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MARYLAND DEPARTMENT OF TRANSPORTATION
STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

LONG-TERM BED DEGRADATION IN MARYLAND STREAMS (PHASE III PART 2): URBAN STREAMS IN THE PIEDMONT PLATEAU PROVINCE

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16. Abstract

Estimation of potential long-term down-cutting of the stream bed is necessary for evaluation and design of bridges for scour and culverts for fish passage. The purpose of this study has been to improve predictions of this potential long-term bed degradation (LTBD) in Maryland streams through the measurement and analysis of stream bed and waterway structure survey data and bridge plans. Long-term bed degradation was defined as the vertical change in the channel profile other than that caused by local or contraction scour. A total of 41 sites in Frederick, Carroll, Montgomery, Baltimore, and Howard counties, Baltimore City, and Washington, DC, were selected for data collection. Drainage areas of these sites in the Piedmont Plateau physiographic provinces ranged from 0.2−62.1 mi^2. At each sampling site, the vertical drop at the outlet of the structure was measured with a pocket rod and a hand level. These rapid measurements were conducted where a step, a series of steps, a steep section, or a riprap-protected streambed was at the outlet of a culvert or a bridge with a paved or riprap-protected invert or downstream apron. Four of the six factors that may influence a site's risk of LTBD were also investigated. These include (1) the valley slope, (2) the effective floodplain width, (3) discharge, and (4) downstream channel entrenchment. The possibility of developing regional relations between LTBD and either watershed area or percent impervious area was evaluated for the physiographic province, but the data were inconclusive. Two relations between LTBD and the risk factors were examined: LTBD and valley slope; and LTBD and an index combining Factors 1-4. A comparison of the resulting equations revealed that valley slope was as good a predictor of the susceptibility of a site to LTBD as the index that required additional data and considered more parameters. The relation between valley slope and LTBD was recommended to estimate LTBD for streams with slopes of less than 0.03 ft/ft. The relation should not be applied, however, to structures located in deep deposits of sediment created by backwater from dams or other structures or to structures located in streams with evidence of active channel degradation. The development of rate relationships for LTBD was also considered, but the number of available structure plans was insufficient to develop a rate relation. Future research on LTBD in Maryland should include the development of a method to include the effectiveness of downstream bed controls in limiting degradation, and the development of a rate relation should be explored further.

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GLOSSARY AND ABBREVIATIONS

Variables

A_{ch}	Pre-degradation channel area	(Eq. 6, 7)
BMI	Bed mobility index	
DA	Drainage area (mi^2)	
LTBD	Long-term bed degradation (ft). The vertical change in the channel profile other than that caused by local or contraction scour	(Eq. 3, 9, 12, 10, 11)
n_{ch}	Manning *n* estimated for the channel	(Eq. 6)
n_{fp}	Composite Manning *n* estimated for the effective floodplain width	(Eq. 4)
P_{ch}	Pre-degradation channel wetted perimeter	(Eq. 6)
PIA	Percent impervious area	
Q_{100}	The 100-year recurrence interval peak flow (cfs)	(Eq. 5, 6)
Q_{ch}	Top-of-bank flow in the pre-degradation channel (cfs)	(Eq. 5)
Q_{fp100}	100-year peak flow on the floodplain	(Eq. 4, 5)
S_{ch}	Channel slope (ft/ft)	
S_v	Valley slope (ft/ft)	(Eq. 1, 4, 6, 9, 13)
W_{bed}	Width of the channel measured at the toe of the banks (ft)	(Eq. 7, 8)
W_{fp}	Effective floodplain width (ft)	(Eq. 4)
W_{tob}	Width of channel measured at the level of the top of the lowest banks (ft)	(Eq. 7, 8)
Y_{100}	Flood flow depth (ft) for Q_{100}	(Eq. 1, 2)
Y_{ch}	Depth of channel for the top-of-bank flow (ft)	(Eq. 3)
Y_{chp}	Depth of pre-degradation channel for the top-of-bank flow (ft)	(Eq. 2, 3, 7, 8)
Y_{fp100}	Flood flow depth (ft) on the floodplain for Q_{100}	(Eq. 1, 2, and 4)
γ	Unit weight of water (62.4 pcf)	(Eq. 1)
τ_o	Boundary shear stress index (psf)	(Eq. 1, 10, 11)

Units of Measure

cfs	Cubic feet per second
ft	Feet
mi^2	Square miles
pcf	Pounds per cubic foot
psf	Pounds per square foot

EXECUTIVE SUMMARY

Estimation of potential long-term down-cutting of the stream bed (bed degradation) is necessary for evaluation and design of bridges for scour and culverts for fish passage. Equations for estimating this potential long-term bed degradation (LTBD) were developed from field data collected in urban Maryland streams in the Piedmont Plateau region. The conservative upper limit curve that describes LTBD as a function of valley slope (S_v) was given as

$$\text{LTBD (ft)} = 3 \text{ ft for } S_v < 0.0043 \text{ ft/ft} \quad (9a)$$

$$\text{LTBD (ft)} = 48\ S_v^{0.51} \text{ for } 0.0043 \text{ ft/ft} \leq S_v < 0.03 \text{ ft/ft} \quad (9b)$$

These equations can be used as a general guide for the prediction of long-term bed degradation in streams that have all of the following characteristics:

1. Valley slope of less than 0.03 ft/ft.
2. Drainage area from 0.2−60 mi^2.
3. A majority of the watershed drainage area in the Piedmont Plateau physiographic province of Frederick, Carroll, Montgomery, Baltimore, and Howard counties, Baltimore City, and Washington, DC.
4. Impervious area of less than 58% of the contributing watershed’s surface area.

Until further study has been completed, the research team recommends that use of these equations be limited to sites not located in deep deposits of sediment created by backwater from dams or other structures or in streams with evidence of active channel degradation. For stream channel networks already experiencing significant degradation or at structures located in thick dam deposits, the value of LTBD may be substantially greater than those given in this study.

A thorough examination of the site and downstream valley should be made to determine whether either of these conditions applies to the site being evaluated. Indicators of bed degradation problems may include perched culverts, exposed utility crossings, exposed bridge foundations, and/or channel headcuts. A search of historical documents should be made to determine the location of historic mill dams or other dams that may have caused deep and extensive backwater deposits. Evidence of backwater deposits include exposure of clay in the streambed, no evidence of gravel at the base of eroding stream banks, or banks greater than 4 ft composed completely of fine-grained sediment. None of the equations derived in this study should be used to predict LTBD for

1. Structures located in channels with ongoing degradation problems.
2. Structures located in the backwater deposit of a dam.
3. Locations where other structures may have been or may be removed during the life of the structure being evaluated.

In such cases, an LTBD assessment should be completed in accordance with the procedures in Chapter 14 of Maryland’s *Hydrology and Hydraulics Manual* [1].

A channel should be evaluated as follows for signs of active channel degradation within approximately 1000 ft upstream and downstream of the structure location:

1. Examine records of the site including bridge inspection reports and reports from sewer line authorities and other utility companies that may have pipeline crossings. A step in the channel profile at any of these structures is an indication of an existing bed degradation problem.
2. Examine bridges that cross the channel upstream and downstream of the site for exposed foundations or other signs of bed degradation.
3. Examine the channel bed for signs of ongoing bed degradation problems.

If any of these evaluations indicate that the channel is degrading, or if the valley slope is greater than 0.03 ft/ft, then the LTBD equations should not be used. Instead, the techniques recommended in Chapter 14 of Maryland's *Hydrology and Hydraulics Manual* [1] should be used to evaluate bed degradation potential.

If the channel shows no evidence either of existing degradation problems in the stream system or of a deep deposit of sediment created by backwater from a dam or other structure, then the LTBD equation may be used as follows for Piedmont sites that meet the four conditions (valley slope, drainage area, county/physiographic province, and impervious area) listed at the beginning of the executive summary:

1. Compute the valley slope, S_v, from a USGS 7.5-minute topographic map. For most sites, the contour lines directly upstream and downstream of the structure location should be used to compute the slope as follows:

   $$S_v = (\text{contour interval}) / (\text{distance between contours}) \qquad (13)$$

   At sites where the downstream contour is immediately downstream of the structure, the slope should be calculated using the two contour lines downstream of the site. Where the structure is located directly upstream of the confluence with a much larger stream, the slope upstream of the site should be averaged with the slope of the larger, receiving stream's valley.
2. Use Eq. 9a or Eq. 9b from this study to estimate LTBD.

The LTBD values computed by Eqs. 9a and 9b are likely to be conservative for most sites to which they are applicable. Engineers should consider other site-specific factors not included in the development of Eqs. 9a and 9b. Two factors that could be used to reduce the values obtained in Eqs. 9a and 9b are bed controls and the time required for the full potential for LTBD to be realized. Bed controls such as durable bedrock and large immobile bed material may limit degradation. Unlike other forms of localized scour that can obtain their maximum values under a single flood event, the full potential LTBD is realized over multiple flood events extending over time periods of a few years to decades. The long-term nature of LTBD allows time for the degradation to be observed during bridge inspections and for countermeasures to then be installed.

Engineers should also consider other site-specific factors that may increase the potential for LTBD beyond those predicted by Eqs. 9a and 9b. In particular, structures founded on sediment deposits upstream of existing dams that may be removed during the life of the structure have the potential to experience much larger values of LTBD than those predicted by Eqs. 9a and 9b. Man-made structures, such as culverts and utility crossings, may also provide downstream grade control that once removed may cause degradation upstream beyond those values predicted by Eqs. 9a and 9b. This is particularly the case if these man-made controls or structures are founded on soils formed from sediments trapped upstream of historic milldams. The final depth of LTBD used for the placement of structure foundations should be determined using Eqs. 9a and 9b and the additional site-specific information.

Long-Term Bed Degradation in Maryland Streams (Phase III Part 2): Urban Streams in the Piedmont Plateau Province

1.0 INTRODUCTION

Federal and Maryland state standards and policies require that bridge foundations be evaluated and designed to resist worst-case conditions of scour and channel instability that may occur over the service life of a bridge. Recently implemented policies also require that crossings accommodate passage of aquatic organisms. An important component of the evaluation and design processes is the estimation of long-term changes in stream bed elevations which may occur due to down-cutting of the stream bed (degradation) or raising of the bed by deposition of sediment (aggradation).

Existing guidelines for assessing potential long-term bed degradation in Maryland streams [1] require expertise that may not be available and/or field studies that, depending on the project budgets, may be cost prohibitive, especially for replacement of county structures. The morphological techniques recommended by those guidelines also lack verification data and may lead to overly conservative estimates, unnecessarily large foundation depths, and consequently, significantly higher costs. For this reason, the Structure Hydrology and Hydraulics Division initiated a study to improve predictions of long-term bed degradation in Maryland streams. Due to funding limitations, the study is being completed in phases. Phase 1 [2] and Phase 2 [3], examined long-term bed degradation (LTBD) of streams in non-urbanized watersheds of the Allegany Plateau, Blue Ridge, and the Western Piedmont physiographic provinces. Phase 3 Part 1 [4] was limited to urban watersheds (those with impervious ground cover greater than 10%) of the Piedmont Plateau province in Montgomery, Baltimore, and Howard counties and Baltimore City. Preliminary analysis of the data collected in Phase 3 Part 1 indicated significant data gaps. Phase 3 Part 2 was completed in an effort to fill those gaps.

