobility may be sufficient for examining the tendency of the stream to aggrade or degrade. They are insufficient, however, for determining rates of channel change along the profile; a determination of rates of change would require models that incorporate sediment transport and storage rates for multiple grain size fractions. In the future, sediment transport and storage models may be used evaluate the rate of channel degradation and aggradation. At this time, the OBD does not recommend the use of numerical sediment transport models for detailed stream morphology studies; however, the cost effectiveness of using these models will continue to be evaluated as numerical sediment transport models are improved.

Bed Load Gradation

Sieve analysis for the pit trap samples, bulk bar samples, and subsurface samples should be conducted using the complete sieve series shown in Table 14-20. Sieve analysis must be completed using the sieves specified in Table 14-20. The sieve sizes, j, are based on what is known as the ϕ-scale ($j = 2^{-\phi}$). For particles smaller than 2 mm, ϕ-scale increments are used. For particles greater than or equal to 2 mm, $\phi/2$-scale increments are used. For an explanation of the ϕ-scale, see Bunte and Abt (2001) or Boggs (2001). Small differences exist between some of the standard and widely available sieve sizes and the ϕ-scale; however, the errors introduced by these differences are negligible in the gradation analysis.

The cumulative size distribution and the size histogram for the gradation analysis for all samples used to represent the bed load should be developed and plotted as indicated in Figures 14-7 and 14-8. The median particle size of the load, D_{50L}, should be obtained from the cumulative curve of Figure 14-7. In addition, the largest two particles in each of the samples should be identified, weighed, and all three axes (smallest, intermediate, and largest) of the particles should be measured and recorded. On the bed load histogram, the most frequent size interval for the coarse-grained particles should be identified as the mode and labeled as $D_{mode\text{-}L}$. Because the intervals for gravel, cobble, and boulders are based on $\phi/2$ increments, sieve sizes double every two intervals, whereas for sand, silt, and clay, the sieve sizes double at every interval. Thus, the ϕ-scale intervals for sand are twice as large as the $\phi/2$-scale intervals for gravel, cobbles, and boulders. Therefore, any comparison of the weight percentages of sand particles with the weight percentages of larger particles requires that the sand weight percentages be halved in order to make the values consistent. For example, Figure 14-8 shows that 1 to 2 mm sand accounts for 12% of the total weight of the bed load sample. This value should be viewed as approximately 6% when comparing it to the fine gravel size category, 2 mm to 2.8 mm, which accounts for 13.4% of the total weight.

Largest Particles on the Bar A frequency distribution of the intermediate-axis size of the particles should be developed. The mode of the 30 larges particles obtained from the surface of

Table 14-20 Complete Sieve Series for Analysis of Bedload Data

Material Type	Phi Scale	Sieve ASTM No.	Sieve Opening Size (in)	Sieve Opening Size (mm)	Equivalent ϕ- or ϕ/2-Scale Size (mm)
Silt/clay	4	230		0.063	0.063
Sand	3	120		0.125	0.125
	2	60		0.25	0.25
	1	35		0.5	0.5
	0	18		1.0	1.0
	–1	10		2.0	2.0
Gravel	–1.5	7		2.8	2.8
	–2	5		4.0	4.0
	–2.5	3-1/2		5.6	5.7
	–3		5/16	8.0	8.0
	–3.5		7/16	11.2	11.3
	–4		5/8	16.0	16.0
	–4.5		7/8	22.4	22.6
	–5		1-1/4	31.5	32.0
	–5.5		1-3/4	45	45
	–6		2-1/2	63	64
Cobble	–6.5		3-1/2	90	91

the bar should be used to examine the mobility of the bar material during bankfull flow conditions. The median size of the 30 largest particles is typically used as D_{max} for the bar and should be compared to D_{max} obtained from the samples of the bedload (Figure 14-8). One or both of these estimates of D_{max} should be used in the assessment of bed load mobility described below.

If possible, the source of the largest bar material should be identified as either local or part of the load transported from another area of the watershed. The occurrence of large pieces of broken bedrock derived from either the bed or the banks in the vicinity of the measurement location should be evaluated to determine their effect on channel stability. These large particles may be limited or may not be an important factor when considering the load that must be transported in all but the largest flow events. In other cases, the production, transport, and deposition of the large pieces of bedrock may have a significant effect on local channel stability.

Analysis of Riffle Pebble Count Data

The cumulative curve and size histogram for the pebble count data set for each riffle being evaluated should be developed and plotted as shown in Figures 14-8 and 14-9. The median particle size of the riffle should be labeled as the D_{50R} on both the cumulative curve and the histogram. Likewise, the particle size that equals or exceeds the diameter of 84% of the particles based on the pebble count of the riffle surface should be labeled as D_{84R} on both plots. On the histogram, the most frequent size interval for the coarse-grained particles should be identified as the mode and labeled as $D_{mode\text{-}R}$.

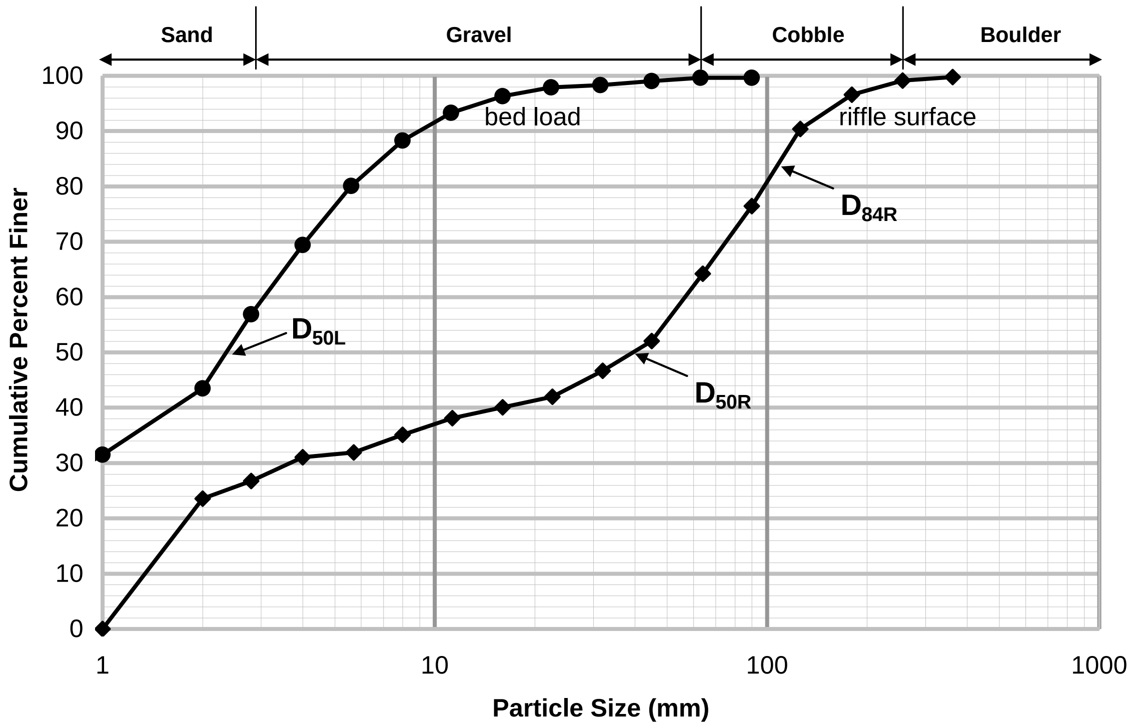


Figure 14-7 Grain size cumulative distribution curve for the sieve analysis of pit trap samples (bed load) and riffle pebble count (riffle surface).

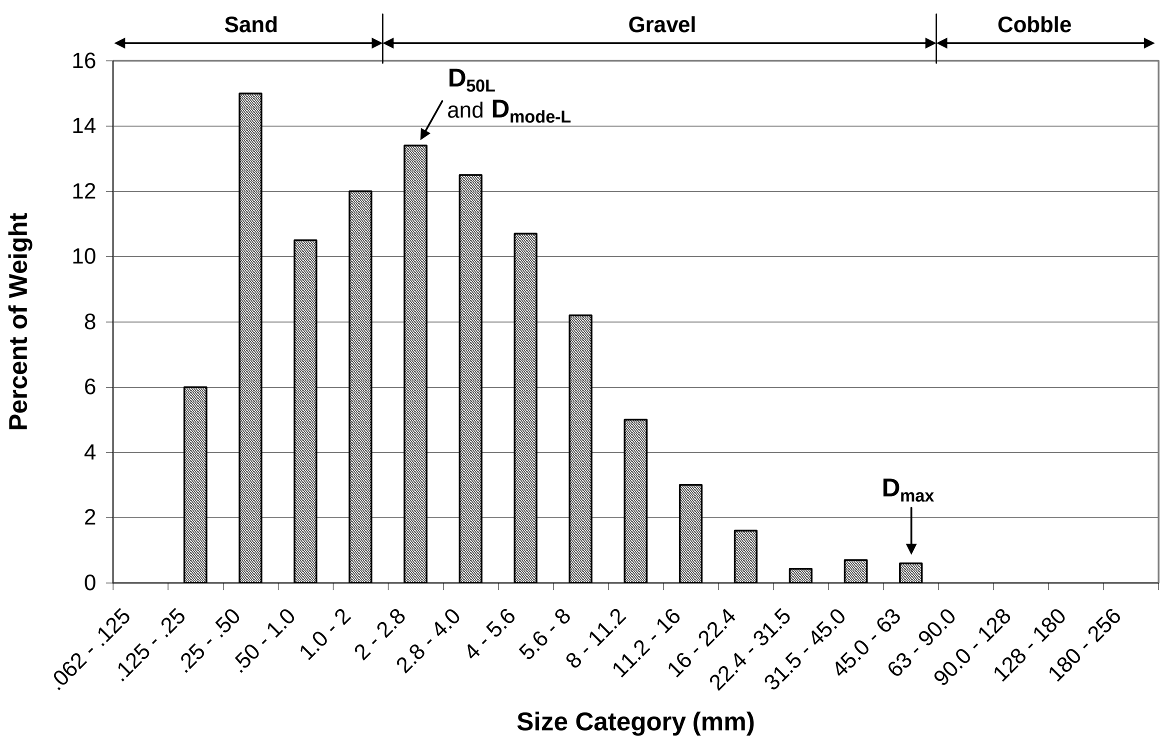


Figure 14-8 Size histogram (based on mass) for bed load samples obtained from pit traps. Note that the category size changes from ϕ-scale for sizes less than 2 mm (sand) to ϕ/2-scale for sizes larger than 2 mm (gravel and larger).

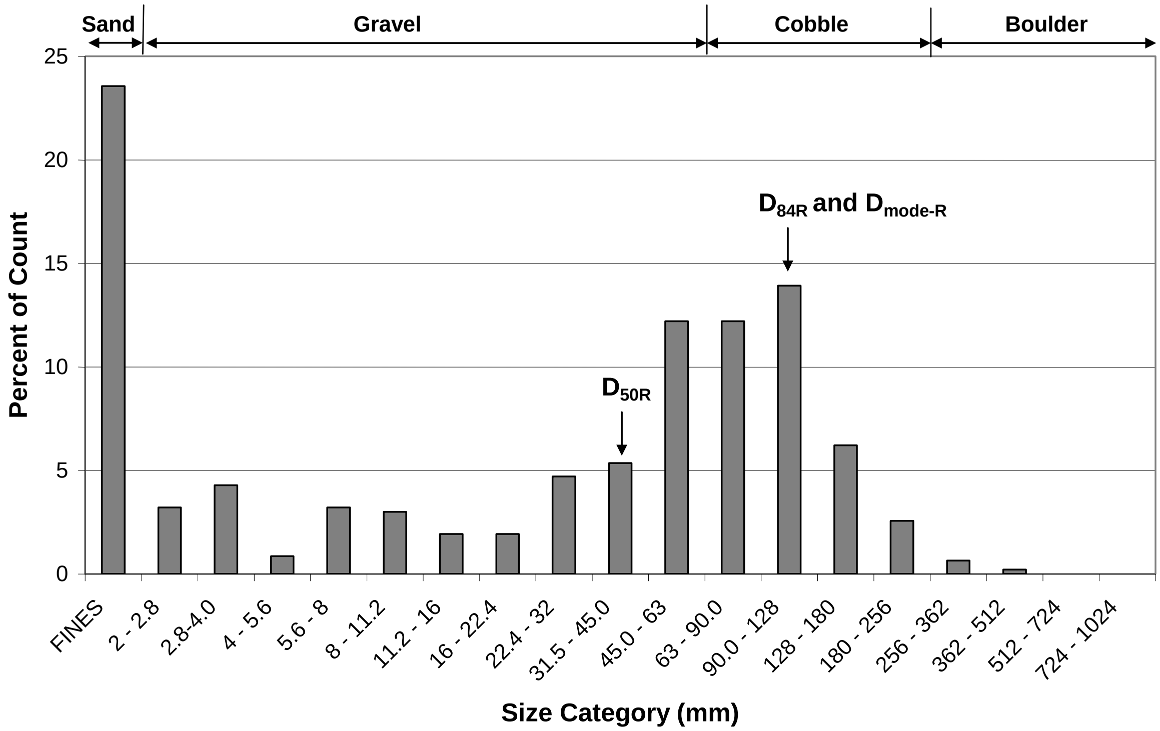


Figure 14-9 Size histogram of riffle surface.

Assessment of Bed Load Mobility

One method for assessing channel stability recommended by Rosgen (2006) is to examine the mobility of the bed load in a riffle in an assessment reach. In this method, the boundary shear stress required to mobilize the largest particle of bed load material over the riffle in the assessment reach (i.e., the critical boundary shear stress) is computed and compared to the estimated average stress on the channel boundary to determine whether the bankfull flow has the capacity to transport the particle; the channel is then considered to be stable if it is just capable of moving the particle, aggrading if the largest particle cannot be transported, and degrading if the boundary stress is larger than required to mobilize the particle.

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 critical boundary stress, $\tau_{c\text{-}L}$, is estimated from the dimensionless boundary stress, τ_c^*, which is calculated using the relation developed by Andrews (1994). The Andrews (1994) relation, modified for use with the parameters measured in the detailed morphology study, is

$$\tau_c^* = 0.0384\left(\frac{D_{max}}{D_{50R}}\right)^{-0.887} \qquad (14\text{-}6)$$

where τ_c^* is the dimensionless boundary shear stress required for critical conditions, D_{max} represents the maximum-sized transported bed material, converted from millimeters to ft, and D_{50R} represents the characteristics of the bed surface, converted from millimeters to ft. In this assessment, D_{max} is considered to be the size of the largest particle either (1) on the bar, (2) in the subsurface sample, or (3) in the pit trap, or D_{max} may be the mode of the 30 largest particles measured on the bar. Equation 14-6 provides a dimensionless critical shear stress that compensates for the gradation of the bed material, including the effect of particle hiding and protrusion. The critical boundary shear stress for the largest particles in the bed load, $\tau_{c\text{-}L}$, is computed from the dimensionless boundary stress as

$$\tau_{c\text{-}L} = \tau_c^* \, (S - 1) \, \gamma \, D_{max} \qquad (14\text{-}7)$$

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). Values for the Table 14-21 parameters should be used to estimate critical boundary stress using the Andrews (1994) relations. Note that consistent units are required in Equations 14-6 and 14-7.

The results of the computed critical boundary shear stress, $\tau_{c\text{-}L}$, and the estimation of average boundary stress provided in Table 14-19 indicate the bed load mobility during both bankfull conditions and top-of-bank conditions. Channel aggradation may occur if the channel boundary stress is inadequate to mobilize and transport any size fraction of the bed load; therefore, an evaluation of the rate of supply of each sediment size fraction and the capacity to mobilize and transport each size fraction is necessary. The OBD is evaluating and developing practical techniques that may be useful in determining the potential for bed aggradation.

According to Rosgen's (2006) method, if the critical boundary stress ($\tau_{c\text{-}L}$) is estimated to be greater than the average boundary stress (τ_b) at bankfull conditions (i.e., $\tau_{c\text{-}L} > \tau_b$), then bed aggradation is indicated. Conversely, if the critical boundary stress is estimated to be less than the average boundary stress at bankfull conditions (i.e., $\tau_{c\text{-}L} < \tau_b$), then bed degradation is indicated. An important assumption that should be acknowledged in this analysis is that the estimated average boundary stress on the channel may be affected by planform resistance or bank resistance that is significantly different from the bed resistance. This analysis should corroborate the findings of the visual assessment and the following analysis for riffle stability.

Stability of Riffles

Comparison of the frequency distribution curves developed from data that represent the bed load and from pebble count data from riffles that control channel grade can provide an indication of bed stability. The sediment and bed material size frequency analysis must be viewed in the context of site conditions that may include effects such as backwater from downstream obstruction, local sediment sources from bedrock or deep scour holes, or tributaries.

Table 14-21 Sediment Characteristics and Estimated Critical Boundary Shear Stress Required for Weak Transport of the Largest Particles in the Bed Load

Parameter	Channel Cross Section
D_{50R} (riffle pebble count, mm)	
D_{50L} (bar sample or pit trap, mm)	
D_{max} (bar sample, median of 30 largest particles on bar, or pit trap, mm)	
Andrews (1994) τ_c*	
Andrews (1994) $\tau_{c\text{-}L}$ (lb/ft^2)	

The riffle parameters (D_{50R} and D_{mode-R}) developed from the riffle pebble count analysis should be compared to the bedload sediment parameters (D_{50L} and D_{mode-L}) of the bed load sieve analysis. In aggrading channels and in channels experiencing high sediment transport conditions where the entire bed is mobile, the particle size parameters of the riffle and those of the load tend to be similar, with the riffle D_{mode-R} and D_{50R} being slightly greater than bed load D_{mode-L} and $D_{50L,}$ respectively. If the riffle and load parameters were identical, then the flows that would mobilize the riffle would be similar to those that would mobilize the load. Under these conditions, the transport of gravel into and out of the reach would have to be in a near perfect balance in order for the riffle-crest elevation to remain constant. Observations in Maryland indicate that where the riffle particle size parameters are nearly identical to those of the bedload, the transport of gravel into and out of stream reaches is not balanced. Rather, the stream has a high sediment load, is typically aggrading, and is unstable vertically and laterally.

Where the riffle D_{50R} and D_{mode-R} are substantially larger than the D_{50L} and D_{mode-L} of the bed load, respectively, as is the case for the samples shown in Figures 14-8 and 14-9, the stress conditions required to mobilize the riffles (high-gradient features) that tend to provide grade control for the streambed are substantially higher than the stress conditions required to mobilize the bed load. Under many scenarios, the channel will change only slightly until stress conditions exceed those required to destabilize the riffle gravels. Large differences between the gradation of the riffle and the gradation of the load tend to occur in three circumstances: (1) under highly stable bed conditions and often, but not always, under low sediment load conditions; (2) in regions of gradual channel degradation; and (3) at the location of steep degrading features such as headcuts or less obvious boulder or cobble knick zones.

14.3.4 DETAILED MORPHOLOGY REPORT

A report should be developed to communicate the results of the detailed morphology study to the OBD. The purpose of the stream geomorphic report is to describe the methods used for collection and analysis of data, to explain the study results, and to provide recommendations for the design of the crossing based on those results. The general organization and content of the report are outlined below. The report should be written in narrative form. Some of the suggested items may not be necessary in every detailed morphology report; the items to be included should be those considered by the lead engineer and OBD to be relevant to the crossing for which the study is completed. An example of a detailed morphology report is provided in Appendix D.

A draft of the report should be submitted to the OBD in either a portable document format (PDF) or a standard word processor format compatible with MS Word 2000. A final version of the report that addresses OBD comments and suggestions may be submitted as a PDF; however, the document must also be submitted in a standard word processor format compatible with MS Word 2000. A printed copy of the entire final report should be provided, except as noted for Appendix I. In addition, data used to create all of the report's graphs and figures should be provided in the form of spreadsheets compatible with MS Excel 2000.

Detailed Stream Geomorphic Report

Executive Summary

I. Introduction

A. Identify the associated road designation, stream name, and purpose of constructing a new crossing or replacing an existing one.

B. Identify the project location: the part of the county, the watershed, and the physiographic region in which the project is located.
C. State the purpose/scope of the detailed study.

II. General Findings

Briefly summarize the most significant findings of the detailed study. Address any or all of the following elements:

A. Historic and recent modifications to the channel
B. Channel characteristics at the crossing
C. Rosgen channel classification in the project reach
D. Causes and extent of vertical bed instability
E. Causes and extent of lateral instability
F. Sediment dynamics
G. Supply and characteristics of debris
H. Backwater flooding
I. Scour and deposition at the crossing
J. Bankfull flow parameter summary
K. Existing and potential effects of channel morphology and debris on the crossing
L. Effect of the existing structure on channel morphology and the potential for crossing-channel interaction to be detrimental to the structure and/or the environment.
M. Environmental considerations

III. Summary of Design Recommendations and Considerations

Chapter 1: Introduction

I. Purpose and Objectives: State the purpose and objectives of the detailed morphology study.

II. Project Description

A. Describe the purpose of the associated project, such as bridge replacement or construction of a new highway, and include the road designation.
B. Describe the project location, including the part of the county, the watershed, and the physiographic region in which the project is located.
C. The location of the existing or proposed crossing(s) and associated streams should be identified in relation to (1) the boundaries of upstream watersheds, and (2) the transportation network in the immediate area. Provide at least two maps: (1) a vicinity map of the contributing watershed, the crossing, and approximately 1 mile of the area downstream of the project site and (2) a location map of the region within approximately 1 mile of the project.
D. Provide a topographic map that covers the extent of the geomorphic assessment.
E. Describe the problems that were known prior to the evaluation.
F. Refer readers to the appendix of extensive photo-documentation of the verification of the visual assessment.

III. Scope: Identify the study’s upstream, downstream, floodplain, and valley limits.

Chapter 2: Existing Reach Stability Analysis

I. Summary of Hydrologic Analysis

   A. Show existing and ultimate development conditions of the watershed as shown in Table 14-18. Cite the hydrologic report.
   B. Compare the flow interval for the existing and ultimate development flows to morphologically significant flows such as bankfull and top-of-bank flows.
   C. Describe the influence of current and potential future hydrologic conditions on channel morphology.

II. Physiographic Region and Channel Morphology

   A. Indicate the physiographic region in which the project is located.
   B. Provide a brief description of the basin and site geology and its relation to channel morphology.
   C. If tidal fluctuations influence channel flow, briefly describe their effects.

III. Historic and Recent Land and Valley Use

   A. Identify the historic documents and maps reviewed and the information obtained on milldams, historic channel locations, and other valley and watershed modifications.
   B. If possible, include historic maps or draw the approximate locations of historic channels or valley modifications on available topographic maps.

IV. Site Examination and Valley Profile

   A. Plot a valley profile that shows the elevation of the streambed thalweg, the top of the stream banks, and the water surface along valley stations. The detailed profile plot should be produced on at least 11 x 17-in paper at standard horizontal (e.g., 1 in = 100 ft) and vertical scales (1 in = 5 ft).
      1. Identify and label the locations of the existing and/or the proposed crossing centerline and other import crossing features, including upstream and downstream foundation and embankment limits.
      2. Identify and label the locations of base level points (Table 14-4), the degraded local base level point (DLBLP), and the locations where the minimum degraded slope, S_{dgr}, was estimated (Section 14.3.3, Figure 14-3).
      3. Plot the degraded riffle-crest line described by Z_{DBL} (Equation 14-1 and Figure 14-3).
   B. Plot all points that represent the bedrock elevation obtained from profile surveys or from subsurface investigations (trenches, Geoprobe® samples, or borings), if available. Develop a bedrock profile if a sufficient number of points exist.
   C. Provide a description of the results of site probing, if any (i.e., site borings, Geoprobe® sampling, or trenches).
   D. Describe the factors affecting channel morphology and channel stability that were observed during site examinations with reference to the valley profile, historic assessment, and the spatial extents and associated factors listed below. Note that while the same features should be described for each reach, the focus of the assessment will differ between reaches.

1. Base level reach. Assessment of the base level reach should emphasize base level changes and channel degradation.
   a. Limits of reach
   b. Valley bottom width, slope, and curvature
   c. Any factors that may influence the hydraulic engineering study: recommend supplemental cross sections to represent the effects of dams, abandoned roadways, channel constrictions that were not surveyed for the hydraulic modeling study.
   d. Degree of channelization
   e. Bank height and strata changes and the effect of each on sediment supply (see Tables 14-6 and 14-15)
   f. Descriptions of incision and entrenchment
   g. Bed sediment description of riffles and bars
   h. Evidence of a change of bed materials in successive pools: clay, cobble, or bedrock (see Table 14-7)
   i. Locations of bedrock and the associated features (e.g., pools, steps, banks)
   j. Evidence of channel aggradation (e.g., channel bars—see Table 14-8) or degradation and their effect on sediment and debris supply
   k. General response of the channel to historic and existing watershed and channel conditions and, if possible, the anticipated evolution of the streambed and banks
   l. Location of water surface profile controls
   m. Low-flow high-gradient features (Tables 14-5a and 14-5b)
   n. Riparian vegetation
   o. Stream types observed
   p. Tributary confluences: locations; supply of sediment and debris; evidence of base level changes
2. Project reach. All of the elements addressed in the base level reach should be evaluated for the project reach as well; each of the following factors should also be discussed. Emphasis should be on the potential instability of the channel at the crossing location and on problems with an existing structure.
   a. Alignment of channel and existing structure
   b. Alignment of flood flows to the existing structure
   c. Existing scour
   d. Evidence of existing headcuts and the potential for instability from the base level reach propagating into the project reach
   e. Potential for debris jam formation in the channel and on the existing structure
   f. Potential for channel avulsion to a new location
   g. Potential for lateral migration of specific bends
3. Supply reach. In this reach, the supply of debris and sediment to the crossing location should be emphasized. All of the elements addressed in the base level reach should be discussed; the potential for lateral movement (avulsion or migration) of the channel upstream to affect the channel and flow at the crossing should also be discussed.

