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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

LONG-TERM BED DEGRADATION IN WESTERN MARYLAND STREAMS

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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. A total of 26 sites—15 bridges, 9 culverts, 1 utility crossing, and 1 concrete ford— in Garret, Allegany and Washington counties were selected for data collection. Drainage areas of these sites in the Appalachian Plateau, Ridge and Valley, and Blue Ridge physiographic provinces ranged from 1.5-55 mi^2. At 18 of the sites, LTBD was rapidly estimated using a pocket rod and hand level. At the 8 other sites, more detailed surveys were conducted using a theodolite and an electronic distance meter. The possibility of developing regional relations between watershed area and LTBD was evaluated for each physiographic province, but the data was inconclusive. Instead, six factors that may influence a site's risk of LTBD in the three western Maryland provinces were identified. These include (1) the valley slope, (2) the effective valley width, (3) discharge, (4) bed material size, (5) downstream channel entrenchment, and (6) downstream grade controls. Three relations between LTBD and these factors were examined: LTBD and valley slope; LTBD and an index combining Factors 1-3; 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 two 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 0.027 ft/ft. The development of rate relationships between LTBD was also considered. The analysis of data indicated only a weak correlation between LTBD and the age of the structure; however, the data was insufficient to develop a rate relation. Additional field data would be required to develop parameters and indices that would capture the influence of other identified factors. Future research on LTBD in Maryland should include some measure of channel entrenchment and the effectiveness of downstream bed controls in limiting degradation. The development of a rate relation should be explored further in future phases of this research.

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GLOSSARY AND ABBREVIATIONS

Variables

BMI Bed mobility index = τ_o/τ_c .....(Eq. 6 and 8)

D Estimated median size of the bed material (ft) ..... (Eq. 7)

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.

n Composite Manning *n* estimated for the effective valley width..... (Eq. 4)

Q_{100} The 100-year recurrence interval peak flow (cfs)..... (Eq. 4)

S Specific weight of the sediment..... (Eq. 7)

Sv Valley slope (ft/ft).....(Eq. 1, 2, 3, 4, and 9)

W_{fp} Effective valley width (ft)..... (Eq. 4)

Y_{100} Flood flow depth (ft) for Q_{100} .....(Eq. 3 and 4)

γ Unit weight of water (62.4 pcf) .....(Eq. 3 and 7)

τ_c Boundary shear stress required to mobilize the native bed material (psf).....(Eq. 6 and 7)

τ_o Boundary shear stress index (psf).....(Eq. 3, 5, 6 and 7)

Units of Measure

cfs Cubic feet per second

ft Feet

mi^2 Square miles

pcf Pounds per cubic foot

psf Pounds per square foot

Long-Term Bed Degradation in Western Maryland Streams

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 the 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 these 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 Hydraulics and Hydrology Division initiated a study to determine long-term bed degradation associated with MD streams. Due to funding limitations, the present study was limited to a few counties in western Maryland. The remaining parts of Maryland will be studied as funding becomes available.

The purpose of this study was to improve predictions of long-term bed degradation in Maryland streams. The study had five primary objectives:

1. Develop a database of field measurements of long-term bed degradation (LTBD).
2. Define the range of degradation depths to be expected in streams of the Ridge and Valley and the Appalachian Plateau physiographic provinces of Maryland.
3. Identify factors that may influence a site's risk (likelihood and magnitude) of LTBD.
4. Develop quantitative relations between the identified factors and measured long-term bed degradation.
5. Evaluate the possibility of developing a regional relation for LTBD by physiographic province.

The database and the relations between risk factors and LTBD would serve as a basis for decisions related both to design and planning projects involving foundations for waterway crossings and to mitigation projects involving stream restoration and/or stream stability. In foundation designs, the database would establish a baseline for evaluating reasonable values of degradation for use in designing shallower foundation depths with assurance, and thus it will save significant structure costs. 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

Data was collected in three western Maryland Counties: Garret, Allegany and Washington. These three counties contain all of the Maryland portion of the Appalachian Plateau and the Ridge and Valley physiographic provinces. Although the research team concentrated its field data collection on these provinces, data was also collected in the small section of the Blue Ridge province that lies within Washington County near its eastern border.

The Appalachian Plateau, Ridge and Valley, and Blue Ridge provinces of Maryland consist of a series of mostly parallel ridges and valleys formed from folded, fractured, and eroded rock. The Appalachian Plateau province is underlain by gently folded sedimentary rock consisting of shale, siltstone, and sandstone. Ridges in this province have elevations exceeding 3000 ft. Major streams and rivers in this province (Potomac River, Savage River, and Georges Creek) flow mostly parallel to the ridges, and tributaries flow perpendicular to these ridges, forming a trellis drainage network. The central and northeastern parts of this province are dissected by the Youghiogheny River and its tributaries, forming a dendritic drainage network.

