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RESEARCH REPORT

LONG-TERM BED DEGRADATION IN MARYLAND STREAMS (PHASE IV): WESTERN SHORE OF THE COASTAL PLAIN 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 was 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. LTBD was defined as the vertical change in the channel profile other than that caused by local or contraction scour. A total of 22 sites in Baltimore City and Harford, Baltimore, Anne Arundel, Prince George's, Calvert, Charles, and St. Mary's counties were selected for data collection. Drainage areas of these sites in the Western Shore of the Coastal Plain province ranged from 0.7−30.5 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. Five of the six factors that may influence a site's risk of LTBD were investigated. These include (1) the valley slope, (2) the effective floodplain width, (3) discharge, (4) downstream channel entrenchment, and (5) bed material characteristics. The possibility of developing regional relations between LTBD and percent impervious area was evaluated for the physiographic province, but the data were inconclusive. Three relations between LTBD and the risk factors were examined: LTBD and valley slope; LTBD and an index combining Factors 1-4; and LTBD and an index of bed mobility. Data indicated no trend in LTBD with either of the two indices. The relation based on valley slope was compared to a relation based on drainage area. The comparison revealed that valley slope was a better predictor of the susceptibility of a site to LTBD than drainage area. The relation between valley slope and LTBD was recommended to estimate LTBD for streams with slopes of less than 0.014 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 or recent downstream channelization. The development of rate relationships for LTBD was also considered, but 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 research on LTBD in Maryland.

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GLOSSARY AND ABBREVIATIONS

Variables

$\mathbf{A_{ch}}$	Pre-degradation channel area	(Eq. 3, 5)
BMI	Bed mobility index = τ_o/τ_c	(Eq. 9)
$\mathbf{D_{50}}$	Median size of the bed material (ft)	(Eq. 10)
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. 2, 11, 12, 13, 14)
LWD	Large woody debris	
n_{ch}	Manning *n* estimated for the channel	(Eq. 5)
n_{fp}	Composite Manning *n* estimated for the effective floodplain width	(Eq. 7)
$\mathbf{P_{ch}}$	Pre-degradation channel wetted perimeter	(Eq. 4)
PIA	Percent impervious area	
$\mathbf{Q_{100}}$	The approximate 100-year recurrence interval peak flow (cfs)	(Eq.6)
$\mathbf{Q_{ch}}$	Top-of-bank flow in the pre-degradation channel (cfs)	(Eq. 6)
$\mathbf{Q_{fp100}}$	Approximate 100-year peak flow on the floodplain	(Eq. 6, 7)
$\mathbf{S_{ch}}$	Channel slope (ft/ft)	
$\mathbf{S_g}$	Specific weight of the sediment	(Eq. 10)
$\mathbf{S_v}$	Valley slope (ft/ft)	(Eq. 1, 7, 11, 12, 15)
$\mathbf{W_{bed}}$	Width of the channel measured at the toe of the banks (ft)	(Eq. 3, 4)
$\mathbf{W_{fp}}$	Effective floodplain width (ft)	(Eq. 7)
$\mathbf{W_{tob}}$	Width of channel measured at the level of the top of the lowest banks (ft)	(Eq. 3, 4)
$\mathbf{Y_{100}}$	Approximate flood flow depth (ft) for Q_{100}	(Eq. 1, 8)
$\mathbf{Y_{ch}}$	Depth of channel (ft)	(Eq. 2)
$\mathbf{Y_{chp}}$	Depth of pre-degradation channel for the top-of-bank flow (ft)	(Eq. 2, 3, 4, 8)
$\mathbf{Y_{fp100}}$	Approximate flood flow depth (ft) on the floodplain for Q_{100}	(Eq. 6, 7, and 8)
γ	Unit weight of water (62.4 pcf)	(Eq. 1, 10)
τ_c	Boundary shear stress required to mobilize the native bed material (psf)	(Eq. 9, 10)
τ_o	Boundary shear stress index (psf)	(Eq. 1, 9, 13)

Units of Measure

cfs	Cubic feet per second
ft	Feet
$\mathbf{mi^2}$	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 Maryland streams in the Western Shore of the Coastal Plain province. The conservative upper limit curve that describes LTBD as a function of valley slope (S_v) was given as

$$\text{LTBD (ft)} = 3 \text{ ft for } S_v < 0.0034 \text{ ft/ft} \quad (12a)$$

$$\text{LTBD (ft)} = 4.6 \log(S_v) + 14.4 \text{ for } 0.0034 \text{ ft/ft} \leq S_v < 0.014 \text{ ft/ft} \quad (12b)$$

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 0.014 ft/ft.
2. Drainage area from 0.7–30.5 mi^2.
3. A majority of the watershed drainage area in the Coastal Plain physiographic province for structures in Anne Arundel, Prince George’s, Calvert, Charles, and St. Mary’s counties. In Harford and Baltimore counties and Baltimore City, the majority of the watershed drainage area is likely to be in the Piedmont Plateau province.
4. Impervious area of less than 31% 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, for streams that have experienced recent channelization downstream, 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. 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 upstream of a recently (past 50 years) channelized section of stream.
3. Structures located in the backwater deposit of a dam.
4. 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 Office of Structures (OOS) *Hydrology and Hydraulics Design Manual* [1].

A channel should be evaluated as follows for signs of active channel degradation for at least 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.

In addition to the site examination, county LiDAR and high-resolution aerial mapping should be evaluated for at least 3000 ft downstream of the site to identify any potential signs of channel degradation, especially where site access is limited. Signs of channel instability and degradation that may be indicated in LiDAR mapping and aerial photos include rapid decreases in channel bed elevation, rapid widening of a channel, or highly irregular bank lines and fallen trees.

If any of these evaluations indicate that the channel is degrading, or if the valley slope is greater than 0.014 ft/ft, then the LTBD equations should not be used. Instead, the techniques recommended in Chapter 14 of Maryland's OOS *Hydrology and Hydraulics Design Manual* [1] should be used to evaluate bed degradation potential.

If the channel shows no evidence either of existing degradation problems or recent channelization 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 Western Shore coastal plain streams with valley slopes less than 0.014 ft/ft and drainage areas from 0.7−30.5 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:

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

   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. 12a or Eq. 12b from this study to estimate LTBD.

The LTBD values computed by Eqs. 12a and 12b 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. 12a and 12b. Two factors that could be used to reduce the values obtained in

Eqs. 12a and 12b are bed controls and the time required for the full potential for LTBD to be realized. Bed controls such as clay 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 and bed weathering that 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. 12a and 12b. 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. 12a and 12b. Man-made structures, such as culverts and utility crossings, may also provide downstream bed control that, once removed, may cause degradation upstream beyond those values predicted by Eqs. 12a and 12b. 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. 12a and 12b and the additional site-specific information.

Long-Term Bed Degradation in Maryland Streams (Phase IV): Western Shore of the Coastal Plain 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 Plateau physiographic provinces. Phase 3 [4] was limited to urban watersheds (those with impervious ground cover greater than 10%) of the Piedmont Plateau province in Frederick, Carroll, Montgomery, Baltimore, and Howard counties, Baltimore City, and Washington, DC. The present study, Phase IV, was limited to the Western Shore of the Coastal Plain Province: Baltimore City and Harford, Baltimore, Anne Arundel, Prince George's, Calvert, Charles, and St. Mary's counties.

The Phase IV study had four primary objectives:

1. Continue development of a database of field measurements of LTBD in Maryland streams.

2. Collect field measurements that quantify factors identified in Phases 1 and 2 that may influence a site's risk (likelihood and magnitude) of LTBD.

3. Develop quantitative relations between the risk factors and measured LTBD.

4. 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.

2.0 STUDY AREA

The coastal plain begins at the southern border of the Piedmont at the Fall Line, which runs diagonally southwest to northeast from Washington D.C., through Baltimore City and past the head of the Chesapeake Bay. From its western edge, the plain generally grades downward from an elevation of between 300 and 400 ft at the Fall Line to sea level at the Atlantic Ocean [5].

The coastal plain is an area of large river drainages and sedimentary deposits. Formed by fluctuating sea levels and alluvial deposition from rivers draining the western mountains [6], it is underlain by unconsolidated sediments including gravel, sand, silt, clay, and small deposits of iron ore. At the Atlantic coast, these sediments have a thickness of more than 8000 ft. They range in age from Triassic to Quaternary [7]. Metamorphic rocks are typically absent [5].