V. Detailed Stream Profile

A. Briefly describe the method used to collect the data. Provide the reduced survey data in an appendix. The cross section elevations, channel profile elevations, and valley profile elevations should all be referenced to the same datum.
B. Plot a detailed stream profile based on the distance along the stream thalweg as shown in Figure 14-3. The detailed profile plot should be produced on at least 11 x 17-in paper at standard horizontal and vertical scales.
C. Plot the point data and lines representing the elevation of the stream thalweg, the top of banks, and the water surface at a sufficient number of points to characterize pools and riffles and to detect headcuts or other high-gradient bed features.
D. Plot all points that represent the bedrock elevation obtained from profile surveys or from subsurface investigations (trenches, Geoprobe® samples, or borings), if available. Develop a bedrock profile if a sufficient number of points exist.
E. Identify and label locations of base level points (Table 14-4), the degraded local base level point (DLBLP), and the locations where the minimum degraded slope, S_{dgr}, may have been estimated (Section 14.3.3, Figure 14-3). Plot the line represented by Z_{dbl} (Equation 14-1 and Figure 14-3).
F. Describe and interpret the existing channel profile. Include the following:
   1. Bed features near the existing or proposed crossing structure (e.g., pools, riffles, scour holes, debris, utility crossings, riprap)
   2. Indication of channel vertical instability
   3. Correspondence between lateral instability and characteristics of the stream profile
   4. Variation in pool depth
   5. Elevation of bedrock and its effect on the profile
   6. Elevation of the top of banks
   7. Bankfull indicators
   8. Variation in channel slope

VI. Scour in Pools Caused by Bends and Other Obstructions

A. Describe the method used to analyze maximum pool depths, including the use of the riffle-crest line as a reference.
B. Plot a pool depth histogram and specify the pool depth that should be used as an approximation of maximum pool depth at the crossing.
C. Describe how bedrock may or may not limit scour in pools at the crossing.
D. Specify the approximate length and depth of pools and how they may be considered in scour analysis.
E. Acknowledge the potential for the scour in bends to be different if the channel characteristics should change significantly. Note that this analysis is limited to scour in bends and obstructions in the absence of a crossing; flow contraction, abutments, wing walls, piers, and debris at the existing or proposed structure are not considered in this analysis.

VII. Potential Long-Term Degradation

A. Describe the reason for selecting the DLBLP and other base level points (i.e., what feature was chosen, where it is, and why it was chosen over other base level points to serve as the DLBLP). Refer to both the valley profile and the detailed stream profile.

B. Describe the estimation of S_{dgr}, the minimum degraded slope.
C. Describe the method for obtaining the line representing the degraded riffle crest, Z_{dbl}.
D. Show the estimate of ΔZ, the potential long-term degradation that may occur at the crossing based on the chosen DLBLP and the S_{dgr}.
E. If bedrock is present along the valley profile or channel profile, confirm whether or not the estimate of channel degradation approximates the bedrock profile.

VIII. Channel Lateral Movement Zone (CLMZ)

A. Describe the data, documents, and methods used to determine the rate of lateral movement of the existing channel in the vicinity of the crossing.
B. Confirm that measurements obtained from comparison of maps and/or aerial photographs were verified by field measurements.
C. Provide a histogram of the measured lateral movement and the span of time over which the movement occurred. Make a case for whether the largest measured lateral distances represent progressive channel migration through bank erosion or if the movements were caused by sudden channel avulsions.
D. Provide a plan view drawing at the appropriate engineering scale (such as 1 in = 50 ft) of the estimated boundaries of the lateral movement zone and the existing or proposed crossing alignment as shown in Figure 14-5. The former location of the channel and the existing location of the channel should be plotted with the CLMZ boundary lines.
   1. Describe the method used to determine the boundaries.
   2. Identify structural elements within the CLMZ
   3. Describe potential consequences to the crossing structure that may result from future lateral movement of the channel.

IX. Stream Cross Section Characteristics and Flow Estimates

A. Describe the location and the purpose of each measured cross section.
B. Briefly describe the method used to collect the data and refer to the data appendix for the reduced survey data. The cross section elevations, channel profile elevations and valley profile elevations should all be referenced to the same datum.
C. Plot each cross section using appropriate engineering horizontal and vertical scales. Plot lines representing the bankfull and top-of-bank water surface levels as shown in Figure 14-1 using the downstream view convention.
D. Provide a photo of each cross section showing the cross section with a string line (Figure 14-2).
E. Describe the method and equations (Equations 14-3, 14-4, and 14-5) used to obtain estimates of the parameters provided in Table 14-19 for each of the cross sections. Describe the method used for estimating channel slopes and bankfull and top-of-bank flows.
F. Develop a table or tables similar to Table 14-19 for all cross sections except those used to show blockage effects.
G. Compare the magnitude of both the bankfull and the top-of-bank flows with the 2-year, 5-year, and 10-year flows obtained from the hydrologic analysis study.

X. Characteristics of Bed Material and Sediment Load

A. Bedload Gradation

1. Briefly describe the data collection method and the conditions under which the bedload or bar samples were obtained. Identify the locations where the samples were collected.
2. In the data appendix, provide the results of the data and sieve analyses from pit traps, bulk bar samples, or subsurface samples.
3. A plot of the cumulative percent finer (Figure 14-7) and a size histogram (Figure 14-8) should be provided for the bedload data.
4. Label D_{50L} and $D_{mode\text{-}L}$on the cumulative percent finer plot (Figure 14-7) and D_{50L}, $D_{mode\text{-}L}$, and D_{max} on the the size frequency histogram (Figure 14-8).
5. If multiple samples were obtained and composited, a summary table should be provided to show the individual sample characteristics and the composited characteristics.

B. Analysis of Riffle Pebble Count Data

1. Briefly identify the location(s) where the pebble count data were obtained.
2. Include riffle pebble count data and gradation analysis in the data appendix.
3. Plot the cumulative percent finer (Figure 14-7) and the size histogram (Figure 14-9) for the riffle pebble count data.
4. Label D_{50R} and D_{84R} on the cumulative percent finer plot and D_{50R}, D_{84R}, and $D_{mode\text{-}R}$ on the size histogram for each pebble count data set. D_{84R} is needed for the estimation of bed roughness in the estimation of flow.

C. Largest Particles on the Bar

1. Describe the location and general method for obtaining 30 particles from a bar. Include the data in the data appendix.
2. Plot a histogram of the 30 largest particles obtained from a bar. Use the same intervals as provided in the bedload sediment histogram.
3. Plot the median of the largest particles on the bar (D_{max}) in the histogram.
4. Justify the particle size selected to represent the largest particle transported under bankfull conditions: compare the D_{max} from the bar and the D_{max} obtained from the bedload sample. Typically, D_{max} adequately represents the largest particle sizes mobile during bankfull flows; however, recent floods may have deposited material on bars that would not be mobile under bankfull events.

D. Assessment of Bedload Mobility

1. Describe the method and parameters used to determine the mobility of the largest particles in the bedload.
2. Complete and include a Table 14-21.
3. Explain the capacity of the channel at bankfull stage to transport D_{max} and what it means in terms of the stability of the channel according to the Rosgen (2006) method for assessing the bedload mobility.

E. Stability of the Riffles

1. Compare the riffle surface parameters (D_{50R} and $D_{mode\text{-}R}$) developed from the riffle pebble count analysis to the bedload sediment parameters (D_{50L} and $D_{mode\text{-}L}$) of the bed load sieve analysis.

2. Based on the comparison of riffle and load parameters, determine whether the bed appears to be aggrading or degrading or whether the riffles are indicated to be stable.

F. Summary of Bankfull and Top-of-Bank Flows and Channel Classification
   1. Summarize each of the assessed cross sections in the format of Table 14-22. The tables should provide a summary of parameters for the estimated bankfull flow conditions at cross sections where this data was developed, including at least one representative cross section and one cross section where bankfull flow conditions were assessed.
   2. Using the bankfull flow, channel cross section characteristics, profile data, and the material characteristics, classify the channel (Rosgen 2006) at each cross section that was located at a riffle.

Table 14-22 Bankfull Flow Parameter Summary for Cross Section(s)

Bankfull Flow Parameter	Bankfull Flow	Top-of-Bank Flow
Cross Section Area, A (ft^2)		
Width, W (ft^2)		
Mean Depth, d (ft)		
W/d		
Maximum Flow Depth, d_{max} (ft)		
Hydraulic Radius, R_h (ft)		
Channel Roughness Coefficient, Manning *n*		
Width of Flood-Prone, W_{fpa} (ft)		
Entrenchment Ratio, ER = W_{fpa} /W		
Channel Incision from Valley Flat, I_{vf} (ft)		
Channel Incision Ratio, IR = I_{vf} /d_{max} (no incision IR = 0)		
Sinuosity, K		
Riffle Surface D_{50R} (mm)		
Riffle Surface D_{84R} (mm)		
Riffle Surface D_{mode-R} (mm)		
Estimated Friction Slope, S_f (ft/ft)		
Flow, Q (ft^3/s)		
Average Channel Boundary Stress, τ_{avg} (lb/ft^2)		
Largest Mobile Particle Size, D_{max} (mm)		
Bed Load D_{50L} (mm)		
Bed Load D_{mode-L} (mm)		
Average Channel Velocity, V (ft/s)		
Critical Boundary Shear Stress for Largest Mobile Particle Size, τ_{c-L} (lb/ft^2)		
Critical Boundary Stress for Riffle Framework, τ_{c-R} (lb/ft^2)		
Rosgen Channel Type		

3. Describe important features of the tables and/or assumptions that were necessary to provide estimates of specific parameters. Add notes to the bottom of the table(s) to indicate specific assumptions that may be important when examining a specific table value.

Chapter 3: Summary and Recommendations

I. Summary of Geomorphic Processes Affecting Channel Stability in the Project Reach
   A. Summarize channel conditions. Address each of the following:
      1. Channel conditions and response to historic and current land-use, valley-use and channel modifications.
      2. Current vertical conditions (slope, incision and entrenchment) and potential causes of continued vertical instability.
      3. Channel planform conditions and potential causes for lateral movement.
   B. Summarize estimated vertical degradation, assumptions and issues related to the estimation, and the observed trends in vertical bed movement.
   C. Summarize lateral movement, including an estimate of potential movement of particular bends near foundation or embankments, the potential for rapid channel avulsions, effect of debris, and movement because of channel aggradation. If piers and abutments are determined to be in the CLMZ, then this fact needs to be addressed in the bridge design. Transfer of information regarding the potential for lateral movement may prompt the structural designer to select foundation elements, such as round piers, that are not sensitive to the angle of attack of the stream. Bridge span arrangements can also be designed to accommodate the CLMZ by minimizing the number of foundation elements in the zone.
   D. Summarize the bed material and its mobility at a range of flow levels including bankfull and top-of-bank flows. Also consider the effect of potential headcuts propagating upstream or into tributaries and the associated effect on bed load.
   E. Summarize the potential for woody debris supply from riparian vegetation and potential for transport to the project area.

II. Design Considerations and Recommendations
   A. Suggest design considerations such as maximum depth of long-term degradation or aggradation that pertain to the long-term stability of the project, including the following:
      1. Depth of long-term degradation and how it should be considered in scour analysis and foundation design
      2. The need for downstream grade control
      3. Scour depth in pools and its potential effect on foundations or embankments
      4. The effect of potential headcuts propagating upstream or into tributaries and their effect on bedload
      5. Conceptual design alternatives that should be considered including countermeasures (depth of key for riprap at abutments)
   B. Suggest design considerations based on the width of the lateral movement zone of the main channel or channels.
      1. Identify considerations associated with the effect of main channel lateral movement on scour around foundations or near embankments.

        a. Pier foundation depths with respect to potential scour after channel migration
        b. Angle of attack of the main channel flow to piers, abutments, wingwalls, embankments, or retaining walls
        c. Effects of large trees immediately upstream of the structure that could form jams in the opening
    2. Provide considerations and recommendations for determining the span of the structure because of lateral movement considerations.
    3. Provide recommendations on the orientation of piers and abutments because of the potential changes in flow direction that may occur as a result of channel lateral movement. Recommendations should consider the following:
        a. Main channel flow under exiting conditions
        b. Main channel flow after vertical degradation, potential widening and channel lateral movement
        c. Alignment of flood flows with down valley direction
        d. Effect of partial blocking by debris on an adjacent opening or pier
    4. Recommend floodplain or channel modifications to reduce lateral instability.
    5. Recommend countermeasures to reduce lateral instability or protect foundations from the effects of lateral movement
C. Suggest considerations for the potential effects of the project on aquatic resources and provide recommendations to avoid impacts or, where appropriate, enhance aquatic and riparian habitat and/or provide for fish passage. The following questions should be considered in these recommendations:
    1. What are the identified riparian and aquatic habitat by others (environmental analysis)
    2. Can wetlands or other valuable aquatic resources be avoided?
    3. Existing channel and riparian vegetation conditions and stability of the channel
    4. Long-term response of the channels – is future degradation of the channel and habitat expected?
    5. Can the channel be restored or stream instability countermeasures designed to enhance habitat?

III. Conceptual Design Alternatives. Provide a series of design alternatives that include drawings and a list of benefits for each alternative.

A. Bridge considerations
    1. Type, size, and location of the crossing structures
    2. Overall bridge length and individual span lengths, minimize piers in the channel, minimum 80-foot spans in channel
    3. Piers – type, shape alignment and location to minimize obstructions to the flow; scour countermeasures not generally recommended. Flood plain piers, channel piers
    4. Abutments – type, setback, skew (open spans with stub abutments versus vertical wall abutments), use of scour countermeasures
    5. Countermeasures
    6. Bankfull channel width and floodplain width in the bridge opening
    7. Relief structures
    8. Culvert versus bridge
B. Culvert crossing considerations

1. Slope and length (bridge versus culvert)
2. Bankfull channel width and floodplain width
3. Multi-cell/pipe structures
4. Fish passage considerations
5. Buried culvert inverts
6. Outlet scour hole and protection
7. Bottomless culverts

C. Roadway embankments and walls
D. Channel modifications
E. Benefits and problems of each alternative, including environmental effects
F. Embankment skew angle

Appendices

Field data, including photographs and measurements, and reduced data tables should be provided in the appendices.

I. Photo-Documentation of the Verification of the Visual Assessment

A. A complete set (electronic and printed) of the digital photographs taken for the detailed morphology study. The electronic files should be provided in a standard image format (e.g., JPG or TIF). If the complete set consists of more than 20 photographs, print only those that illustrate problems identified and discussed in the detailed report.
B. Spreadsheet that briefly describes each photograph (Table 14-2). The spreadsheet should be printed and should also be provided in a format compatible with Excel 2000.

II. Geomorphic Field Data and Plots at Existing or Proposed Crossing

A. Longitudinal profile survey data
B. Sediment assessment reach longitudinal profile survey data
C. Sediment assessment reach longitudinal profile plot
D. Cross section(s) data and plot(s)

III. Sediment Gradation and Mobility Analysis

A. Particle size distribution report
B. Modified Wolman (1954) pebble count(s)
C. Grain size distributions plots and histograms
D. Sediment mobility analysis, Andrews methodology
E. Information regarding scour soils and bed material

IV. Study Area Topographic Map

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Appendix 14-A: Historic and Contemporary Modifications to Channels and Valleys

Awareness of modifications made to channels and valleys is essential for identifying causes of instability and may lead to practical alternatives for designs to accommodate or provide countermeasures for future channel changes. In Maryland, legacy effects persist from historic and recent modifications that include deforestation and cultivation, milldam construction, flood control projects, the installation of sewer lines and other utility crossings, channelization, local widening or deepening of channels, and mining.

Early Land-Use Practices, Milldams, and Legacy Sediments

Milldams or other dams should be located on historic documents. In the field, persons conducting the assessments should pay particular attention to high banks composed of laminated fine-grained sediments. These sediments are common in most of the valleys of the Piedmont and Coastal Plain physiographic regions. The banks are formed in floodplain deposits believed to be the result of legacy sediments (fine-grained sediments deposited during periods of past land use) introduced primarily during the colonial agricultural period (Costa 1975; Cravens 1925; Jacobson and Coleman 1986). During early European settlement of Maryland, deforestation and poor agricultural practices resulted in rapid soil erosion and extensive development of gullies. The eroded soils produced a high supply of sediment to stream channels and floodplains that continued at least until the early 20th century. During much of this same period, milldams were common on streams (Hopkins 1975; Scott 1807) and created backwater conditions that resulted in massive deposition of sediment that buried the pre-settlement floodplains and may have buried pre-settlement channels. Throughout Maryland's Piedmont and Coastal Plain regions, the effects of this massive deposition can be observed today as thick laminated deposits of sand, silt, and clay that cover most of the valley bottoms. In the Piedmont and Coastal Plain, these "post-settlement" alluvial deposits typically overlay an organic (peat-like) layer of sediment that represents the pre-settlement floodplain. In parts of the valley bottom, sandy quartz gravel and cobble typically lie between the organic, pre-settlement floodplain and the underlying bedrock. In other locations, the organic layer lies directly on bedrock. The buried bedrock is often highly fractured and weathered. In some locations, saprolite (very weak and highly weathered and erodible bedrock) underlies the quartz gravel. Channel incision into these fine-grained sediments results in entrenched channels over parts of the Coastal Plain and much of the Ridge and Valley, Appalachian Plateau, and Piedmont physiographic regions.

Flood Control Projects

Persons conducting the assessment should look for signs of flood control projects and their effect on the stream channel. Levees and walls have been constructed and channels have been relocated, straightened and enlarged to contain flood flows along many Maryland streams and rivers. As a consequence of these projects, the channel depth, velocity, and bed stresses for a range of flood levels has increased significantly, resulting in channel incision that frequently causes channel degradation through the post-settlement and pre-settlement alluviums and into the underlying bedrock. In some locations, the incision of the channel into bedrock and the deposition of boulders where the slope decreases or the valley widens downstream are both serious problems that cause channel instability and decreased flood capacity in the region of these flood control projects.

Sewer Lines and Other Utility Crossings

All utility crossings should be identified through available mapping and/or in the field. Crossings for sewer lines and other utilities are often encased and protected with stone or concrete. These utilities were frequently installed decades ago into the legacy sediments. As the channels degrade through these sediments, the armored crossings become a temporary base level or grade control with a steep bed slope or step on the downstream side of the crossing. Although these crossings currently provide grade control and prevent bed degradation from traveling upstream, they may be replaced or lowered in the future, especially to provide for fish passage. Their removal or deterioration allows the bed degradation to continue upstream. In some locations, these utilities also parallel the stream at elevations near or above the current or pre-settlement bed levels. The parallel utility lines may limit lateral migration and evolution of the channel planform. Moreover, as the channel’s sinuosity increases, the flow will begin to erode the material around the utility lines, eventually exposing them.

Channelization

Persons conducting the assessment should look for signs of channelization on available mapping and in the field. Channel straightening and channel enlargement result in increased channel gradient and entrenchment, which causes channel incision (Parker and Andres 1976). Experience in conducting channel morphology studies by OBD indicates that over various periods, sections of streams in all farmable valley bottoms examined to date appear to have been straightened and relocated to improve drainage for agriculture, to accommodate embankments for railways and roads, or to support various other valley uses. A general trend of channel incision (degradation) is observed throughout the Piedmont physiographic region and in some parts of the Coastal Plain region. The streams have incised in response to increased channel gradients and reduced planform resistance caused by channel straightening, channel confinement by embankments and other valley fills, and the reduction in fine-grained sediment load from improved erosion control and land-use practices. The channels incise into the previously deposited post-settlement alluvium, forming high banks composed of fine-grained laminated sediments. Quartz gravels and cobbles are common on sections of stream channel; however, fine-grained sediment, typically with a high content of silt and clay, is present below many streambeds, indicating that the channel may be “perched” on post-settlement alluvial deposits. Other signs of perched stream channels include streams along the valley hillslope on degrading bedrock or the lack of a consistent gravel layer in the banks along the stream bed. Although culvert inverts, utility crossing protection, dams, and other grade controls may prevent some channels from degrading, channels in the Piedmont may continue to degrade until the pre-settlement gravels are exposed. Exposure of bedrock in the center of the valley or exposure of the organically rich peat-like sediment may indicate that the stream has incised to the pre-settlement level. Further degradation may be inhibited for two reasons: (1) the bedrock or cobbles may become exposed, limiting degradation, or (2) gravels at the base of the otherwise cohesive stream banks are prone to erosion, which results in the undermining of banks. Collapse of undermined banks and associated tree fall result in development of bends, which in turn causes a rapid increase in channel length, an increase in channel width, and a reduction in channel gradient. Consequently, channel incision is somewhat inhibited once the underlying gravel, cobble, or bedrock is exposed.

Where historic mapping and/or site information indicate the presence of a mill, the channel was probably relocated and protected to accommodate the milldam, mill pond, and mill race (Evans 2003; Hunter 1979; Leffel 1881). A typical milldam of 8 to 10 ft could have a far-reaching impact upstream, depending on the valley slope. Because of the subsequent pervasive manipulation of valley bottoms and channels for agriculture or transportation, discerning all of the details of the early channel modifications may not be necessary; however, awareness of the substantial manipulations of the streams and the valley can help in determining the magnitude and direction of future channel response.

Local Widening or Deepening of Channels at Crossings

All instances of local channel widening should be identified, particularly if the assessment is being conducted for an existing crossing that will be replaced. A common practice for increasing local conveyance to increase flood flow capacity and meet design storms has been to increase the local flow area. The increase is usually accomplished through a gradual expansion of the channel as it approaches the crossing and then a contraction of the channel immediately downstream of the crossing. The bridge or culvert is then constructed to match the enlarged cross section. Typically, the width of the structure is substantially wider than the channel upstream or downstream of the structure. Although these locally expanded channels may initially convey the design flow, a large percentage of the expanded cross section typically fills with sediment over a short period of time. The reduction in designed flow area over time is a function of many parameters that include the characteristics of the sediment load and the frequency of flow contraction during floods caused by waterway crossing embankments.

Mining

The person conducting the assessment should examine current mapping and historic documents for evidence of mining. Some Maryland streams were relocated for mining operations. Entire floodplains were excavated to expose quartz gravel and cobble that contained gold (Griscom 1830, Goetz 1996). Streams in the vicinity of quarries or other mining operations should be examined for the possibility of channel armoring, relocation, and adjustment initiated in response to the relocation. Although armoring of the channel may have maintained a stable channel in the past, evidence of the failure of the armoring may indicate that the channel will become unstable. These mining operations may have also altered the valley bottom and foundation of the stream/floodplain materials. Pre-settlement streams that once flowed over a foundation of gravels and possibly bedrock may currently flow over wash-pond or other fine sediments left over from the mining operations. These systems will frequently show high erosion of fine sediments, deep pools, and large gravel bars. The streams will continue to remove the fine sediments of the banks and bed while leaving behind sands and gravels as floodplain and bed material.

Appendix 14-B: Evaluation of Soil and Bed Load Materials for Scour Studies

Selection of the appropriate D50 particle size is an important aspect of the scour evaluation study. As a general rule, the description of channel bed materials should be included in the geomorphology report along with an evaluation as to whether the type of scour used for scour analysis should be clear-water or live-bed scour.

The extent of scour to be expected at a bridge foundation is dependent on the surface and subsurface materials in the stream channel and its flood plain. The engineer needs to evaluate, among other matters, the types of scour (clear water or live-bed) that may occur at the bridge. If there is a significant sediment bed load passing through the structure at flood stage, use the live bed scour equation developed by Laursen to estimate the extent of contraction scour at the bridge. The scour depth at the bridge is computed using the ratio of the unit flow through the bridge to the unit flow in the upstream channel as described in Chapter 11 of the H&H Manual. Use of this equation also assumes that the material in the channel bed is the same upstream of the bridge as it is under the bridge. This is rarely the case.

If there is an insignificant bed load transported to the bridge from the upstream sediment supply reach, use the clear water scour equations developed by Neill (and modified by the Office of Structures as incorporated in the ABSCOUR 9 Program) to estimate the extent of contraction scour. This method uses the D_{50} particle size of the bed material under the bridge and the velocity and depth of flow through the bridge to estimate the contraction scour depth.

Alluvial streams in flood stage will normally carry some sediment load. Stream morphology studies conducted to date in Maryland indicate that the sediment supply for many non-tidal streams is limited and that the scour mode is more likely to be clear water than live bed. Therefore, for many scour evaluations there will be no clear-cut resolution of the scour type (live bed or clear water) that causes the deepest scour to occur.

The engineer needs to use judgment in the evaluation of both types of scour to determine the most reasonable estimate for the contraction scour depth for a given flood flow. Information obtained during the stream morphology study, along with the bridge borings, will serve as the sources of the data used to make this judgment. The following guidance is provided for the collection and evaluation of this information.

Observations and/or representative soil samples should be taken and careful observations made at the location of the structure crossing and at the upstream approach section to the bridge as indicated in Figure 14B-1. If the location of the approach section has not been identified by SHA, select an upstream section typical of the channel and flood plain, located two or more bridge lengths above the crossing site. The objective is to select a cross-section that is representative of the approach reach above the bridge.

Approach Section

The purpose of the evaluation of the approach section (Locations 1, 2 and 3) is to evaluate the nature of the sediment transport in the reach above the bridge. Essentially, the question to be answered is whether the flood flow will be carrying a significant bed load.