The Ridge and Valley province contains strongly folded and fractured sedimentary rock. The eastern portion of this province is comprised of the Great Valley (approximately 17 mi wide), which extends from South Mountain of the Blue Ridge Province in the east to the first high ridge in the Ridge and Valley province to the west. Drainage networks in the Great Valley tend to have a block or dendritic pattern. Generally, small and steep tributary streams with drainage areas on the order of 1 mi^2 flow from and perpendicular to the ridge tops to main stem streams in relatively wide valleys. The much larger main stem streams then flow parallel to the ridges and valleys. Carbonate rocks are present in parts of the Great Valley and in some other valleys of this province. The western portion of the province consists of a series of parallel ridges and valleys, with the valleys generally getting narrower in the western direction. West of the Great Valley, the drainage network tends to have a trellis pattern, with small streams aligned perpendicular to the ridges and larger streams in the valleys aligned parallel to the ridges.

The Blue Ridge Province of Maryland is composed mainly of two high, discontinuous ridges—Catoctin Mountain on the east and South Mountain on the west—and between them, a valley containing minor dissected ridges [2]. The major ridges are composed of quartzite that is highly weather and erosion resistant. The broad valley is floored with gneiss and volcanic rock [2]. Most of the central and southern parts of the Blue Ridge province are dissected and drained by the headwaters of Catoctin Creek. The northern part of the province is dissected by smaller streams that join to form larger streams that have eroded through the main ridges to the east or west and flow into streams of the adjacent physiographic provinces.

3.0 METHODS

3.1 Site Selection

Initial Screening

Long-term bed degradation was defined as the vertical change in the channel profile other than that caused by local or contraction scour. All streams in the three western Maryland counties of

Allegany, Garrett, and Washington with contributing drainage areas between about 1 and 55 mi^2 were considered in the selection of a sample of at least 20 sites.

The research team expected that measurable (greater than 1 ft) LTBD could be identified where inspection reports mention foundation exposure or undermining, fish passage barriers, or exposure of utility crossing protection. Plan sheets for box culverts provide the elevation of the culvert outlet invert and the elevation of the downstream channel, and the depth to which the culvert may have been countersunk relative to the downstream channel. This plan information provides an accurate reference from which to measure changes in bed elevation. Changes in the channel invert elevation of more than 1 ft in repeated cross section measurements obtained by the USGS at their gage stations also can indicate measureable LTBD. Several sources of information were used to identify sites where LTBD near a culvert or bridge might be measureable:

- Bridge inspection reports
- Plan sheets for box culverts
- Phases I and II of Item 113 bridge inspection ratings
- Inspection reports for bridges or culverts known to have aquatic organism blockages
- USGS gage station records
- Utility line surveys
- Prior knowledge acquired by research team members and county engineers

This method of site screening proved to be inadequate for selection of more than a few sample sites. Information for many of the potential sites was not immediately available, and the information that was available was often insufficient to determine whether significant LTBD had occurred or was likely to have occurred. Therefore, field reconnaissance was the primary method used for site selection.

Field Identification

Field identification was effective because of the trellis pattern of drainage in the Appalachian Plateau, Ridge and Valley, and Blue Ridge physiographic provinces. At least one roadway parallels each main stem stream and often crosses the main stem stream several times. Also, many tributaries must cross the roadway before they confluence with the main stem stream. By driving along the valley roads, a large percentage of the bridges and culverts with contributing drainage areas between about 1 and 50 mi^2 could be examined rapidly. The research team biased its selection of stream valleys to be examined based on information received from the sources listed above.

In some very wide valleys—for example, in the region around Hagerstown—the drainage and roadway pattern were different. The density of roadways was typically higher in these areas, and the research team was able to locate and examine several roadway crossings for streams with drainage areas between 1 and about 25 mi^2.

Final Site Selection

A total of 26 sites—15 bridges, 9 culverts, 1 utility crossing, and 1 concrete ford—were selected for data collection (Table 1 and Figure 1). Drainage areas of sites in the Ridge and Valley and Allegheny Plateau provinces ranged from 1.7-55 mi^2, and drainage areas of sites in the Blue Ridge province ranged from 1.5-13.1 mi^2 (Figure 2).

Table 1. Long-Term Bed Degradation Estimates and Site Characteristics (This page is formatted to fit on 8½ x 14-inch paper.)