The Chesapeake Bay divides the coastal plain into two parts, the Eastern Shore and the Western Shore. The study area comprised only the Western Shore. Its topography is moderately rolling with steeply cut ravines; some upland and lowland areas are fairly flat. Land use is predominantly farmland but includes urban and high-density residential development within commuting distance of Baltimore, Washington, Wilmington, or Annapolis [5]. Some drainage patterns have been considerably altered by mining of sand and gravel [6].

3.0 METHODS

3.1 Site Selection

Field Identification

The research team conducted a windshield survey along state, county, and city roads. 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. These locations were selected for addition to the sample if their estimated drainage areas were between about 0.5 mi^2 and 50 mi^2. The lower limit was based on the assumed limitations of GISHydro for conducting hydrologic analysis on small watersheds. The upper limit was selected because streams with drainage areas of more than 50 mi^2 are typically not wadeable, and the data collection techniques in the approved project scope would not be feasible.

Rapid measurements (see Section 3.2) were also taken at each site during this field investigation. Even though some of the collected data was not used because some sites were ultimately excluded from the final sample, collecting data during the initial field visit was more efficient than making a second visit to every sample site to collect the data.

Final Site Selection

Following the field investigation, the watershed boundaries of each sample site were delineated using 30-meter national elevation data [8] in the web-based version of GISHydro [9], and their surface drainage areas were estimated. A total of 22 sampling sites were selected (Fig. 3.1 and Table 3.1)

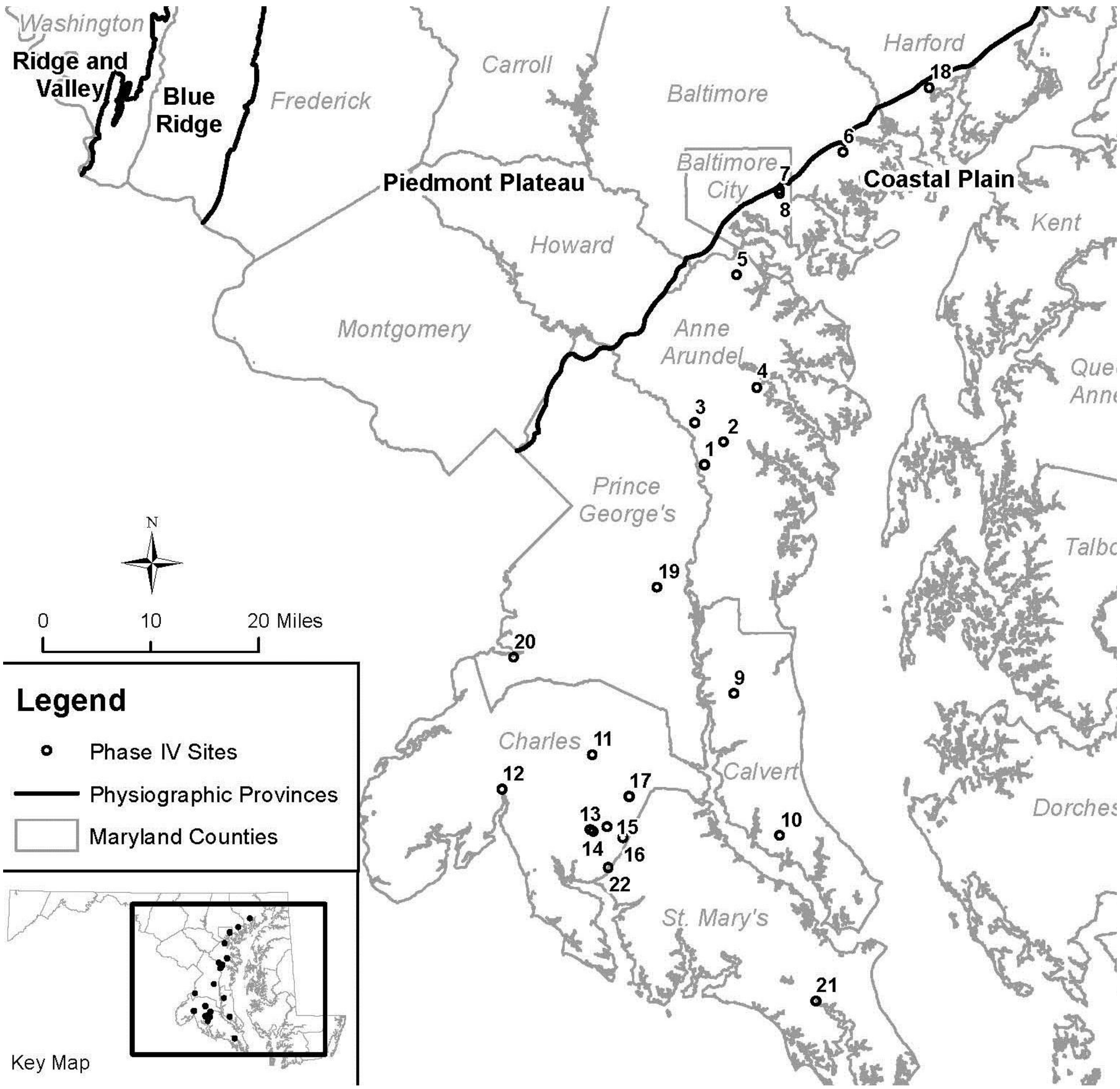

Figure 3.1. Sample site locations.

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	Estimated D_{50} (mm)		Y_{ch} (ft)	W_{tob} (ft)	W_{bed} (ft)	DA (mi^2)
1			Single-barrel 3 CMP 6.7-ft diam	Culvert outlet invert	Anne Arundel	Coastal Plain	Kings Branch	Patuxent River Road	4.4	LWD (large woody debris) and weakly cemented sand	16	Gravel	10.0	30	17	1.7
2			Two culverts—Main flow in pipe arch (12.5 x 7.8) and floodplain	Culvert outlet invert	Anne Arundel	Coastal Plain	Bell Branch	Bell Branch Road	1.9	LWD and weekly cemented sand	0.2	Sand	5.2	17	7	1.2
3			Single pipe arch culvert—(12.5 x 7.5)	Culvert outlet invert	Anne Arundel	Coastal Plain	Tributary to Little Patuxent River	Croften Parkway	3.4	LWD and MD 3 Culvert (2000 ft d/s)	8	Gravel	5.2	28	16	2.0
4			Single CMP 5.5-ft diam	Culvert outlet invert	Anne Arundel	Coastal Plain	Plum Creek	Old Harold Harbor Road	2.9	Clay	8	Gravel	5.5	16.5	11	0.7
5			No structure—Headcut between two culverts both under Cedar Ave.	Upstream channel bed	Anne Arundel	Coastal Plain	Cabin Branch 2	Cedar Avenue	4.0	Culvert downstream Cedar Avenue	Cohesive clay		5.5	19	9	2.5
6	0303700	1935	Single-span bridge	Paved invert	Baltimore	Coastal Plain	Whitemarsh Run	US-40	5.9	Unknown	0.5	Sand	8.8	91	63	10.8
7			Utility crossing	Baseflow water surface upstream of crossing	Baltimore City	Coastal Plain	Herring Run	None	3.8	Utility crossing	8	Gravel	8.8	131	35	16.5
8			Utility crossing	Baseflow water surface upstream of crossing	Baltimore City	Coastal Plain	Herring Run	None	5.2	Bridge constriction and armor	8	Gravel	6.8	82	26	11.4
9			Two-barrel CMP 4.5-ft diam	Culvert outlet invert	Calvert	Coastal Plain	Cocktown Creek	Warren Drive	1.3	Clay and LWD	0.2	Sand	4.4	30	13	3.7
10			Two-barrel CPP 2.3-ft diam	Bank height difference	Calvert	Coastal Plain	Island Creek	Ross Road	4.5	Clay, LWD, tree roots	0.2	Sand	5.8	16	6.5	0.8
11	0804500	1991	Two-span slab bridge with rock protected invert	Low flow water surface on rock protection near outlet of structure	Charles	Coastal Plain	Piney Branch	MD-488	1.8	Clay and LWD	Cohesive clay		5.7	26	20	7.2
12	0801000	1955	Single-cell box culvert	Culvert outlet invert	Charles	Coastal Plain	Hoghole Run	MD-6	4.8	Clay	Cohesive clay		8.2	23	15	3.6
13			6-ft diam CMP	Culvert outlet invert	Charles	Coastal Plain	Hells Bottom Run	Bowling Driver	2.8	LWD	Cohesive clay		7.0	20	11.5	2.9
14			Two-span slab bridge	Partially paved and rock protected	Charles	Coastal Plain	Gillber Swamp Run	Trinity Church Road	6.0	Clay	Cohesive clay		12.7	89	15	30.5
15			Four 3-ft diam HDP	Culvert outlet invert	Charles	Coastal Plain	Denton Run	Dubois Road	2.9	LWD and gravel transport	Cohesive clay		6.0	25	9	1.4
16			Two 5-ft diam CMP	Culvert outlet invert	Charles	Coastal Plain	Tributary to Trinity Church Run	North Ryceville Road	2.0	Culvert 200 ft downstream	8	Gravel	5.0	14	8	1.1
17			Two-cell 5-ft CMP	Culvert outlet invert	Charles	Coastal Plain	Gilbert Creek	Oaks Road	2.4	V. flat slope to Von Hainberg Pl bridge & riprap bed protection 4600 ft	16	Gravel	6.7	49	11	6.0
18	1208100	1976	Five-cell 5-ft diam	Culvert outlet invert	Harford	Coastal Plain	Haha Branch	MD-7	1.8	Utility crossing riprap	16	Gravel	4.6	25	19	2.1
19			Two-span slab bridge with paved invert	Paved invert	Prince George's	Coastal Plain	Charles Branch	Crom Station	2.2	Clay	0.2	Sand	11.5	50	40	14.5
20			Two-cell 3.5-ft concrete pipe	Culvert outlet invert	Prince George's	Coastal Plain	Piscataway Creek	Farmington Creek Road	5.8	Clay and Piscataway Creek tidal	Cohesive clay		6.7	28	16	0.8
21			Single-barrel 3-CMP 3-ft diam	Culvert outlet invert	St. Mary's	Coastal Plain	Tributary to St. Marys River	Flat Iron Road	4.8	Clay	64	Cobble	4.8	12.5	3	1.6
22	1801400	1960	Two-cell concrete box	Culvert outlet invert	St. Mary's	Coastal Plain	Budds Creek	MD-234	3.0	Clay	Cohesive clay		8.0	30	16	4.1