Locations 1 and 3 should be selected on the flood plain within the active flood plain which carries overbank flow. At locations 1 and 3, describe in detail the nature of the vegetative cover. Flood flows on the flood plain generally have low velocities. If there is a heavy protective cover

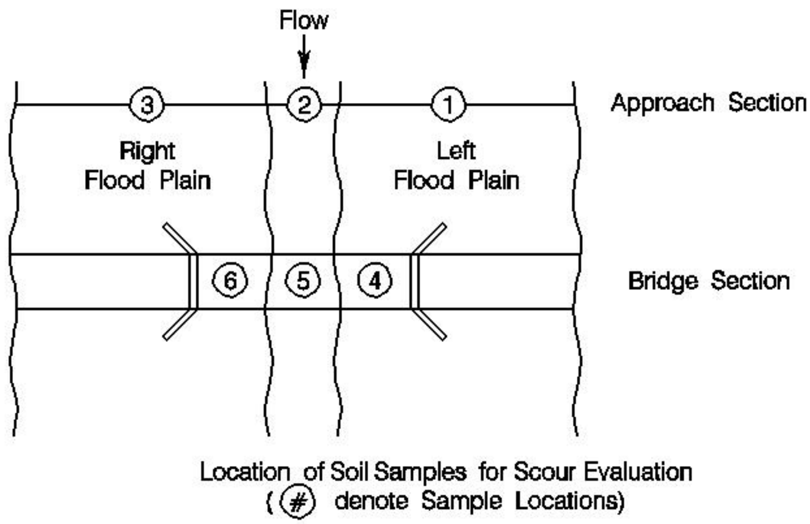

Figure 14B-1

on the flood plain, it is likely that the surface soils will not be mobilized and that the flood plain flow approaching the bridge will be clear water. Describe the nature of the surface material, as to whether it is sand, gravel cobbles or a mixture of sizes. If sand, make a note as to whether it is fine or coarse sand. For other materials, take a representative pebble count as appropriate at each location 1 and 3 and include this information in the preliminary report. Note the D_{50} size.

Take photos of the general flood plain area and its vegetation and of specific areas in which the pebble counts and soil observations are made.

For Location 2, the upstream channel, the following actions should be taken:

- Take a pebble count of the channel bed material. Ideally, this sample should be taken on a riffle upstream of the bridge. This information will be helpful in determining whether the stream will mobilize the bed material in the riffle during flood flows
- Sample the upstream bars using the procedures discussed elsewhere in Chapter 14, and determine particle size distribution plots for this material. This material will normally be carried by flood flows as a part of the sediment load.
- Take photos of the channel reach in which the measurements and observations were made.
- Review the information obtained from the stream morphology report to evaluate the nature and magnitude of the sediment load in the supply reach above the bridge.

The above information will be used in the scour studies to estimate the type of sediment load moving through the bridge for the hydraulic conditions used in the scour estimate.

Bridge Section

Information on surface and subsurface soils is needed at the bridge section (Locations 4, 5 and 6 in Figure 14B-1) for use in the scour evaluation. Essentially the information needed is a description of the surface soil characteristics, including the D_{50} particle size, of the material comprising the channel and flood plain under the bridge. The engineer leading the morphology study will need to determine the best location to obtain these samples for the particular site crossing, and to determine whether this material is characteristic of the sediment load passing through the structure waterway opening.

The engineer leading the morphology study can also provide valuable information on surface soils and make informed judgments about the shallower subsurface soils using the following methods and observations as appropriate:

1. Description of surface soils in the flood plain and channel, using pebble counts. If the flood plain consists of sand or cohesive materials, describe the material in the preliminary report as sand, silt or clay using the following as a guide.

Class	D_{50} Size
Coarse or Medium Sand	0.25 to 2 mm
Fine Sand	0.06 to 0.25 mm
Silt	Visual observation/field tests
Clay	Visual observation/field tests

1. Observe the channel banks to assess the nature of the shallow subsurface flood plain material.
2. Make a note of the existence of rock or rock outcroppings in the vicinity of the bridge crossing.
3. Take photos of the locations where measurements and observations were made.

Include the findings of these investigations in the preliminary and detailed morphology reports in a section entitled “Evaluating Soil and Bed Load Materials for Scour Studies.”

Borings

Since scour depths can approach 20 feet or more at some structures, information on the variation of subsurface soils or rock with depth will be important to the accuracy of the scour estimates. Borings will serve to provide this information for deeper subsurface soils.

- One or more borings should be taken at each foundation element. In addition, at least one boring should be taken in the channel at the bridge location.
- Depths reported on the standard borings log sheet should be tied in to survey information so that the elevations can be related to the water surface, channel bottom and foundation design elements.

- The material removed from the boring should be classified as to whether it is clay, silt sand, gravel, etc. using standard procedures. For cohesive materials, classify the soils accordingly. Take Shelby Tube samples of each cohesive soil layer encountered.
- For cohesionless soils take samples and run a particle size distribution of the sample. Use the standard Maryland DOT forms to list and plot the various sample sizes. As a minimum, the sample particle size report should include the D50 median grain size, the 84% finer and the 95% finer grain sizes
- If there is a significant change in the composition of the soil, note the elevation where the change occurs. Take additional samples of the soil below the change, gathering the same information as that discussed above.
- Note the elevation of the soil/rock interface. Record the standard data on rock characteristics including RQD, elevations, depths recovery, etc.
- The rock cores should be reviewed with an SHA geologist to determine whether the rock is scourable or scour-resistant.

Appendix 14-C: Preliminary Study Letter 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 preliminary study letter report.

Appendix C
Example of a Preliminary Stream Morphology Report

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 preliminary study letter report.

September 2007

Crossing of Catoctin Creek at MD 464 (Structure 10091)

Preliminary Stream Morphology Report

Prepared For:

SHA

Maryland State Highway Administration
Structure Hydrology and Hydraulics Unit
Bridge Design Division
707 North Calvert Street
Baltimore, Maryland 21202

Prepared By:

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AUGUST 2007

August 29, 2007

Mr. Andrzej J. Kosicki, M.S., P.E.
Maryland State Highway Administration
Bridge Design Division
707 N. Calvert St.
Baltimore, MD 21202

RE: Preliminary Stream Morphology Report, Bridge 10091, MD Route 464 over Catoctin Creek

Dear Andy,

What follows is our preliminary stream morphology report for Bridge 10091. Based on the information obtained from the visual assessment, I recommend that further studies and assessments be undertaken. Detailed information concerning the visual assessment is included in Attachment A; photo documentation of the visual assessment is included in Attachment B.

The study site is located in Bells Mill, about 12 miles southwest of Frederick, at the MD Route 464 crossing of Catoctin Creek in Frederick County, Maryland (see Attachment A, Figures 1, Vicinity Map, and 1A, Location Map). This bridge, built in 1933, is to be replaced because it is nearing the end of its design life. In general, Catoctin Creek flows north to south. The bridge crossing is about 2.5 miles downstream of MD Route 340, about 3,000 feet upstream of an unnamed tributary, about two miles upstream of Boss Arnold Road, and about 3 miles upstream of Catoctin Creek's confluence with the Potomac River. The drainage area is approximately 113 square miles.

The MD Route 464 bridge crossing and the entire associated watershed are located within the Blue Ridge Province (see Attachment A, Figure 2, Physiographic Provinces and Their Subdivisions in Maryland). The stream flow is perennial, driven by rainfall and occasionally by snowmelt. The largest floods in the region are driven by rain or snow events, hurricanes, and tropical storms. Bankfull flows may occur as a result of a variety of rain events including rain or snow, frontal storm events, and tropical storms.

Catoctin Creek powered many mills within the watershed in the 18th, 19th, and 20th centuries. As observed in the field assessment, the banks along the Catoctin Creek consist mostly of fine, laminated sediments (Photo 70), consistent with mill dam deposits, that are now being eroded. The linear pattern of the Creek shown in the 1808 Map of Frederick County differs significantly from its current path. There appears to be significant relocation of the Creek, with the majority of its length located along the east and west valley walls (Photo 109). This relocation possibly occurred as a result of the construction of the mill dams and/or roads. Bore or blast holes were found in the bedrock downstream of the bridge (Photo 37). The bank sediments represent mill pond or dam sediments. The stream is currently going through vertical degradation and, in some locations, severe lateral movement. Using Rosgen Stream Classification and based on the thick, high banks of fine laminated sediments (mill pond sediments) and the low, recent depositional features (Photo 121), the stream is classified as an F-4 channel type.

The purpose of this preliminary study is to evaluate the existing channel morphology and the interaction of the channel with the existing MD Route 464 bridge, and to determine the scope of additional studies, if need

SUMMARY OF GENERAL FINDINGS

The existing stream channel was found to be degraded, unstable, and undergoing significant change. Effects of past channel straightening, damming, and relocation efforts have contributed to past and current channel degradation. The stream is moving laterally away from its previously straightened alignment. There is evidence of the potential for long-term channel degradation and abutment scour. In addition, a number of other problems are present at the existing bridge including lateral channel movement and bar development, aggradation and deposition within the bridge spans (Photo 83), pier scour, backwater flooding and flow obstructions (Photos 67 and 101), tributary confluence at the bridge, and debris accumulation. Of particular importance are two bends that form an offset (i.e. abruptly bending out of line) channel reach within 1,000 feet of the crossing (Photos 59 and 133). Based on the vegetation, the movement is recent.

The old bridge plans, dated 1933, show a stone mill dam (Photo 96) extending from the west hillside to a land feature between the easternmost pier (Pier D) and the east abutment of the proposed bridge. That land feature has since eroded away, leaving the two retaining walls that tied the concrete gates to Pier D and the east abutment. The mill race went over concrete gates along the east abutment to the mill building (Photo 56) approximately 1,000 feet downstream. Portions of the retaining wall have collapsed, as have the concrete gates. The remnants are located immediately upstream of Pier D (Photo 91). Scour around the existing crossing is primarily due to the partial breach of the stone mill dam. This partial breach occurred on the left side, while the remaining 60 to 70 percent of the stone mill dam encroaches on the west side of the channel, redirecting low and moderate flows (flows up to 6 feet) to the extreme left of the channel. Pier D is placed directly in the center of the opening in the stone mill dam, causing a substantial amount of scour around the pier. Grout bags have been placed around Pier D and a scour pool 4 feet deep currently exists Photo 89). There is a scour hole more than 5.5 feet deep at the old bridge abutment downstream (Photo 69).

Existing conditions of the channel in the vicinity of the bridge are exacerbated by the mill dam. However, because of the height of and erosive soils in the banks and the existing location of the channel, the greatest threat to the structure will be from lateral movement of the channel to the east. The channel will continue to move east, in the direction of the east abutment, or Abutment E. Over time, this lateral movement may increase scour or encroach on the roadway embankment or bridge substructure units.

There are some signs of pier scour within the deposition at Piers B and C (Photo 83). This is likely due to the steep gradient of the high flows overtopping the 6-foot-high dam. It is difficult to determine the actual scour depths because fine material surrounds the piers to an unknown depth. Farther downstream on the left bank is an old abutment from the previous bridge that has never been removed. A scour hole around the abutment has formed to a depth of more than 5.5 feet. This, too, is caused by the location of the breach in the dam and by flows being directed through the existing bridge to the old bridge abutment.

RECOMMENDATIONS

Based on the assessment of the morphological processes summarized above and the information presented in Attachments A and B, additional studies and evaluations are recommended to provide greater detail and accuracy in determining:

1. Long term degradation;
2. Lateral channel movement, particularly in the vicinity of the replacement structure;
3. Measurements and observations of floodplain soils and channel bed load materials for the purpose of scour evaluation and analysis;
4. The removal of flow obstructions immediately upstream and downstream of the bridge that may reduce conveyance, cause deposition, or increase the risk of scour at the crossing.

I will be pleased to meet with you at your convenience to discuss the findings of this preliminary stream morphology report and to make arrangements for conducting the recommended studies and evaluations.

Sincerely,

Ward Oberholtzer, P.E.
Vice President

Attachment A:

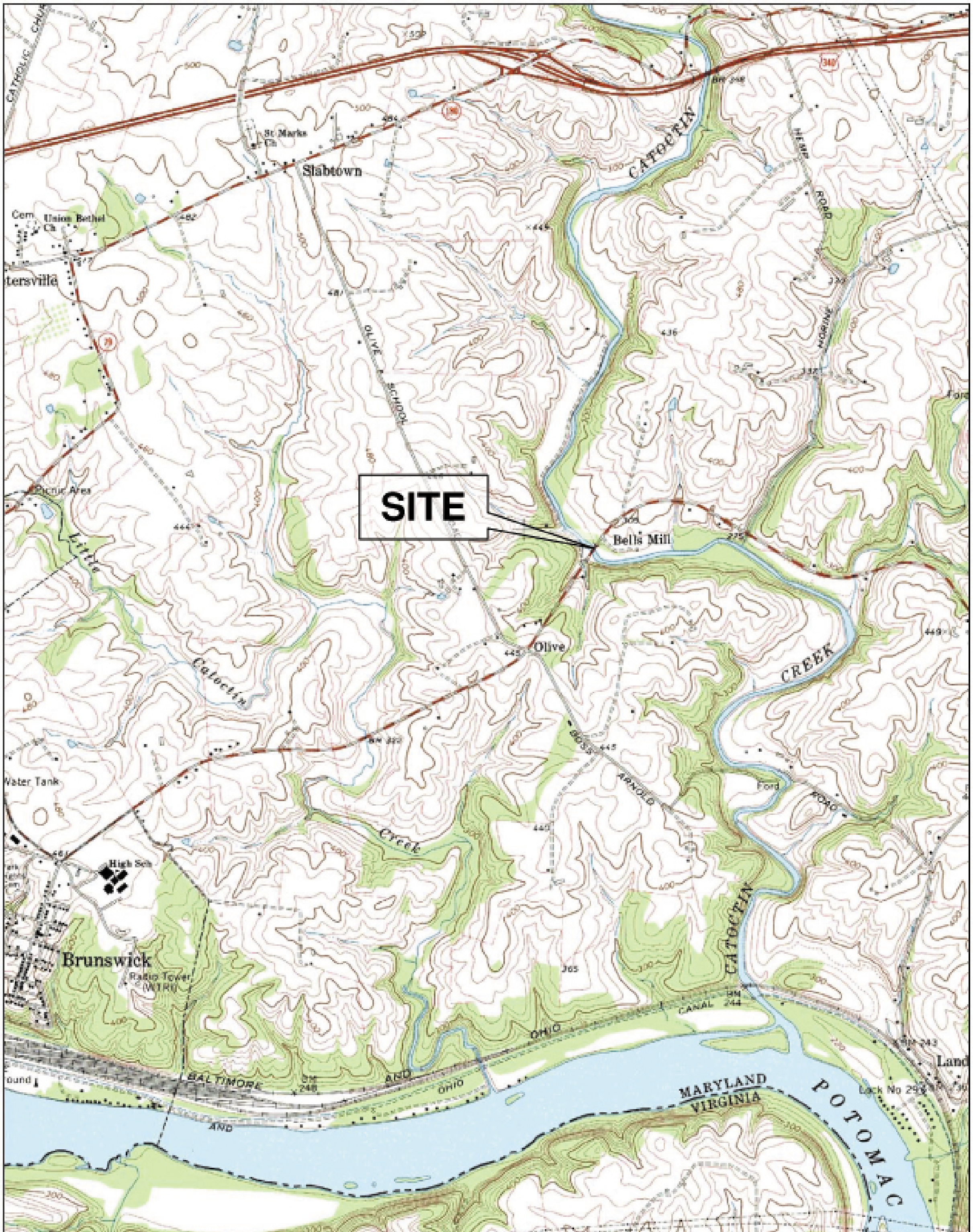
I. Background and Analysis

A. Existing Land Use and Existing and Ultimate Development Hydrology

B. Estimated Bankfull Flow and Channel Geometry Based on USFWS Curves

C. Historical and Contemporary Channel and Valley Modifications

Figure 1. MD Route 464 Catoctin Creek Vicinity Map



Point of Rocks, MD USGS MAP
Scale: NTS

NORTH

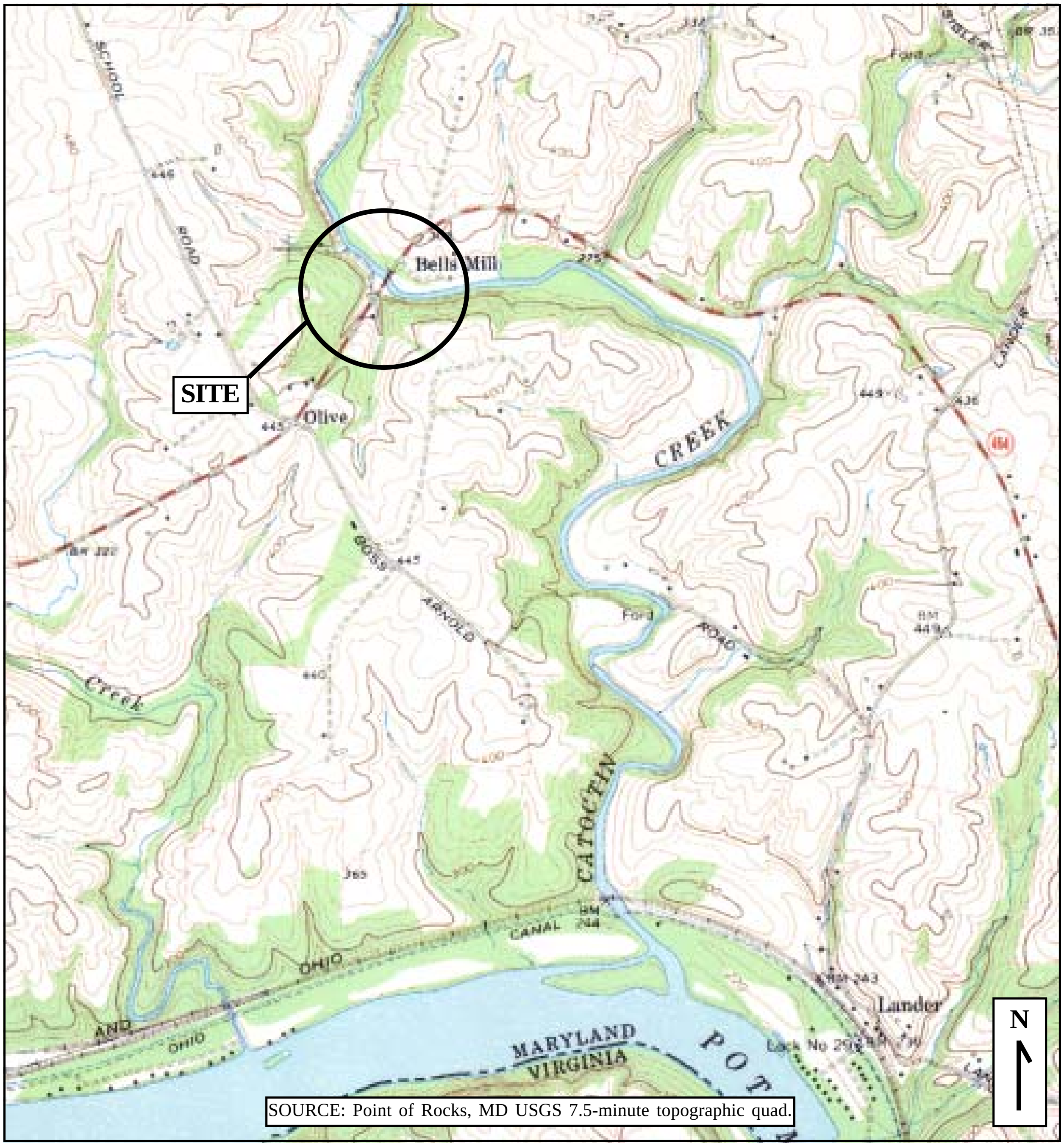


Figure 1A. Project Location Map

Scale

1 inch equals 2000 feet

500 0 1000 2000

MD 464 over Catoctin Creek

LandStudies

A. Existing Land Use and Existing and Ultimate Development Hydrology

Table 1: Summary of Watershed Land Use Areas at MD Route 464 over Catoctin Creek.

Land Use	Acres	Percent
Low Density Residential	4457	6.17
Medium Density Residential	1402	1.94
High Density Residential	27	0.04
Commercial	208	0.29
Industrial	73	0.10
Institutional	89	0.12
Open Urban Land	167	0.23
Cropland	33227	45.96
Pasture	4705	6.51
Orchards	103	0.14
Row Crops	12	0.02
Deciduous Forest	23919	33.09
Evergreen Forest	117	0.16
Mixed Forest	612	0.85
Brush	227	0.31
Water	23	0.03
Res.: 1.00 <= X < 2.00 ac	1276	1.77
Res.: 0.33 <= X < 0.50 ac	1283	1.77
Res.: X < 0.25 ac	111	0.15
Feeding Operations	24	0.03
Agricultural Buildings	232	0.32

Watershed Area approximately 113 mi^2.

Table 2: Summary of TR-20 Flows Simulated at MD Route 464 over Catoctin Creek.

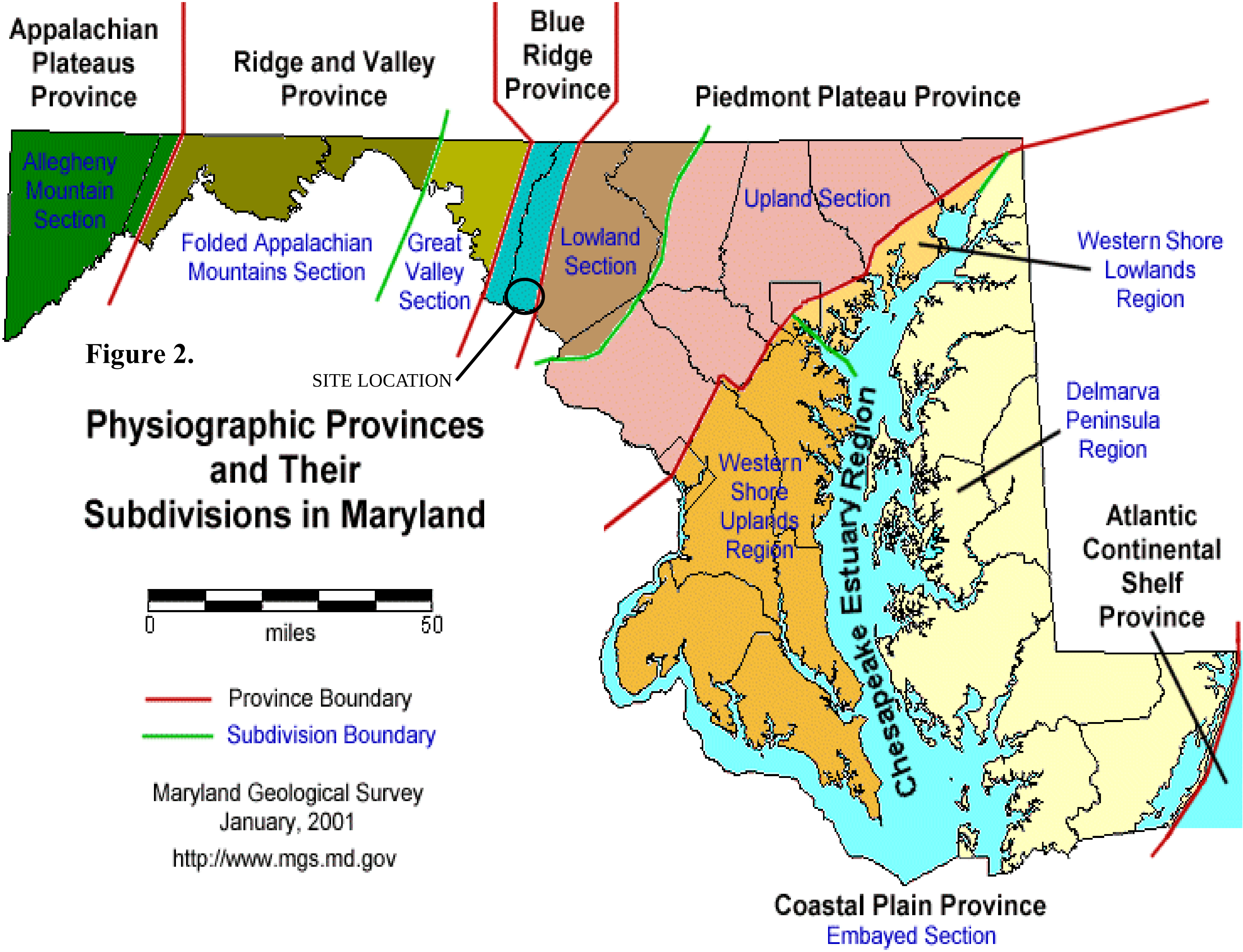
Return Period (years)	Storm Duration (hours)	Existing TR-20 (cfs)	Ultimate TR-20 (cfs)
2	24	4330	4360
10	24	9650	9690
25	24	13920	13980
50	24	17990	18050
100	24	22760	22830

B: Estimated Bankfull Flow and Channel Geometry Based on USFWS Curves

Table 3: Summary of Stream Parameters for MD Route 464 over Catoctin Creek.

Stream Parameter	Value
Physiographic Region	Blue Ridge Province
Drainage Area (mi^2)	113
Bankfull Width (ft)	93.4
Bankfull Depth (ft)	5.9
Cross Section Area (ft^2)	549
Width/Depth Ratio	15.9
Bankfull Velocity (ft/s)	5.6
Bankfull Discharge (ft^3/s)	3073

Figure 2.


Appalachian Plateaus Province
Ridge and Valley Province
Blue Ridge Province
Piedmont Plateau Province
Allegheny Mountain Section
Folded Appalachian Mountains Section
Great Valley Section
Lowland Section
Upland Section
Western Shore Lowlands Region
SITE LOCATION
Physiographic Provinces and Their Subdivisions in Maryland
Delmarva Peninsula Region
Western Shore Uplands Region
Chesapeake Estuary Region
Atlantic Continental Shelf Province
0
miles
50
Province Boundary
Subdivision Boundary
Maryland Geological Survey
January, 2001
http://www.mgs.md.gov
Coastal Plain Province
Embayed Section

C. Historical and Contemporary Channel and Valley Modifications

Catoctin Creek powered many mills within the watershed in the 18th, 19^{th,} and 20th centuries. There are numerous articles and maps describing and identifying the dams and mills along Catoctin Creek (previously Abraham Creek). These references include:

(a) "The Grist Mills of Frederick County," Moser, Harold, The Valley Register, Middletown, MD, December 7, 1984;
(b) "Old Mills on Catoctin Creek," Martz, Ralph, The News, Frederick, MD, February 26, 1973;
(c) 1873 Atlas of Frederick County Maryland; C.O. Titus &Co.; and
(d) Map of Frederick and Washington Counties, 1808, Charles Varle.