Sample No.	Structure No.	Yr Built/ Modified	Structure	Reference	County	Physiographic Province	Stream Crossing	Route	LTBD (ft)	Pre-Incision Bed Material	D (mm)	DA (mi^2)	S_v (ft/ft)	W_{fp} (ft)	Composite *n*	Q_{100} ft^3/s	Y_{100} (ft)	τ_c (psf)	τ_o (psf)	BMI
1	11006	1932	Bridge	Thalweg from plans	Garrett	AP	Big Shade Run	US 40 Alt	4.3	Medium gravel	16	4.5	0.0216	263	0.07	763	0.9	0.22	1.16	5.4
2	11027	1950	Culvert	Culvert outlet invert	Garrett	AP	Branch of Glade Run	MD 560	2.0	Fine gravel	4	2.9	0.0072	359	0.04	477	0.5	0.05	0.24	4.5
3	11010	1933	Bridge	Top of foundation	Garrett	AP	Buffalo Run	MD 42	0.0	Coarse gravel	32	7.1	0.0110	200	0.10	1,110	1.9	0.43	1.34	3.1
4	11045	1973	Culvert	Culvert outlet invert	Garrett	AP	Buffalo Run	IS 68	3.0	Coarse gravel	32	5.5	0.0163	185	0.07	904	1.3	0.43	1.31	3.0
5	1018 (Barton 1)		Bridge	Top of foundation	Allegany	AP	Butcher Run	935	3.1	Very coarse gravel	64	2.2	0.0914	72	0.07	436	0.9	0.86	4.97	5.8
6	11023	1922	Bridge	Thalweg from plans	Garrett	AP	Cherry Creek	US 219	2.9	Fine gravel	4	12.9	0.0038	760	0.07	1,700	1.3	0.05	0.30	5.6
7	Utility Crossing (Barton 2)		Utility	Existing stream bed	Allegany	AP	Georges Creek		4.9	Very coarse gravel	64	55.3	0.0174	156	0.07	7,160	4.8	0.86	5.21	6.0
8	11009	1933	Bridge	Top of foundation	Garrett	AP	Glade Run	MD 42	3.0	Very coarse gravel	64	3.1	0.0190	40	0.05	509	1.8	0.86	2.14	2.5
9	1006	1996	Bridge	Thalweg from plans	Allegany	AP	Jennings Run	MD 36	3.1	Very coarse gravel	64	14.2	0.0103	231	0.06	2,190	2.0	0.86	1.27	1.5
10	Private driveway		Bridge	Existing stream bed	Allegany	AP	Jennings Run	Off MD 36	4.0	Very coarse gravel	64	14.3	0.0213	170	0.07	2,210	2.1	0.86	2.81	3.3
11	Proenty		Bridge	Top of foundation	Allegany	AP	Jennings Run	Proenty Rd	6.4	Very coarse gravel	64	36.2	0.0270	136	0.07	4,990	3.7	0.86	6.18	7.1
12	Mt Savage US		Bridge	Top of foundation	Allegany	AP	Jennings Run (above confluence)		5.1	Very coarse gravel	64	5.3	0.0221	48	0.07	932	2.7	0.86	3.68	4.2
13	Mt Savage DS		Bridge	Top of foundation	Allegany	AP	Jennings Run (below confluence)		5.3	Very coarse gravel	64	13.0	0.0175	48	0.07	2,010	4.5	0.86	4.96	5.7
14	G-13		Bridge	Top of foundation	Garrett	AP	Snow Creek	Crellin-Underwood Rd	3.0	Small gravel	8	4.9	0.0014	610	0.07	723	1.2	0.11	0.10	1.0
15	RR culvert at Water Station Run		Culvert	Culvert outlet invert	Allegany	AP	Waterstation Run		4.0	Coarse gravel	32	2.1	0.0159	100	0.10	411	1.4	0.43	1.43	3.3
16	11/07		Bridge	Existing stream bed	Washington	BR	Israel Creek	Keep Tryst Rd	4.0	Very coarse gravel	64	13.1	0.0260	50	0.07	5,500	6.9	0.86	11.15	12.9
17	07/19		Culvert	Culvert outlet invert	Washington	BR	Little Antietam Creek	Hells Delight	6.0	Very coarse gravel	64	1.5	0.0566	50	0.10	1,400	3.0	0.86	10.46	12.1
18	07/11		Culvert	Culvert outlet invert	Washington	BR	Little Antietam Creek	Pleasant Valley Rd	2.0	Cobble	128	1.6	0.0478	70	0.10	1,410	2.6	1.73	7.64	4.4
19	21072	1959	Culvert	Culvert outlet invert	Washington	BR	Trib of Little Antietam Creek	MD 67	6.0	Medium gravel	16	2.3	0.0256	40	0.10	1,220	4.0	0.22	6.39	29.5
20	21032	1932	Ford	Concrete ford	Washington	R&V	Beaver Creek	MD 66	4.0	Medium gravel	16	6.7	0.0126	46	0.04	1,390	2.9	0.22	2.26	10.4
21	1068	2008	Bridge	Existing stream bed	Allegany	R&V	Branch of Wills Creek	MD 35	0.0	Very coarse gravel	64	2.0	0.0176	192	0.05	402	0.6	0.86	0.68	0.8
22	W-6061C (Dog Creek)	1958	Culvert	Culvert outlet invert	Washington	R&V	Dog Creek	Amasi-Reeder Rd	1.0	Coarse gravel	32	2.7	0.0120	570	0.07	1,850	1.0	0.43	0.78	1.8
23	1003	1930	Bridge	Thalweg from plans	Allegany	R&V	Jennings Run	MD 831C	0.0	Very coarse gravel	64	37.9	0.0080	622	0.07	5180	2.2	0.86	1.08	1.3
24	1004	1985	Bridge	Thalweg from plans	Allegany	R&V	Jennings Run	MD 36	0.0	Very coarse gravel	64	37.7	0.0080	622	0.07	5,180	2.2	0.86	1.08	1.3
25	21024	1950	Culvert	Culvert outlet invert	Washington	R&V	Marsh Run	MD 60	3.0	Medium gravel	16	29.6	0.0029	120	0.07	2,960	5.6	0.22	1.02	4.7
26	21070	1965	Culvert	Culvert outlet invert	Washington	R&V	Munson Spring Branch	IS 68	2.2	Coarse gravel	32	1.7	0.0078	220	0.10	317	1.0	0.43	0.47	1.1