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)	BMI	Land Use Coverage	Soil Coverage	Forested Area (%)	Urban Area (%)	Impervious Area (%)	Extensive Recent Channelization
1	0.0067	106	0.04	0.1	5.6	235.0	43.5	1590	1590	0.0	2.69	12	2010 MOP	SSURGO	22.2	10.9	6.5	
2	0.0050	160	0.04	0.1	3.3	62.4	22.4	326	825	1.9	2.22	822	2010 MOP	SSURGO	50.0	12.7	3.9	
3	0.0086	80	0.05	0.1	1.8	114.4	32.4	732	2110	4.5	5.21	48	2010 MOP	SSURGO	16.9	63.7	31.1	
4	0.0089	145	0.04	0.1	2.6	75.6	24.8	239	239	0.0	1.45	13	2010 MOP	SSURGO	54.8	44.3	14.2	
5	0.0079	400	0.04	0.1	1.5	77.0	25.0	541	2250	2.0	3.72	—	2010 MOP	SSURGO	15.4	64.2	40.4	Y
6	0.0022	216	0.04	0.1	2.9	677.6	94.6	4396	9842	8.6	2.38	353	2010 MOP	SSURGO	18.0	67.4	42.5	Y
7	0.0038	400	0.04	0.1	5.0	730.4	100.6	6306	10006	4.0	3.05	28	2010 MOP	SSURGO	6.2	74.2	47.2	Y
8	0.0038	200	0.04	0.1	1.6	367.2	67.6	2612	7457	7.1	3.31	31	2010 MOP	SSURGO	8.3	68.6	47.5	Y
9	0.0048	160	0.04	0.1	3.1	94.6	30.3	523	1320	2.6	2.10	775	2010 MOP	SSURGO	36.8	49.9	16.5	
10	0.0105	120	0.04	0.1	1.3	65.3	22.9	203	203	0.0	1.66	614	2010 MOP	SSURGO	72.7	17.3	6.0	
11	0.0033	560	0.04	0.1	3.9	131.1	34.4	688	3121	2.6	1.74	—	2010 MOP	SSURGO	45.7	24.4	15.7	
12	0.0071	818	0.04	0.1	3.4	155.8	35.4	1317	2180	0.9	4.05	—	2010 MOP	SSURGO	81.4	6.8	2.6	Y
13	0.0072	63	0.04	0.07	4.2	110.3	29.8	837	2100	4.2	5.07	—	2010 MOP	SSURGO	48.8	31.5	11.9	
14	0.0020	1300	0.04	0.05	6.7	660.4	77.4	4573	7660	1.4	1.74	—	2010 MOP	SSURGO	51.6	14.4	6.1	Y
15	0.0078	230	0.04	0.1	3.1	102.0	29.0	775	1250	1.3	3.54	—	2010 MOP	SSURGO	53.2	8.9	3.1	Y
16	0.0057	140	0.04	0.1	3.0	55.0	21.0	295	1210	2.9	2.82	26	2010 MOP	SSURGO	43.0	7.8	6.0	
17	0.0032	880	0.04	0.1	4.3	201.0	43.4	1170	3140	1.8	1.68	8	2010 MOP	SSURGO	42.8	26.2	10.0	Y
18	0.0063	215	0.04	0.1	2.8	101.2	31.2	653	2379	3.2	3.03	14	2010 MOP	SSURGO	48.7	37.7	26.8	
19	0.0026	742	0.04	0.1	9.3	517.5	68.0	2460	2460	0.0	1.21	449	2010 MOP	SSURGO	46.6	34.0	16.2	
20	0.0143	288	0.04	0.1	0.9	147.4	35.4	1100	1100	0.0	3.81	—	2010 MOP	SSURGO	51.7	39.7	19.2	
21	0.0088	22	0.04	0.1	0.0	37.2	17.4	216	1810	10.7	8.50	10	2010 MOP	SSURGO	55.6	20.2	11.5	
22	0.0038	495	0.04	0.1	5.0	184.0	39.0	1181	1900	1.3	2.18	—	2010 MOP	SSURGO	70.4	8.2	3.8	Y

Note: Parameters denoted by symbols/abbreviations are defined in the glossary. Those related to the 100-year flow (i.e., W_{fp}, Q_{ch}, Q_{100}, and Y_{fp100}) are approximations (see Section 3.3). Forested, urban, and impervious areas were obtained from GISHydro [9].

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 watersheds of the physiographic region. The field data in combination with readily available mapping data was also sufficient to examine the relation between LTBD, percent impervious area (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:

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

where τ_o is the boundary shear stress on the channel, γ is unit weight of water (62.4 pcf), Y 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 bed controls]	No durable downstream bed 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 bed 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

Although bedrock does exist in the coastal plain, none was observed at the sample sites. Consolidated resistant clay was found at many of the sites. This clay provided downstream control at several sites. The clay is more susceptible than most bedrock to gradual degradation through both slaking and other weathering processes in addition to direct erosion. Degradation due to weathering would be most significant in channels that dry, exposing the clay.

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 over time in elevations of high points in the bed profile (e.g., bedforms composed of gravel, sand, and/or a combination of these materials and large woody debris (LWD)). 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 high points in the profile, 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 (Fig. 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’s outlet invert (Figs. 3.2 and 3.3). LTBD was measured as the vertical drop in the water surface at the downstream step (Fig. 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 (Fig. 3.2).

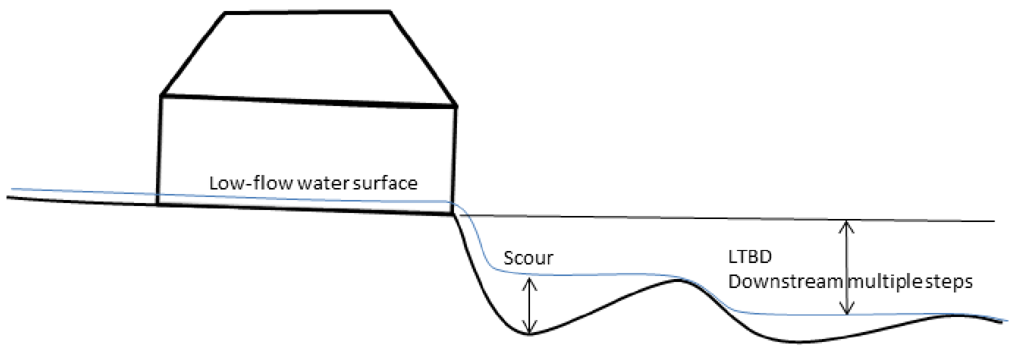

Figure 3.2. Typical bed profile of a culvert with downstream bed degradation and a scour pool.