As of 1808, there were 104 grist mills operating within Frederick County. Within Catoctin Creek and its tributaries, there were more than 67 mill sites identified, with approximately 48 mills along the Catoctin Creek. Besides the grist and flour mills on the Catoctin Creek, there were saw, cider, fulling, linseed oil, plaster, and powder mills. Some of the previous dams and roads that had a more direct influence on the MD Route 464 crossing of Catoctin Creek include the dam/mills located approximately 1.6 miles downstream at the previous Arnold Road crossing of Catoctin Creek and Bells Mill, which is located a few hundred feet downstream of MD Route 464, with the dam located at the crossing of MD Route 464. There are many other dams located within the watershed including one near MD Route 180 over the Catoctin Creek, approximately 1.5 miles upstream of the crossing.

As observed in the field assessment, the banks along the Catoctin Creek consist mostly of fine, laminated sediments, consistent with mill dam deposits, that are now being eroded. The more linear pattern of the Creek shown in the 1808 Map of Frederick County differs significantly from its current path. There appears to be significant relocation of the Creek, now typically located along the east and west valley walls. This relocation possibly occurred as a result of the construction of the mill dams and roads. This relocation also appears to have occurred when the bed elevation was significantly higher. The bank sediments represent mill pond or dam sediments. The stream is currently going through vertical degradation in some locations and exhibiting lateral movement in others. The stream is predominately located along the valley wall and is currently eroding bedrock outcrops, with lateral movement being away from the bedrock.

The 1873 Atlas of Frederick County (See Attachment A for Map) also shows a road (currently abandoned) that runs parallel to Catoctin Creek with two crossings from Arnold Road to existing MD Route 464. There are numerous locations where large bedrock boulders are scattered along the Creek. One of the boulders approximately 1,500 feet downstream of the bridge has a bore hole (Photo 37), which represents blasting of the bedrock for either utilities or dam construction or to improve flow passage for the mill or logging operations.

The old bridge plans, dated 1933 and shown in Attachment A, show the previous two-span bridge located with the east abutment approximately 100 feet downstream, between piers C and D of the current bridge; the west abutment was located at Pier B. The unnamed tributary currently entering upstream and along the west abutment was previously entering Catoctin Creek downstream of the west abutment.

The east abutment (Photo 85) is in severe disrepair and currently obstructing exit flows from the bridge. There are no signs of the older pier or east abutment. However, there is significant deposition in the locations of those older substructure units, so any evidence may be buried (Photo 83). Also, the old drawings show two islands between the dam and the 1933 bridge. Currently, the deposition extends from approximately 100 feet downstream to approximately 100 feet upstream of the dam. There has been significant loss of capacity through the bridge since 1933.

The old bridge plans, dated 1933, show a stone mill dam extending from the west hillside to a land feature between the easternmost pier (Pier D) and the east abutment of the proposed bridge. That land feature has since eroded away, leaving the two retaining walls that tied the concrete gates to Pier D and the east abutment. The mill race went over concrete gates along the east abutment to the mill building approximately 1,000 feet downstream. Portions of the retaining wall have collapsed (Photo 91), as have the concrete gates. The remnants are located immediately upstream of Pier D.

Figure 3: Article Regarding Grist Mills in the Region.

The Grist Mills of Frederick County MD

By Dr. Harold Moser
The Valley Register, Middletown, MD Dec 7, 1984

From 1785 to 1885 much of the industrial and social life In Frederick County was built around its grist and flourmills. Over this span of years the production of wheat, corn, oats and barley increased in volume and this rapid increase in grain cultivation was followed by the construction of an astonishingly large number of small grist and flour mills. When Charles Varle prepared his 1808 map of Frederick County he found 104 grist mills operating along the streams of the county. It seems that along every possible stream where waterpower could be tapped there emerged a swarm of small mills; one fairly recent Inventory has identified as many as 67 mill sites used at one time or another along the Catoctin Creek and its tributaries. Mills that serve a common function and which also are constructed of local building materials are almost certainly going to be similar in appearance and so it is not too surprising to discover that most of the early, small mills were almost as much alike in appearance as the grains of wheat they milled. Any man who owned a mill site and had wood and stone to build the Mill could become a miller. In each Instance a stream was dammed to create a millpond that could be tapped when the mill was used. When the gate were opened water poured into the millrace and turned the big wheel. As the waterwheel went around gears spun an axle to which the millstones, in their boxed enclosure, were attached. Wheat went into the top and came out ground at the bottom. Finally the bran was separated from the flour.

No mill of the Varle era is known to be still operating In Frederick County. However there were 70 water-powered grist mills actively processing grain in 1850 and the Titus map of Frederick County in 1873 Identifies 77 such mills. Among the water-powered mills still operating in 1910 the Point Rock Mill, about 4 miles above Myersville along the Easterday Road. Perhaps came closest in size and general appearance to the many small mills that were built about the time of the Voris survey. This small mill tucked away among the hills of the Catoctin District survived the competition of many larger mills in the county until the very end of the era of mills powered by water. From 1881 to 1925 this mill was known locally as the Duvall mill. Its historical uniqueness was recognized at the beginning of the Twentieth Century and a postcard was designed bearing its likeness. The reproduction of the mill appearing in this article is an enlargement from one of these cards in the collection of Mrs. Leah Spade of Wolfsville.

The photograph reveals all the salient features of one of these early mills. The stream is the little Catoctin. The dam, millpond, sluice and water wheel are clearly shown. The metal water wheel shown here is a refinement over the wooden water wheels used by the earliest mills. Metal water wheels were introduced during the 1880's and so this improvement must have been added by Marcellus Duvall.

The earliest known owner of this mill was George Marker (1756-1827). He may have been the builder but conclusive evidence to support such a claim has never been found. George Marker is known to have, operated the mill between 1816 and the time of his death in 1827.

Jacob Palmer owned the mill between 1839 and 1866 and under his management the mill enjoyed its most prosperous years. By 1850 the mill was processing annually 8000 bushels of grain and turning out 1100 barrels of flour. Miller Palmer added a sawmill to the operation and he employed three laborers to help run the plant. The prevailing wage for a sawmill assistant was $16 per month. Mill hands were paid $20 per month.

The mill barely survived the economic depression in the early 1870's. Mill ownership changed three times between 1866 and 1881 and finally, on April 4, 1881, the mill was sold to Marcellus Duvall who was the last Miller to operate the Facility. At 45 years of age he was an experienced miller coming from a family of millers. However, his experience and skill as a milletr were not enough to overcome the tide of change that was sweeping the milling industry. Improved transportation and the emergence of large urban milling centers gradually brought to an end the era of local, water-powered grist and flour mills.

In 1903, at the age of 67, Marcellus Duvall had the ownership of the mill transferred to his wife, Cornelia (Stottlemyer) Duvall. The mill property remained with the Duvall family until 1926 (Marcellus died In 1925) but the mill must have ceased operation a number of years before the property was sold.

Today only a small fragment of a mill wall remains to mark the site of the once busy center. Neighbors report that much of the mill area has been destroyed by vandals. Dense undergrowth now borders the headwaters of the Catoctin creek and a fine country home now stands at the place where the miller once lived.

Duvall Mill, Myersville MD, along the Easterday Road
also know as Point Rock Mill, and owned by George Marker between 1815-1827

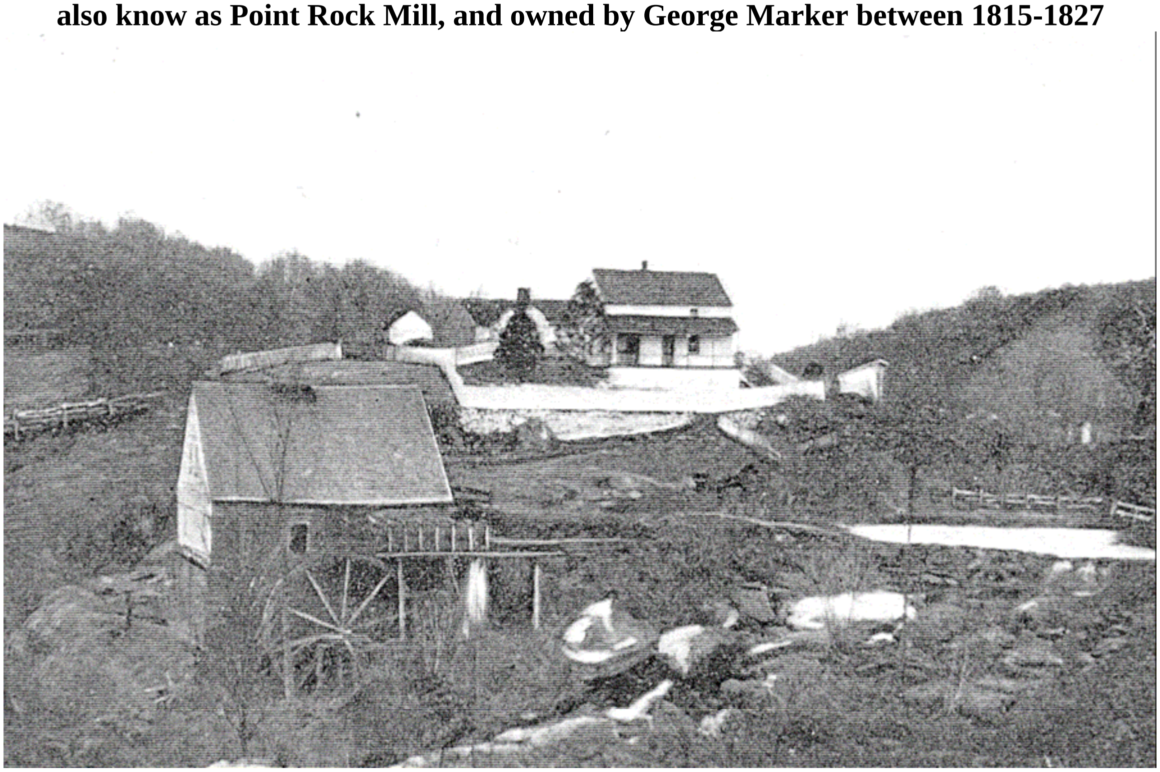


Figure 4. Map Showing Mills and Forges in the Region in 1808

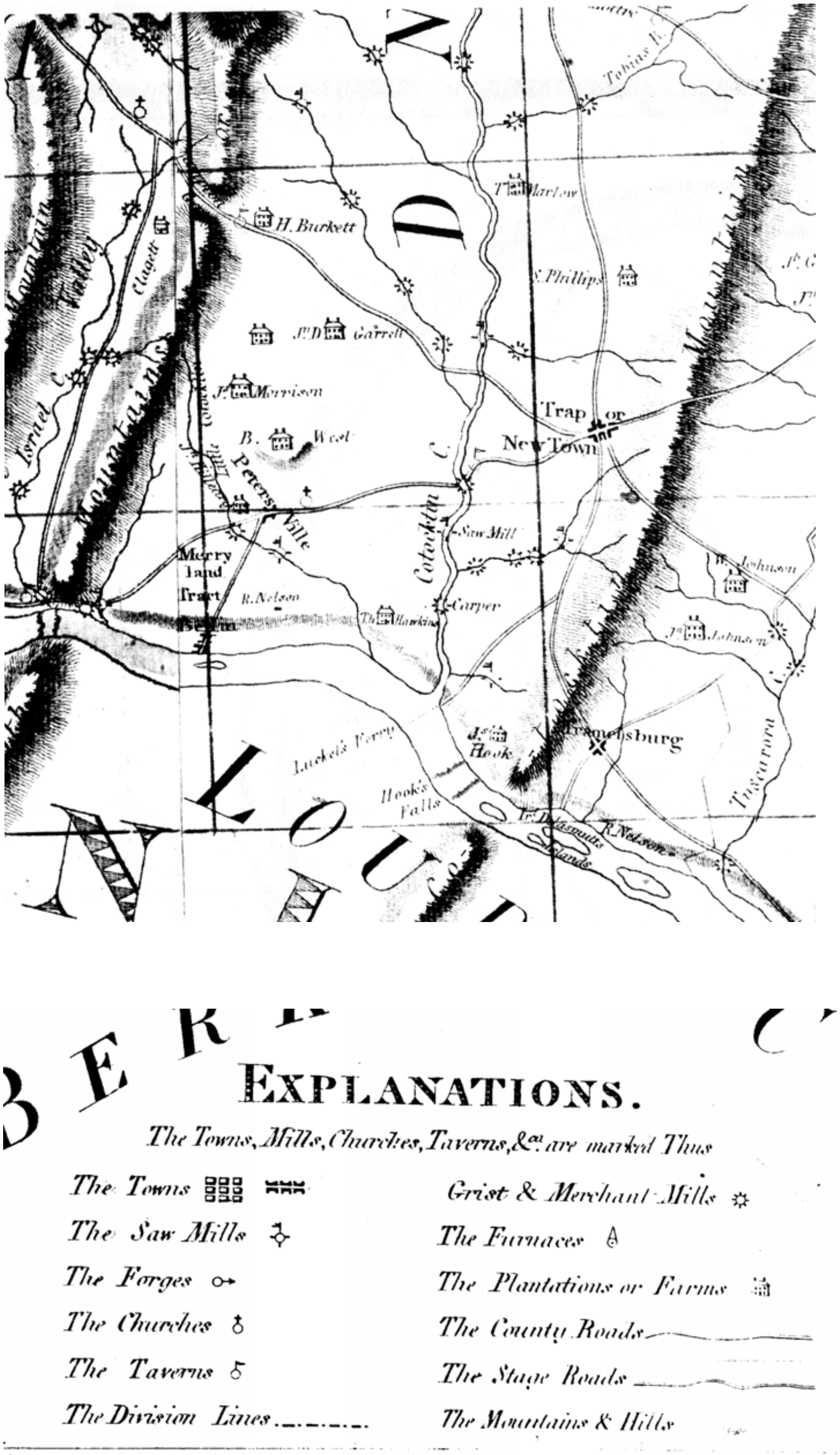
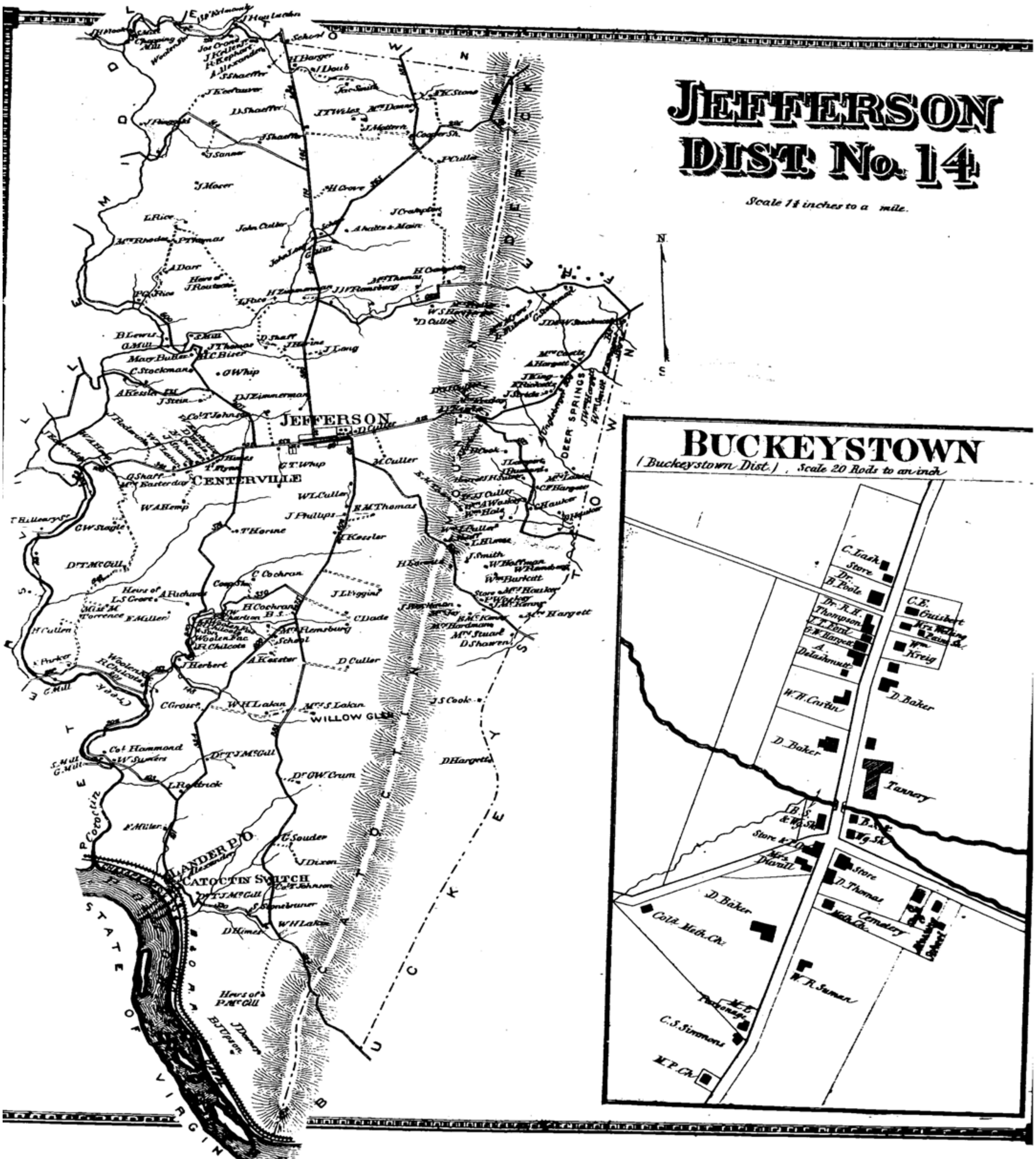


Figure 5. Map Showing Grist and Saw Mills in the Region in 1873



Atlas of Frederick County Maryland by D.J. Lake, C.E. Published by C.O. Titus& Co. 320 Chestnut St. Philadelphia. 1873.

Figure 6. Substructure Details From 1933 Construction Drawings for Current Route 464 Bridge Over Catoctin Creek.

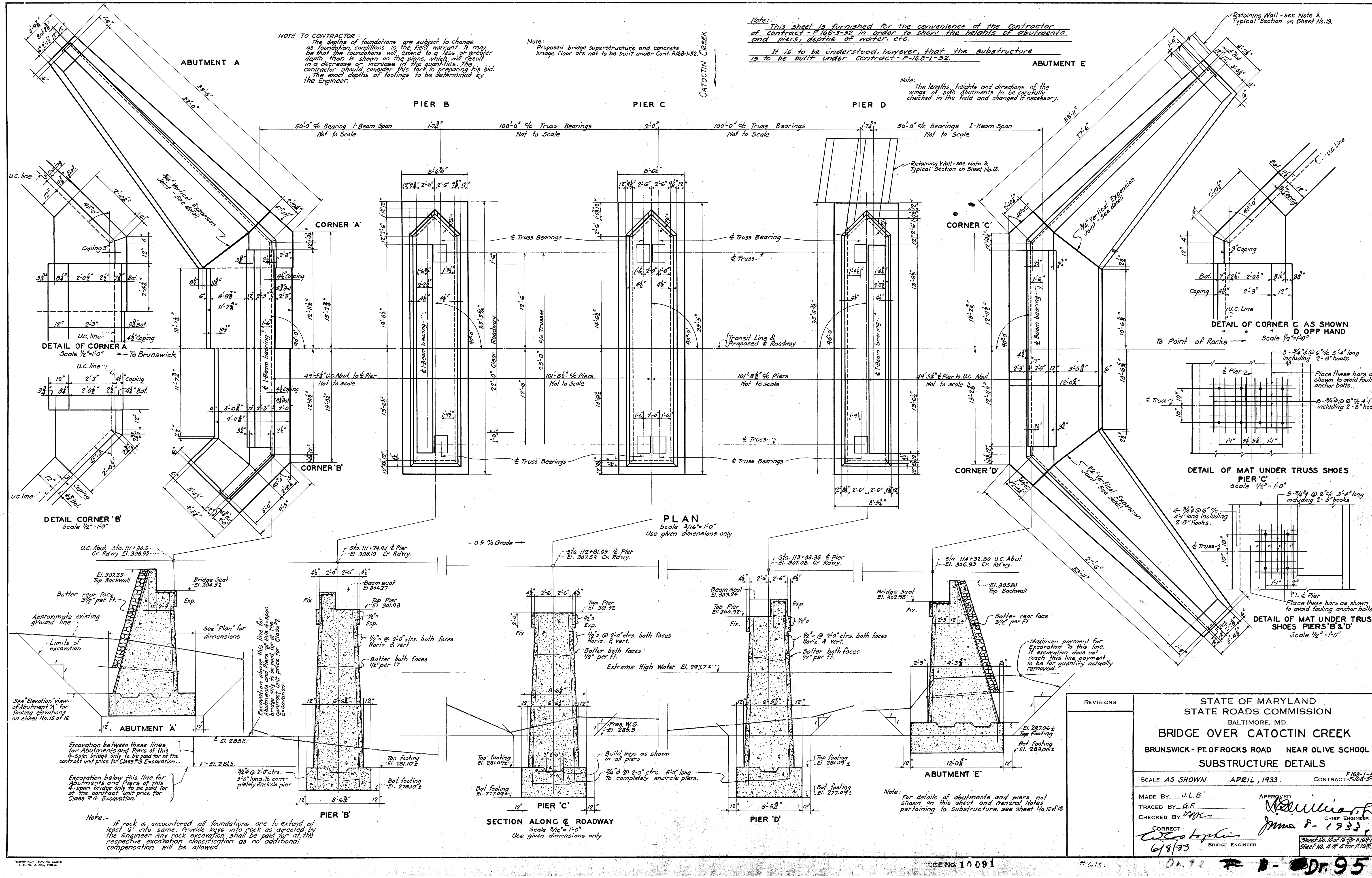
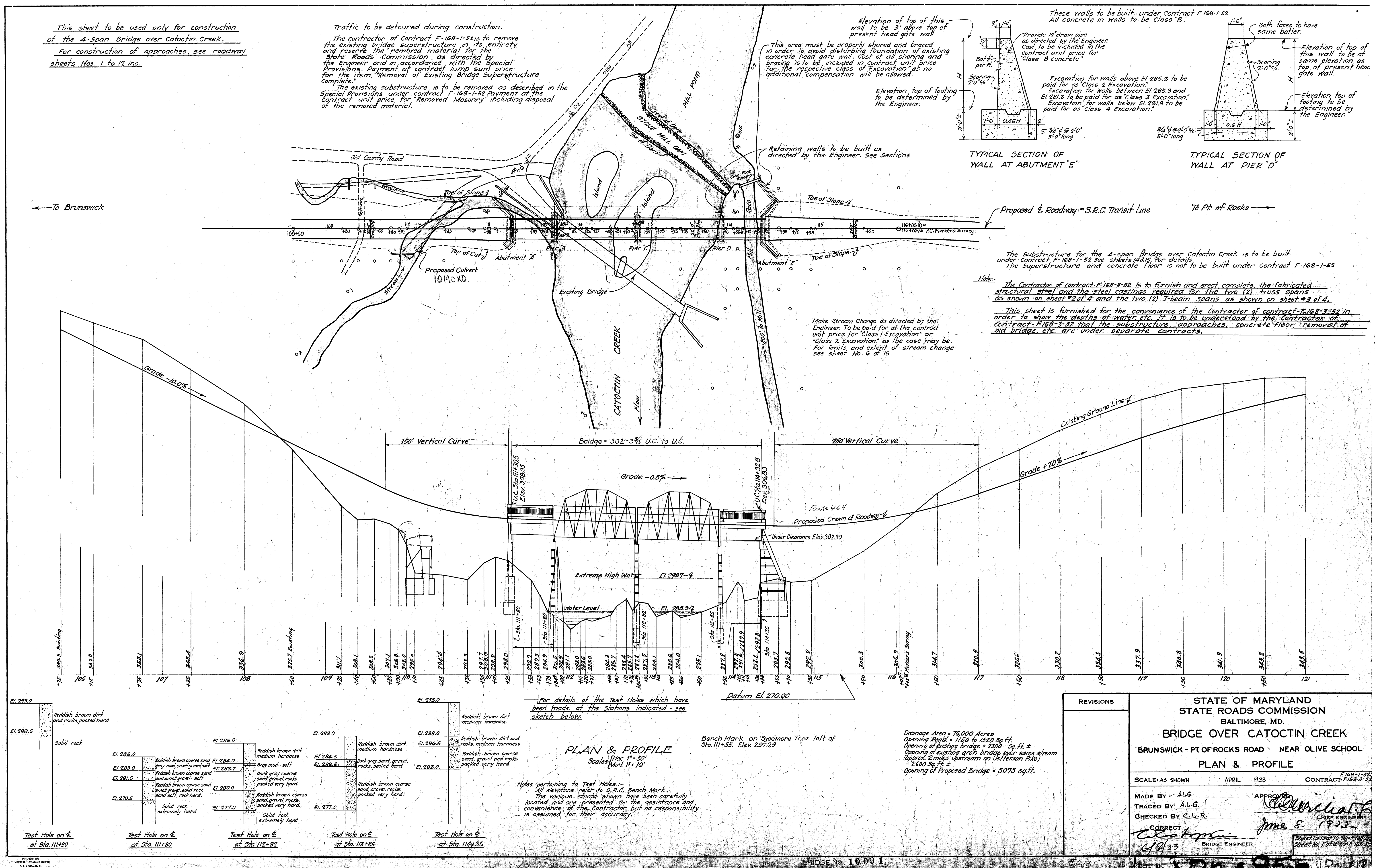


Figure 7. 1933 Plan and Cross Section Views of Current MD Route 464 Bridge Over Catoctin Creek.



Attachment A:

II. Visual Assessment

A. Base Level Reach

B. Project Reach

C.   Supply Reach

II. Visual Assessment

A. Base level Reach.

The downstream-most base-level point used in the assessment is approximately 5,000 feet downstream of MD Route 464 over Catoctin Creek (Structure #10091). The location of the base-level reach begins 5,000 feet downstream and extends to the millrace approximately 1,000 feet downstream of Structure #10091. The description of the base-level reach is broken into four segments highlighting different features.

5,000 feet downstream of Structure #10091 to an Unnamed Tributary Confluence at a distance of 400 feet upstream.