Note: Parameters denoted by symbols/abbreviations are defined in the glossary.

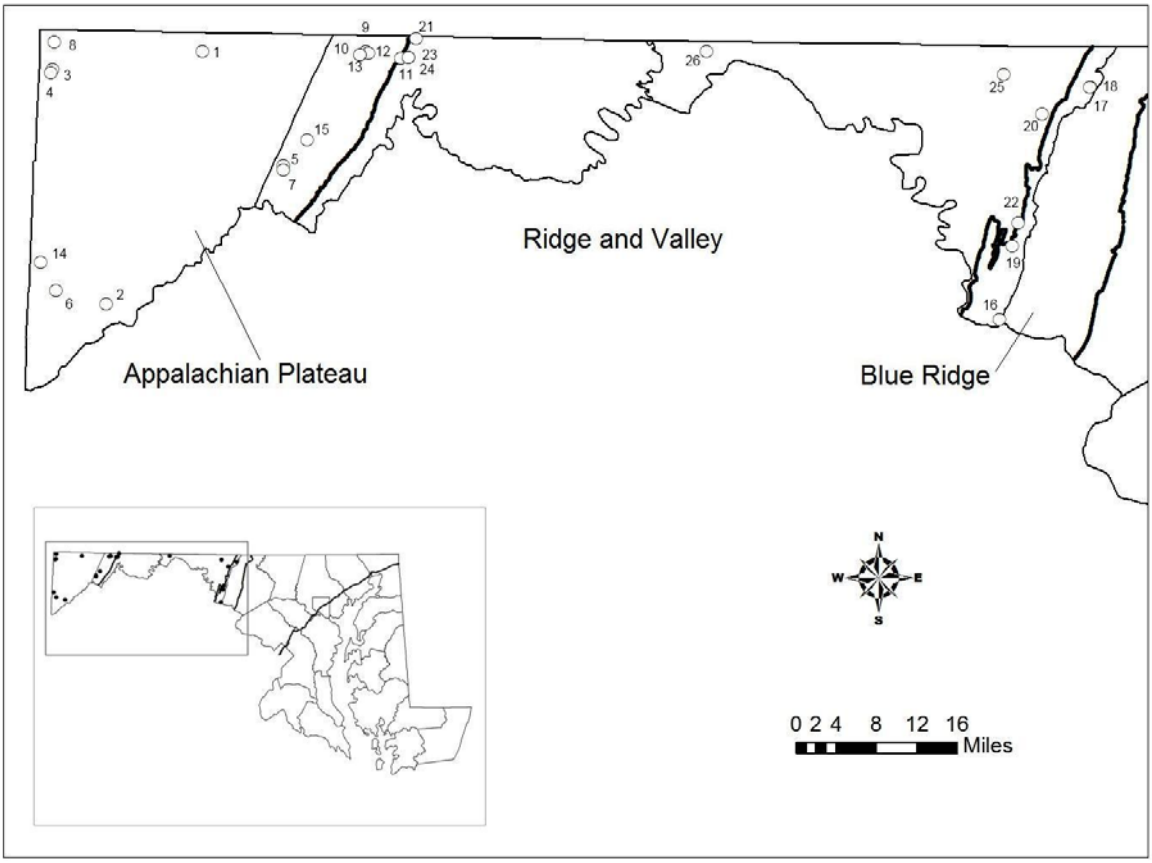

Figure 1. Sample site locations. Bold lines represent physiographic province boundaries.