The Phase 3 Part 2 study had six primary objectives:

1. Continue development of a database of field measurements of LTBD in Maryland streams.
2. Collect data to fill gaps in the Phase 3 Part 1 study of LTBD in urban streams (impervious ground cover greater than 10%) of the Piedmont Plateau province.
3. Using the data collected in Phase 3 Parts 1 and 2, define the range of degradation depths to be expected in urban streams of the Piedmont Plateau province in Montgomery, Baltimore, Harford, and Howard counties and Baltimore City based on the data of both the Phase 3 Part 1 and Part 2.
4. Evaluate the possibility of developing a relation between watershed percent impervious area and LTBD.
5. Develop quantitative relations between the risk factors identified in Phases 1 and 2 and measured LTBD.
6. Evaluate the possibility of developing a regional relation for LTBD by physiographic province.

The database and the relations between risk factors and LTBD may serve as a basis for decisions related both to design and planning projects involving foundations for waterway crossings, depth of utility crossings, culvert replacements requiring fish passage, and mitigation projects involving stream restoration and/or stream stability. In foundation designs, the database would establish a baseline for evaluating reasonable values of degradation, and thus it will save significant structure costs. Where the potential for bed degradation is high, LTBD data may indicate deeper foundations are needed to prevent structure failure or continuous remediation of the substructure unit. In other locations, the LTBD data may provide assurance that shallower foundation depths are appropriate. In the planning phase, the database could support quick decisions on the type and size of the structures needed for stream crossings in small watersheds. A reliable estimate of this degradation rate could indicate the need to propose a bridge rather than a culvert: assuming the culvert invert needs to be designed well below the expected long-term bed degradation, a culvert would be less practical than a bridge in locations where degradation is predicted to be more than 30% of the culvert diameter. Thus, the database could result in a more accurate consolidated transportation program cost in the planning phase. It would also be of great help to all counties that lack resources to perform detailed stream morphology studies on their waterway crossing projects.

This project was divided into two parts: Part 1 was funded in FY2012, and Part 2 was funded in FY2013. Part 1 involved preliminary screening, selection of sampling sites, and an assessment of data gaps. Part 2 provides completed data collection, analysis, development of prediction equations, and recommendations for application.

2.0 STUDY AREA

The Piedmont Plateau province rises gradually from the coastal plain in the east to the Catoctin Mountains in the west. The western part of the Piedmont Plateau is primarily rolling plains underlain by moderately to slightly metamorphosed volcanic rocks and diverse igneous and metamorphic rocks such as phyllite, slate, and marble. The rocks underlying Frederick Valley, along the Monocacy River, are Cambrian and Ordovician limestones and dolomites [5]. Land use transitions from mostly rural farmland and low-density residential with scattered urban areas in the western portion of the Piedmont to urban and high-density residential on the eastern edge of the Piedmont.

The drainage patterns in the entire Piedmont Plateau are heavily influenced by the geologic structure and resistance of the mostly metamorphic and igneous rock. East of Frederick Valley, two ridges run from northeast to southwest: the Dug Hill Ridge and Pars Ridge [6]. The Potomac River forms the southern border of the Frederick Valley. West of Dug Hill and Pars ridges, the streams of Frederick County and northwestern Carroll County flow mainly west into the Monocacy River, which flows mainly south to its confluence with the Potomac River. East of the ridges, the Patuxent River and other major stream of the eastern Piedmont Plateau generally flow southeast to the Chesapeake Bay.

3.0 METHODS

3.1 Site Selection

Initial Screening

In Part 1 of the Phase 3 study, potentially suitable sites were identified in three of the four targeted counties (Montgomery, Baltimore, and Howard) and Baltimore City. The small section of Prince Georges County in the Piedmont Plateau region had very few suitable sampling sites and was excluded. Data gaps identified during preliminary analysis indicated a need for additional sites with watershed area greater than 6 mi^2, impervious areas between 10% and 20%, and valley slopes less than 0.5% and greater than 3%.

In Part 2 of the Phase 3 study, initial screening targeted sites in urbanized areas that had not been evaluated in Part 1 and would fill the gaps in the Part 1 dataset. Several sources of information were requested from Frederick, Carroll, and Harford counties and Washington, DC, to identify an initial set of Part 2 sampling sites:

- Sites with potential LTBD based on findings in existing reports
  - Bridge inspection reports
  - Phases I and II of Item 113 bridge inspection ratings
  - Inspection reports for bridges or culverts known to have aquatic organism blockages
- Utility line surveys
- Plan sheets for box culverts and bridges

The land use of the watersheds of each potential site was examined visually to remove sites that may have impervious cover less than 10%. The watersheds of the remaining sites were analyzed using GISHydro to compute the percent impervious area (PIA) and other watershed parameters. Sites with PIA greater than 10 % were selected for potential sampling.

The reports and surveys of the selected sites were reviewed to identify any citations of foundation exposure or undermining, fish passage barriers, or exposure of utility crossing protection, any of which would indicate that the channel bed near a culvert or bridge had degraded, and therefore, LTBD would probably be measureable. All structures where any of these problems had been cited were considered for field evaluation.

Plan sheets for box culverts were requested because they usually provide the elevation of the culvert outlet invert, the elevation of the downstream channel, and the depth to which the culvert may have been countersunk relative to the downstream channel. Construction drawings for new or replacement bridges may provide normal water surface elevations or stream profiles through the bridge. This plan information provides an accurate reference from which to measure changes in bed elevation. All box culverts and bridges for which plans were available were considered for field evaluation.

Finally, sites for which reports or plans were not available were considered for field evaluation if bed degradation had been observed by research team members or county engineers. Approximately 60 sites were considered during the screening process for Part 2.

Field Identification

The sites selected for additional evaluation were mapped for reference in the field. An initial field visit was then made to each site to evaluate them for final selection. To increase the sample size, the research team also conducted a windshield survey along state, county, and city roads in urbanized areas. During the windshield survey, the field team looked for structures with vertical drops at the outlet as an indication of LTBD. When a vertical drop was observed, the location was identified on the topographic maps and Google Earth to visually estimate drainage area and impervious area of the watershed. These locations were selected for addition to the sample if their estimated drainage areas were between about 0.25 and 60 mi^2 and watershed impervious area appeared to be between 10% and 20%.

Final Site Selection

Following the field investigation, the watershed boundaries of each sample site were delineated using 30-meter national elevation data [7] in the web-based version of GISHydro [8], and their surface drainage areas and impervious areas were estimated. Sites where PIA was less than 10% were excluded from the final sample.

A total of 41 sampling sites were selected (Figure 3.1 and Table 3.1): 30 Part 1 sites in Baltimore, Howard, and Montgomery counties and Baltimore City; and 11 Part 2 sites in Baltimore County (one site), Carroll (one site), Frederick (three sites), Harford (one site), Howard (one site), Montgomery (three sites) and counties and Washington, DC (one site). The single Carroll County site is on the stream that forms the border with Howard County. The three Frederick County sites are located in suburban areas of Frederick, Maryland. The one site in Washington, DC, is located on Rock Creek approximately 5000 feet downstream of the Montgomery County border.

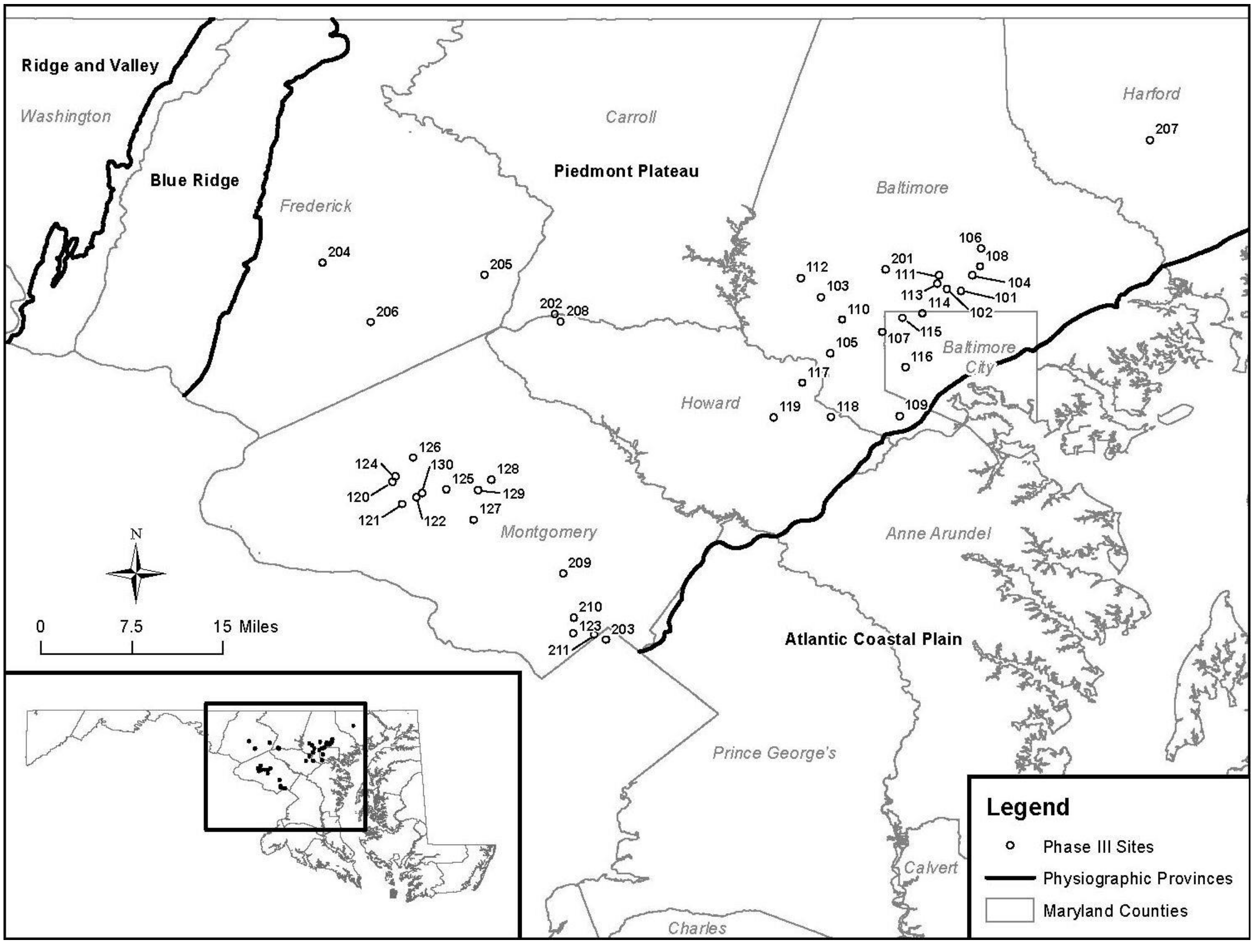

Figure 3.1. Sample site locations.