- Approximately 5,000 feet downstream of MD Route 464 the valley becomes confined by the east and west valley walls at the downstream end of a meander bend. The base-level control consists of exposed bedrock of unknown durability. This location is a degraded, local base-level control (Photo 4).
- A low-flow high-gradient feature (LFHG) or armored riffle, approximately 200 feet long, is composed of bedrock outcrops and large pieces of fractured bedrock.
- Bedrock outcrops and forest constitute most of the banks.
- A large mid-channel bar within this LFHG is heavily vegetated with young trees. The bar material consists of large, angular bedrock fragments and quartz gravels and sands.
- There is some debris collected within the island.
- An unnamed tributary enters from the east along the valley wall. The tributary is an entrenched F-type channel with bed material composed of bedrock and quartz gravels. The channel has a ford to get back and forth through an automobile junk yard. Removal of the downstream LFHG feature will cause further incision and lateral movement to the tributary. This tributary supplements the bed load and sediments forming the large mid-channel bar immediately downstream.
- At the top of the riffle, there are some large exposed bedrock outcrops or boulders, which may indicate the presence of a dam in this location. There are signs of lateral movement in a westerly direction.
- The channel classification in this location is F-type.

Unnamed Tributary Confluence to Hovine Run Confluence at a distance of approximately 2,000 feet upstream.

- The base level for this segment begins at the top of the steep LFHG feature just downstream of the unnamed tributary described above. Degradation of that steep riffle will cause incision and increase lateral movement in an easterly direction.
- Within this segment there is a single, long, and mildly sloped LFHG feature composed of quartz gravels and bedrock fragments with bars. The LFHG feature is located approximately 1,200 feet upstream of the unnamed tributary confluence, where the stream moves from the west valley wall into the east bank or terrace.
- For most of this segment, the channel is located along the west valley wall. Erosion is occurring along the valley wall where bedrock outcrops are being scoured and tree fall is occurring. The east bank height goes from 9 feet at the lower end (Photo 12) to 8 feet at the upper end. The banks consist of fine, laminated sediments, including a highly cohesive layer below and above the water surface. At the downstream end of this segment there are no signs of gravel or bedrock. The east bank at the upper end of the segment has fine, laminated

sediments resting on an organic layer approximately 1 inch above the water surface. A basal quartz gravel layer on top of bedrock fragments lies below the organic layer (Photo 22). The channel appears to be at pre-settlement elevation at this location. Bank mass failure and tree fall/undermining are occurring along the east bank but are more pronounced in the upstream portion where the gravel and organic material are present.

- Immediately upstream of the previous LFGH and at the confluence of the unnamed tributary is the downstream limit of a long pool. At the downstream end along the east bank, the pool is approximately 3.5 feet deep. The depth is related to the height of the downstream LFHG feature. The pool is approximately 1,200 feet long and becomes shallower upstream because of settlement of fines within the pools. There are some local deeper pools, where the flow is impinged along the west valley wall.
- At the upper end of the segment, large transverse and lateral bars are developing at heights typically less than 1.5 feet. The bar material consists of quartz gravels with bedrock fragments. Separation of material is occurring because the bars downstream consist of smaller material and fewer bedrock fragments than those upstream. The vegetation on the bars consist of mostly herbaceous vegetation with some small woody vegetation.
- This segment is wide and relatively straight, allowing woody debris to travel downstream.
- The Hovine Run Confluence is located near the top of the LFHG feature approximately 2,000 feet downstream of the crossing. The tributary is an entrenched F-type channel with bed material composed of bedrock and quartz gravels. There is a remnant of an old bridge abutment near the confluence and an existing culvert crossing just upstream. Hovine Run also supplements the bedload and sediments to Catoctin Creek, forming the large mid-channel bar immediately downstream. However, the upstream culvert will have an impact on the frequency and magnitude of bed load transport.
- Throughout this segment, the channel is showing lateral movement in an easterly direction. The upper portion of the segment has moved significantly more to the east than the lower pool area. The incision of the channel into the gravels and pre-settlement floodplain is likely the cause for the increase in lateral movement and bar formations in the upper portion.
- The channel classification in this location is F-type.

Hovine Run Confluence to a small unnamed tributary (600 feet downstream of Bells Mill) at a distance of approximately 1,200 feet upstream.

- The base-level control for this segment begins at the top of the long, mildly sloped low-flow high-gradient feature just downstream of Hovine Run, described above. This base-level control should not degrade significantly, because the channel appears to be resting on the quartz gravel and bedrock material within the center of the valley. Significant lateral movement and the formation of wide bars are occurring, creating a more vertically stable segment with local aggradation occurring as lateral movement becomes more apparent.
- There is a single, long, and mildly sloped LFHG feature with some short, local, steeper drops within this segment. The LFHG feature within this segment is composed of bedrock outcrops and bedrock fragments. One large bedrock outcrop has a bore or drill hole on the top (Photo 3), indicating that blasting of the bedrock occurred at some time. The LFHG feature is located approximately downstream of the small unnamed tributary, after the channel moves from the center of the valley to the west valley wall.

- ❖ For most of this segment, the channel is located along the west valley wall. Erosion is occurring along the valley wall where bedrock outcrops are being scoured and tree fall is occurring. The east bank height is approximately 7.5 feet in this segment. The banks consist of fine, laminated sediments including a highly cohesive layer below and above the water surface. Bank mass failure and tree fall/undermining are occurring along the east bank but are more pronounced in the downstream portion where the flow is directed off of the west valley wall.
- ❖ Immediately upstream of the previous LFGH and before the channel flows along the west valley wall is the downstream limit of a long pool. At the downstream end along the east bank, the pool is approximately 3.5 feet deep. The depth is related to the height of the downstream LFHG feature. There are some local deeper pools where the flow is impinged along the west valley wall.
- ❖ At the upper end of the segment, benches or side bars have formed along the east bank at heights typically less than 2.5 feet. The bar material consists of quartz gravels with bedrock fragments. The vegetation on the bars consists of mostly herbaceous vegetation with some small woody vegetation.
- ❖ This segment is wide and relatively straight, allowing woody debris to travel downstream.
- ❖ The confluence of a very small, unnamed tributary is located near the top of the LFHG feature approximately 1,500 feet downstream of the crossing. The tributary is an entrenched F-type channel with bed material of fines because it is located within the fine, laminated sediments. The tributary is overgrown with herbaceous and woody vegetation.
- ❖ The channel is showing lateral movement in an easterly direction along the lower portion of this segment. The upper portion of the segment is protected by the large, bedrock outcrops and bedrock bottom. As the lower portion continues to move to the east, the upper portion will continue to move east as well.
- ❖ The channel classification in this location is F-type.

A small unnamed tributary (600 feet downstream of Bells Mill) to the tailrace of Bells Mill(Photo 56), at a distance of approximately 500 feet upstream.

- ❖ The base-level control for this segment begins at the top of the long and mildly sloped low-flow high-gradient feature, where the channel is located along the west valley wall. Degradation of that riffle will cause some incision and increase lateral movement in an easterly direction.
- ❖ This segment typically consists of a pool, except for a very shallow depositional feature within the middle of the segment. This feature consists primarily of quartz gravel and broken bedrock fragments and is located where the stream moves from the west valley wall into the east bank or terrace.
- ❖ For most of this segment, the channel is located along the west valley wall. Erosion is occurring along the valley wall where bedrock outcrops are being scoured and tree fall is occurring. Downstream of the mill race, the east bank height is 11 feet. The banks consist of fine, laminated sediments including a highly cohesive layer below and above the water surface. Approximately 1 foot below the surface an organic layer overlies quartz gravel. The channel appears to be near pre-settlement elevation at this location. Bank mass failure and tree fall/undermining are occurring along the east bank but are more pronounced in the middle to lower portion of the segment, where the channel has moved away from the west valley wall.
- ❖ Most of this segment is a pool with the depth typically less than 2 feet. There are local deeper pool depths up to 4.5 feet, where the flow impinges on the west valley wall. The majority of the pool consists of fine sediments.

- In the middle of this segment, large transverse and lateral bars are developing at heights typically less than 1.5 feet. The bar material consists of quartz gravels with bedrock fragments. The vegetation on the bars consists of mostly herbaceous vegetation.
- This segment is wide and relatively straight, allowing woody debris to travel downstream.
- The tailrace of the mill is located at the top of this segment and provides very little input of bed load. The mill race is eroding and the building is abandoned and in disrepair.
- Throughout this segment, the channel is exhibiting lateral movement in an easterly direction. The middle and lower portions of this segment have moved significantly more to the east than has the upper portion.
- The channel classification in this location is F-type.

B. Project Reach.

The location of the Project Reach begins 1,000 feet downstream and extends to an unnamed tributary approximately 600 feet upstream of Structure #10091. The description of the Project Reach is broken into 3 segments (exit, bridge, and approach) highlighting different features.

1,000 feet downstream of Structure #10091 to the abandoned east bridge abutment shown in the 1933 bridge plans(Photo 67).

- ❖ The base-level control for this segment begins at the very shallow depositional feature within the downstream-most segment. Farther downstream there is a long and mildly sloped low-flow high-gradient feature, where the channel is located along the west valley wall, that more represents the base-level control for this segment. Degradation of that riffle will cause some incision and increase lateral movement in an easterly direction.
- ❖ A LFHG feature or armored riffle is located approximately 600 feet downstream and composed of bedrock outcrops and large pieces of fractured bedrock. This feature is located along the west valley wall. A second LFHG feature or armored riffle is located approximately 175 feet downstream and composed of displaced boulders from the dam and large fractured pieces of bedrock. This LFHG is located downstream of the abandoned east bridge abutment along the west valley wall and is directing the flows exiting the bridge into the west valley wall.
- ❖ Bedrock outcrops and forest constitute most of the banks. There are trees along this segment with roots being undermined; tree fall is occurring.
- ❖ The pool located at the upstream portion of this segment extends through the abandoned bridge abutment. The exact depth of this pool could not be measured because it is deeper than 5.5 feet. This pool depth is caused by local scour of the flows against the abutment (Photo 69).
- ❖ A large side bar is located on the inside of the meander bend (east side). The bar material consists primarily of large angular bedrock fragments with some quartz gravels and sands.
- ❖ There is no debris located in this segment because the channel is wide and open.
- ❖ There are no confluences with tributaries within this segment.
- ❖ An abandoned bridge abutment is located on the east bank. This bridge abutment is an obstruction to the flows exiting the existing bridge. There is significant erosion and degradation of the abutment because the flows exiting the bridge are directed at this obstruction. The tight bend immediately downstream appears to impinge the flows exiting the bridge as evidenced by significant deposition (up to 6 feet) of fines immediately downstream of the bridge. The impingement is caused by the fill material or terrace behind the abutment separating the channel from the mill race.
- ❖ At the top of this segment, the channel is moving east as the bank is severely eroded behind the abandoned bridge abutment. There are signs of lateral movement to the west as well.
- ❖ This channel is classified as an F-type stream

The abandoned East Bridge Abutment shown in the 1933 bridge plans (100 feet downstream of Structure #1009) to150 feet upstream of the crossing..

- The base-level control for this segment begins at the low-flow high-gradient feature or armored riffle located downstream of the abandoned bridge abutment. The LFGH consists of displaced boulders from the dam and large fractured pieces of bedrock. Degradation of that riffle will cause some incision and increase lateral movement in an easterly direction.
- A LFHG feature or armored riffle is located immediately downstream of the bridge face and extends upstream almost to Pier D. This LFHG is short, steep, and composed of displaced boulders – possibly riprap – and large pieces of fractured bedrock. A second LFHG is located immediately upstream of the bridge face. This LFHG is located where the existing dam has breached (Photo 74). The material is large boulders that formed the dam.
- The east bank is 12 feet high and composed of fine, laminated sediments with no indication of gravel or organic layers (Photo 104). The right bank consists primarily of fine sediments upstream and downstream of Structure #10091 and the dam. The depositional areas downstream of the bridge are vegetated with herbaceous plants and mature trees. Depositional areas under and upstream of the bridge are vegetated with herbaceous and small woody vegetation.
- The scour pool located at Pier D is approximately 4 feet deep (Photo 89). A second pool that begins upstream of the breached dam is shallow, with depths typically less than 2 feet.
- A large side bar on the west side extends upstream of the dam and continues through the bridge and downstream of the abandoned bridge abutment (Photo 68). The bar consists mostly of sand and fine gravels. The upstream dam limits any larger material from depositing on this bar. Downstream of the bridge, the bar is heavily vegetated with mature trees.
- In the existing condition, the breach in the dam directs debris to Pier D (Photo 92). There is also other debris scattered below the bridge. Displaced grout bags are visible around the pier, indicating that the debris collected at the bridge increases pier scour. There is also a broken section of stone retaining wall associated with the mill race in the scour hole of Pier D.
- There is an unnamed tributary entering Catoctin Creek from the west, under the bridge in front of the west abutment (Abutment A). The tributary is located within the depositional feature under the bridge and provides very little bed load to the system. It is entrenched and may add to the fine sediment deposition.
- There are retaining walls attached to Pier D and the upstream wingwall of the east abutment (Abutment E). These retaining walls obstruct the flow entering the easternmost span. Downstream of this span a high bank lies between the channel and the abandoned mill race. Immediately upstream of the bridge is an imbricated rock dam that has breached adjacent to Pier D. The height of this dam is typically 6 feet from the upstream water surface. Because of the alignment of the dam, Piers B and C are skewed to the overtopping flows. This dam also provides significant backwater upstream. The upstream pool is filled with fines, and approximately 1,000 feet upstream there is significant aggradation, lateral movement, and bar development. The dam affects the frequency and magnitude of bed load material reaching the bridge. Piers B and C are located downstream of the dam within the high deposition (greater than 6 feet).
- The channel will continue to migrate east in the vicinity of the bridge because of the dam alignment and location, the breach in the dam, and its location within the valley.
- This channel is classified as an F-type stream

From 100 feet upstream of the crossing to the Unnamed Tributary 500 feet upstream (downstream limit of the Supply Reach) .

- The base-level control for this reach begins at the low-flow high-gradient located at the breached rock dam immediately upstream of the bridge. Degradation of that riffle will cause some incision and increase lateral movement in an easterly direction.
- There are no LFHG features in the segment because it is located behind the stone dam.
- The east bank is 10 feet high and composed of fine, laminated sediments with cohesive material above and below the water surface. There is no visual indication of the gravel or organic layers within the banks. The west bank is typically along the west valley wall and consists primarily of bedrock outcrops and trees.
- The pool upstream of the dam is typically less than 2 feet deep, with local scour at bedrock outcrops 2.5 feet deep. The pool is filled with fine sediments that have aggraded above the normal water surface immediately behind the dam.
- A large bar on the west side, which consists of gravels and predominately sand and fine sediments, extends upstream. The vegetation on the bar consists of herbaceous and young woody material.
- This reach is straight and wide and will transport debris from upstream and local sources to the bridge (Photo 107).
- The unnamed tributary is very small and located within the bedrock. The flows and bed load input are insignificant to the bridge.
- The bedrock outcrop located at the upstream limit of this segment directs the flows from the west valley wall into the east bank.
- Because of the locations of (1) the channel within the valley, (2) the location of the dam breach, and (3) the remaining dam segment and its alignment, the channel will continue to migrate eastward toward the east abutment of Structure #10091 (Abutment E).
- This channel is classified as an F-type stream

C. Supply Reach.

The Supply Reach assessed begins approximately 500 feet upstream of MD Route 464 over Catoctin Creek (Structure #10091) and extends upstream another 1,400 feet. The description of the Supply Reach is one segment highlighting different features.

- The base-level control for this reach is the LFHG feature (breached dam) immediately upstream of the bridge.
- A very short and mildly sloped LFHG feature (riffle) exists at the upper segment of the supply reach. This riffle consists primarily of medium to coarse gravel (Photo 19).
- The east bank is 10 feet high, is forested, and consists of fine, laminated sediments to the water surface. An organic layer overlying quartz gravel exists approximately 1.5 feet below the water surface (Photo 112). The west bank at the lower end, along the valley wall, is protected by riprap, bedrock, and trees. A local road parallels the channel. Approximately 1,500 feet upstream of the bridge, the channel moves away from the valley wall to the east, with the roadway immediately adjacent to the channel. The west bank height is 10 feet in this location. There have been numerous repairs, typically riprap or boulder placement, to the roadway embankment at this location and continuing upstream. In unprotected areas, the banks consist of fine legacy sediments with an organic layer and gravel identified near the water surface at a couple locations. The banks are lined with trees and exhibit tree fall and exposed roots. The floodplain to the west, on the west side of the road, is a mowed field.
- This reach can provide and transport debris to the bridge.
- There are no tributaries within the Supply Reach.
- This reach will experience lateral movement in an easterly direction (Photo 121). The channel moves from the west valley wall to the east valley wall approximately 1,500 feet upstream of the bridge. The channel will move in a westerly direction in this location and will have an impact on the local road. Previous problems have occurred, as indicated by the numerous locations of placed riprap and boulders.
- The channel classification in this location is F-type.

Attachment B:

Photographs

I. Photographs of features identified and discussed in the report

II. Geo-referenced Photographic Record

Attachment B:

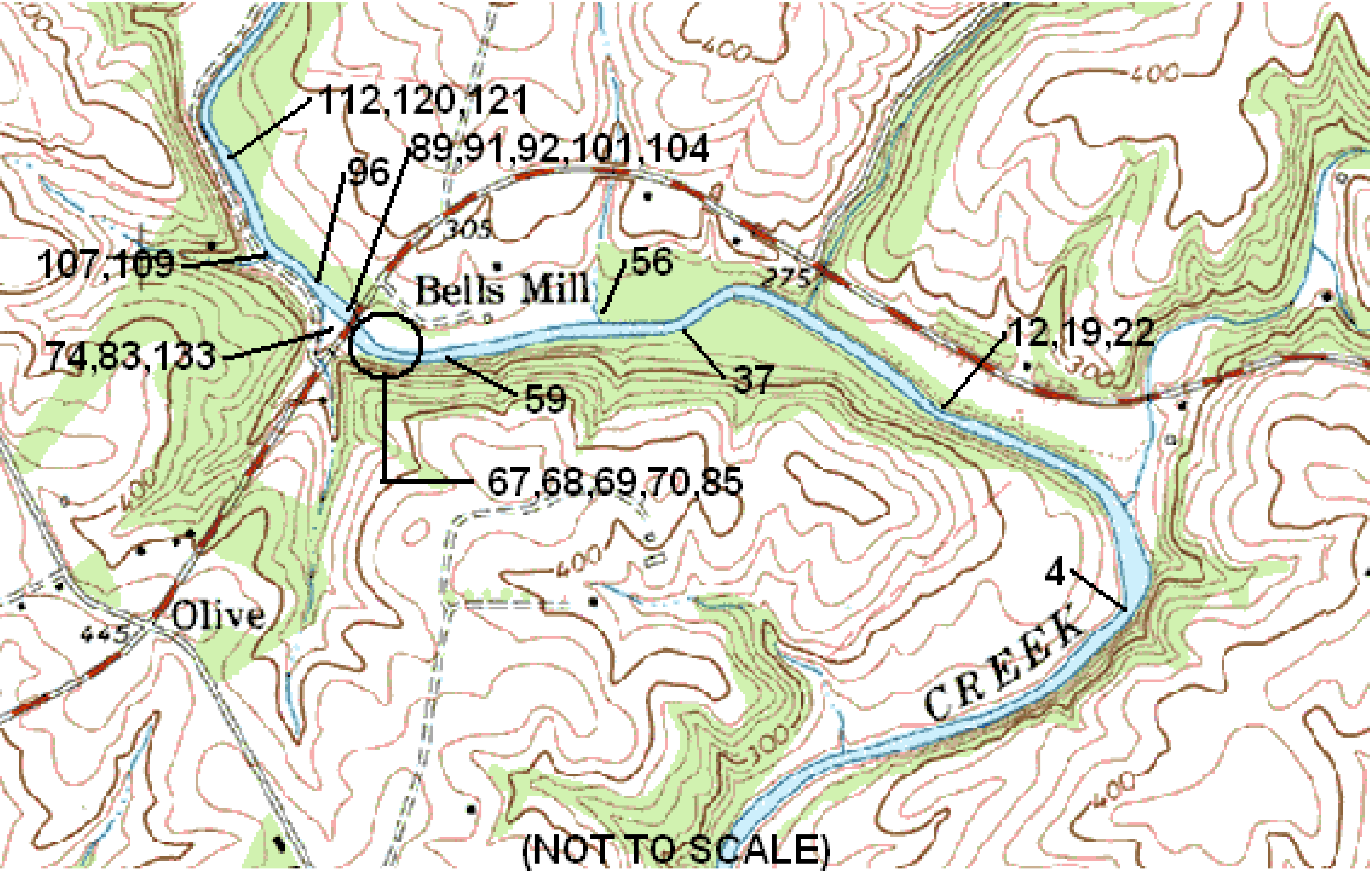
Photographs

I. Photographs of features identified and discussed in the report

A. Photo Locations

B. Featured Photos

PHOTO LOCATION MAP



FEATURED PHOTOGRAPHS

Photo 70: Left bank height (11') between MD 464 Bridge and existing bridge abutment. This vertical bank is composed of legacy sediments and is typical of the banks found throughout the site.

Photo 109: Bedrock outcrop on west (right) bank directing flows to the left.

Photo 37: Bedrock with bore hole indicating blasting activity in this region of Catoctin Creek.

Photo 121: High bank, low depositional features.

Photo 83: Scour at Pier B and deposition in the B-C span.

Photo 67: Looking upstream, old bridge abutment (with 5.5' deep scour hole) on right receiving majority of flow redirected by MD 464 Pier D

Photo 101: Approach flows constricted by 6' high stone mill dam on right (in vegetation) and high banks with debris jam on left.

Photo 59: Channel movement, low depositional feature.

Photo 133: Top of B-C span looking upstream. Mill dam is in vegetation.

Photo 96: Stone mill dam extending from right bank to wall at Pier D.

Photo 56: Mill building and tailrace.

Photo 91: Broken stone wall and grout bags at upstream wall of Pier D.

Photo 89: Scour hole (4.5' deep) and grout bags (left) at Pier D.

Photo 69: Scour hole (>5.5' deep) at old bridge abutment.

Photo 85: Looking downstream from center of C-D span.

Photo 4: Degraded local base level point downstream of MD 464 Bridge.

Photo 12: High vertical banks (9') consisting of laminated sediments.

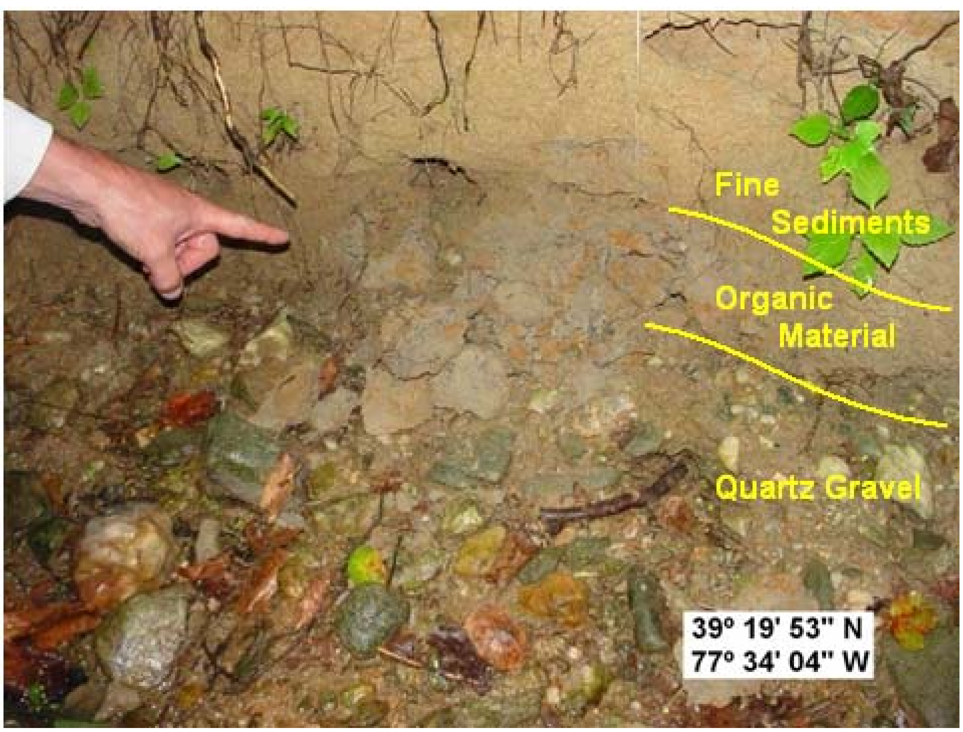


Photo 22: Layers of fine laminated sediments (top), grey/blackish organic material (middle) and quartz gravel (bottom).

Photo 74: Remnants of stone mill dam compose substrate for LFHG feature at MD 464 Bridge.

Photo 104: Vertical banks (10') composed fine laminated sediments.

Photo 89: Looking downstream, scour hole at retaining wall above Pier D, pool depth 4'.

Photo 68: Looking upstream, deposition occurs throughout spans A-B, B-C, and C-D.

Photo 92: Debris collected at wall in front of Pier D.

Photo 107: Approach flow direction and 10' high stream banks on either side. Note bedrock outcrop on right bank.

Photo 19: Quartz gravel forming LFHG feature.

Photo 112: Left bank height 10'.