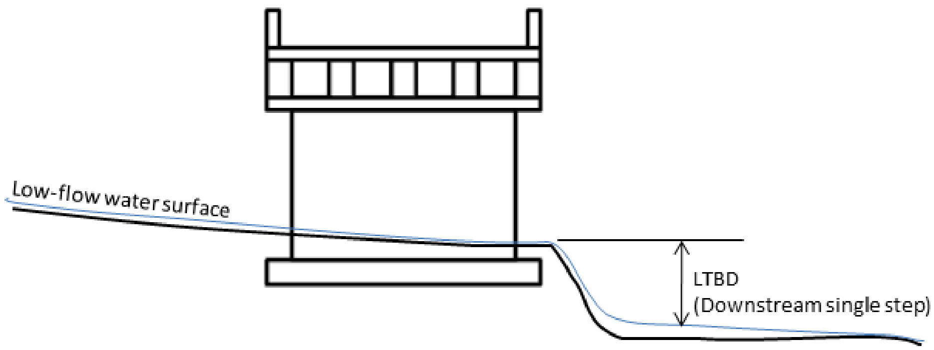

Figure 3.3. LTBD: uniform degradation and single step downstream.

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 (Figs. 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.

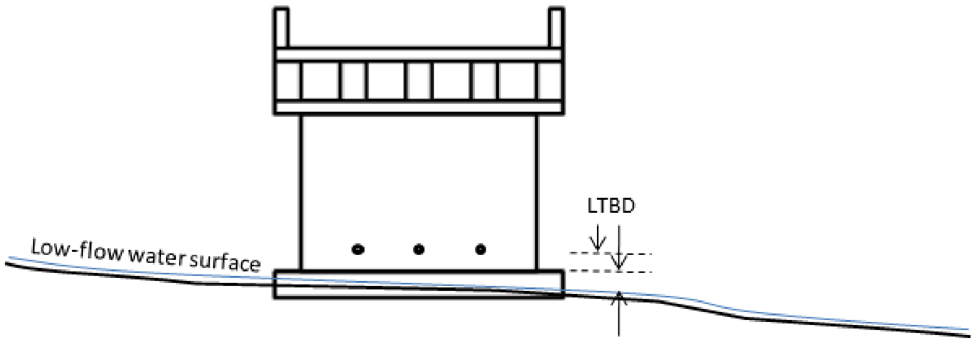

Figure 3.4. LTBD: uniform degradation.

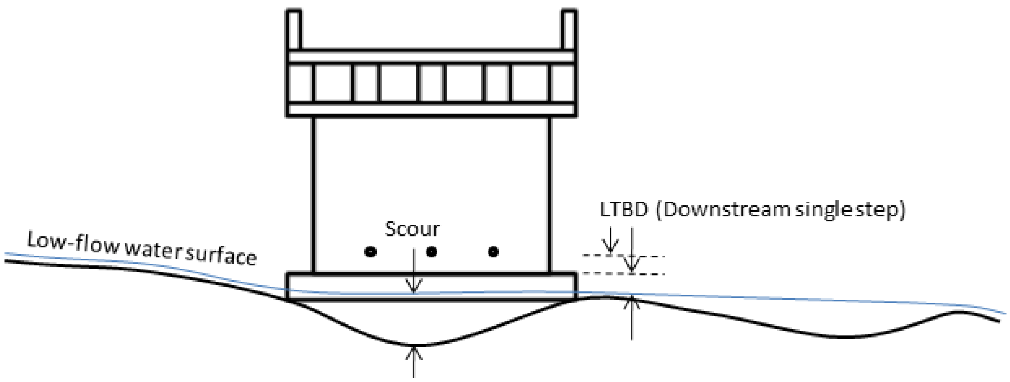

Figure 3.5. LTBD with scour and uniform degradation.

Bed Material

Layers of silty clay, sand, sandy gravel, and in some locations cobble are common in the coastal plain. To obtain a representative sample of the material through which degradation has occurred, bed material from the site was examined. Because bed material in the channel is typically a mixture of bank erosion material, sediment transported along the bed from upstream, and materials introduced near the bridge, the bed material is only a partially representative sample of the material through which the stream has degraded. The team visually examined the bed material and classified it as clay, sand, gravel, or cobble. Sand and gravel were further classified as fine, medium, or coarse, and a median size (D_{50} in Table 3.1) was selected based on the classifications. More detailed sampling of bed material and gradation analysis were considered unwarranted.

Downstream Bed Controls

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

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 structure.
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. It was completely unrelated to FEMA discharges, water surface elevations, or floodplain extents.

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 [9].

Valley Slope

The variation of observed LTBD with estimated valley slope was examined for streams of the Western Shore of the coastal plain. The data was then compared to the conservative upper limit curves developed in Phase 2 and Phase 3.

Estimates of 100-Year Peak Discharges

Each site’s 100-year recurrence interval peak discharge, Q_{100}, was obtained from the web-based version of GISHydro [9] using the Fixed Region equations [10]. Watershed runoff characteristics were based on STATSGO soils data [11] and either 2002 or 2010 Maryland land use data [9].

Channel Boundary Shear Stress Index

The channel boundary shear stress index (τ_o) defined and used in Phases 2 and 3 was used 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 in Phases 2, 3, and 4 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) estimated from USGS topographic maps, and Y_{100} is the depth (ft) of the 100-year peak discharge in the pre-degradation channel. Y_{100} was estimated from a series of equations (Eqs. 2–8) as follows:

The pre-degradation channel depth (ft), Y_{chp}, was approximated as

$$Y_{chp} = Y_{ch} - LTBD \quad (2)$$

where Y_{ch} is the measured existing channel depth, and LTBD is the measured long-term bed degradation.

The measured channel top width, W_{tob}, and bed width, W_{bed}, were used to estimate the pre-degradation channel area, A_{ch}, and the pre-degradation channel wetted perimeter, P_{ch}:

$$A_{ch} = Y_{chp}\,(W_{tob} \text{ and } W_{bed})/2 \quad (3)$$

$$P_{ch} = 2\,Y_{chp} + (W_{tob} \text{ and } W_{bed})/2 \quad (4)$$

The top-of-bank flow in the pre-degradation channel, Q_{ch}, was estimated as

$$Q_{ch} = (1.49/n_{ch})\,A_{ch}\,(A_{ch}/P_{ch})^{0.667} S_v^{0.5} \quad (5)$$

where n_{ch} is the Manning channel roughness. The parameter n_{ch} was selected as 0.04 for all streams.

Q_{fp100}, the 100-year peak discharge (cfs) across the effective floodplain width (W_{fp}), was approximated as

$$Q_{fp100} = Q_{100} - Q_{ch} \quad (6)$$

where Q_{100} is the 100-year peak discharge obtained from GISHydro [9].

Y_{fp100} is an approximation of the average depth (ft) of Q_{fp100}. To simplify the calculations, Y_{fp100} was assumed to be the same over the channel as over the floodplain. Because these estimates were only intended to test whether this method could be used to determine whether a site is at risk for large values of LTBD, a high level of accuracy in the estimates was not required. Y_{fp100} was approximated as

$$Y_{fp100} = [(Q_{fp100}\, n_{fp})/(1.49\, W_{fp}\, S_v^{0.5})]^{0.6} \quad (7)$$

where W_{fp} is the effective floodplain width (ft) estimated from USGS topographic maps, field observations, and aerial photographs; and n_{fp} is the composite Manning *n* estimated for W_{fp}. 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.

Y_{100}, which was needed for calculation of the channel boundary shear stress index (Eq. 1), was estimated from Y_{chp} (Eq. 2) and Y_{fp100}:

$$Y_{100} = Y_{chp} + Y_{fp100} \quad (8)$$

Channel Boundary Bed Mobility Index (BMI)

A bed mobility index was developed to examine the combined effect of τ_o and sediment size on LTBD for data. The bed mobility index was defined as

$$BMI = \tau_o/\tau_c \quad (9)$$

where τ_c is critical shear stress, i.e., the boundary shear stress required to mobilize the native bed material, and is defined as

$$\tau_c = 0.04\ (S_g\text{-}1)\ \gamma\ D_{50} \quad (10)$$

where S_g is the specific weight of the sediment, γ is unit weight of water (62.4 pcf), and D_{50} is the estimated median size of the bed material. Calculation of a BMI for each sample site required an estimate of τ_c from Eq. 10 for each site. Therefore, an estimate of the specific weight of the bed material and the visually estimated bed material grain size (D_{50} in Table 3.1) from each site were used. A constant specific weight of 2.65 was used for all bed materials. The BMI for each site was computed from the estimate of τ_c and an estimate of τ_o from Eq. 1. Sites with clay bed material were excluded from the assessment of BMI. Critical shear stress estimation for clays is complex and dependent on many factors including organic and inorganic material content, mineral composition, gradation, flocculation size and orientation, strength, permeability, and water temperature, salinity, pH and ion concentrations. Sampling and analysis required to develop useful estimates of critical shear stress for the sites with clay bed material was beyond the scope of this project.