Table 3.1. Long-Term Bed Degradation Estimates and Site Characteristics (This page is formatted to fit on 11 x 17-inch paper.)

Sample No.*	Structure No.	Yr Built/ Modified	Structure	Reference	County	Physiographic Province	Stream Crossing	Route	Estimated LTBD (ft)	Bed Control	Y_{ch} (ft)	W_{tob} (ft)	W_{bed} (ft)	DA (mi^2)
101	Unavailable	N.d.	Culvert	Culvert outlet invert	Baltimore County	PM	Towson Run	Versailles Circle Ct	2.1	Bedrock	7.3	54	23	0.2
102	N/A	N.d.	Sewer Line	Top of utility line	Baltimore County	PM	UT Roland Run	Melvin Ave	3.1	Armored Riffle	5	22	7	0.5
103	B-0474020	1986	Culvert	Top of foundation	Baltimore County	PM	Horsehead Branch	McDonogh Rd	1.5	Armored Riffle	2.5	13.7	11.4	0.8
104	57-1794	1957	Culvert	Culvert outlet invert	Baltimore County	PM	Long Quarter Branch	Tenbury Rd	3.7	Bedrock	9.4	50	22.5	0.8
105	B-0347010	1920	Bridge	Top of foundation	Baltimore County	PM	Dogwood Run	Dogwood Rd	1.0	Undetermined	3.2	22.8	16.5	0.9
106	N/A	N.d.	Sewer Line	Top of utility line	Baltimore County	PM	Kelly Branch	MD 146	2.4	Clay	2.1	14.8	10	1.0
107	6028-HB	1960	Culvert	Culvert outlet invert	Baltimore County	PM	Powder Mill Br	Patterson Ave	4.9	Clay	7.9	52	12.8	1.2
108	63-2427	1963	Culvert	Paved bed invert	Baltimore County	PM	Long Quarter Branch	Seminary Ave	2.2	Bedrock	5.7	36	18	1.9
109	None	1972	Culvert	Culvert outlet invert or apron	Baltimore County	PM	East Branch	Sulpher Spring Rd	5.4	Bedrock/ Rock Vane	25	40	15	2.0
110	3003-C	1980	Bridge	Existing riprap channel bed	Baltimore County	PM	Scotts Level Branch	N Rolling Rd	1.0	Armored Riffle	2.5	17.5	14.6	3.3
111	53-1331	1953	Sewer Line	Top of utility line protection	Baltimore County	PM	Roland Run	Essex Farm Rd	2.2	Rock Vane	5	29.2	13	4.3
112	Unavailable	N.d.	Culvert	Culvert outlet invert	Baltimore County	PM	Red Run	Pleasant Hill Rd	1.0	Undetermined	4.7	32.4	27.6	4.5
113	N/A	N.d.	Abandoned Bridge Foundation	Top of foundation	Baltimore County	PM	Roland Run	Roland Ave	3.0	Bedrock/ Culvert Invert	5.5	56	33	5.0
114	Unavailable	N.d.	Culvert	Culvert outlet invert or apron	Baltimore City	PM	UT Western Run	Rogene Dr	1.5	Bedrock	9.5	34	13.5	0.2
115	BC2503001	1955	Bridge	Invert of stormwater outfall	Baltimore City	PM	Western Run	W Strathmore Ave	8.0	Bedrock	13	33	14.8	2.5
116	N/A	N.d.	Sewer line	Top of utility line	Baltimore City	PM	Gwynns Falls	Wetheredsville Rd	3.5	Armored Riffle	9.6	77	23.1	42.0
117	HO0140001	1988	Culvert	Existing channel bed	Howard	PM	Sucker Branch	Rodgers Ave	1.5	Armored Riffle	4.1	27.3	11.4	1.4
118	HO001X	1935/1986	Bridge	Top of foundation	Howard	PM	Bonnie Branch	College Ave	3.5	Armored Riffle	5.6	40.5	18	1.5
119	HO146	1986	Culvert	Culvert outlet invert or apron	Howard	PM	Red Hill Branch	Columbia Rd	1.5	Armored Riffle	5.2	26	22.3	5.9
120	1052	N.d.	Culvert	Culvert outlet invert or apron	Montgomery	PM	UT Bucklodge Branch	Richtor Farm Rd	1.5	Planform instability and aggradation	2.7	10.5	2.5	0.4
121	ET122L0078	N.d.	Culvert	Culvert outlet invert or apron	Montgomery	PM	UT Great Seneca Creek	Riffle Ford Rd	3.5	Weakly cemented gravel	5.2	21.5	7.3	0.5
122	MO252	1997	Culvert	Culvert outlet invert or apron	Montgomery	PM	UT Gunners Branch	Mateny Rd	1.9	Armored Riffle	1.4	10.8	8	0.6
123	15029X0	1925/2004	Culvert	Existing riprap channel bed	Montgomery	PM	Coqueline Run	MD 410	2.9	Bedrock	6.5	37.8	17	0.7
124	MO232	1994	Culvert	Culvert outlet invert or apron	Montgomery	PM	UT Bucklodge Branch	Ranworth Dr	1	Planform instability and aggradation	4.3	20.2	12.8	0.9
125	MO224	1990	Culvert	Culvert outlet invert or apron	Montgomery	PM	UT Great Seneca Creek	Game Preserve Rd	1.6	Planform instability and aggradation	5.5	34.7	5.9	1.0
126	MO231	1994	Culvert	Culvert outlet invert or apron	Montgomery	PM	UT Little Seneca Creek Lake	Kinster Dr	0.5	Armored riffle	2	24	4.8	1.2
127	N/A	N.d.	Abandoned Bridge Foundation	Top of foundation	Montgomery	PM	Muddy Branch	D/S I-270	3.3	Bedrock	6.1	41.7	14	1.6
128	MO065	1925	Culvert	Existing riprap channel bed	Montgomery	PM	Cabin Branch	Snouffer School Rd	1.1	Clay	4.3	34.8	4.5	2.5
129	1516700	1990	Bridge	Gabion basket in channel	Montgomery	PM	Whetstone Run	MD 124	3.3	Lake	5.9	46.6	6.2	2.6
130	1509400	1951	Culvert	Culvert outlet invert or apron	Montgomery	PM	Gunners Branch	MD 117	0.1	Planform instability and aggradation	3.4	20	9.2	2.9
201	0307400	1900/1934	Bridge	Top of foundation	Baltimore County	PM	North Branch Jones Falls	MD 130	2.3	Tortuous series of bends and deposition	4	27	19.5	6.5
202	CL307	1976	Culvert	Culvert outlet invert or apron	Carroll	PM	South Branch Patapsco River	Watersville Rd	1.5	Armored riffle	4.5	33.5	24.8	6.5
203	N/A	1925	Sewer Line	Top of utility line	District of Columbia	PM	Rock Creek		0.7	Utility crossing	9.6	97	73	62.1
204	F13-03X	1983	Culvert	Culvert outlet invert or apron	Frederick	PM	UT to Monocacy River	Monocacy Blvd	4	Confluence with Monocacy River	8	25	15	1.2
205	F18-17X	N.d./2007	Culvert	Culvert outlet invert or apron	Frederick	PM	Woodville Branch	Bottom Rd	0.5	Severe downstream planform instability causing deposition and aggradation downstream	3	14	10	4.5
206	F07-05	1982	Bridge	Top of foundation	Frederick	PM	Bush Creek	Ijamsville Rd	1.5	Severe planform instability causing deposition and aggradation downstream	3.5	31	15	21.4
207	12008X0	N.d./1997	Culvert	Culvert outlet invert	Harford County	PM	Bear Cabin Branch	MD23	3.5	Temporary logs in channel downstream	3.6	16.7	13.4	0.3
208	HO043	1935	Bridge	Top of foundation	Howard	PM	Hay Meadow Branch	Watersville Rd	0	Not found	3.5	26	15	2.6
209	Unavailable	N.d.	Bridge	Top of foundation	Montgomery	PM	Rock Creek	Gaynor Rd (Abandoned)	1.6	Dam	8	75	50	37.2
210	N/A	N.d.	Sewer Line	Top of utility line	Montgomery	PM	Rock Creek		0.6	Moderate planform instability	7	75	50	51.6
211	Unavailable	N.d.	Bridge	Top of foundation	Montgomery	PM	Rock Creek	Trail Bridge	2	Moderate channel planform instability	6.4	61.2	50	59.9

Cont'd.

Table 3.1. Long-Term Bed Degradation Estimates and Site Characteristics (*Continued*) (This page is formatted to fit on 11 x 17-inch paper.)