Attachment B:

Photographs

II. Geo-referenced Photographic Record

A. Photo Index

PHOTO INDEX

Photo No.	GPS Point No.	LATITUDE				LONGITUDE				Description
		o	'	"		o	'	"		
1	1	39	19	40	N	77	33	45	W	Downstream of degraded local base point with exposed bedrock along hillslope and bar formation.
2	2	39	19	40	N	77	33	45	W	Bar material consists of broken bedrock cobble with quartz gravel.
3	3	39	19	40	N	77	33	45	W	Exposed bedrock on left bank at degraded local base level point, island on right.
4	4	39	19	40	N	77	33	45	W	Upstream view of low-flow high gradient-feature (LFHG). Degraded local base point with exposed bedrock showing signs of weathering. Island shown on right.
5	5	39	19	42	N	77	33	47	W	Bottom of LFHG at local degraded base level point, island on right.
6	6	39	19	42	N	77	33	47	W	Bar material.
7	7	39	19	47	N	77	33	50	W	Upstream of LFHG feature looking downstream, island in middle.
8	8	39	19	48	N	77	33	48	W	Looking up tributary, pool depth at confluence 3.5'.
9	9	39	19	48	N	77	33	48	W	Bar material in tributary, quartz gravel and broken bedrock.
10	10	39	19	48	N	77	33	48	W	Looking upstream in tributary, ford shown leading to junkyard.
11	11	39	19	47	N	77	33	50	W	Looking upstream Catoctin Creek at confluence.
12	12	39	19	51	N	77	34	0	W	Looking at left bank, fine laminated sediments, 9' bank height.
13	13	39	19	51	N	77	34	0	W	Looking downstream, stream along right valley wall.
14	14	39	19	49	N	77	33	58	W	Looking at bedrock outcrop on right bank, pool depth 2.4'.
15	15	39	19	51	N	77	34	0	W	Rebar in legacy sediment, resistance met at 3' below water surface.
16	16	39	19	51	N	77	34	0	W	Clay material 2' below water surface.
17	17	39	19	53	N	77	34	4	W	Bottom of second LFHG feature looking downstream.
18	18	39	19	53	N	77	34	4	W	Bottom of LFHG feature looking upstream.
19	19	39	19	53	N	77	34	4	W	Quartz gravel forming LFHG feature.
20	20	39	19	53	N	77	34	4	W	Quartz bar material.
21	21	39	19	53	N	77	34	4	W	Looking at left bank, quartz gravel layer below 8' of fine laminated sediments.
22	22	39	19	53	N	77	34	4	W	Organic pre-settlement floodplain just above quartz gravel layer.
23	23	39	19	55	N	77	34	7	W	Looking upstream at second LFHG feature.
24	24	39	19	55	N	77	34	9	W	Bed substrate forming second LFHG feature.
25	25	39	19	56	N	77	34	9	W	Top of second LFHG feature looking upstream.
26	26	39	19	56	N	77	34	9	W	Tributary with bridge and old abutment on right.
27	27	39	19	57	N	77	34	10	W	Bed substrate typically broken bedrock.
28	28	39	19	58	N	77	34	13	W	Looking downstream at bedrock outcrop on left bank, 3.5' pool depth.
29	29	39	19	58	N	77	34	13	W	Looking at left bank, height of 7.5'.
30	30	39	19	59	N	77	34	16	W	Quartz gravels, riffle substrate.
31	31	39	19	58	N	77	34	17	W	Quartz gravels, bar material.
32	32	39	19	58	N	77	34	15	W	Looking downstream at bottom third of LFHG feature
33	33	39	19	58	N	77	34	15	W	Looking upstream at third LFHG feature.
34	34	39	19	58	N	77	34	17	W	Middle of third LFHG feature, looking upstream.
35	35	39	19	57	N	77	34	19	W	Looking downstream at top of third LFHG feature.
36	36	39	19	58	N	77	34	17	W	Looking upstream at bedrock within third LFHG feature.
37	37	39	19	57	N	77	34	19	W	Bore hole in bedrock.
38	38	39	19	57	N	77	34	19	W	Bore hole in bedrock.
39	39	39	19	57	N	77	34	19	W	Fracturing and weathering occurring in bedrock along right bank.
40	40	39	19	57	N	77	34	19	W	Top of third LFHG feature, looking upstream.
41	41	39	19	56	N	77	34	20	W	Looking at left bank, pool depth 2.0' bank height 11'.
42	42	39	19	57	N	77	34	30	W	Looking at left bank, pool depth 1.3' bank height 12'.
43	43	39	19	57	N	77	34	30	W	Left bank, low soil formation.
44	44	39	19	57	N	77	34	30	W	Possible pre-settlement floodplain, resistance 1.3' below water surface.
45	45	39	19	57	N	77	34	30	W	Looking downstream, bar on right.
46	46	39	19	56	N	77	34	29	W	Bar height 1.2'.
47	47	39	19	55	N	77	34	30	W	Bar material, quartz gravels.
48	48	39	19	57	N	77	34	30	W	Looking downstream, bedrock outcrop on right bank and bar formation on left bank.
49	49	39	19	56	N	77	34	31	W	Looking at right bank, pool depth 4.5'.
50	50	39	19	55	N	77	34	30	W	LFHG feature substrate, quartz gravels.
51	51	39	19	55	N	77	34	30	W	LFHG feature substrate, quartz gravels.
52	52	39	19	55	N	77	34	36	W	Bar formation by LFHG feature.
53	53	39	19	55	N	77	34	36	W	Bar material, fractured bedrock.
54	54	39	19	55	N	77	34	40	W	Bar height 1.7'.
55	55	39	19	55	N	77	34	33	W	Looking downstream from Millrace confluence.
56	56	39	19	55	N	77	34	33	W	Millrace and Mill.
57	57	39	19	55	N	77	34	33	W	Looking upstream from Millrace confluence.
58	58	39	19	56	N	77	34	32	W	Left bank bar formation immediately below Millrace confluence.
59	59	39	19	56	N	77	34	33	W	Bar width = 65', stream width = 40'.
60	60	39	19	55	N	77	34	35	W	Bottom of LFHG 4 looking downstream.
61	61	39	19	55	N	77	34	35	W	Looking upstream at LFHG feature 5.
62	62	39	19	54	N	77	34	37	W	Looking downstream at armored LFHG feature 5 composed of fractured bedrock.
63	63	39	19	54	N	77	34	37	W	Looking upstream of LFHG feature 5.
64	64	39	19	55	N	77	34	41	W	Looking downstream from bottom of LFHG feature 6 with stream along right valley wall.
65	65	39	19	55	N	77	34	40	W	Exposed roots and fractured bedrock.
66	66	39	19	55	N	77	34	40	W	Looking upstream at exit conditions of MD 464 bridge.
67	67	39	19	56	N	77	34	42	W	Top of LFHG looking upstream at exit conditions of bridge.
68	68	39	19	56	N	77	34	42	W	Looking upstream, old bridge abutment obstructs exit flows.
69	69	39	19	57	N	77	34	43	W	Scour pool at old bridge abutment, pool depth >5.5'
70	70	39	19	57	N	77	34	43	W	Left bank height 11' downstream of MD 464 bridge upstream of old abutment.
71	71	39	19	56	N	77	34	42	W	High depositional feature downstream of B-C span.

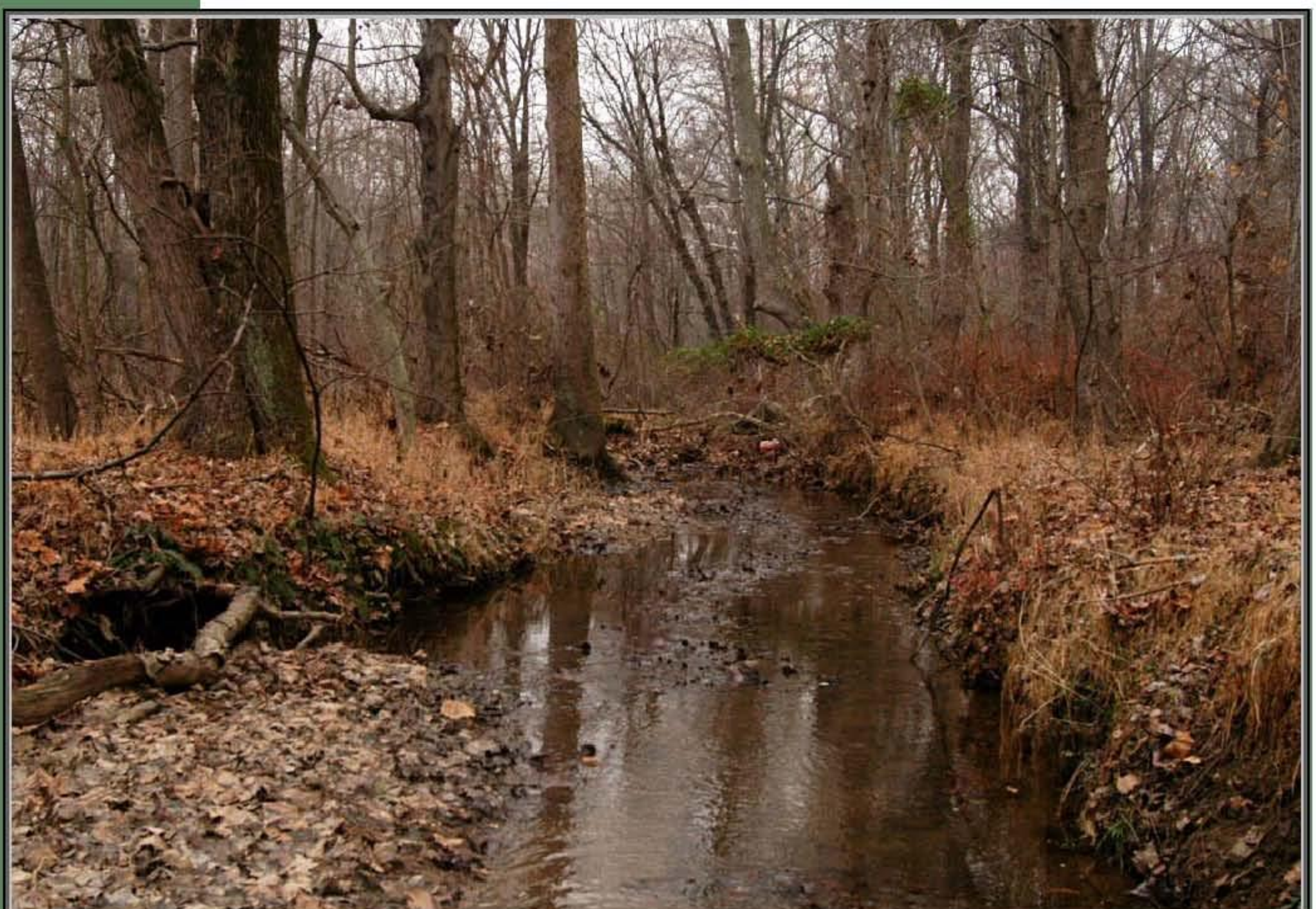
PHOTO INDEX (continued)

72	72	39	19	56	N	77	34	42	W	Looking upstream at A-B span, high bank encroaches on flow.
73	73	39	19	56	N	77	34	42	W	Looking upstream at Pier B and high sediment deposit.
74	74	39	19	57	N	77	34	43	W	Span C-D, looking upstream.
75	75	39	19	56	N	77	34	42	W	Looking upstream to C-D span, Justin standing on stone mill dam. Dam height is 6’, obstructing flows entering the C-D span.
76	76	39	19	56	N	77	34	43	W	Broken dam matter forms HGLF 6 at bridge.
77	77	39	19	56	N	77	34	43	W	Looking upstream at D-E span, high bank separates Millrace from stream.
78	78	39	19	57	N	77	34	43	W	Abandoned Millrace entrance downstream of D-E span.
79	79	39	19	56	N	77	34	45	W	Looking downstream from center of A-B span, high bank obstructs high flow.
80	80	39	19	56	N	77	34	45	W	Looking upstream from center of A-B span.
81	81	39	19	57	N	77	34	44	W	Looking downstream from center of B-C span.
82	82	39	19	57	N	77	34	44	W	Looking upstream from center of B-C span.
83	83	39	19	57	N	77	34	46	W	Scour at Pier B and deposition in the B-C span.
84	84	39	19	57	N	77	34	46	W	Looking upstream from center of C-D span. 6’ stone mill dam not visible due to vegetation.
85	85	39	19	58	N	77	34	44	W	Looking downstream from center of C-D span.
86	86	39	19	58	N	77	34	44	W	Looking upstream from center of D-E span.
87	87	39	19	58	N	77	34	44	W	Looking downstream from center of D-E span. Millrace visible on left.
88	88	39	19	58	N	77	34	44	W	Looking at concrete wall hidden in vegetation at D-E span.
89	89	39	19	58	N	77	34	43	W	Looking downstream, scour hole at retaining wall above Pier D, pool depth 4’.
90	90	39	19	58	N	77	34	44	W	Grout bag for scour protection at Pier D.
91	91	39	19	58	N	77	34	44	W	Broken stone wall and grout bags at upstream wall of Pier D.
92	92	39	19	58	N	77	34	46	W	Debris collected at wall in front of Pier D.
93	93	39	19	58	N	77	34	44	W	Remnants of stone mill dam that previously extended wall upstream of Pier D.
94	94	39	19	57	N	77	34	46	W	Rock dam immediately upstream of bridge extends from right valley wall to more than ½ of C-D span.
95	95	39	19	58	N	77	34	44	W	Remnants of corduroy road immediately upstream of bridge.
96										Stone mill dam extending from right bank to wall at Pier D.
97	97	39	19	58	N	77	34	46	W	Looking downstream, wall at Pier D and debris obstruct flow to left, dam on right obstructs flows up to 6’ in depth.
98	98	39	19	58	N	77	34	44	W	Looking upstream from end of stone mill dam.
99	99	39	19	58	N	77	34	46	W	Quartz gravel bar material upstream of dam.
100	100	39	19	58	N	77	34	46	W	Looking upstream of dam at pool.
101	101	39	19	58	N	77	34	46	W	Looking downstream at dam and deposition upstream of dam.
102	102	39	19	58	N	77	34	46	W	Low bank feature on left bank composed of fine sediments and clay.
103	103	39	20	0	N	77	34	47	W	Rebar driven to resistance, pool depth = 2.2’, rebar 3.8’ below WS.
104	104	39	19	58	N	77	34	46	W	Left bank 10’ high.
105	105	39	19	59	N	77	34	47	W	Looking upstream at depositional bar on left bank and bedrock outcrop on right bank.
106	106	39	19	59	N	77	34	47	W	Quartz gravels on bar.
107	107	39	20	1	N	77	34	50	W	Looking downstream, stream against bedrock outcrop along valley wall.
108	108	39	20	1	N	77	34	49	W	Bedrock on right bank directing flow to left, pool depth = 2.6'.
109	109	39	20	1	N	77	34	49	W	Bedrock outcrop on right bank directing flow to left.
110	110	39	20	1	N	77	34	50	W	Looking upstream at mid-channel bar and vertical left bank.
111	111	39	20	5	N	77	34	52	W	Pebble count LFHG feature, looking at left bank.
112	112	39	20	5	N	77	34	52	W	Left bank height 10’.
113	113	39	20	5	N	77	34	52	W	Low bank feature.
114	114	39	20	5	N	77	34	52	W	Pre-settlement layer 1.6’ below water surface.
115	115	39	20	5	N	77	34	52	W	Headcut migrating upstream, 1.6’ below water surface.
116	116	39	20	5	N	77	34	52	W	Looking downstream of pebble count LFHG feature.
117	117	39	20	5	N	77	34	52	W	Large particle size from mid-channel bar.
118	118	39	20	8	N	77	34	50	W	Mid-channel bar formation.
119	119	39	20	8	N	77	34	50	W	Gravel material on bar.
120	120	39	20	5	N	77	34	52	W	Looking upstream of pebble count LFHG feature.
121	121	39	20	5	N	77	34	52	W	Bar width = 85’, stream width = 25’.
122	122	39	19	55	N	77	34	46	W	Riprap armor along right bank, protecting road.
123	123	39	20	5	N	77	34	52	W	Rebar driven to resistance, water depth = 0.4’, rebar = 2.0’.
124	124	39	20	10	N	77	34	53	W	Looking downstream at LFHG feature.
125	125	39	20	10	N	77	34	53	W	Looking upstream, stream along east valley wall.
126	126	39	20	10	N	77	34	53	W	Bedrock on East (left) bank.
127	127	39	20	10	N	77	34	53	W	Bedrock on East (left) bank.
128	128	39	19	55	N	77	34	46	W	Western approach looking eastbound.
129	129	39	19	56	N	77	34	34	W	Center of Bridge looking westbound.
130	130	39	19	56	N	77	34	34	W	Center of Bridge looking eastbound.
131	131	39	19	56	N	77	34	34	W	Top of A-B span looking upstream.
132	132	39	19	56	N	77	34	34	W	Top of A-B span looking downstream.
133	133	39	19	56	N	77	34	34	W	Top of B-C span looking upstream. Mill dam is in vegetation.
134	134	39	19	56	N	77	34	34	W	Top of B-C span looking downstream at old bridge abutment.
135	135	39	19	57	N	77	34	44	W	Top of C-D span looking upstream.
136	136	39	19	57	N	77	34	44	W	Top of C-D span looking downstream.
137	137	39	19	57	N	77	34	43	W	Top of D-E span looking upstream.
138	138	39	19	57	N	77	34	43	W	Top of D-E span looking downstream, Millrace shown at pink ribbon.
139										Downstream of bridge looking upstream at B-C and C-D spans.
140										Upstream of bridge looking downstream at Pier D and Abutment E.

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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Note: Some pages in this document have been left intentionally blank so that the document will copy or print correctly when duplexed.

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.

Contents

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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 semi-permanently 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.

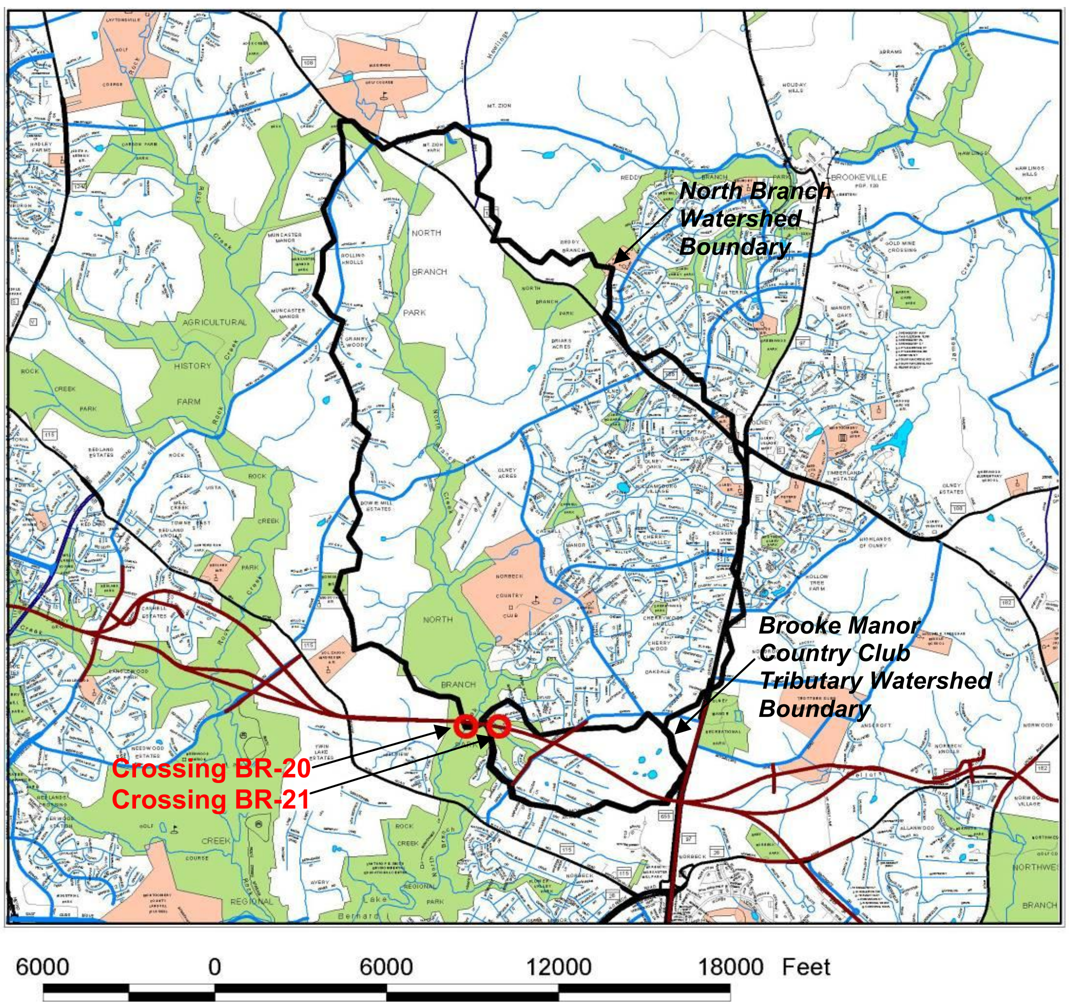


Figure 1 Crossing BR-21 vicinity map and watershed delineation.

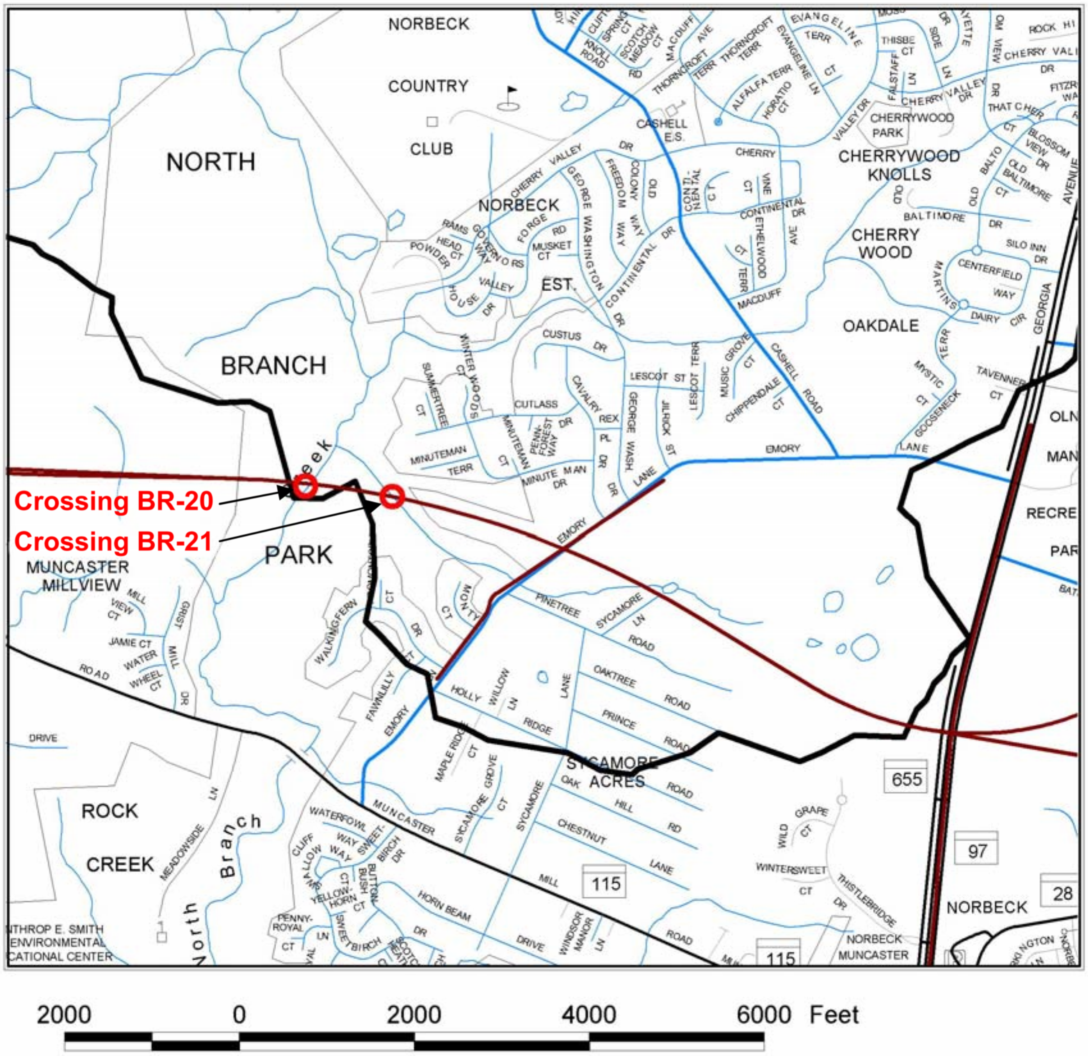


Figure 2 Crossing BR-21 location map.

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

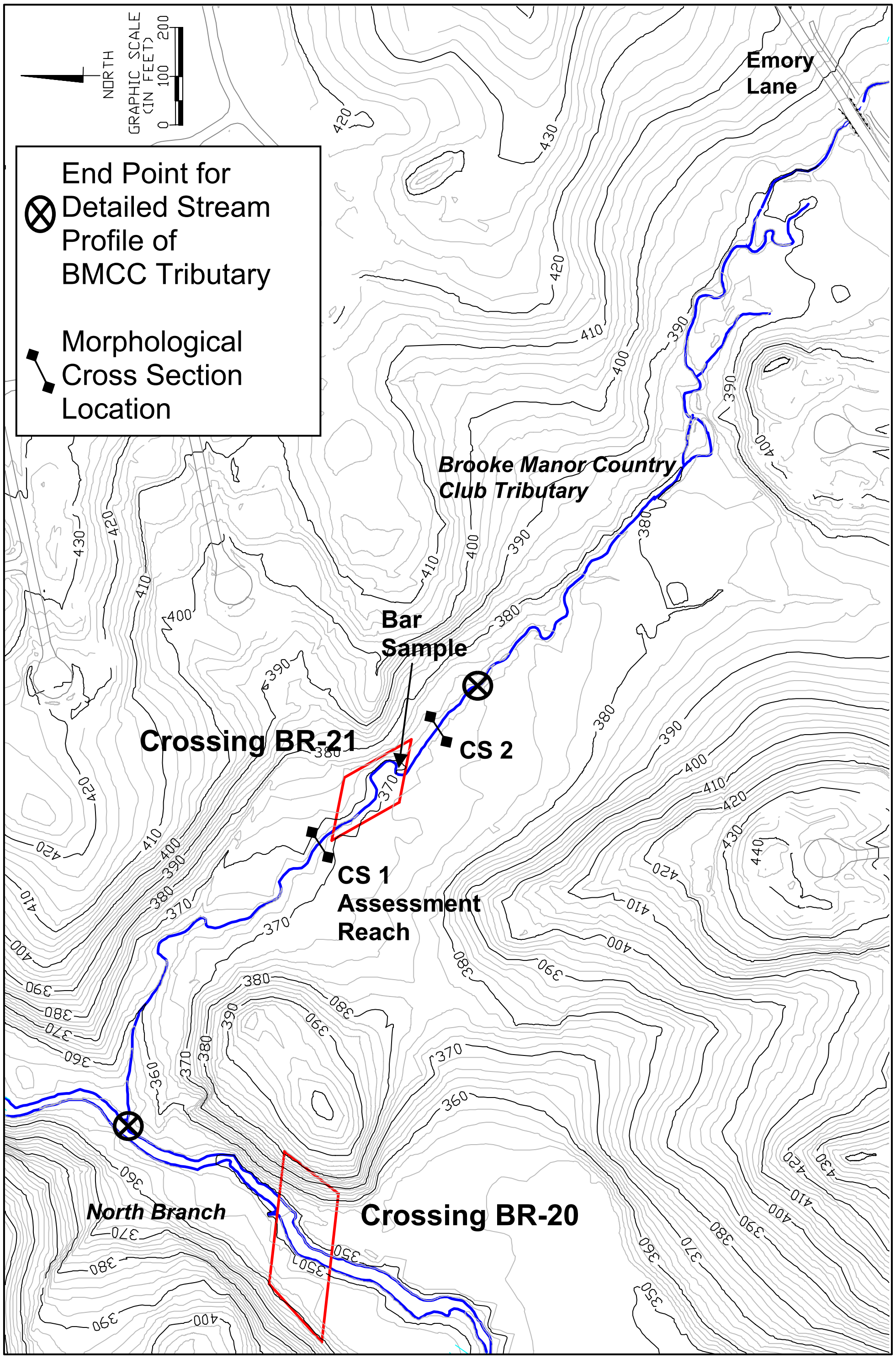


Figure 3 Crossing BR-21, topographic features, and geomorphic assessment sampling and data collection locations.