A plot of LTBD as a function of BMI was then developed and examined for trends in the maximum observed LTBD with BMI.

4.0 RESULTS

The possibility of developing regional relations between watershed area and LTBD was evaluated, and four relations were examined between LTBD and PIA, valley slope, τ_o , and BMI. Extensive relatively recent channelization that resulted in long reaches of straightened channel downstream of many of the sites sampled and the lack of bedrock controls resulted in high values of LTBD over the full range of parameters analyzed. The data set was partitioned into sites that showed evidence of relatively recent channelization (straightening, deepening, and/or widening estimated to have occurred since the late 1960s) and those that did not indicate evidence of recent channelization to determine whether correlations could be developed.

Drainage Area

No correlation was indicated when considering both recently channelized and other sites in the region (Fig. 4.1). However, a correlation could be developed between maximum value of LTBD and drainage area at sites that had not shown signs of relatively recent channelization. The maximum values of LTBD decreased with increased drainage area between 0.7 square miles and 30.5 square miles. An equation representing the maximum values of LTBD for sites that do not indicate recent channelization is

$$LTBD = -2.85\ Log(DA) + 5.5 \qquad 0.7 < DA < 30.5 \qquad (11)$$

where DA is drainage area (square miles).

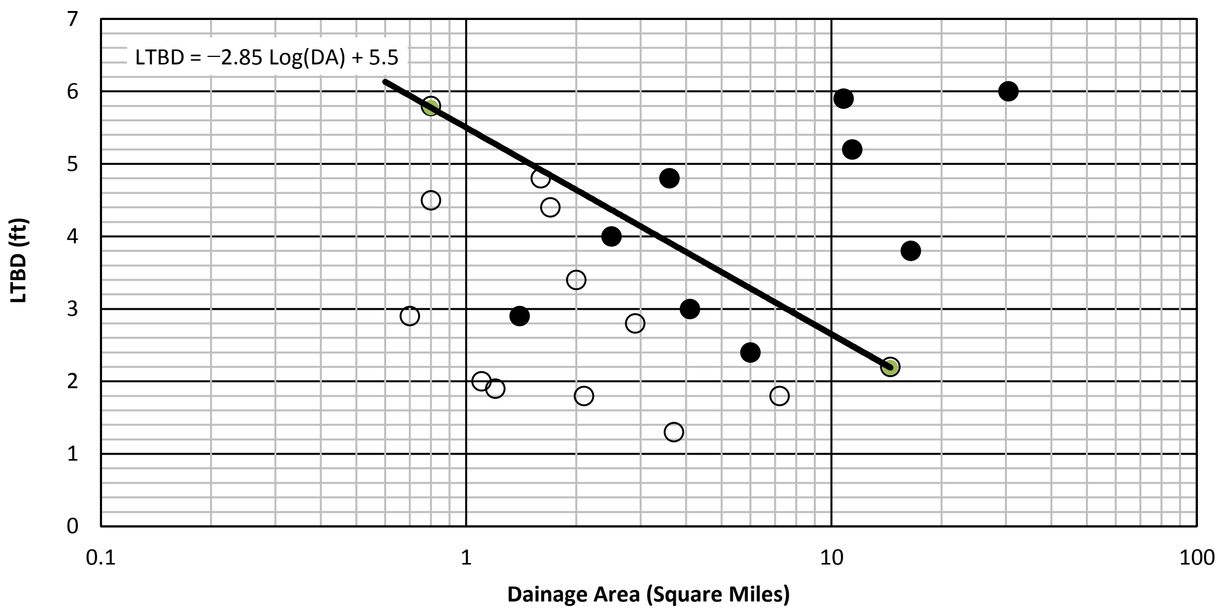

Figure 4.1. Variation of LTBD with drainage area for streams of the Western Shore of the coastal plain. Marker-filled data points represent LTBD values from sites where extensive recent channelization was identified.

Impervious Area

Impervious area varied from 2.6% to 47.5%. The variation of LTBD (Fig. 4.2) indicates that PIA is not even weakly correlated with LTBD for Western Shore coastal plain streams within the watershed imperviousness range sampled.

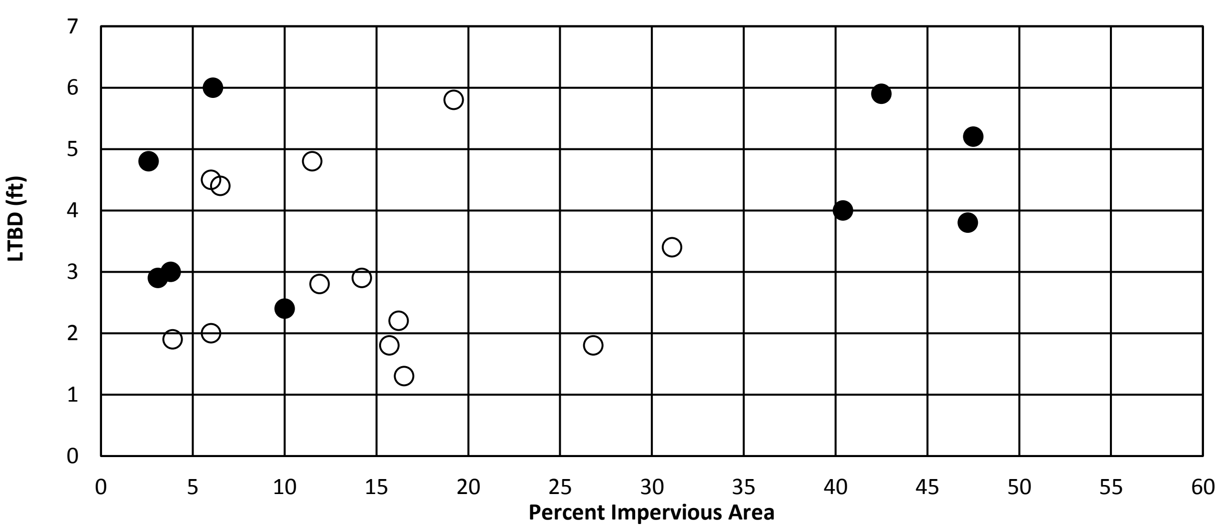

Figure 4.2. Variation of LTBD with percent impervious area. Marker-filled data points represent LTBD from sites where extensive recent channelization was identified.

Valley Slope

Maximum values of LTBD increased in the Western Shore coastal plain streams without significant recent channelization in the range of slopes from 0.0026 to 0.0143 ft/ft (Fig. 4.3). This trend of increased maximum LTBD with slope in the Western Shore coastal plain 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 IV sites as a function of valley slope (S_v) is

$$\text{LTBD (ft)} = 3 \text{ ft for } S_v < 0.0034 \text{ ft/ft} \quad (12a)$$

$$\text{LTBD (ft)} = 4.6 \log(S_v) + 14.4 \text{ for } 0.0034 \text{ ft/ft} \leq S_v < 0.014 \text{ ft/ft} \quad (12b)$$