Sample No.*	S_v (ft/ft)	W_{fp} (ft)	n_{ch}	n_{fp}	Y_{chp} (ft)	A_{ch}	P_{ch}	Q_{ch} (cfs)	Q_{100} (cfs)	Y_{fp100} (ft)	τ_o (psf)	Land Use Coverage	Soil Coverage	Forested Area (%)	Urban Area (%)	Impervious Area (%)
101	0.0136	119	0.04	0.1	5.2	281.05	53.1	770	770	0.0	2.12	2010 MOP	SSURGO	0.0	68.4	43.4
102	0.0284	124	0.04	0.07	1.9	72.5	24.5	939	1260	0.8	10.3	2010 MOP	SSURGO	10.9	55.9	30.2
103	0.0084	423	0.04	0.07	1.0	31.375	17.55	158	1640	1.4	2.05	2010 MOP	SSURGO	23.4	56.2	27.0
104	0.0075	106	0.04	0.1	5.7	340.75	55.05	1930	1930	0.0	2.52	2010 MOP	SSURGO	8.6	67.8	57.5
105	0.0231	237	0.04	0.1	2.2	62.88	26.05	641	1890	1.7	7	2010 MOP	SSURGO	15.9	47.8	37.0
106	0.0122	422	0.04	0.1	-0.3	26.04	16.6	145	1900	1.7	2.93	2010 MOP	SSURGO	13.9	60.8	28.5
107	0.0108	223	0.04	0.1	3.0	255.96	48.2	2380	2380	0.0	3.94	2010 MOP	SSURGO	5.0	80.8	47.2
108	0.0097	348	0.04	0.1	3.5	153.9	38.4	1422	3170	2.1	4.69	2010 MOP	SSURGO	6.9	75.8	48.0
109	0.0124	133	0.04	0.07	19.6	687.5	77.5	2666	2666	0.0	5.14	2010 MOP	SSURGO	7.1	68.4	49.4
110	0.0082	402	0.04	0.1	1.5	40.125	21.05	208	4220	3.3	2.97	2010 MOP	SSURGO	13.5	79.4	37.1
111	0.0093	182	0.04	0.07	2.8	105.5	31.1	855	5120	4.3	5.4	2010 MOP	SSURGO	8.9	76.3	42.6
112	0.0056	329	0.04	0.1	3.7	141	39.4	920	4440	3.9	3	2010 MOP	SSURGO	41.2	40.7	19.1
113	0.0064	150	0.04	0.1	2.5	244.75	55.5	1955	5580	6.1	4.6	2010 MOP	SSURGO	7.3	77.9	41.1
114	0.0301	118	0.04	0.1	8.0	225.625	42.75	708	708	0.0	4.7	2010 MOP	SSURGO	0.7	64.3	29.5
115	0.0301	40	0.04	0.1	4.5	298.75	48.9	3630	3630	0.0	12.5	2010 MOP	SSURGO	6.0	69.9	41.1
116	0.0091	320	0.04	0.1	6.1	480.48	69.25	6219	20400	7.9	9.94	2010 MOP	SSURGO	19.9	64.5	36.8
117	0.0121	128	0.04	0.1	2.6	79.335	27.55	658	2450	3.6	5.83	2010 MOP	SSURGO	22.9	55.3	35.1
118	0.0348	85	0.04	0.1	2.1	163.8	40.45	2380	2380	0.0	9.51	2010 MOP	SSURGO	19.2	73.7	25.1
119	0.0021	249	0.04	0.1	3.7	125.58	34.55	504	6000	8.1	1.72	2010 MOP	SSURGO	14.2	71.6	35.6
120	0.0165	208	0.04	0.1	1.2	17.55	11.9	109	1090	1.7	4.55	2010 MOP	Ragan	14.1	51.3	30.3
121	0.0163	194	0.04	0.1	1.7	74.88	24.8	744	1240	1.2	6.49	2010 MOP	Ragan	18.1	67.6	28.2
122	0.0143	202	0.04	0.1	-0.5	13.16	12.2	62	1510	2.3	3.31	2010 MOP	Ragan	12.8	64.2	41.6
123	0.0221	128	0.04	0.1	3.6	178.1	40.4	1700	1700	0.0	5.88	2010 MOP	Ragan	0.0	89.5	47.0
124	0.0078	176	0.04	0.1	3.3	70.95	25.1	467	1930	3.0	3.57	2010 MOP	Ragan	24.5	68.7	40.9
125	0.0124	186	0.04	0.1	3.9	111.65	31.3	1082	2120	2.1	5.86	2010 MOP	Ragan	18.1	42.1	46.5
126	0.0068	363	0.04	0.1	1.5	28.8	18.4	119	2470	2.7	2	2010 MOP	Ragan	6.9	71.9	56.1
127	0.0137	228	0.04	0.1	2.8	169.885	40.05	1945	2880	1.7	6.66	2010 MOP	Ragan	2.6	71.1	50.4
128	0.0099	402	0.04	0.1	3.2	84.495	28.25	650	3550	2.6	4.25	2010 MOP	Ragan	17.5	62.7	36.8
129	0.0065	561	0.04	0.1	2.6	155.76	38.2	1199	3770	2.2	3.32	2010 MOP	Ragan	11.9	71.6	43.6
130	0.0068	361	0.04	0.1	3.3	49.64	21.4	267	4090	3.6	2.99	2010 MOP	Ragan	22.1	57.7	46.6
201	0.0104	200	0.04	0.07	1.7	93	31.25	731	5220	4.1	5.23	2010 MOP	SSURGO	24.6	43.2	13.9
202	0.0104	390	0.04	0.07	3.0	131.175	38.15	1136	5540	2.7	4.67	2010 MOP	SSURGO	31.0	31.3	18.6
203	0.0006	470	0.04	0.1	8.9	816	104.2	2938	25100	18.5	1.05	2010 MOP/2011 NLCD	SSURGO/STATSGO	20.4	61.0	37.6
204	0.0347	120	0.04	0.05	4.0	160	36	2340	2340	0.0	11.8	2010 MOP	SSURGO	4.3	67.3	43.6
205	0.0119	340	0.04	0.07	2.5	36	18	232	4060	2.6	4.14	2010 MOP	SSURGO	25.4	34.5	12.5
206	0.0070	600	0.04	0.07	2.0	80.5	30	485	10600	3.9	3.21	2010 MOP	SSURGO	29.7	30.8	11.8
207	0.0225	70	0.06	0.07	0.1	54.18	22.25	365	804	1.5	7.16	2010 MOP	SSURGO	1.3	56.3	16.4
208	0.0140	150	0.04	0.07	3.5	71.75	27.5	600	2980	3.0	5.69	2010 MOP	SSURGO	12.9	34.1	14.5
209	0.0024	510	0.04	0.1	6.4	500	78.5	3157	17400	8.9	2.56	2010 MOP	SSURGO	23.1	53.7	25.4
210	0.0029	520	0.04	0.1	6.4	437.5	76.5	2808	22200	10.0	3.08	2010 MOP	SSURGO	18.9	59.6	30.3
211	0.0027	650	0.04	0.1	4.4	355.84	68.4	2069	24500	9.8	2.72	2009 MOP/2011 NLCD	SSURGO/STATSGO	20.4	60.8	31.5

Note: Parameters denoted by symbols/abbreviations are defined in the glossary. Forested, urban, and impervious areas were obtained from GISHydro [8].

* Sites were numbered in two groups: Part 1 (100 series) and Part 2 (200 series).

3.2 Data Collection

The primary focus of the field data collection effort was to obtain measurements of LTBD and other parameters listed in Table 3.1 This data provided the information necessary to examine the relation between watershed area and LTBD in urban watersheds of the physiographic region. The field data in combination with readily available mapping data was also sufficient to examine the relation between LTBD, PIA, and some of the other risk factors identified in the Phase 1 and 2 studies.

Factors that influence LTBD (Table 3.2) were determined in the Phase 1 [2] and 2 [3] studies to include those that influence the boundary shear stress on the channel bed and those that influence the mobility and transport of the bed material. The risk factors that affect the boundary shear stress on the channel bed can be related using the uniform flow equation for wide channels:

$$\tau_o = \gamma\, Y_{ch}\, S_{ch}$$

where τ_o is the boundary shear stress on the channel, γ is unit weight of water (62.4 pcf), Y_{ch} is the flow depth, and S_{ch} is the channel slope.

Table 3.2. Factors that Influence LTBD from Phase 1 and Phase 2 Studies

	Hydraulic Parameter	Risk Factors	Increased Risk	Reduced Risk
Channel boundary stress	Channel slope	1. Valley slope	Steep valley slope	Mild valley slope
		[6a. (See below) Proximity of downstream durable grade controls]	No durable downstream grade control points to limit slope change. Removal of a dam, culvert or other downstream structure that had caused aggradation prior to the installation of the sampling site’s structure.	Durable grade control point or points that limit slope change
	Depth of flow in the channel	2. Effective downstream floodplain width	Constriction of downstream floodplain by obstruction, walls, or an embankment	No constriction of downstream floodplain by obstruction, walls, or an embankment
		3. 100-yr return interval discharge	Increased 100-yr discharge	Decreased 100-yr discharge
		4. Top-of-bank channel dimensions	Downstream channelization including widening, and deepening	Lack of obvious channelization; often associated with natural valley geometry, such as a narrow, meandering valley, that limits potential channel reconfiguration
Resistance to stress	Bed material	5. Bed material median size	Size small relative to bed stresses	Size large relative to bed stresses
		6b. Downstream proximity and depth of bedrock below channel bed	Lack of durable downstream bed control including degradation of bedrock	Durable downstream bed control including bedrock

Field Measurements

Bed Profile

Long-term bed degradation was defined as the vertical change in the channel profile other than that caused by local or contraction scour. Scour and LTBD were distinguished based on their effect on the bed morphology and associated bed profile. Local and contraction scour result in the formation of pools with extents limited to the region of the bed beneath and immediately downstream of the structure. Scour holes appear as sags in the channel profile. LTBD is a more extensive lowering of the bed profile that can be represented as a decrease in riffle crest elevations over time. The main observable morphological indicator of LTBD is an increase in the distance between the low-flow water surface and the top of the bank along the entire reach over which LTBD has occurred. LTBD progresses from downstream to upstream and is halted by fixed-bed sections of channel. Where a portion of the bed is fixed, such as a culvert invert, paved bridge invert, or riprap-protected bed, an abrupt change in bed elevation and bank height occurs at the transition from the upstream fixed-bed reach to the downstream reach that has undergone LTBD. The abrupt change in the streambed often occurs as a step or series of steps in the bed profile.

Based on this interpretation of scour and LTBD, the research team used the low-flow water surface, which represented the approximate elevation of riffle crests, as the demarcation between scour and LTBD when measuring vertical drops at structures. At each sampling site, LTBD was measured with a pocket rod and a hand level. Scour was considered to extend below the water surface to the streambed, with a maximum scour depth represented by the maximum pool depth (Figure 3.2). LTBD was considered to be the vertical drop from an approximated pre-degradation channel bed elevation to the existing low-flow water surface. The approximation of the pre-degradation channel bed was based on whether the channel bed was fixed (utility crossings, paved bridge inverts, riprap protected sections of streambed, and culverts that were not countersunk) or not fixed.

Before about 1975, Maryland culverts were constructed such that the outlet invert was set approximately at the bed elevation of the channel. In culverts constructed after 1975, the inlets may have been countersunk below the streambed to support fish passage.

At fixed-bed sites, the pre-degradation channel bed elevation was assumed to be the same as the existing channel bed elevation at the structure (Figures 3.2 and 3.3). LTBD was measured as the vertical drop in the water surface at the downstream step (Figure 3.3). Where multiple downstream steps were observed, such as where partial failure and displacement of riprap downstream formed a series of two or more drops in the channel profile, the cumulative vertical drop over all of the steps was measured (Figure 3.2).

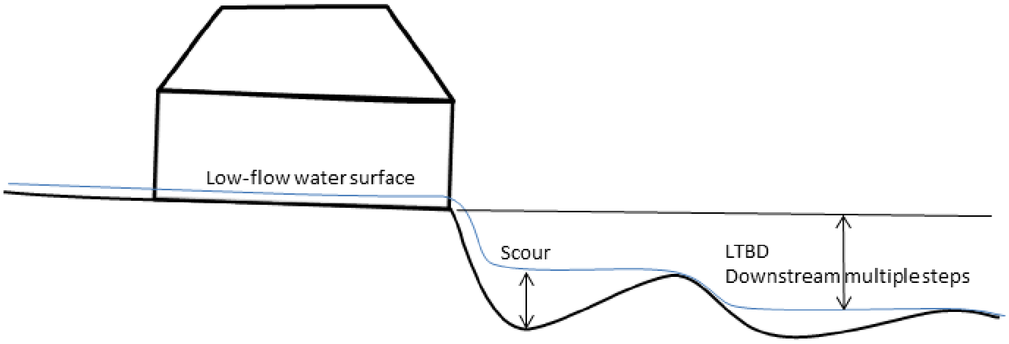

Figure 3.2. Typical bed profile of a culvert with downstream bed degradation and a scour pool.

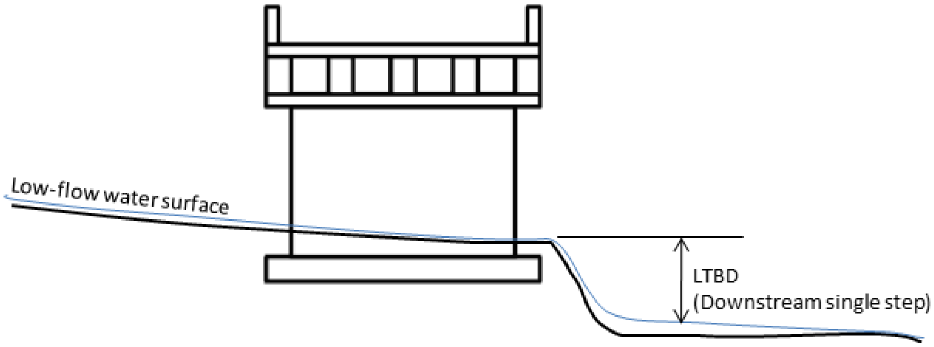

Figure 3.3. LTBD: uniform degradation and single step downstream.