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

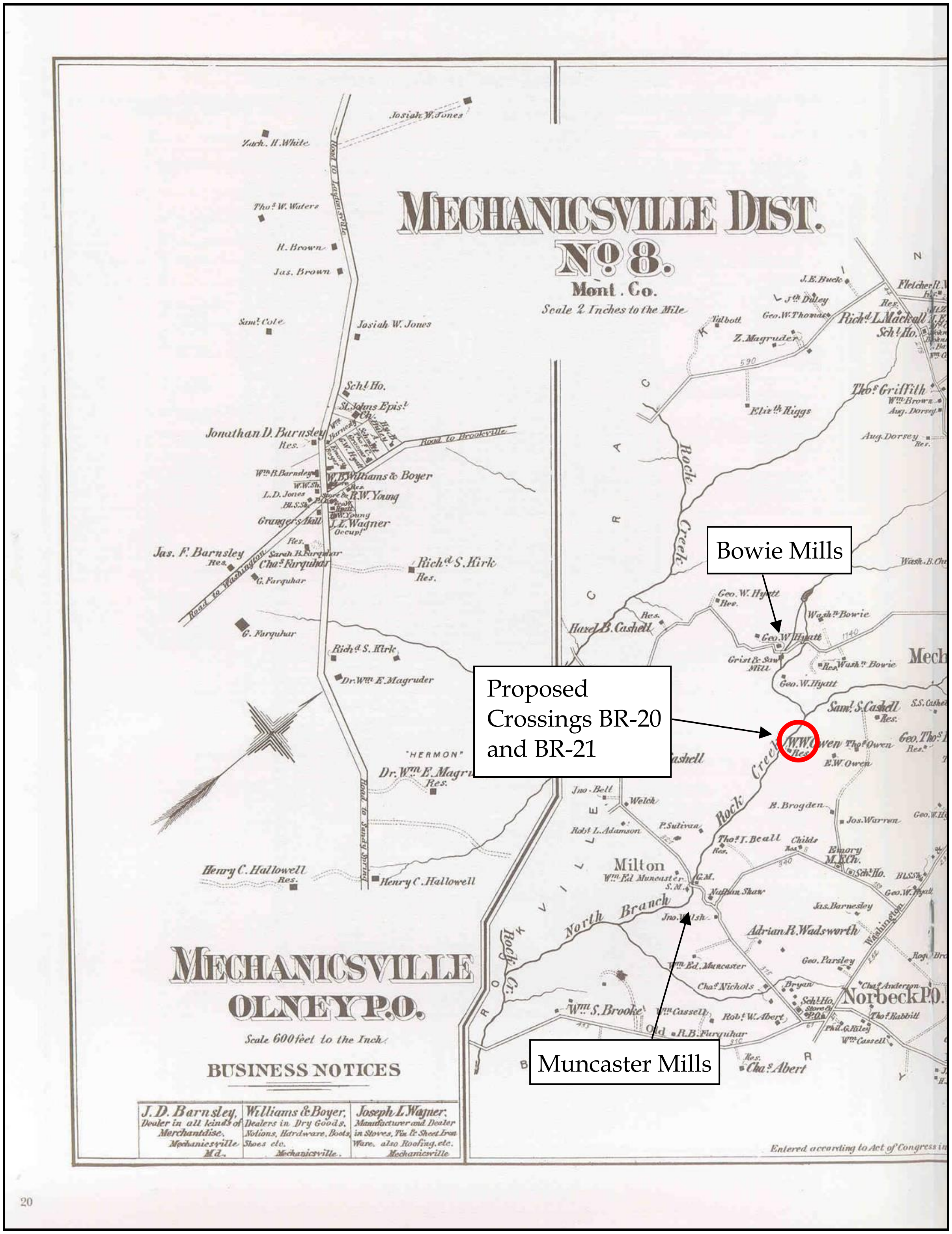


Figure 4 Historic map from Hopkins (1879).

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

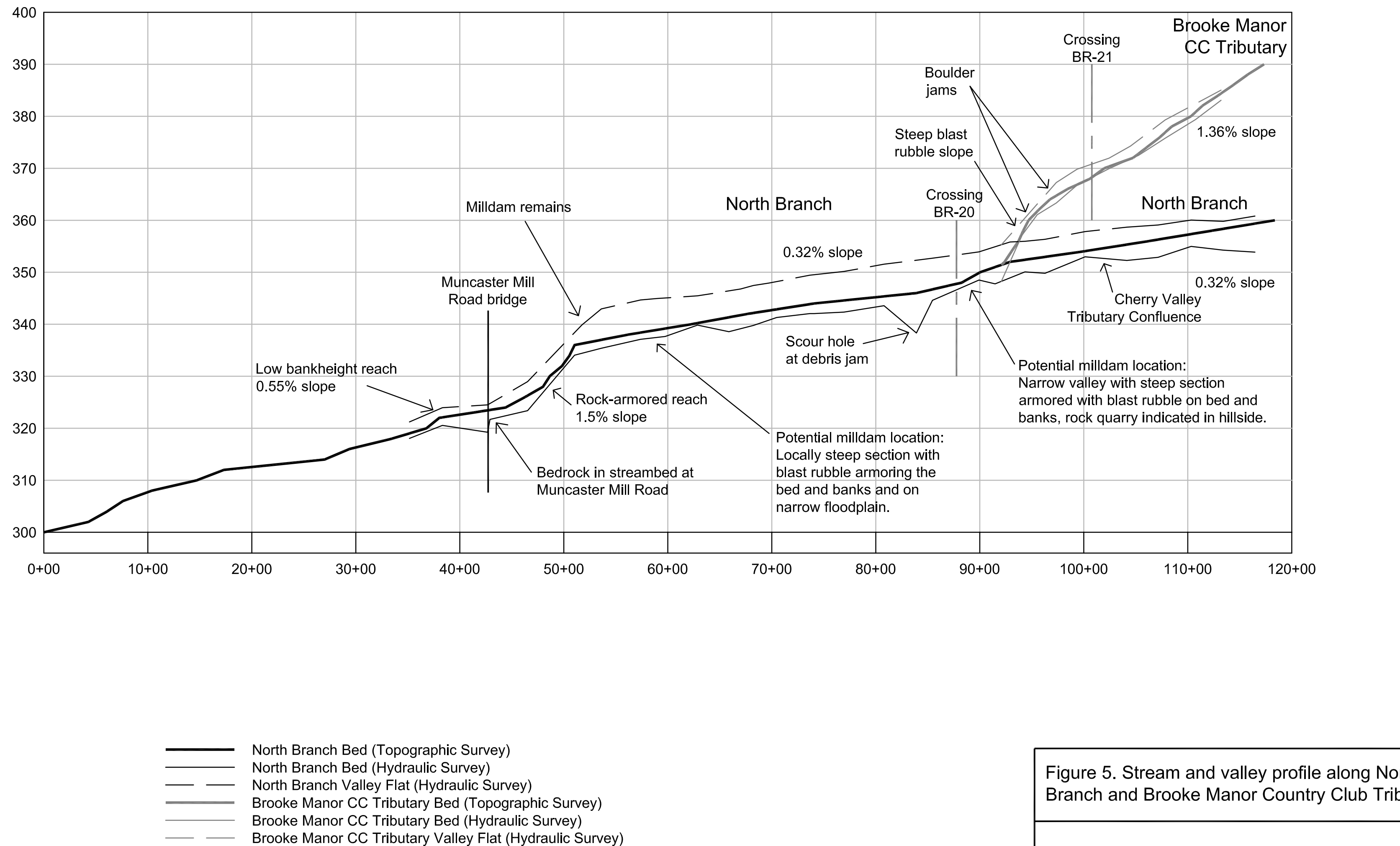
Note that the proposed location of crossing BR-21 is at valley station 101+00 feet on the BMCC tributary; stations increase in the upstream direction.

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.



Note : All slopes calculated using valley stations.

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

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.

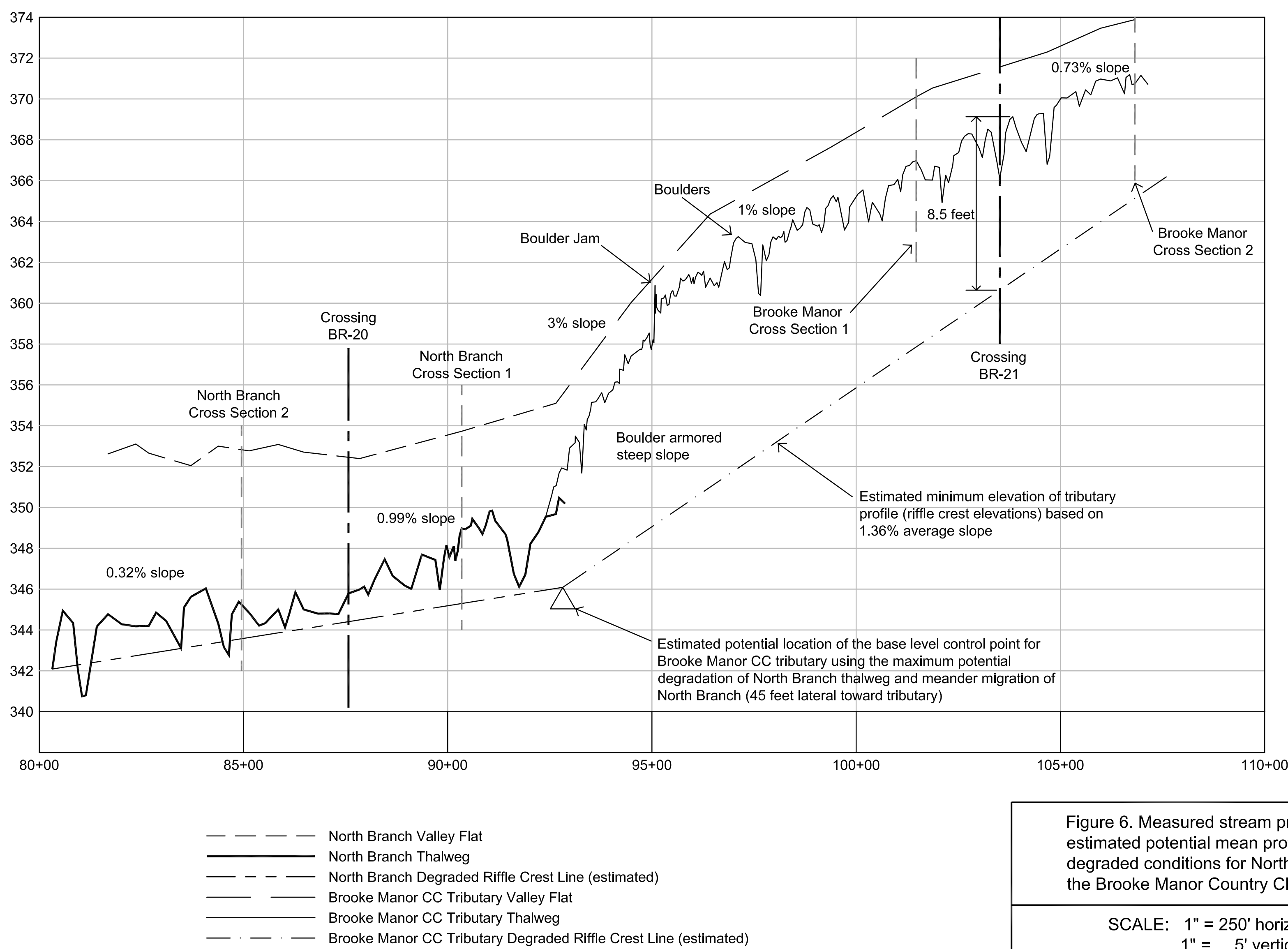


Figure 6. Measured stream profile and estimated potential mean profile under degraded conditions for North Branch and the Brooke Manor Country Club tributary.

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

Note: Scaled for 11 x 17 paper size

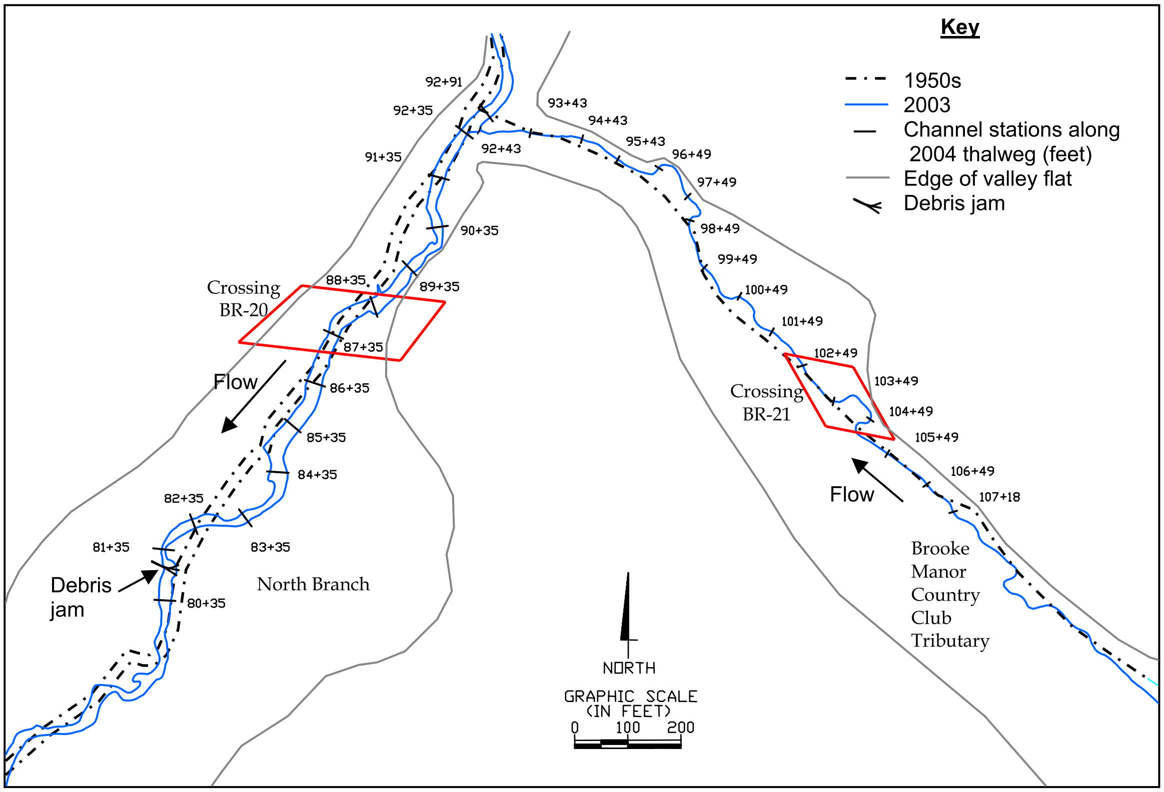


Figure 7 Alignment of North Branch and the Brooke Manor Country Club tributary in the 1950s and 2003.

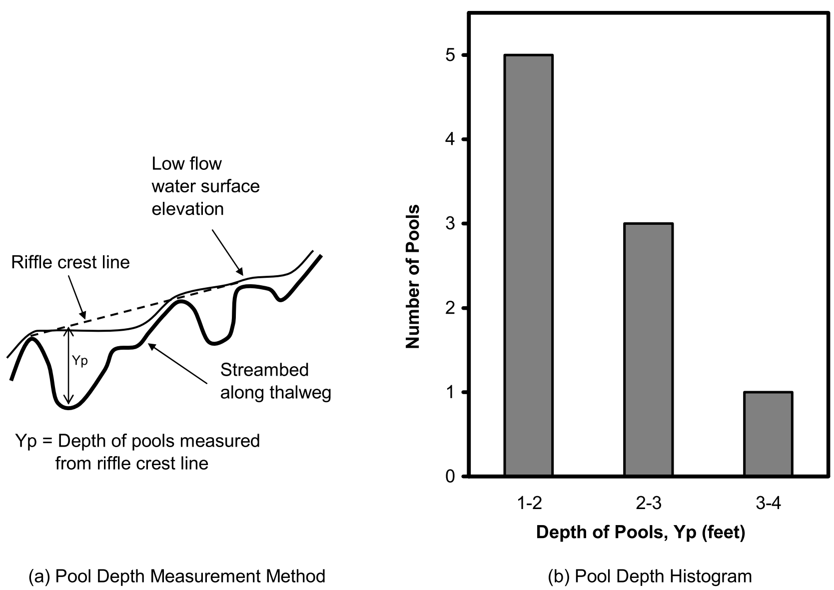


Figure 8 The (a) method of measuring pool depths and (b) distribution of major pool depths in the vicinity of proposed crossing BR-21 over Brooke Manor Country Club tributary.

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

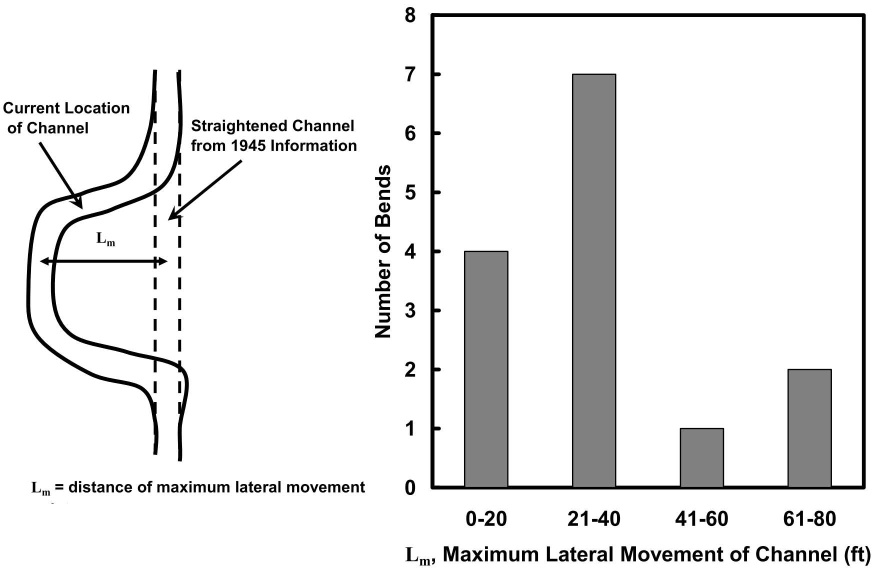
In Figure 6, both the maximum degradation line and the triangle representing the likely future location of the BMCC confluence are plotted based on the following considerations: (1) that the North Branch will degrade approximately 4 feet at the tributary confluence; (2) that the main stem of North Branch 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.

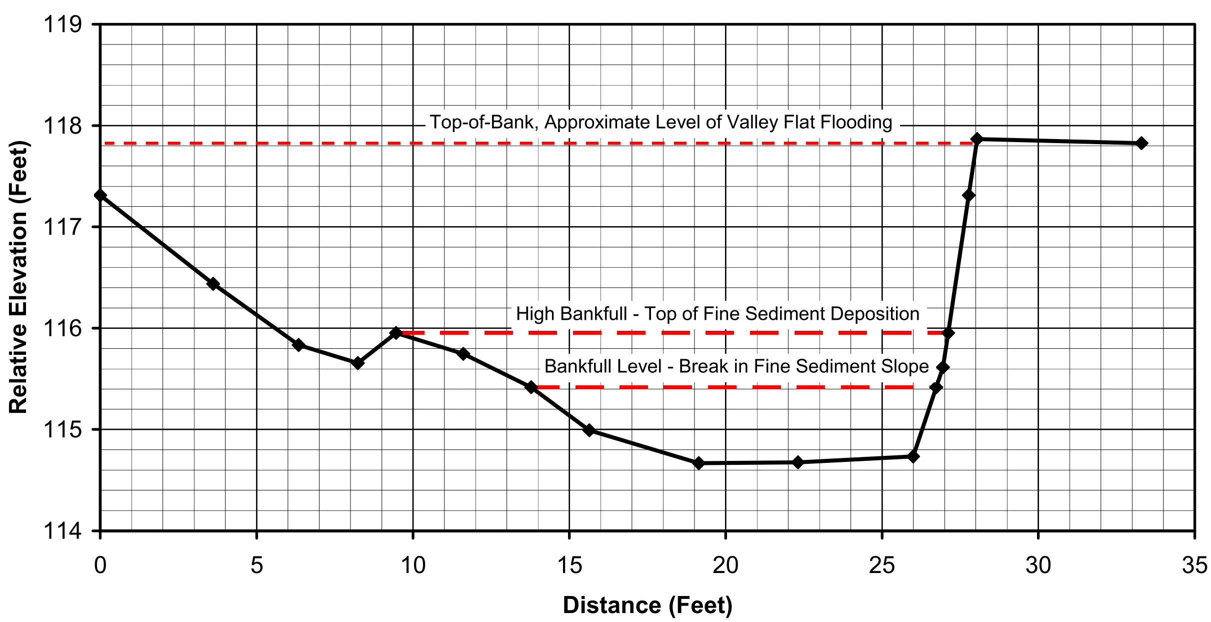


Figure 11 Cross Section 1 plot obtained from the channel section shown in Figure 10. Note that the view in the Figure 10 photo is upstream while the cross section view is downstream. For scaled version, see Attachments.

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.

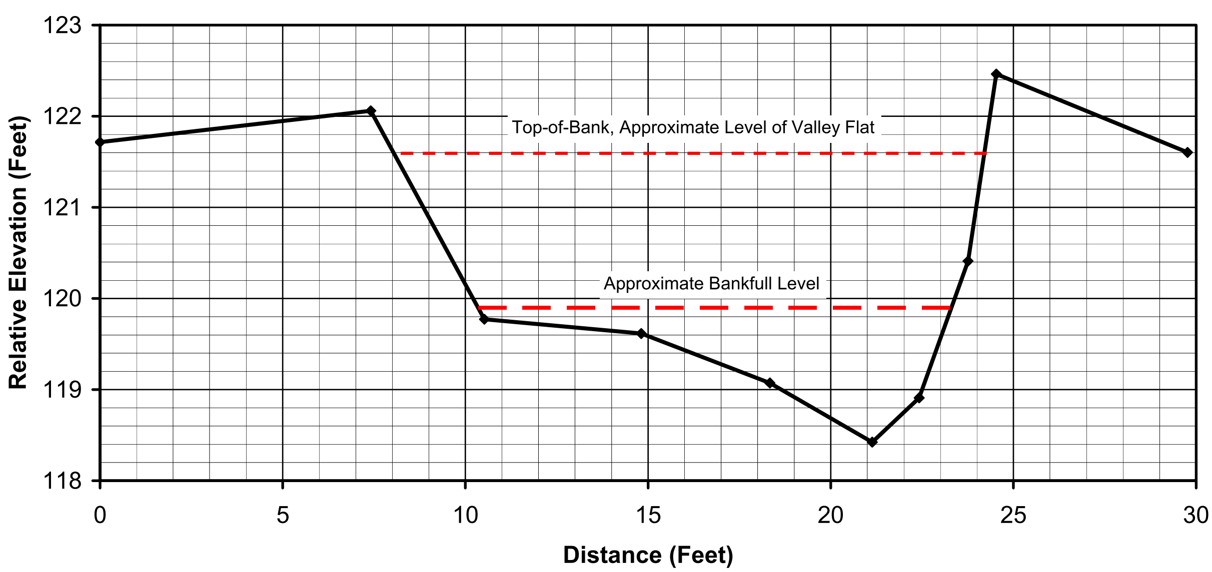


Figure 13 Channel Cross Section 2 is representative of straightened and gradually shifting and widening channels downstream of the proposed crossing. The Cross Section is located in the downstream end of the reach shown in Figure 12. For scaled version, see Attachments.

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

$$n = R_h^{1/6} \frac{0.0926}{1.16 + 2 \text{ Log} \dfrac{R_h}{D_{84riffle}}}$$

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:

$$Q = \frac{1.49}{n} \text{ A } R_h^{2/3} S_f^{1/2}$$

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.