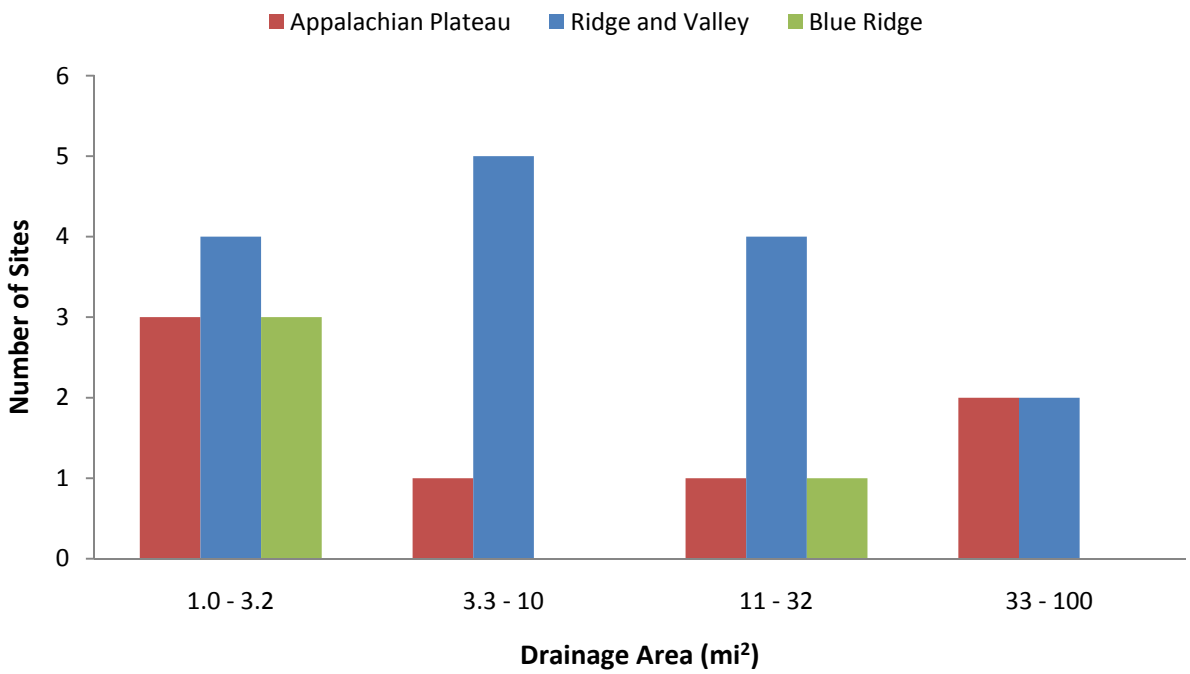

Figure 2. Distribution of sampling sites according to watershed drainage area and physiographic province.

3.2 Data Collection

At 18 of the sites, LTBD was rapidly estimated using a pocket rod and hand level. At the 8 other sites, more detailed surveys were conducted using a total station, an optical survey device that combines a theodolite and an electronic distance meter. The decision to conduct detailed surveys at these sites was based on the need for data along the channel profile to develop an accurate estimate of LTBD. At some locations, both rapid and detailed measurements were made. In general, the estimates developed from rapid measurements were within 0.5 ft of the estimate based on detailed measurements. Where degradation estimates were made over distances of more than 50 ft and the degradation was greater than 4 ft, the difference in rapid and detailed measurements was as much as 1.5 ft.

Channel Morphology

Rapid Measurement

At some locations, the vertical drop at the outlet of the structure could be measured simply and accurately with a pocket rod and a hand level. These rapid measurements were conducted where a step, a series of steps, or a steep section or riprap-protected streambed occurred at the outlet of a culvert or a bridge with a paved or riprap-protected invert or paved or riprap-protected downstream apron. The distance from the paved or riprap-protected invert to the low-flow water surface at the downstream side of the structure (Figure 3) was used as an estimate of LTBD. The outlets and protected inverts were constructed at about the same elevation as the bed of the channel at the time of construction. Because these structures provide effective grade control for the channel, preventing further upstream migration of degradation from downstream impacts, their elevations are good estimates of the initial streambed elevation (i.e., the elevation at the time of construction).

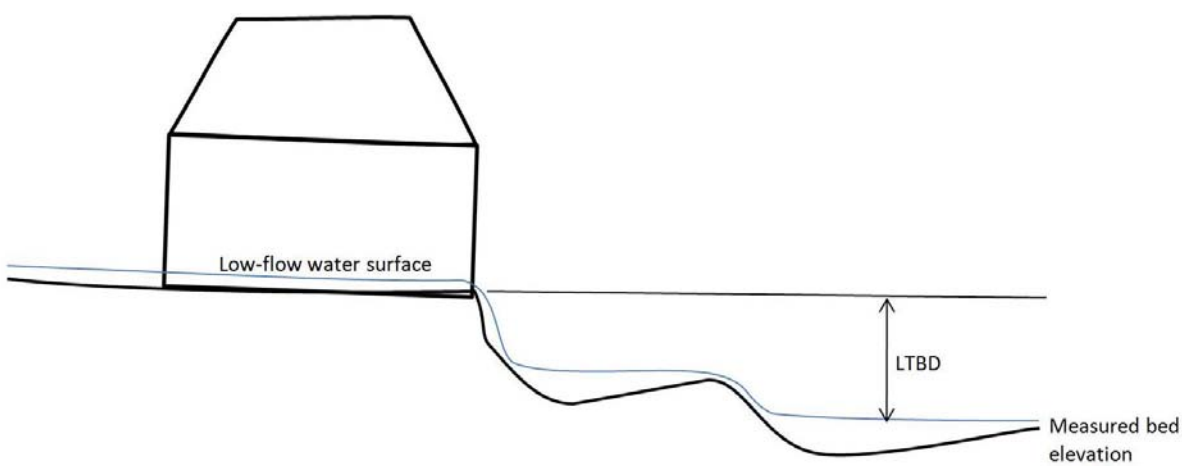

Figure 3. Typical bed profile of a culvert with downstream bed degradation and a scour pool.