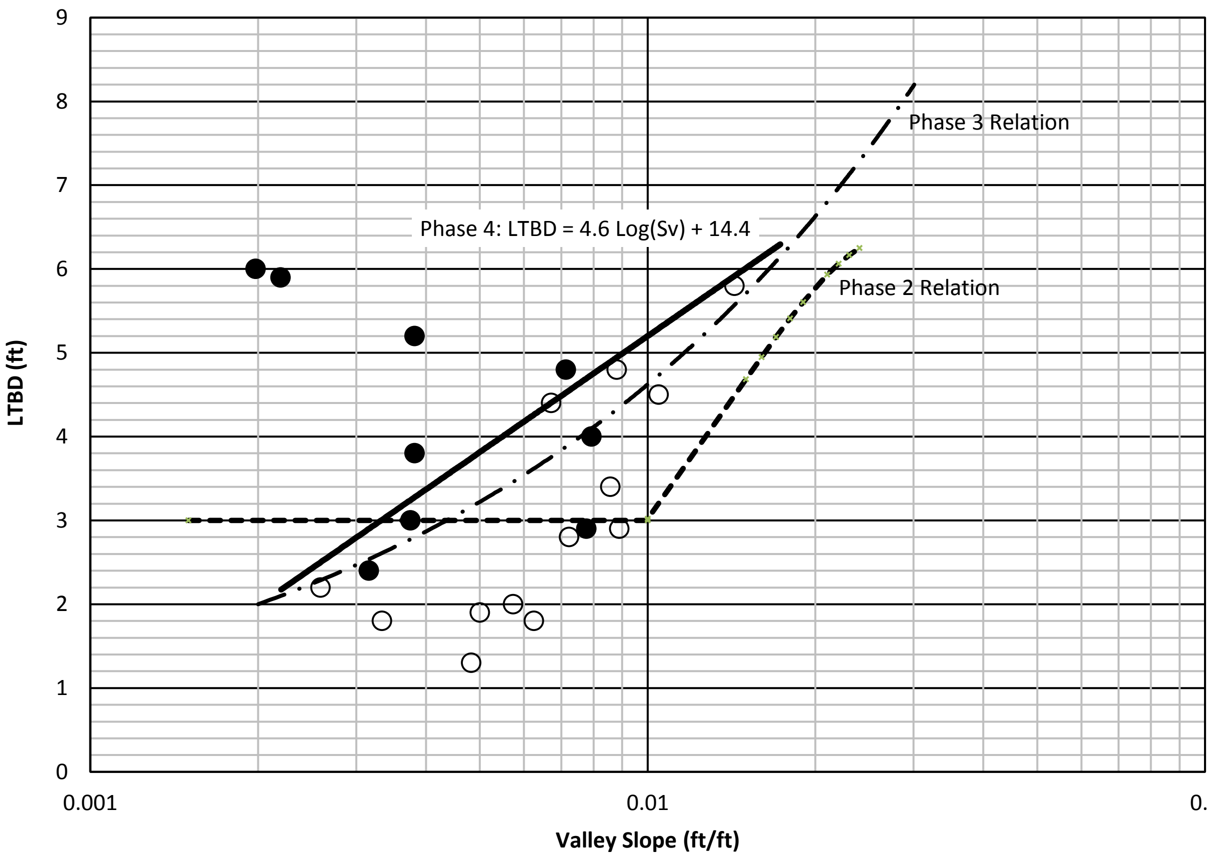

Figure 4.3. LTBD as a function of valley slope. A minimum value of 3 ft should be used for all sites with slopes less than 0.0034 ft/ft. Marker-filled data points represent LTBD values from sites where extensive recent channelization was identified.

LTBD versus Channel Boundary Shear Stress Index

Data from the Western Shore coastal plain streams indicate no trend in LTBD with increases in the channel boundary shear stress index, τ_o (Fig. 4.4).

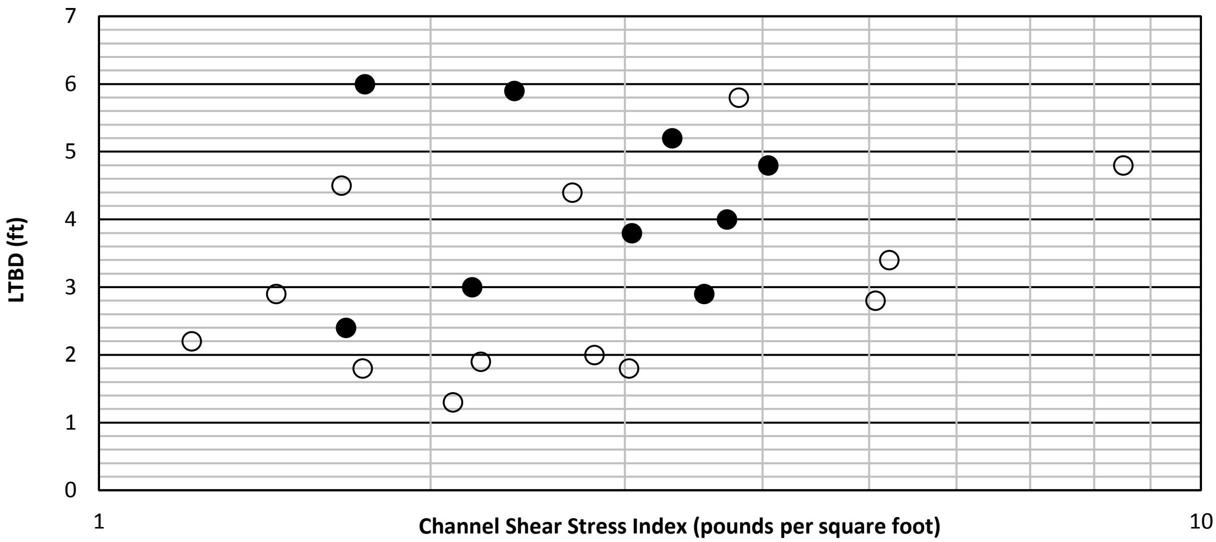

Figure 4.4. LTBD as a function of shear stress index. Markers filled data points represent LTBD values from sites where extensive recent channelization was identified.

LTBD versus Bed Mobility Index (BMI)

Data from the Western Shore coastal plain streams indicate no trend in LTBD with BMI (Fig. 4.5).

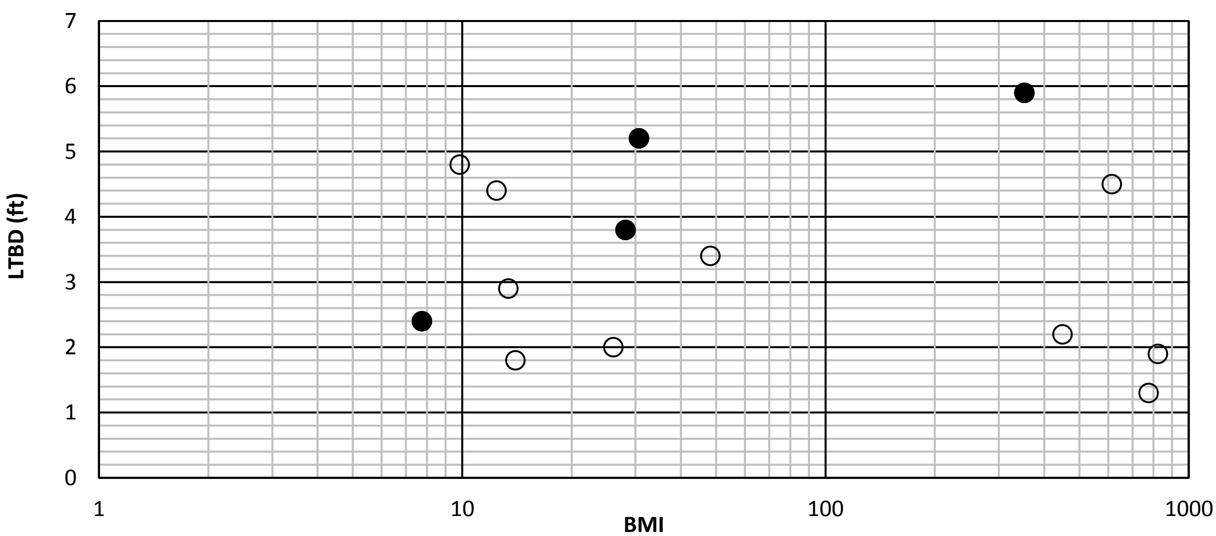

Figure 4.5. LTBD as a function of bed mobility index. Marker-filled data points represent LTBD values from sites where extensive recent channelization was identified.

LTBD versus Bed Material Type

A box plot (Fig. 4.6) was developed to examine the potential for correlations between gross material size classes (clay, sand, gravel, cobble) and LTBD. Box plots indicate the minimum, median, maximum, first quartile, and third quartile data values for each group of data.

In this analysis, streambeds currently composed of clay showed deeper maximum LTBD than did all other sites. Sites with sand and gravel bed material were about the same. The one site with cobble (Site 21, Flat Iron Road crossing in St. Mary's County) had an LTBD value greater than all the gravel and sand sites. Sites with sand and gravel are not necessarily less susceptible to LTBD than sites with cobble and clay. The plot most likely indicates that deep LTBD exposes underlying clay and, in some locations where cobble may exist in the banks, cobble may be found in the bed material. The bank material at all sites was composed mostly of layers of silt and sand, and at sites with gravel and cobble in the bed, relatively thin layers of gravel and cobble were present in the banks.