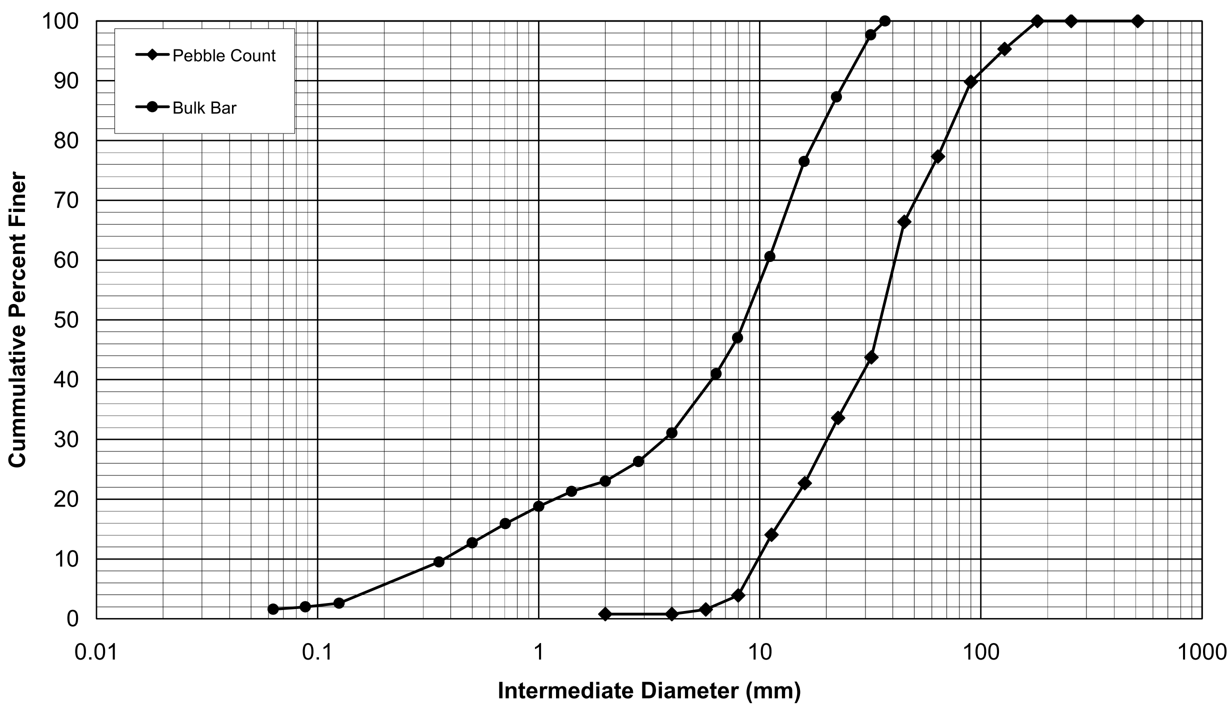


Figure 14 Bulk bar sample gradation curve with riffle surface pebble count obtained near Cross Section 1.

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.**

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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)

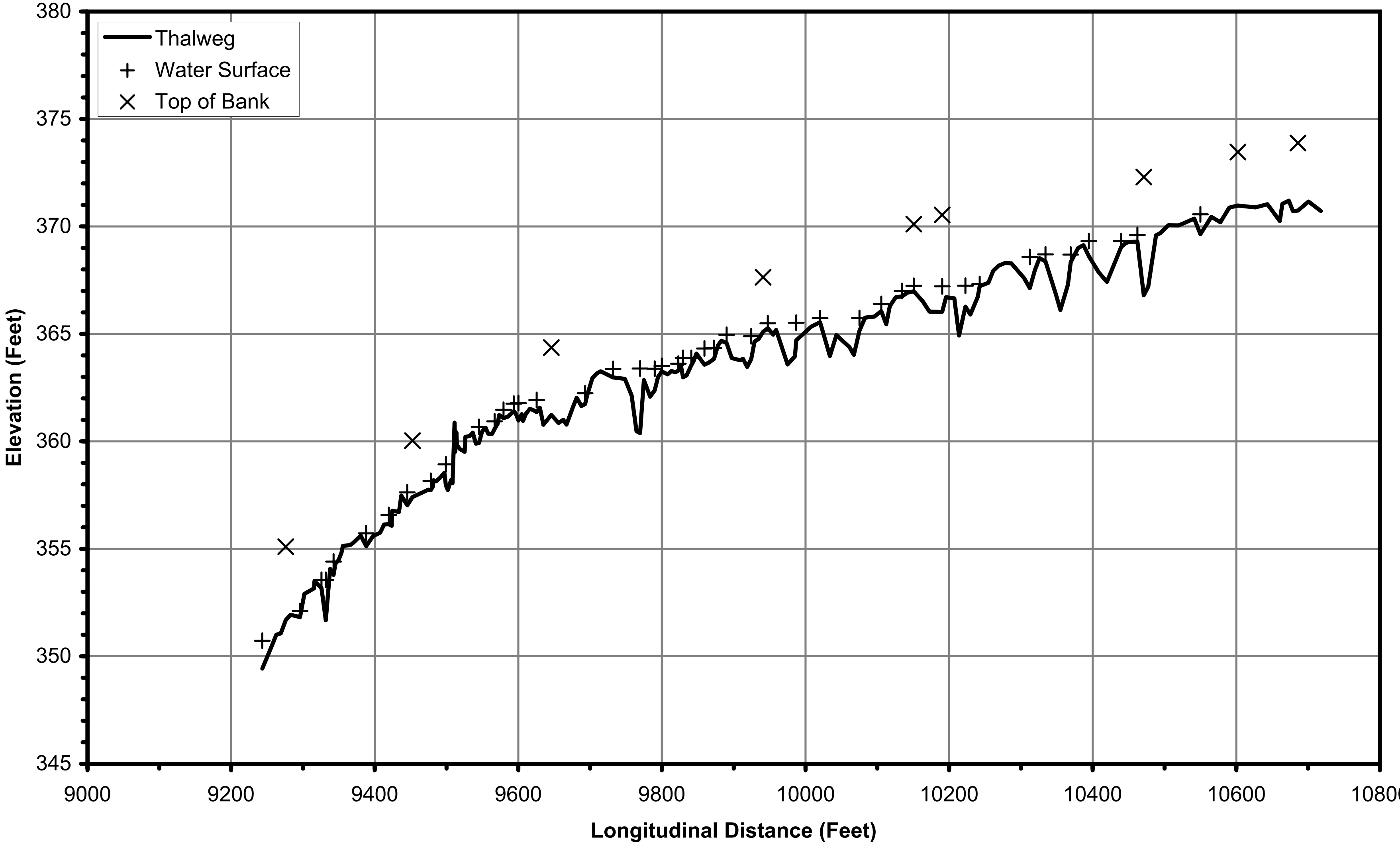
Brooke Manor Country Club Longitudinal Profile
Survey Date: 9-Jun-04
Survey by: Riverine Systems LLC

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

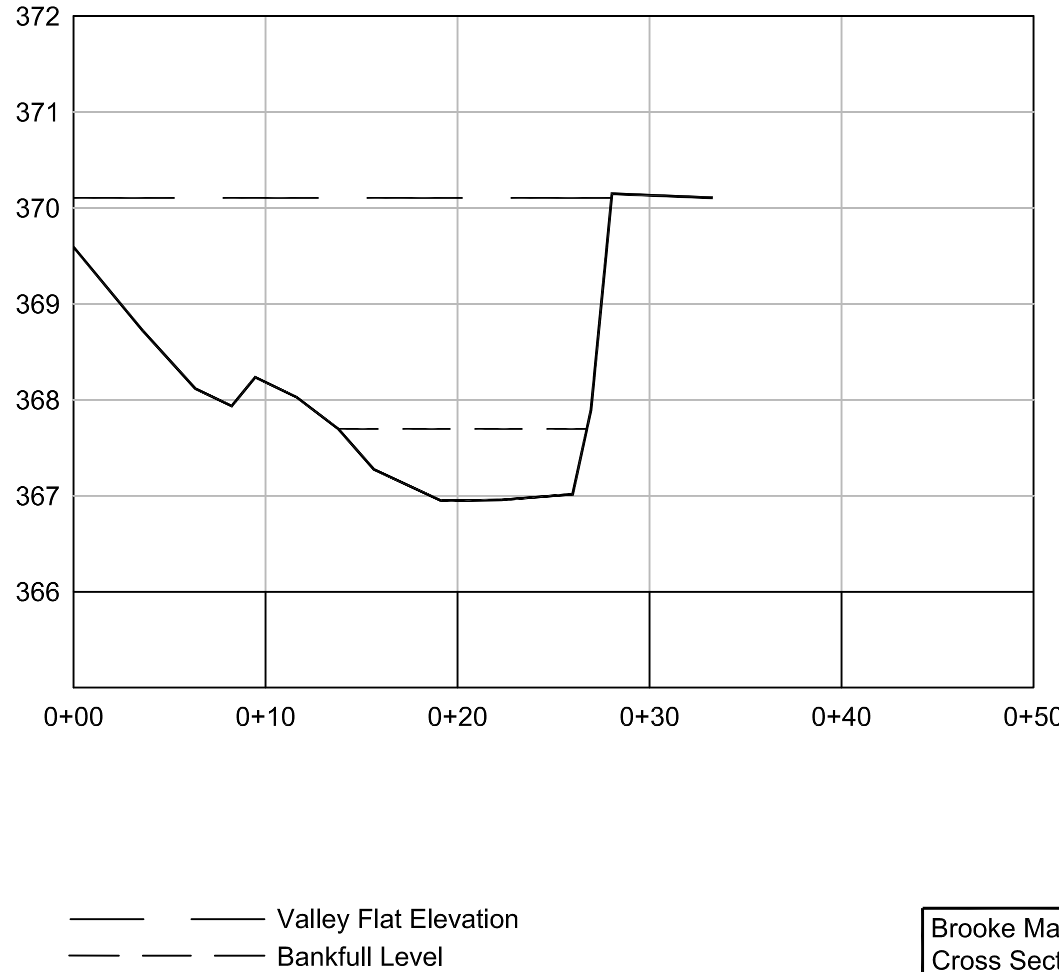
subwidth (feet)	mean d (feet)	subarea (sqr. feet)	subWP (feet)
1.86	0.21	0.40	1.91
3.50	0.59	2.05	3.51
3.17	0.75	2.36	3.17
3.68	0.71	2.62	3.68
0.74	0.34	0.25	1.01

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

Scale: 1" = 2' vertical
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

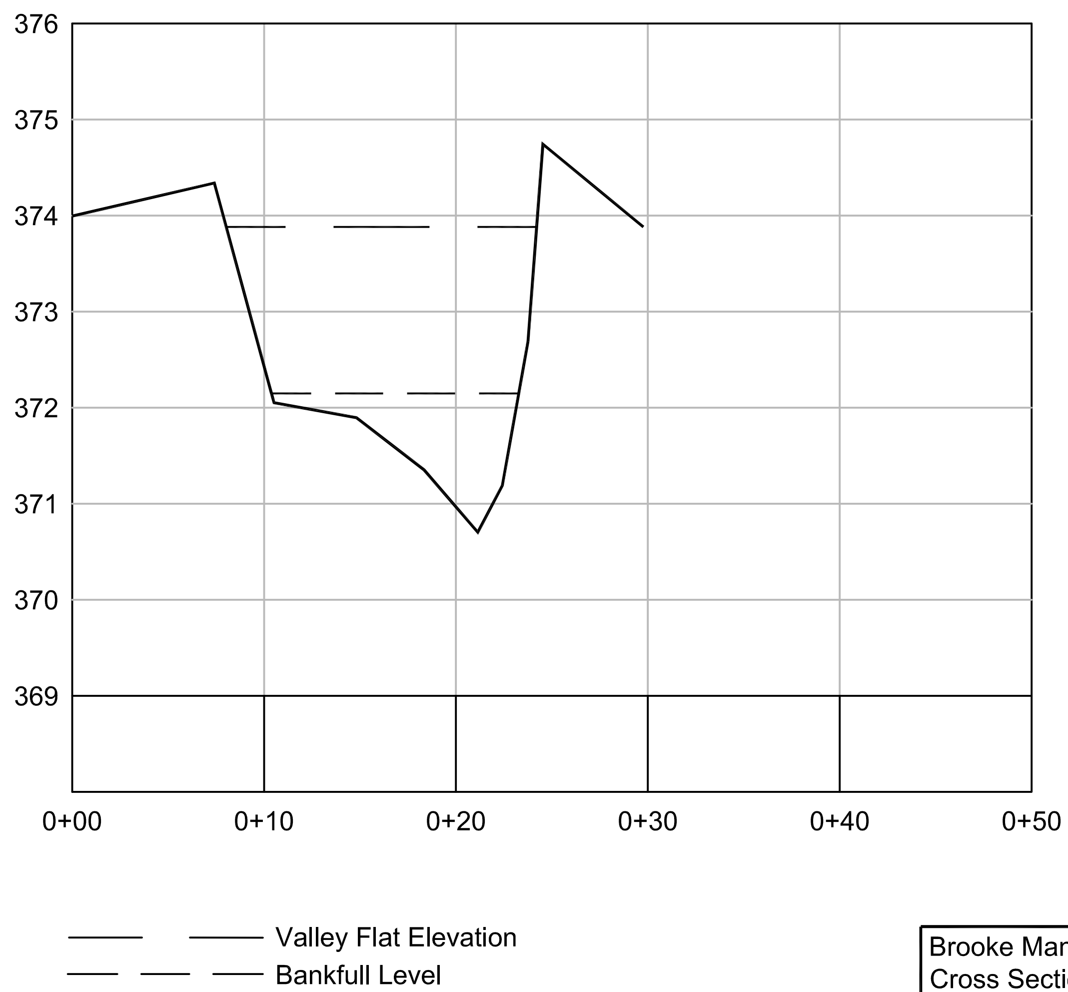
Bankfull Computations

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	

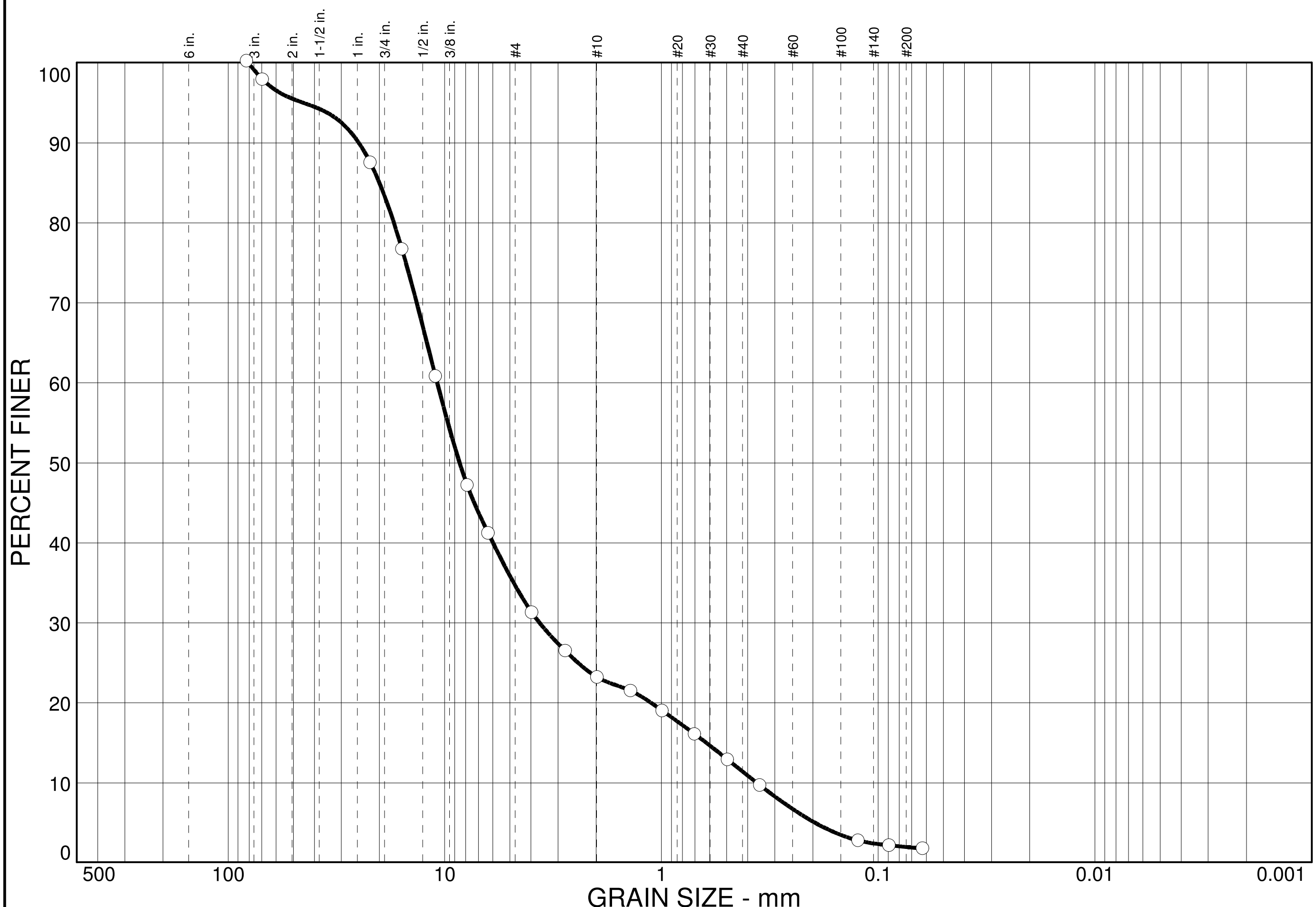
* - Set to area of cross section 1



Brooke Manor Country Club Tributray
Cross Section 2

Scale: 1" = 2' vertical
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=

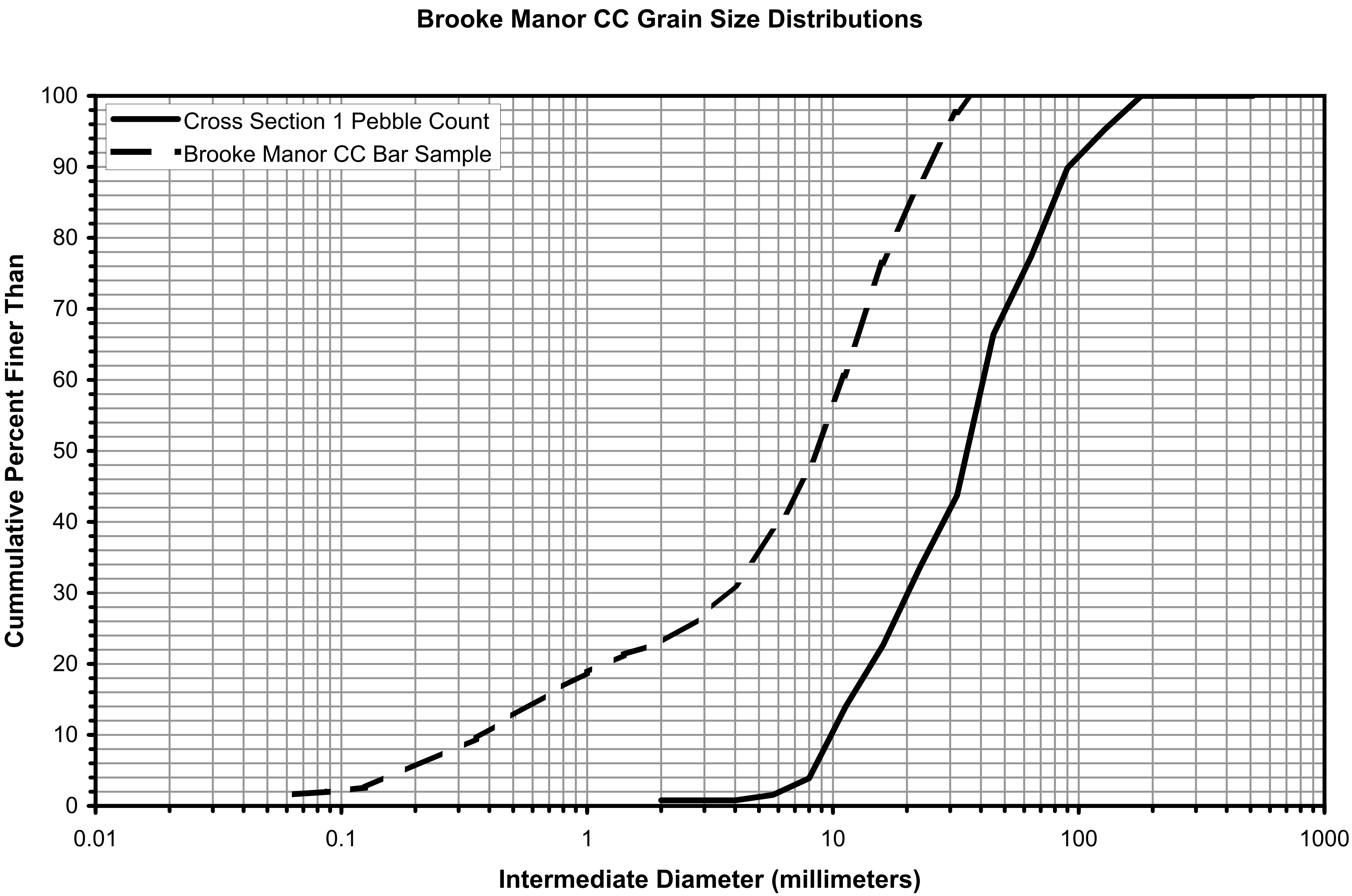
Remarks

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
		$D_i \leq 2.0$	2.0	1	0.8	0.8
Project	MD ICC, BR-21	$2.0 < D_i \leq 4.0$	4.0		0.0	0.8
		$4.0 < D_i \leq 5.7$	5.7	1	0.8	1.6
Location	Brooke Manor CC Tributary	$5.7 < D_i \leq 8.0$	8.0	3	2.3	3.9
		$5.7 < D_i \leq 11.3$	11.3	13	10.2	14.1
Sample site	Cross-Section 1 Riffle Surface	$11.3 < D_i \leq 16.0$	16.0	11	8.6	22.7
		$16.0 < D_i \leq 22.6$	22.6	14	10.9	33.6
Date	6-Oct-04	$22.6 < D_i \leq 32.0$	32.0	13	10.2	43.8
		$32.0 < D_i \leq 45.0$	45.0	29	22.7	66.4
Operator(s)	WSV, MAC	$45.0 < D_i \leq 64.0$	64.0	14	10.9	77.3
		$64.0 < D_i \leq 90.0$	90.0	16	12.5	89.8
Comments:	Sample truncated at 2mm. All data finer than threshold are excluded from this analysis, after Kondolf (1997)	$90.0 < D_i \leq 128.0$	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
Intermediate Diameter (millimeters)
0
10
20
30
40
50
60
70
80
90
100
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

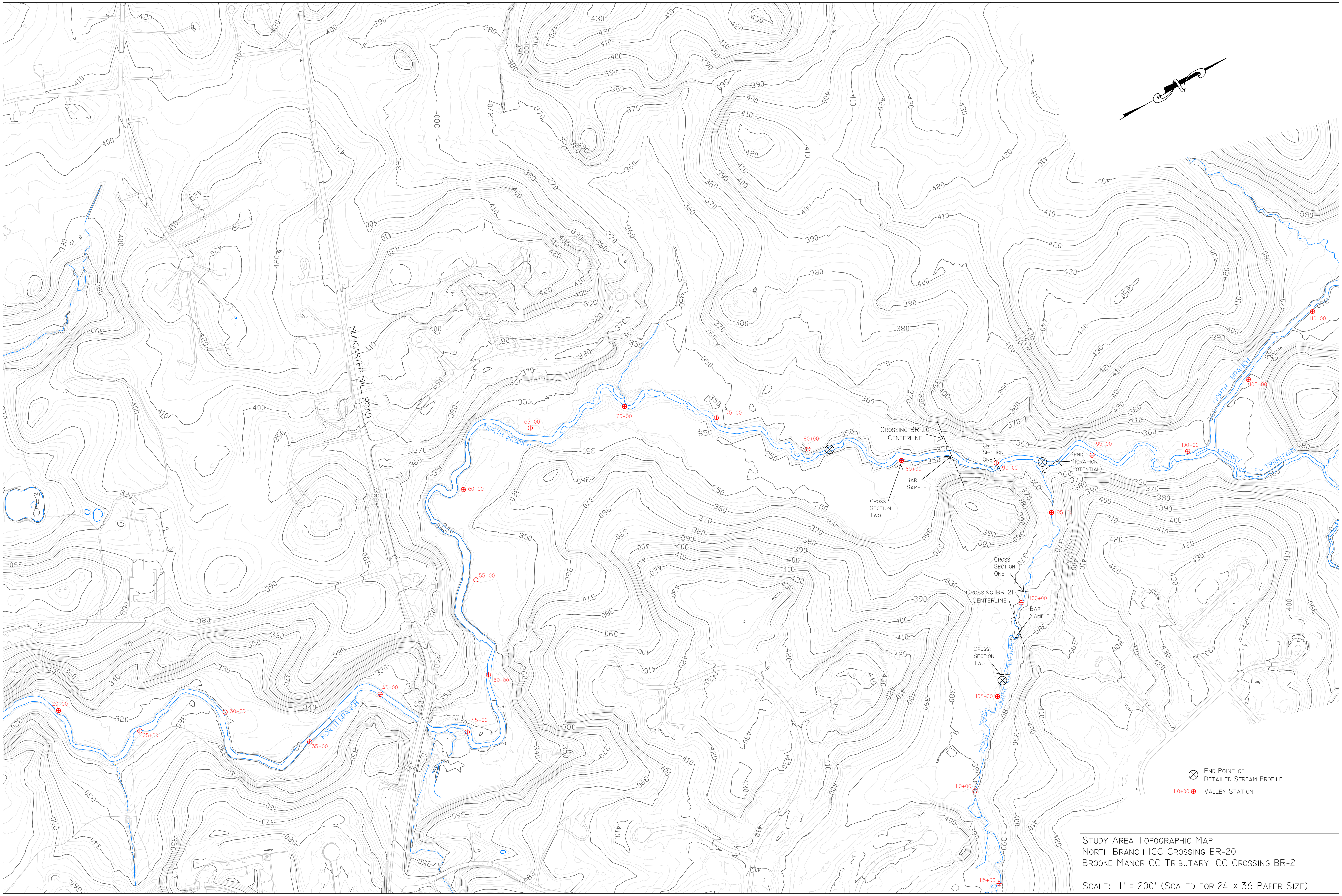
Depth (1994)
0.67 feet

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



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)