Detailed Measurement

Surveys using total stations were conducted at one utility crossing and at bridges where evidence of the degradation extended over a series of several steps or a combination of steps and steep slopes. A thalweg survey was conducted at the utility crossing. At the bridges, a thalweg profile, the top surface of exposed bridge abutment footings or pier footings, a cross section at the downstream face of the structure, and reference elevations on the structure were surveyed. The thalweg survey was extended downstream of the structure to measure any steps or very steep

riffles made of riprap or other channel protection where the change in bed elevation over the step or riffle was more than about 0.5 ft. Where bridge footings were not exposed, bridge plans indicating an initial bed level were not available, and the slope was relatively constant with no steep local drops, LTBD could not be estimated; these sites were not included in the study. In some cases, a survey of the downstream channel thalweg was required to capture the transition between a series of steps and the channel slope downstream of the steps. In most cases, steep local drops were present, and thalweg surveys were relatively short (50 to 100 ft). At sites with stream slopes greater than 1.5%, the thalweg survey was extended upstream of the structure approximately 100 ft to determine the approach channel slope to the structure and to examine the difference between the approach channel slope and the channel slope downstream of the structure.

Bed Material

The streambed material at each site was visually assessed. If bar material was present, the bar material and the material armoring downstream riffles were assessed separately. The dominant bed material was identified as belonging to one of six categories: bedrock, boulder, cobble, coarse gravel, medium gravel, or fine gravel.

3.3 Data Reduction and Analysis

Estimation of LTBD

Culverts

The inverts of culverts constructed after 1975 may have been countersunk below the streambed to support fish passage. At these sites, determination of the initial bed elevation would require review of the culvert construction plans. Culverts at the sites used in this study were determined to have been constructed prior to 1975 based on construction dates imprinted in the structure or by estimated age of woody vegetation that grew on the embankment around the culverts. Before about 1975, Maryland culverts were constructed such that the outlet invert was set approximately at the bed elevation of the channel. Because these culverts provide effective grade control for the channel, preventing further upstream migration of degradation from downstream impacts, the culvert outlet invert is a good estimate of the streambed elevation at the time of culvert construction.

The research team considered the culvert outlet invert at the time of observation to be a good representation of the initial channel bed elevation. LTBD was estimated as the difference between the culvert outlet invert elevation and the riffle crest elevation downstream of the culvert. Where surveys were not extended to the downstream riffle crest, the low-flow water surface elevation was considered to be an estimate of the downstream riffle thalweg elevation because flow depth at the riffle crest was shallow during data collection, and the low-flow water surface was essentially level during measurement.

At some culverts, one drop in bed elevation occurred immediately downstream of the culvert, and a second drop formed downstream of riprap or other materials placed within 50 ft of the culvert to prevent degradation (see Figure 3). Estimates of LTBD were developed by summing the measured drops that occurred in the riprap.

Bridges

Reference bed elevations on bridge plans are required for definitive estimates of channel degradation. Bridge plans often provide a channel cross section that shows the elevation of the streambed within the bridge opening. For bridge sampling sites for which plans were obtained, LTBD was estimated as the difference between the thalweg elevation provided in the plans and the existing riffle crest elevation or water surface elevation downstream of the structure (Figures 4-7). Few sites that were selected had bridge plans, however. For those few sites, the elevation of the thalweg was at or within approximately 1 ft of the top surface of the abutment footing elevation. Therefore, at other sites where bridge plans were not available but the footings were exposed, the top surface of abutment and pier footings was used as a reference elevation from which to measure LTBD. Where plans did not exist and foundations were not exposed, the existing low-flow water surface elevation at the downstream face of the structure was used as the reference surface from which to measure LTBD.

A variety of channel profiles were observed at bridges. Figure 4 shows a channel profile where bed degradation has propagated through the bridge opening without indications in the channel bed. Exposure of the bridge foundations and signs of channel incision in the upstream and downstream channel indicated that the streambed had degraded. LTBD was measured at one site using a rapid measurement technique where this type of profile was observed. At that site, no bridge plans were available. LTBD was estimated as the elevation difference between the top of the exposed foundation and the low-flow water surface.