LTBD was estimated at utility line crossings. The research team considered the drop from the top of the pipe to the existing streambed to be the LTBD that occurred since the placement of the pipe.

At bridge locations where the bed was not fixed, three main indicators were considered in approximating the pre-degradation channel bed elevation: the top surface of the footings; the elevation of weep holes used to drain the backfill of abutment walls; and the top-of-bank elevation downstream of the structure. Because plans for some bridges showed that the top surface of the foundation was at or within approximately 1 ft of the pre-degradation channel bed, all bridge foundations were assumed to have been constructed within approximately 1 ft of the pre-degradation channel bed unless other indicators suggested otherwise. The top of the stream bank and the weep holes in bridge abutments provide upper bounds because weep holes are generally placed higher than the streambed to allow for free drainage and because the stream probably would have had a depth greater than 1 ft. Depending on the indicators at each site where the bed was not fixed, LTBD was measured as the distance from the low-flow water surface to the exposed top surface of foundations or weep holes (Figures 3.4 and 3.5).

Channel Dimensions

Downstream of each sampling site, the channel base width, top width, and depth were measured to approximate trapezoidal channel geometry. These measurements were made to evaluate the entrenchment of the channel with respect to the extensive flat of the valley bottom that may be inundated during a 100-year recurrence interval flood.

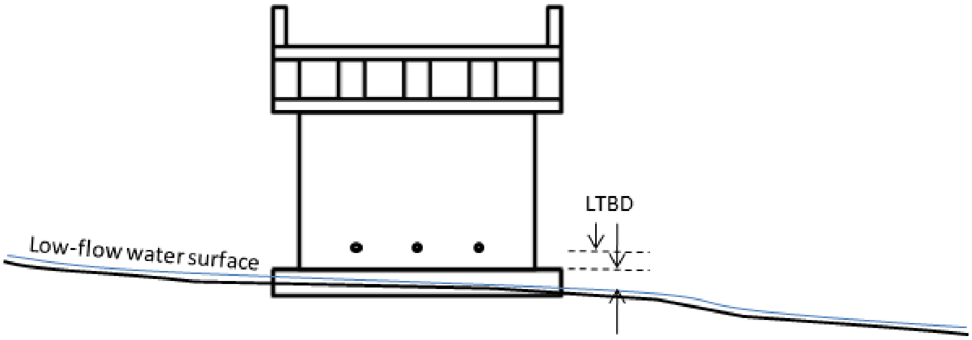

Figure 3.4. LTBD: uniform degradation.

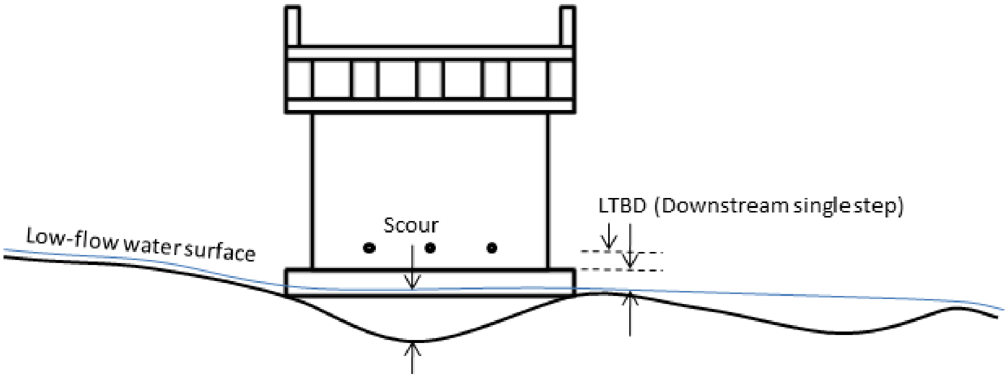

Figure 3.5. LTBD with scour and uniform degradation.

Bed Material Gradation

The bed material size in most of the urban sites consisted of a mixture of man-made materials including riprap, brick, and concrete, and some locations had a high content of glass. A decision was made by the team that measurement of the bed material would not be useful in these highly manipulated urban streams because the measurement would not be representative of the bed material prior to channel incision.

Downstream Bed Controls and Grade Controls

In-channel features that would either limit rapid degradation of the bed ("bed controls") or were controlling the slope of the low-flow water surface ("grade controls") were identified if they could be located within approximately 1000 ft of the sampling site's structure. These controls consisted features such as bedrock in the streambed, boulder and cobble in the streambed, utility crossing protection, and dams.

Remote Measurements

Valley slope and effective floodplain width were estimated for each site as follows:

1. Valley slope. The valley slope, S_v, was estimated from contour lines shown on USGS 7.5-minute topographic maps. For most of the sites, the change in elevation between contours was divided by the distance between the contour lines directly

upstream and downstream of the structure location. At sites where the downstream contour was immediately downstream of the structure, using the above method would have resulted in the estimated slope being biased heavily in the upstream direction. For those instances, the slope was calculated using the two contour lines downstream of the site.

2. Effective 100-yr floodplain width, W_{fp} (the same variable referred to as “effective valley width” in Phase 1). Valley constrictions or sharp bends that could create backwater during 100-yr recurrence interval floods were identified from 7.5-minute USGS topographic maps, field observations of floodplain obstructions and channelization, and recent aerial photographs obtained from Google Earth. The effective floodplain width was estimated from the smallest width of the floodplain unobstructed by embankments or structures or, where channelization was evident, from the width of the widened and deepened channel.

3.3 Data Reduction and Analysis

Percent Impervious Area

The variation of LTBD with PIA was examined using the GIS land use coverages and methods provided in GISHydro [8].

Valley Slope

The variation of observed LTBD with valley slope was examined for the urban streams in the Piedmont Plateau region. The high PIA data was then compared to the conservative upper limit curve developed in the Phase 1 and Phase 2 data that describes the observed LTBD as a function of valley slope (S_v) for the low PIA streams.

Estimates of 100-Year Peak Discharges

Each site’s 100-year recurrence interval peak discharge was obtained from the web-based version of GISHydro [8] using the Fixed Region equations [9]. Watershed runoff characteristics were based on STATSGO soils data [10] and either 2002 or 2010 Maryland land use data [8] for watersheds located entirely within Maryland or 1970s USGS land use data [8] for watersheds that extended into Pennsylvania.

Channel Boundary Shear Stress Index

A channel boundary shear stress index (τ_o) was developed to examine the combined effect of valley slope, valley confinement, channel incision, and the potential discharge that could be produced by each sample site drainage area (Table 3.1). The estimation of τ_o used here is different than that included in the Phase 1 report because it includes the effect of the pre-degradation channel geometry and flow capacity. The τ_o (psf) was defined as

$$\tau_o = \gamma \; Y_{100} \; S_v \qquad (1)$$

where γ is unit weight of water (62.4 pcf), S_v is the valley slope (ft/ft), and Y_{100} is the depth (ft) of the 100-year peak discharge in the pre-degradation channel. Calculation of the channel boundary shear stress index required an estimate of Y_{100} as

$$Y_{100} = Y_{chp} + Y_{fp100} \tag{2}$$

where Y_{chp} is the pre-degradation channel depth (ft), and Y_{fp100} is the average depth of the 100-year peak discharge (ft) on the floodplain. The pre-degradation channel depth was approximated as

$$Y_{chp} = Y_{ch} - \text{LTBD} \tag{3}$$

where Y_{ch} is the measured existing channel depth.

Y_{fp100} was approximated as

$$Y_{fp100} = [(Q_{fp100}\, n_{fp})/(1.49\, W_{fp}\, S_v^{0.5})]^{0.6} \tag{4}$$

where Q_{fp100} is the 100-year peak discharge on the floodplain, W_{fp} is the effective floodplain width (ft), and n_{fp} is the composite Manning *n* estimated for the effective floodplain width. One value of *n* representative of the roughness of the effective floodplain width downstream of the structure was used at each site and was given a value of either 0.1 for floodplains that were mostly forested or 0.07 for all other floodplains. The parameter Q_{fp100} was estimated as

$$Q_{fp100} = Q_{100} - Q_{ch} \tag{5}$$

where Q_{100} is the 100-year peak discharge, and Q_{ch} is the top-of-bank flow in the pre-degradation channel, estimated as

$$Q_{ch} = (1.49/n_{ch})\, A_{ch}\, (A_{ch}/P_{ch})^{0.667} S_v^{0.5} \tag{6}$$

where n_{ch} is the Manning channel roughness, A_{ch} is the pre-degradation channel area, and P_{ch} is the pre-degradation channel wetted perimeter. The parameter n_{ch} was selected as 0.04 for all streams. The parameters A_{ch} and P_{ch} were estimated as

$$A_{ch} = Y_{chp}\, (W_{tob} \text{ and } W_{bed})/2 \tag{7}$$

$$P_{ch} = 2\, Y_{chp} + (W_{tob} \text{ and } W_{bed})/2 \tag{8}$$

where W_{tob} and W_{bed} are the measured channel top width and bed width, respectively.

4.0 RESULTS

The possibility of developing regional relations between watershed area and LTBD was evaluated, and three relations were examined between LTBD and PIA, valley slope, and τ_o (Table 3.2). Factors associated with bed material properties could not be evaluated. The research team determined that obtaining a good estimate of the representative mean size of pre-degradation bed material was not possible because of the abundance of introduced material that included riprap, brick, and concrete waste.

Drainage Area

Although the dataset is too small to draw a reliable conclusion about a relationship between LTBD and drainage area for urbanized channels of the Piedmont region, the data do not suggest even a weak correlation between the two variables (Figure 4.1).