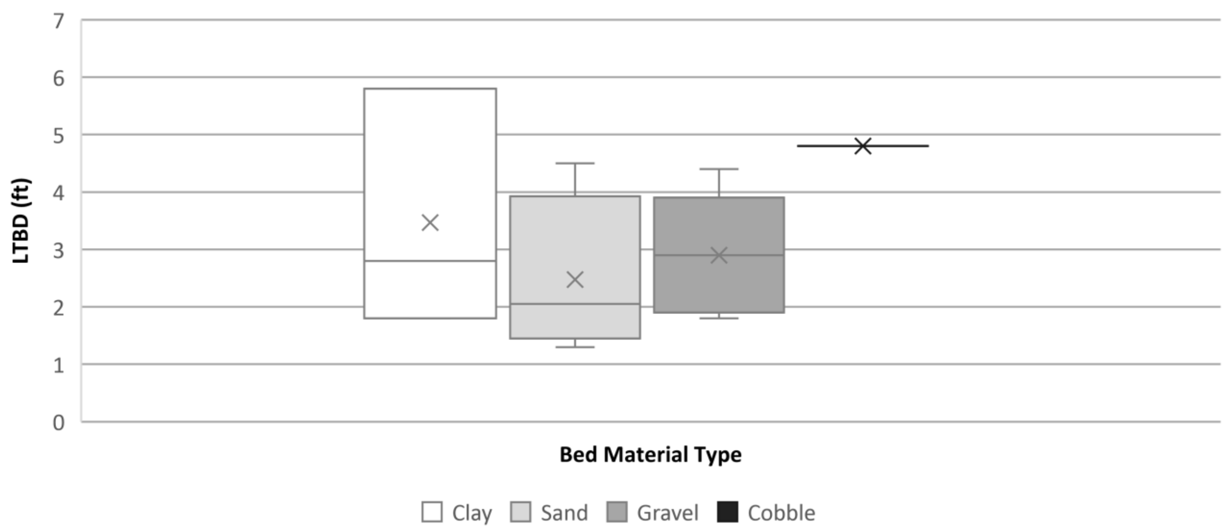

Figure 4.6. Box plot of LTBD as a function of bed material type. This plot excludes data from sites where extensive recent channelization was identified.

Bed Controls

Seven forms of downstream bed control (Fig. 4.7) were observed at 22 sampling sites; controls at one sampling site could not be identified:

- **A clay streambed or exposure of an extensive clay layer beneath unconsolidated bed material** was observed as the bed control in 41% of the sites. The clay was extensive and consolidated. The clay is susceptible to gradual degradation through both slaking and other weathering processes in addition to direct erosion from high shear stresses during flood flows, especially in steep channel reaches and at headcuts, although headcuts were not observed at any of the sites where clay was identified as a control. Degradation of the clay may be gradual where channel flow prevents exposure of the bed to weathering processes and flood flow shear stress is less than 2 psf.

- **Large woody debris (LWD) partially buried in sand or loose gravel** provided bed control in reaches with slopes of less than 0.9%. LWD was identified as the bed control in 23% of the sampled sites. Low flow water surface drops occurred mostly over LWD in the form of single logs or low-profile (under or slightly above the low flow water surface) jams with sediment partially burying the LWD. This form of control comprised several LWD pieces and/or jams distributed along the channel. These controls may be transient and dependent on the rate of LWD supply to the channel and rate of LWD degradation and channel lateral stability. This type of control may be outflanked where the stream erodes around the LWD, or it may be undermined where flow pipes under the LWD. The reliability of this type of control is uncertain because it depends on the supply, stability, and degradation rate of LWD pieces and jams and the stability of the channel. In the relatively low slope reaches of the Western Shore coastal plain, LWD is an important feature of bed control; however, little is known about factors that contribute to its long-term reliability as a vertical control.
- **Armored riffles** were identified as bed control in 9% of the sites. 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.
- **Utility protection** in the form of riprap or concrete casing was identified as a control in 9% of the sites.
- **Culverts** inverts were identified as bed controls for 9% of the sites.
- **Tidal estuary** was identified as a control for only one site.

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 clay exposure downstream of the site, it likely was not the control prior to development of LTBD. The most frequent forms of bed control observed in the Western Shore coastal plain stream dataset were clay and LWD. It is also important to consider that the research team intentionally included sites where LTBD was measurable, and therefore, the controls observed were those near locations where some degradation was observed. Most sites examined during the site selection process 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 bed control.

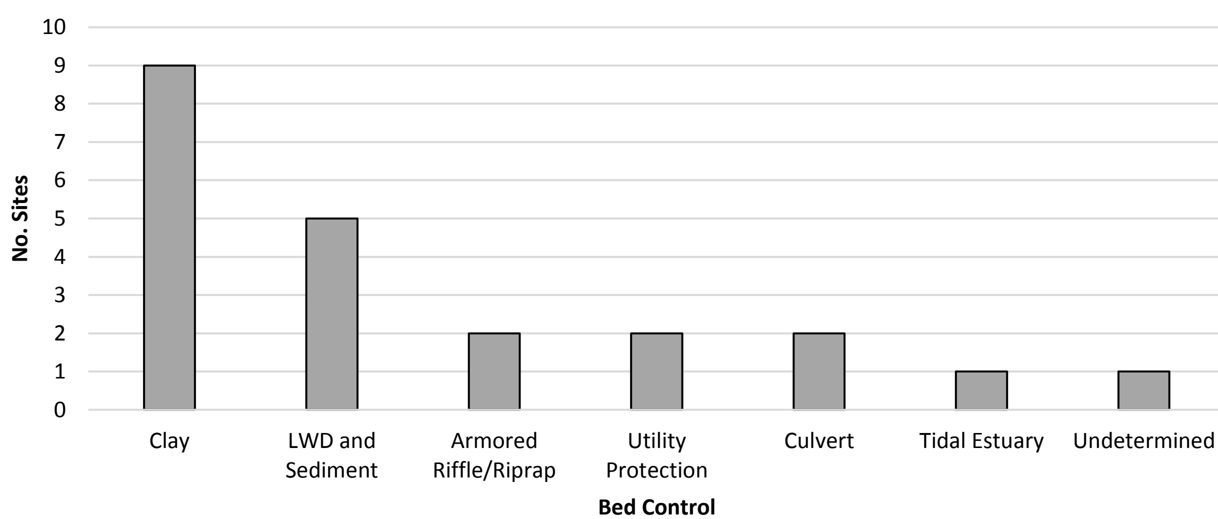

Figure 4.7. Frequency of bed control types downstream of LTBD measurement sites.

Structure Age versus LTBD

Insufficient information was available on the age of the crossings to examine the rate of LTBD.

Comparison of LTBD Equations

Observed values of LTBD were compared to those predicted by the use of the DA-based equation (Eq. 11) and the S_v-based equation (Eq. 12b). The residuals were defined as

$$\text{Residual LTBD} = \text{Predicted LTBD} - \text{Observed LTBD} \qquad (13)$$

Residuals were computed and plotted for sample sites that were not identified as having significant recent channelization. Linear regression was used to develop a relation between the residuals for Eq. 11 and Eq. 12b (Fig. 4.8). The regression lines indicated that the predicted residual for the DA-based equation is significantly higher than for the Sv-based equation for the lowest observed values of LTBD. The S_v-based equation has residuals only slightly higher than the DA-based equation in the highest observed LTBD sites. At one site the DA-based equation predicted 1.46 ft more LTBD than did the S_v-based equation.