At many other bridges, riprap protection was placed on the streambed at the time of construction or later. The riprap protection appeared to act as grade control, stalling the upstream migration of channel degradation and contributing to the formation of a profile similar to that shown in Figure 5. The partial failure of the riprap and displacement of the riprap downstream formed a series of two or more drops in the channel profile (Figure 6). Where no foundations were exposed, LTBD was estimated to be the elevation change in the downstream steps, as shown in Figure 5. The elevation change was measured as the difference in the low-flow water surface elevation controlled by the existing channel bed protection at the bridge and the low-flow water surface elevation downstream of the steps in the profile. Where foundations were exposed and were above the low-flow water surface elevation, the top surface of the foundations was used as the upper reference elevation to measure LTBD rather than the low-flow water surface at the bridge. At bridge sampling sites, plans with indications of a thalweg elevation at the bridge were available at 5 sites, the top surface of exposed foundations were used as references at 7 sites, and the existing low-flow water surface controlled by channel protection was used as a reference at 3 sites.

Utility Crossings

LTBD was estimated at one utility line crossing of Georges Creek near Barton. The concrete protection of the utility line provided a grade control that prevented upstream migration of a headcut in bedrock. The research team considered the step in the profile at the utility crossing to be the LTBD since the construction of the protection.

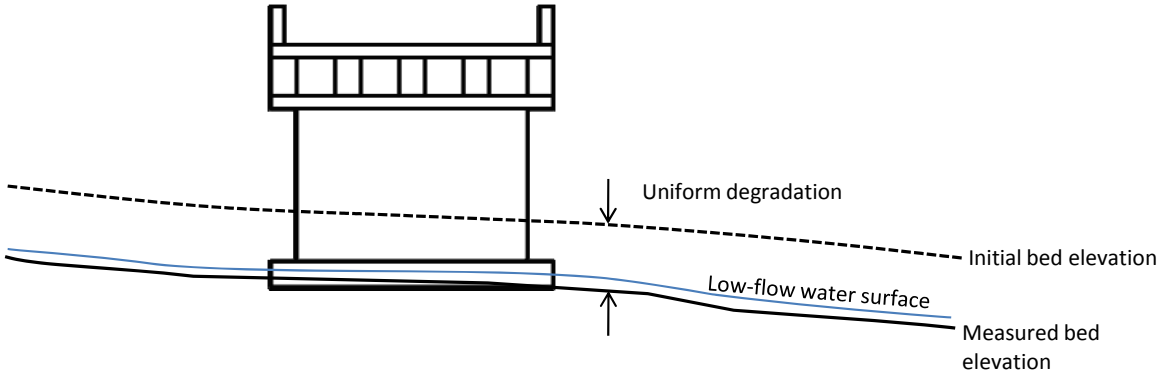

Figure 4. LTBD: uniform degradation.

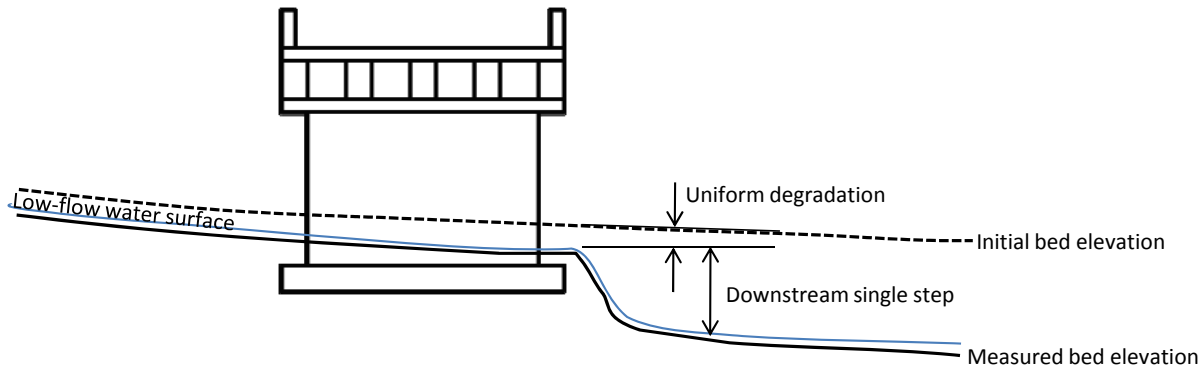

Figure 5. LTBD: uniform degradation and single step downstream.