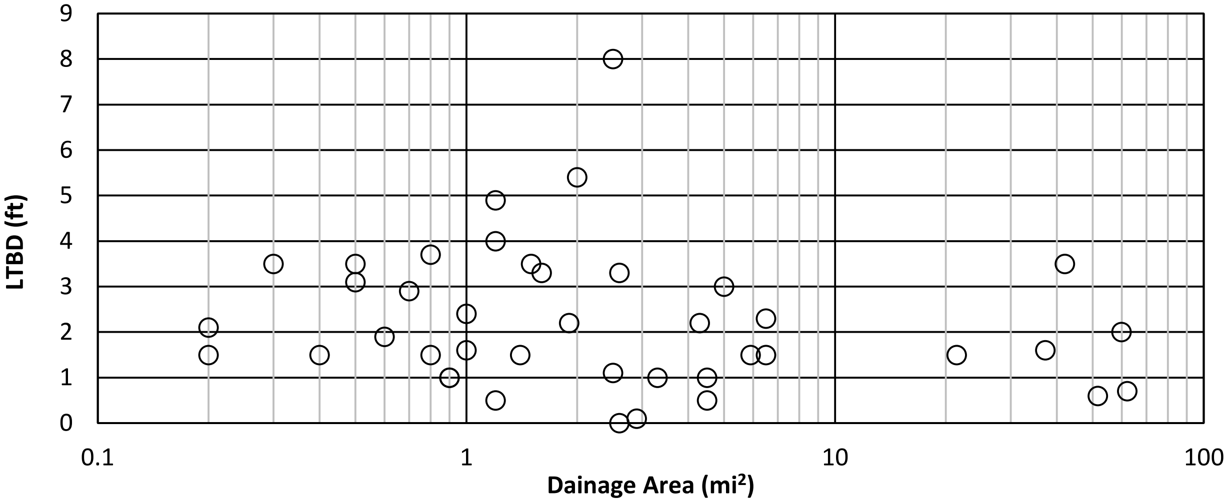

Figure 4.1. Variation of LTBD with drainage area for urbanized streams of the Piedmont Plateau province.

Impervious Area

Impervious area varied from 11.8% to 57.5%. The effect of impervious area was examined to determine whether use of sample sites with PIA between 11% and 58% would introduce another factor that would influence LTBD. The variation of LTBD (Figure 4.2) indicates that PIA is not even weakly correlated with LTBD for Piedmont streams with watershed imperviousness of 11% to 58%.

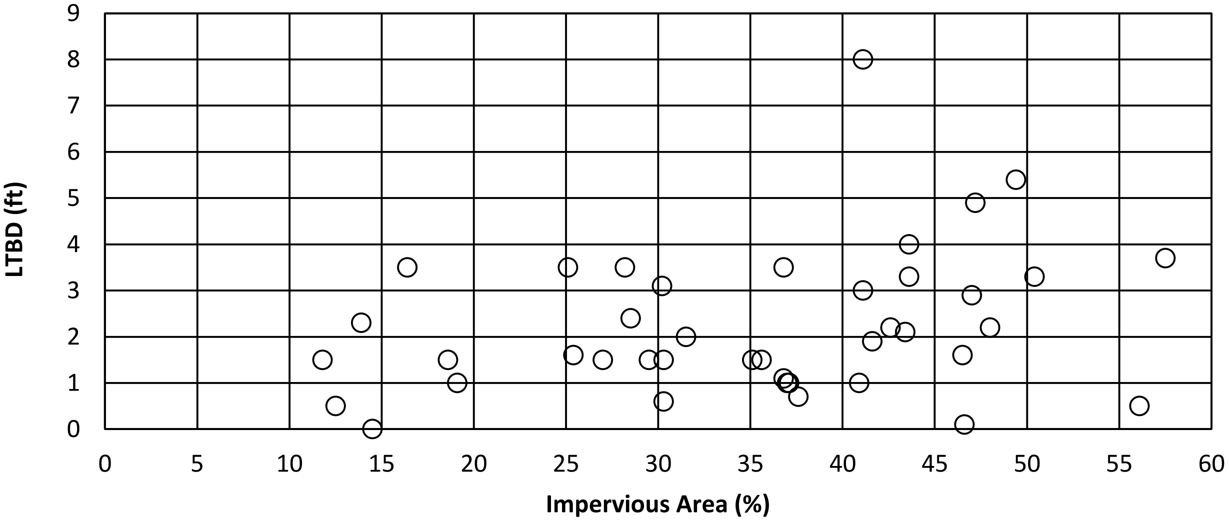

Figure 4.2. Variation of LTBD with percent impervious area.

Valley Slope

Maximum values of LTBD increased in the urban Piedmont streams in the range of slopes from 0.006 to 0.03 ft/ft (Figure 4.3). This trend of increased maximum LTBD with slope in the urban Piedmont streams is similar to that found in the same range of valley slopes in the studies for non-urban streams in western Maryland (Phase 1 and Phase 2 reports). A conservative curve that describes the LTBD observed at Phase 3 sites as a function of valley slope (S_v) is

$$\text{LTBD (ft)} = 3 \text{ ft for } S_v < 0.0043 \text{ ft/ft} \quad (9a)$$

$$\text{LTBD (ft)} = 48\, S_v^{0.51} \text{ for } 0.0043 \text{ ft/ft} \le S_v < 0.03 \text{ ft/ft} \quad (9b)$$

Eq. 9b predicts values as much as 1.6 ft higher than the valley slope equation for non-urban streams (Phases 1 and 2) with slopes greater than 0.005 ft/ft and as much as 1 ft lower for valley slopes less than 0.004 ft/ft. It should be noted that LTBD of 3 ft or more was observed at three sites in the non-urban regions of the Western Piedmont (Phase 2) [3] for slopes less than 0.004 ft/ft. Given the small number of observations of LTBD for urban streams with slopes less than 0.004 ft/ft, a minimum value of 3 ft should be used for all sites with slopes less than 0.0043 ft/ft—the value of the slope at which Eq. 9b predicts LTBD is equal to 3.0 ft.

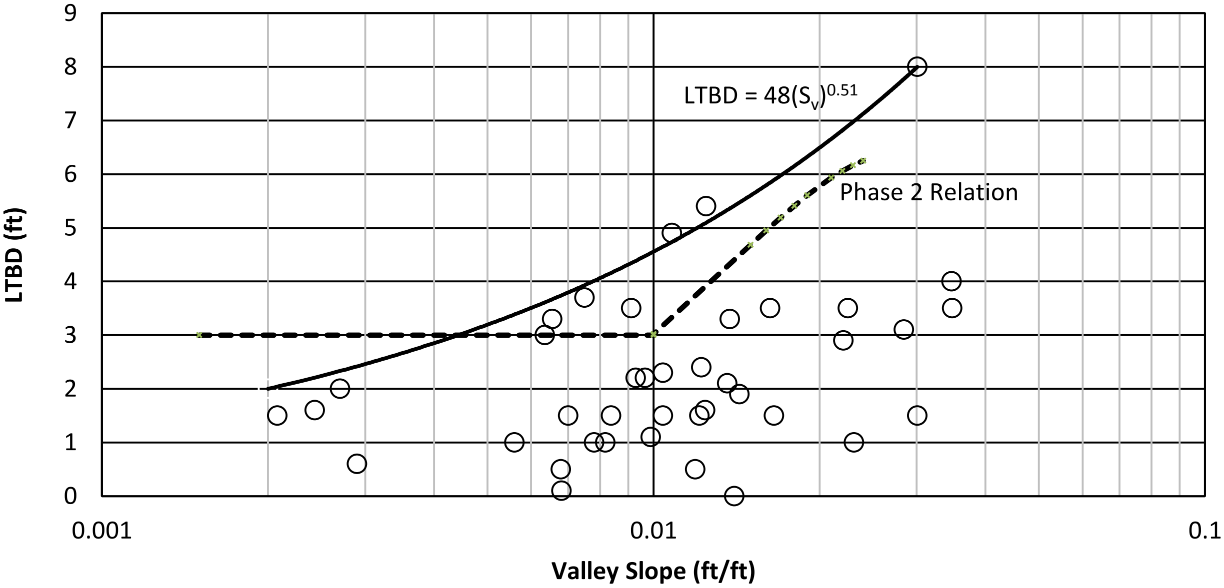

Figure 4.3. LTBD as a function of valley slope. A minimum value of 3 ft should be used for all sites with slopes less than 0.0043 ft/ft

LTBD versus Channel Boundary Shear Stress Index

Data from the urban streams show an increase in LTBD with increases in the channel boundary shear stress index, τ_o. A conservative upper curve (Figure 4.4) that describes the LTBD as a function of τ_o for urban streams in the Piedmont is

$$\text{LTBD} = 6.32 \text{ Log}_{10} (\tau_o) + 1.08 \quad (10)$$

This equation produces significantly larger values of LTBD than the equation developed for the non-urbanized streams in the Blue Ridge and western Piedmont Plateau provinces of Maryland [3] represented by

$$\text{LTBD} = 4.21\ \text{Log}_{10}\ (\tau_o) + 0.910 \qquad (11)$$

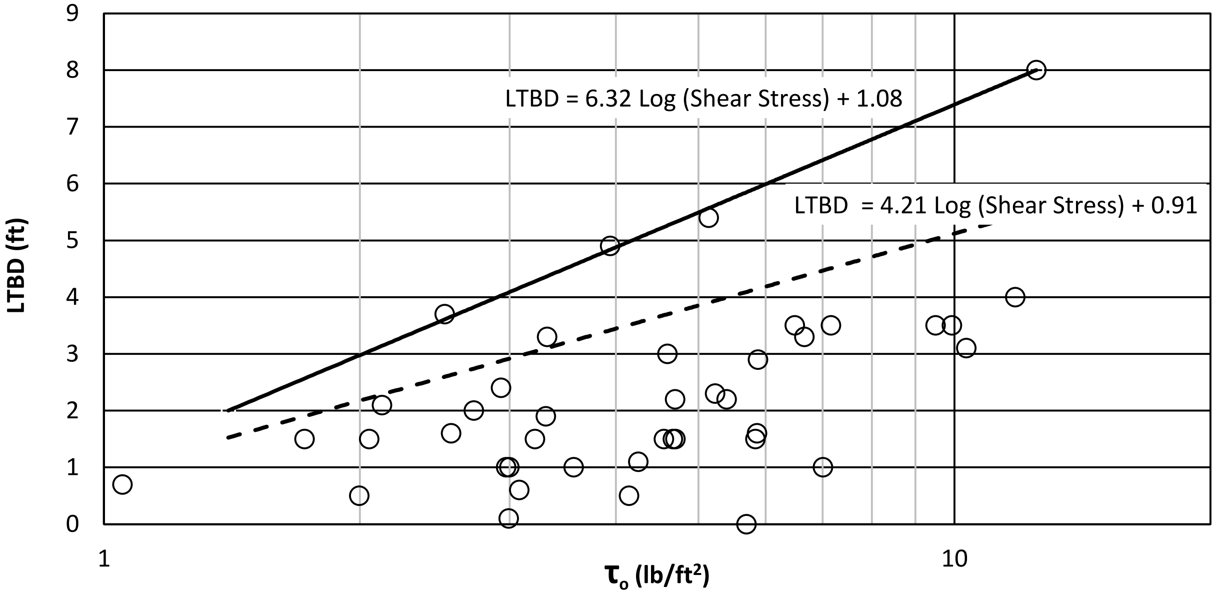

Figure 4.4. LTBD as a function of shear stress index.

Bed Controls

Eight forms of downstream bed control (Figure 4.5) were observed at 37 sampling sites; controls at the other four sites could not be identified:

- **Armored riffles** were the most frequent form of bed control (25% of sites) in the Piedmont. Riffles were formed of riprap eroded from high stress areas upstream and deposited in lower stress regions downstream, where they were capable of providing at least temporary local control.
- **Planform instability and associated bed aggradation** were found downstream of 23% of the sample sites. These reaches consisted of two or more low radius and high arc length bends, bars that extended across the channel, and rapidly eroding banks. These reaches appear to be incapable of transporting the coarse sediment supplied from upstream. and as a result they migrate laterally and aggrade. These depositional reaches appear to be preventing LTBD or reducing previous bed degradation at upstream structures and may explain the relatively low LTBD values obtained for slopes less than 0.004 ft/ft. Although these reaches are not stable controls, they have a significant effect on LTBD. Because these streams are dynamic, the downstream level of the streambed and their control on upstream reaches may fluctuate. Although the aggradation in these reaches may explain why certain reaches have not experienced significant degradation, the extent to which they can be relied upon as a form of long-term control is unknown.