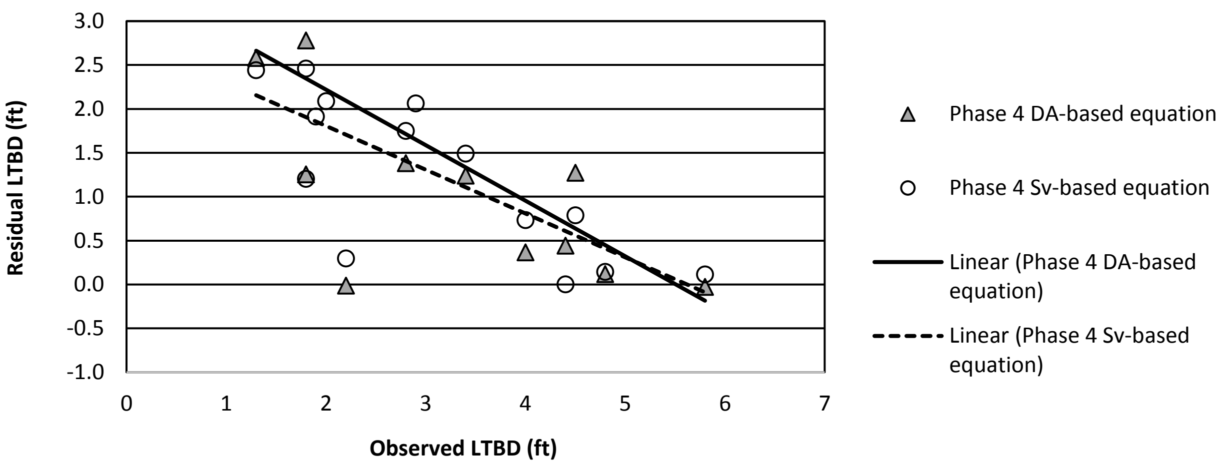

Figure 4.8. Comparison of residual LTBD values and observed LTBD for DA-based and Sv-based equations. Note that these residuals are for sample sites in streams without resent channelization.

Comparison of Phase II, Phase III, and Phase IV LTBD Values

LTBD values for the Western Shore coastal plain streams were generally higher than those for the Phase II non-urban Blue Ridge and western Piedmont Plateau provinces streams and Phase III urban Piedmont Plateau province streams based on a comparison of S_v-based equations (Fig. 4.3) for the slope range examined in the Western Shore coastal plain. The research team believes that the high LTBD values relative to other regions can be partially attributed to the lack of bedrock, boulder, and cobble controls and the long history (greater than 50 years) of manipulation of the stream channels for agricultural purposes.

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 streams of the Western Shore coastal plain that do not indicate signs of significant recent channelization. The equations can be used for streams with valley slopes from 0.0026−0.014 ft/ft and drainage areas from 0.7−30.5 mi^2.

This study included streams with PIA up to 47.5%; however, sites above 31.1% all indicated significant recent channelization. Given that none of the urban Piedmont sites or the sites in this study indicated a significant increase in LTBD with increases in PIA, the Phase IV equations 12a and 12b could be used for sites with PIA up to at least 31%.

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. Further, the equations should not be used in streams that have had downstream channelization work within the last several decades. The value of LTBD may be substantially greater than those given in this report for stream channel networks already experiencing significant LTBD, for streams that have experienced recent channelization downstream, or at structures located in thick dam deposits.

A thorough examination of the site and downstream valley should be made to determine whether any 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. 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 upstream of a recently (past 50 years) channelized section of stream.
3. Structures located in the backwater deposit of a dam.
4. 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 part of a site examination as follows for signs of active channel degradation for at least 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 and banks for signs of ongoing bed degradation problems or recent channelization activities—straightening, deepening, or widening.

In addition to the site examination, county LiDAR and high-resolution aerial mapping should be evaluated for at least 3000 ft downstream of the site to identify any potential signs of channel degradation, especially where site access is limited. Signs of channel instability and degradation that may be indicated in LiDAR mapping and aerial photos include rapid decreases in channel bed elevation, rapid widening of a channel, or highly irregular bank lines and fallen trees.

If any of these evaluations indicate that the channel is degrading, or if the valley slope is greater than 0.014 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 or recent channelization 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 Western Shore coastal plain streams with valley slopes less than 0.014 ft/ft and drainage areas from 0.7−30.5 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:

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

   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.

   Alternatively, recently provided LiDAR mapping may be used to estimate valley slope. This may be the preferred method because of the lack of contours shown on USGS 7.5-minute maps in the mild valley slopes that exist in much of the Western Shore coastal plain.

2. Use Eq. 12a or Eq. 12b from this study to estimate LTBD.

The LTBD values computed by Eqs. 12a and 12b 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. 12a and 12b. Two factors that could be used to reduce the values obtained in Eqs. 12a and 12b are bed controls and the time required for the full potential for LTBD to be realized. Bed controls such as clay 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 and bed weathering that 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. 12a and 12b. 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. 12a and 12b. Man-made structures, such as culverts and utility crossings, may also provide downstream bed control that, once removed, may cause degradation upstream beyond those values predicted by Eqs. 12a and 12b. 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. 12a and 12b and the additional site-specific information.

6.0 CONCLUSIONS

Field Data Collection

A database of 22 field measurements of LTBD was obtained in the Western Shore coastal plain. These measurements were adequate for the intended purpose of providing a range of LTBD observed in this province. Two important sources of error in these measurements should be addressed in future studies:

1. Precise pre-degradation reference elevations were not available to estimate LTBD at any of the sites. Pre-degradation reference elevations were approximated as the top surface of the culvert invert, or they were approximated as the low flow water surface over the existing bed protection. 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 measurable 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 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 shear stress index. The research team found that inclusion of this effect did not significantly improve the prediction of LTBD over that of the relation developed for valley slope.

The research team examined the utility of including existing bed material resistance and bed material types in predictions of LTBD through the development of a bed mobility index (BMI) and box plots for each of the bed material size classes observed. The research team found correlation between bed material size class and LTBD. The results for maximum values of LTBD and bed material size class appear contradictory because the largest and smallest material corresponded to the highest LTBD; this indicates that LTBD at those sites has already progressed through more mobile material that composed the bed before LTBD occurred.

The research team located bed controls at all but one site. Clay appeared to be limiting LTBD at many sites similar to the way that bedrock controlled LTBD in other regions. In many cases the clay was observed in shallow pools (less than 1.5 ft) and runs below the base flow water surface. Bedforms composed of gravel, sand, and/or a combination of these materials and LWD had formed on top of the clay. At some sites where clay was not found, LWD in combination with sediment that accumulated in jams or partially buried individual pieces controlled the low flow profile. Both the clay and the jams were distributed over long reaches and acted as a group of controls rather than a point control such as a culvert invert or riprap armored riffle. Unlike hard fixed controls, the reliability of the clay that may be susceptible to weathering and high shear stress degradation and the LWD that may degrade but also may be replaced is unclear. The team expected tidal estuaries to have a more significant role in affecting LTBD; however, it was identified as the main control in only one site. This may be because significant LTBD was not observed where tidal estuaries provide significant downstream control.

Several sites that were examined during site selection indicated repairs from floods that occurred over the past 10 years. 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 the Western Shore coastal plain. A relation between drainage area and LTBD was developed for sites identified as not having significant recent (since late 1960s) channelization. The relation was less accurate than the valley slope based equation and therefore was is not recommended for estimation of LTBD.

LTBD Risk Factors

The variation of LTBD was examined with respect to five of the six risk factors: (1) the valley slope, (2) the effective floodplain width, (3) discharge, (4) downstream channel entrenchment, and (5) bed material characteristics. Three 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), and LTBD and an index combining factors 1-5 (bed material 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 indices 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 0.014 ft/ft and drainage areas from 0.7−30.5 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 prevented acquisition of 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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APPENDIX: SITE PHOTOS

Site 1 – Kings Branch at Patuxent River Road (Anne Arundel County)
Site 2 – Bell Branch at Bell Branch Road (Anne Arundel County)
Site 3 – Tributary to Little Patuxent River at Croften Parkway (Anne Arundel County)
Site 4 – Plum Creek at Old Harold Harbor Road (Anne Arundel County)
Site 5 – Cabin Branch 2 at Cedar Avenue (Anne Arundel County)
Site 6 – Whitemarsh Run at US-40 (Baltimore County)
Site 7 – Utility crossing Herring Run (Baltimore City)
Site 8 – Utility crossing Herring Run (Baltimore City)
Site 9 – Cocktown Creek at Warren Drive (Calvert County)
Site 10 – Island Creek at Ross Road (Calvert County)
Site 11 – Piney Branch at MD-488 (Charles County)
Site 12 – Hoghole Run at MD-6 (Charles County)
Site 13 – Hells Bottom Run at Bowling Drive (Charles County)
Site 14 – Gillber Swamp Run at Trinity Church Road (Charles County)
Site 15 – Denton Run at Dubois Road (Charles County)
Site 16 – Tributary to Trinity Church Run at North Ryceville Road (Charles County)
Site 17 – Gilbert Creek at Oaks Road (Charles County)
Site 18 – Haha Branch at MD-7 (Harford County)
Site 19 – Charles Branch at Crom Station (Prince George's County)
Site 20 – Piscataway Creek at Farmington Creek Road (Prince George's County)
Site 21 – Tributary to St. Marys River at Flat Iron Road (St. Mary's County)
Site 22 – Budds Creek at MD-234 (St. Mary's County)

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