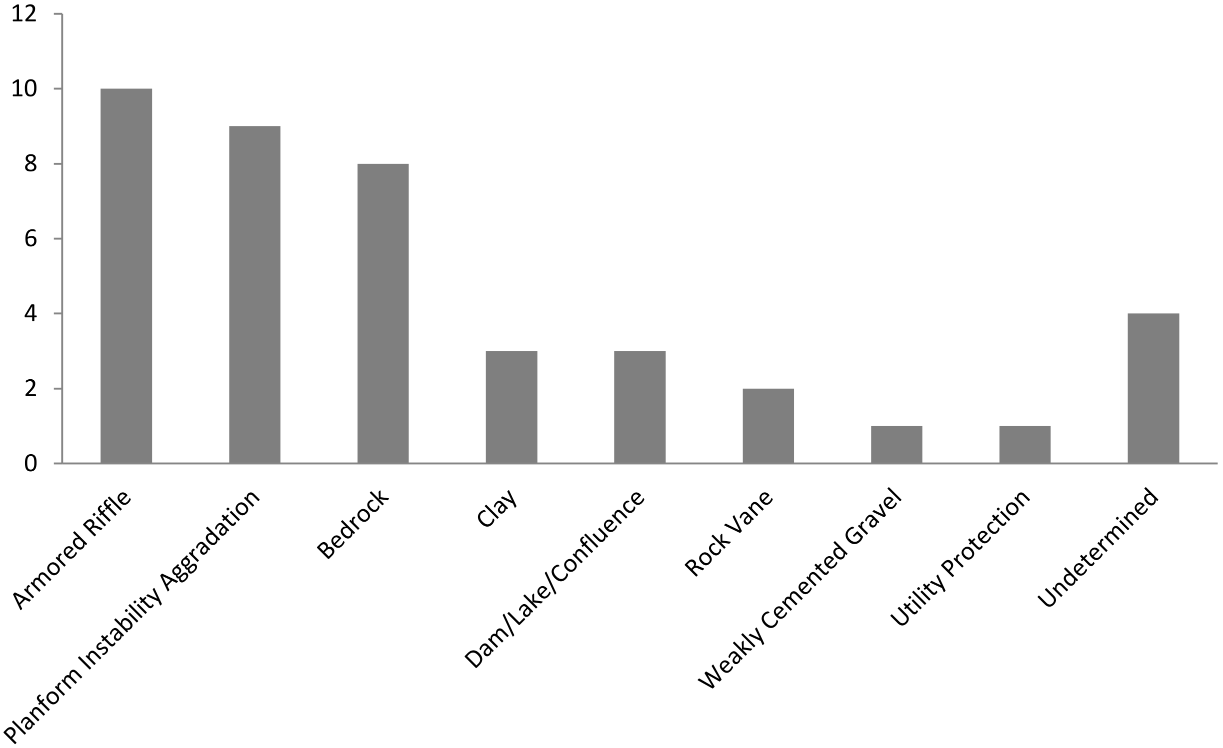

Figure 4.5. Frequency of bed control types downstream of LTBD measurement sites.

- **Bedrock exposure** formed the current bed control in 20% of the sites. Bedrock exposure was typically but not always observed in stream reaches along the edge of valleys near the base of hillsides. Unlike bedrock steps that formed bed controls in highly resistant bedrock observed in western Maryland, fractured and weathered bedrock was most commonly observed in pools, shallow runs, or riffles with drops as small as 0.1 ft. The low-flow water surface slope was rarely controlled by exposed bedrock. Instead, it was controlled by cobble or gravel riffles. Because the fractured and weathered bedrock does not form the highest points in the channel profile during low flow, it may or may not be controlling the stream grade.
- **A clay streambed** was observed as the control in 8% of the sites. This control is temporary. Eventually, the stream may erode through the clay and may expose underlying gravel that would rapidly erode, removing this control.
- **Dam/lake/confluence**: One instream dam and one large dam that formed a lake provided controls at two sites. Another site was located near the confluence of a larger waterway. These controls accounted for 8% of the controls in the dataset.
- **Rock vanes**: At two sites, rock vanes controlled the grade downstream of the sampling point (5% of sites).
- **A weakly cemented gravel layer and a utility crossing** provided bed controls at the two remaining sites where a control was identified (5% of sites).

It is important to realize that the identified controls are the current forms of control; the control at the time LTBD occurred may have been different. In the case of bedrock exposure downstream of the site, it likely was not the control prior to development of deep LTBD. The most frequent forms of bed control observed in the urban stream dataset were boulder and cobble riffles, unstable planform reaches that are aggrading, and bedrock exposure. It is also important to consider that the research team intentionally included sites where LTBD was measureable, and therefore, the controls observed were those near locations where some degradation was observed. Most sites had no degradation and/or no reference from which to measure degradation. Many of the sites where LTBD was not observed may have been protected from LTBD by culverts or a utility crossing that provided downstream grade control.

A means of incorporating the present bed controls into the assessment of observed LTBD has not yet been identified, particularly in cases when the features may have become exposed or developed as bed degradation has occurred. For example, the fractured bedrock that was identified at several sites was not exposed above the low-flow water surface; therefore, it may have degraded at the same rate as the rest of the channel profile. Additional effort needs to be focused on determining the role of bedrock exposure in controlling the bed profile.

Structure Age versus LTBD

The relationship between the age of the structure and LTBD was examined (Figure 4.6) with the intent of developing a relation between site parameters and the rate of LTBD. For replacement structures, the date of completion for the replaced structure was used to compute the age. The research team confirmed the age of 28 structures. An LTBD value of more than 4.0 feet was observed at only three structures, and LTBD at seven older structures was less than 4.0 feet. An increase in LTBD over time is not indicated. The dataset is inadequate to develop a reliable rate relationship based on these observations.

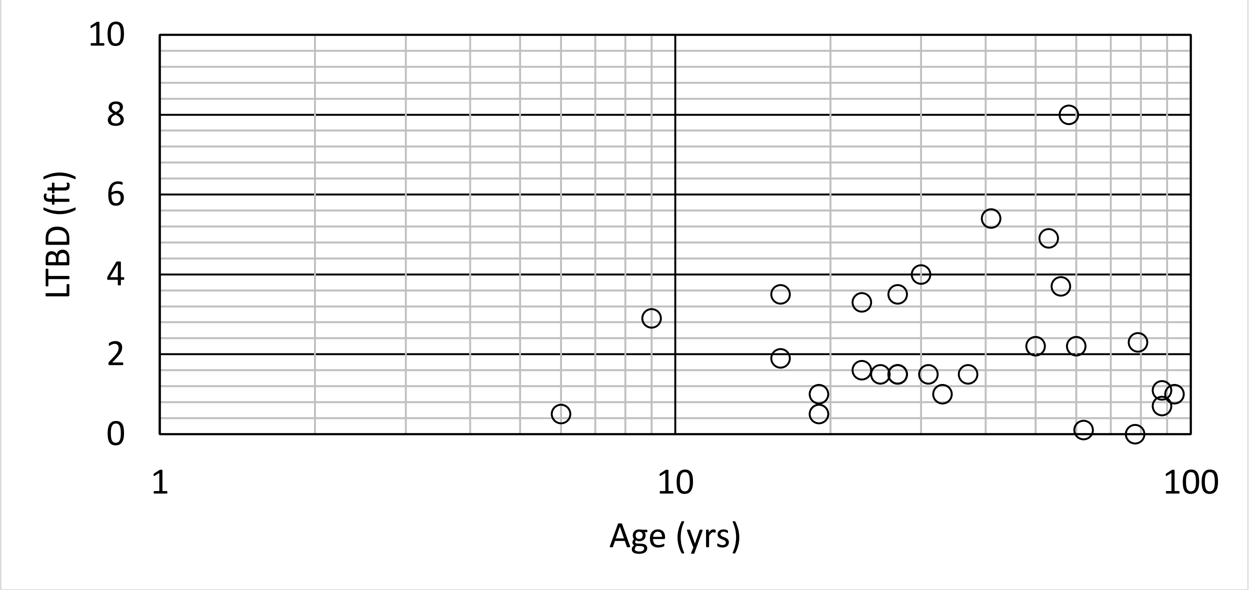

Figure 4.6. Variation of LTBD with structure's age. Plotted data points for two structures overlapped: the structures have an age of 27 years and an LTBD of 1.5 feet.

Comparison of LTBD Equations

Observed values of LTBD were compared to those predicted by the use of the S_v-based equation (Eq. 9b) and the τ_o–based equation (Eq. 10). The residuals were defined as

$$\text{Residual LTBD} = \text{Predicted LTBD} - \text{Observed LTBD} \qquad (12)$$

Residuals were computed and plotted for all samples. Linear regression was used to develop a relation between the residuals for Eq. 9b and 10 (Figure 4.7). The regression lines for both equations are nearly identical. This means that use of the more data-intensive Eq. 10 would only be expected to provide an estimate less than 0.2 ft lower than Eq. 9b for low estimates of LTBD.

Given the simplicity of using S_v obtained from topographic maps and the lack of substantial improvement in the prediction of observed LTBD values by Eq. 10, Eq. 9b is recommended for use in assessing LTBD in urban Piedmont streams with slopes of less than 0.03 ft/ft.

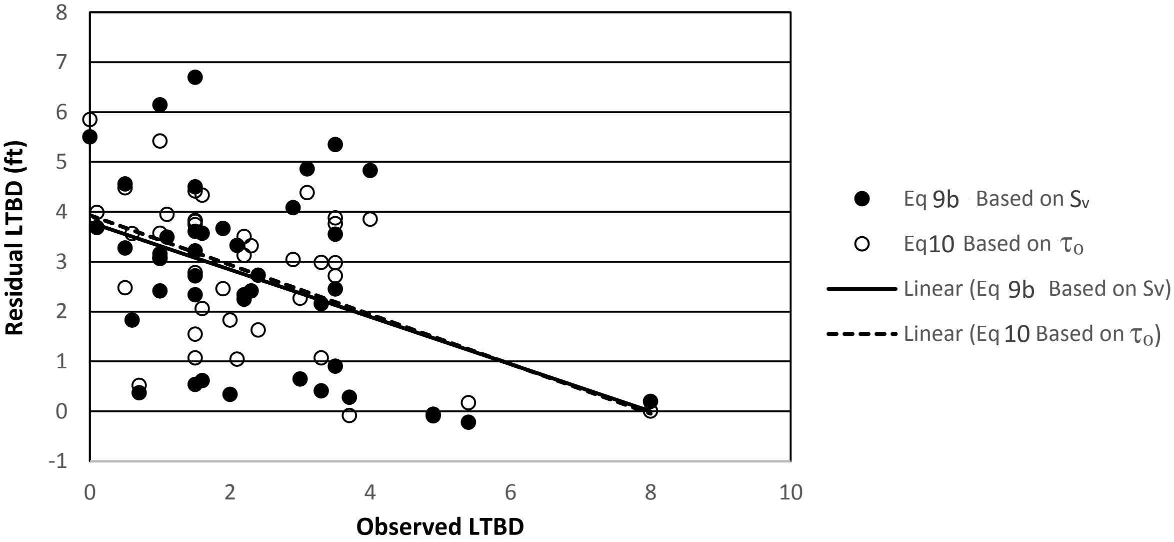

Figure 4.7. Comparison of residual LTBD values and observed LTBD for urban stream Piedmont data.

Comparison of Phase 2 and Phase 3 LTBD Values

LTBD values for the urbanized Eastern Piedmont streams were lower than for the Phase 2 non-urban Blue Ridge and western Piedmont Plateau provinces streams [3] for slopes less than 0.5% (Figure 4.3). Planform instability coupled with aggradation may have reduced the observed values of LTBD in urbanized streams with low slopes. In addition, the change in stream bed elevation between consecutive utility crossings (bed controls) is relatively small, and the utilitiy crossings are therefore more likely to limit LTBD. For slopes greater than 0.5%, LTBD values were higher in the urbanized streams than in the Phase 2 streams. In those steeper reaches of urban streams, channel aggradation was generally not found, and large elevation differences can occur between utility crossings, which therefore are less likely to limit LTBD. Urban streams are also more likely to have more valley confinement in steep valleys.

5.0 APPLICATION

The equations developed from field data in this study can be used as a general guide for the prediction of long-term bed degradation in urban streams of the Piedmont physiographic province. The equations can be used for streams with valley slopes from 0.0043−0.03 ft/ft and drainage areas from 0.2−60 mi^2. Given the small number of observations of LTBD for urban streams with slopes less than 0.004 ft/ft, a minimum value of 3 ft should be used for all sites with slopes less than 0.0043 ft/ft—the value of slope at which Eq. 9b predicts LTBD is equal to 3.0 ft. Although this study included only streams with PIA greater than 10%, the equations developed could be applicable to streams with PIA values less than 10% because there was no evidence that PIA had a significant effect on LTBD for PIA less than 58% for sites in the Piedmont. **Until further study has been completed, however, the research team recommends that use of these equations be limited to sites not located in deep deposits of sediment created by backwater from dams or other structures or in streams with evidence of active channel degradation.** The value of LTBD may be substantially greater than those given in this study for stream channel networks already experiencing significant LTBD or at structures located in thick dam deposits.

A thorough examination of the site and downstream valley should be made to determine whether either of these conditions applies to the site being evaluated. Indicators of bed degradation problems may include perched culverts, exposed utility crossings, exposed bridge foundations, and/or channel headcuts. A search of historical documents should be made to determine the location of historic mill dams or other dams that may have caused deep and extensive backwater deposits. Evidence of backwater deposits include exposure of clay in the streambed, no evidence of gravel at the base of eroding stream banks, or banks greater than 4 ft composed completely of fine-grained sediment. None of the equations derived in this study should be used to predict LTBD for

1. Structures located in channels with ongoing degradation problems.
2. Structures located in the backwater deposit of a dam.
3. Locations where other structures may have been or may be removed during the life of the structure being evaluated.

In such cases, an LTBD assessment should be completed in accordance with the procedures in Chapter 14 of Maryland’s *Hydrology and Hydraulics Manual* [1].

A channel should be evaluated as follows for signs of active channel degradation within approximately 1000 ft upstream and downstream of the structure location:

1. Examine records of the site including bridge inspection reports and reports from sewer line authorities and other utility companies that may have pipeline crossings. A step in the channel profile at any of these structures is an indication of an existing bed degradation problem.
2. Examine bridges that cross the channel upstream and downstream of the site for exposed foundations or other signs of bed degradation.
3. Examine the channel bed for signs of ongoing bed degradation problems.

If any of these evaluations indicate that the channel is degrading, or if the valley slope is greater than 0.03 ft/ft, then the LTBD equations should not be used. Instead, the techniques recommended in Chapter 14 of Maryland's *Hydrology and Hydraulics Manual* [1] should be used to evaluate bed degradation potential.

If the channel shows no evidence either of existing degradation problems in the stream system or of a deep deposit of sediment created by backwater from a dam or other structure, then the LTBD equations may be used as follows for urban streams in the Piedmont Plateau province with valley slopes less than 0.03 ft/ft and drainage areas from 0.2−60 mi^2:

1. Compute the valley slope, S_v, from a USGS 7.5-minute topographic map. For most sites, the contour lines directly upstream and downstream of the structure location should be used to compute the slope as follows:

   $$S_v = \text{(contour interval)/(distance between contours)} \qquad (13)$$

   At sites where the downstream contour is immediately downstream of the structure, the slope should be calculated using the two contour lines downstream of the site. Where the structure is located directly upstream of the confluence with a much larger stream, the slope upstream of the site should be averaged with the slope of the larger, receiving stream's valley.

2. Use Eq. 9a or 9b from this study to estimate LTBD.

The LTBD values computed by Eqs. 9a and 9b are likely to be conservative for most sites to which they are applicable. Engineers should consider other site-specific factors not included in the development of Eqs. 9a and 9b. Two factors that could be used to reduce the values obtained in Eqs. 9a and 9b are bed controls and the time required for the full potential for LTBD to be realized. Bed controls such as durable bedrock and large immobile bed material may limit degradation. Unlike other forms of localized scour that can obtain their maximum values under a single flood event, the full potential LTBD is realized over multiple flood events extending over time periods of a few years to decades. The long-term nature of LTBD allows time for the degradation to be observed during bridge inspections and for countermeasures to then be installed.

Engineers should also consider other site-specific factors that may increase the potential for LTBD beyond those predicted by Eqs. 9a and 9b. In particular, structures founded on sediment deposits upstream of existing dams that may be removed during the life of the structure have the potential to experience much larger values of LTBD than those predicted by Eqs. 9a and 9b. Man-made structures, such as culverts and utility crossings, may also provide downstream grade control that once removed may cause degradation upstream beyond those values predicted by Eqs. 9a and 9b. This is particularly the case if these man-made controls or structures are founded on soils formed from sediments trapped upstream of historic milldams. The final depth of LTBD used for the placement of structure foundations should be determined using Eqs. 9a and 9b and the additional site-specific information.

6.0 CONCLUSIONS

Field Data Collection

A database of 41 field measurements of LTBD was obtained in urban streams of the Piedmont Plateau province. These measurements were adequate for the intended purpose of providing a range of LTBD observed in the urban streams of the Piedmont Plateau province. Two important sources of error in these measurements should be addressed in future studies:

1. Precise pre-degradation reference elevations were available to estimate LTBD at only a few of the bridge sites. Pre-degradation reference elevations at the rest of the sites were approximated as the top surface of the foundations, or they were approximated as the existing bed protection elevation. These approximations resulted in an underestimation of LTBD. Locating bridge sites where degradation is measurable and bridge plans with streambed reference elevations are available would remedy this situation. A more efficient means of locating sites that have both measureable degradation and plans with stream bed reference elevations is needed.

2. Consideration needs to be given to the fact that the measurements may not represent the maximum degradation that may have occurred. The estimates of LTBD developed in this study were based on a single set of bed profile measurements. In some locations, the bed may have degraded, and subsequent deposition may have changed the channel profile such that the measured LTBD is less than the maximum that may have occurred during the life of the structure. This problem is envisioned to be most significant at bridge sites on lower-sloped streams and least significant downstream of culverts on higher-sloped streams.

The effects of entrenchment were included in this study by adding the effects of the estimated pre-degradation channel geometry on the index shear stress. The research team found that inclusion of this effect did not significantly improve the prediction of LTBD over that of the relation developed for slope. The research team recommends that future phases continue to collect the same channel geometry data, as the effect may be more significant in other regions.

In previous phases, the research team examined the utility of including bed resistance in predictions of LTBD through the development of a bed mobility index (BMI). This index requires an estimate of the representative mean size of bed material prior to degradation. The research team determined that obtaining a good estimate of pre-degradation bed material was not possible because of the abundance of introduced material that included riprap, brick, and concrete waste. Therefore, the BMI was not used in this study.

The research team located bed controls at most sites; whether or how these bed controls were controlling the profile of the channel to limit LTBD, however, was unclear. Highly weathered and fractured bedrock was present near the low-flow water surface (within 1 ft) and in the base of pools at multiple locations; however, bedrock rarely controlled the low-flow water surface slope, indicating that coarse material downstream may be controlling the channel profile. A method for incorporating the effects of weak near-surface bedrock and coarse material needs to be developed to quantify their role in LTBD.

Lateral instability at many sites in the Piedmont appears to be protecting waterway crossing structures from LTBD at least temporarily, but the extent to which this can be relied upon as a form of long-term control is unknown. At these sites, downstream channel planform instability and sediment splays caused aggradation downstream of the crossing structure. These depositional areas appeared to prevent vertical degradation and in some cases caused aggradation upstream at the structure. Where slopes are mild, the backwater effect of these laterally unstable reaches may prevent or reverse degradation upstream. Although these highly unstable and dynamic reaches are not true controls, they may be a reason for the lack of degradation at many sites in the Piedmont.

Remedial activities employed after flood events may conceal LTBD where structures were damaged. Soon after severe flood events and before maintenance crews can repair structures, a team of SHA engineers should obtain rapid measurements at damaged structures. The most severe cases of channel degradation are likely to endanger structures, and they are repaired as soon as possible after floods recede. For this reason, the most severe degradation may not have been measured in this study. Measurements by SHA engineers after floods may exceed those of this study.

Regional Relations

The possibility of developing regional relations between drainage area and LTBD was evaluated for urban stream in the Piedmont Plateau province. The data did not indicate even weak trends in the variation of LTBD with drainage area. Development of regional relations based solely on drainage area was not pursued in this study.

LTBD Risk Factors

The variation of LTBD was examined with respect to four of the six risk factors: (1) the valley slope, (2) the effective floodplain width, (3) discharge, and (4) downstream channel entrenchment. Two relations between LTBD and these factors were examined: LTBD and valley slope; and LTBD and an index combining Factors 1-4 (boundary shear stress index). A comparison of the resulting equations revealed that valley slope was as good a predictor of the susceptibility of a site to LTBD as the index that required additional data and considered more parameters. The relation between valley slope and LTBD was recommended to estimate LTBD for streams with slopes of less than 0.03 ft/ft and drainage areas from 0.2−60 mi^2.

Rate of LTBD

The number of available structure plans was insufficient to develop a rate relation. The development of a rate relation should be explored further in future phases of this research. The lack of success in obtaining plans during the time period of each study and the lack of plans for each individual study area for each phase does not provide sufficient data for the evaluation of the rate of degradation. Although data from any one region has been insufficient, the composite data from regions with similar degradation causes and values of LTBD may be grouped in future research to provide sufficient data for an analysis of degradation rates.

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