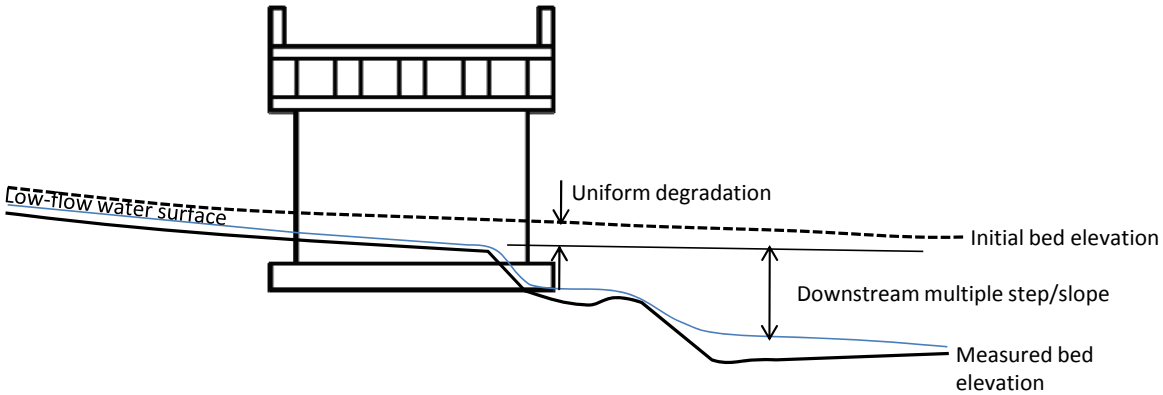

Figure 6. LTBD: uniform degradation and multiple steps downstream.

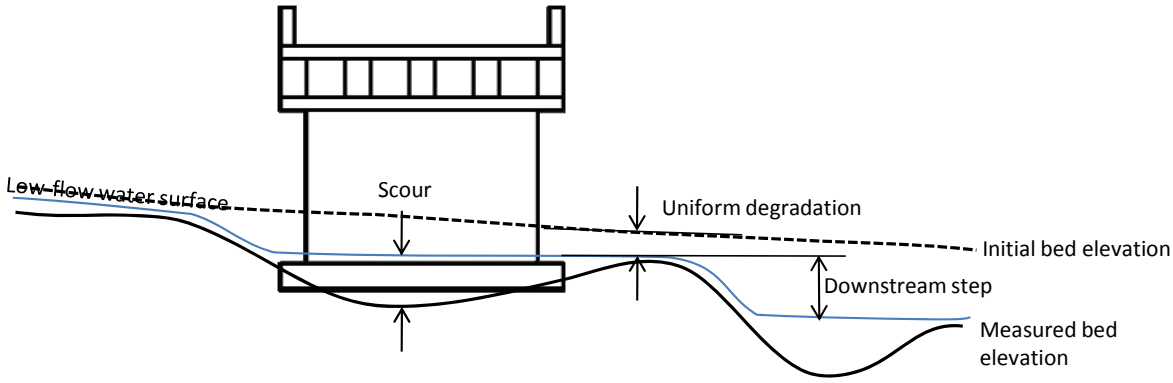

Figure 7. LTBD with scour: uniform degradation and multiple steps downstream.

Watershed Area and 100-Year Peak Discharge Estimate

Watershed areas were delineated and 100-year recurrence interval peak flow discharges were estimated for each site using the web-based version of GISHydro2000 [3]. Watershed areas were delineated using 30-meter national elevation data [4]. Peak discharges for the 100-year recurrence were estimated for each site using the Fixed Region equations [5]. Watershed runoff characteristics were based on STATSGO soils data [6] and either 2002 Maryland land use data [3] for watersheds located entirely within Maryland or 1970s USGS land use data [3] for watersheds that extended into Pennsylvania.

4.0 RESULTS

Observed LTBD ranged from negligible (less than 1.0 ft) to a maximum of 5 ft in the Ridge and Valley and approximately 6 ft in the Appalachian Plateau and Blue Ridge provinces.

Risk Factors

To determine factors that could increase the risk of LTBD (Table 2), each sample site was examined in the field and on aerial photographs. Because many sites did not have significant (less than 1 ft) LTBD, a list of factors that may reduce the risk of LTBD was also developed.

Table 2. Factors That Potentially Influence LTBD

Factor	Increased Risk	Reduced Risk
1. Valley slope	Steep valley slope.	Mild valley slope.
2. Effective downstream valley width	Constriction of downstream valley by obstruction, walls or an embankment.	Unrestricted downstream valley width approximately equal to total valley width.
3. Discharge	Increased 100-yr discharge	Decreased 100-yr discharge
4. Bed material	Size small relative to bed stresses.	Size large relative to bed stresses.
5. Downstream channel entrenchment	Downstream channelization including widening, deepening, and straightening of channel.	Lack of obvious channelization; often associated with natural valley geometry, such as a meandering valley, that limits potential channel reconfiguration.
6. Downstream grade controls	Lack of durable downstream grade control including degradation of bedrock.	Dams, culverts, or bedrock downstream providing grade control.

The primary focus of the field data collection effort was to obtain measurements of LTBD. This data provided the information necessary to examine the relation between watershed area and LTBD in each physiographic region. The field data in combination with readily available mapping data was also sufficient to examine the relation between LTBD and Factors 1, 2, 3, and 4. Additional field data would be necessary to evaluate the remaining factors.

Land use could potentially influence LTBD as well, but the effects of large impervious areas and other land use modifications associated with urbanization were not examined in this study. Less than 10% of the watershed area was impervious in the watersheds contributing flow to the sites selected. The land-use parameters are provided in Table 3.

Table 3. Land Use [3]*

Sample No.	Structure No.	County	Watershed Area (mi^2)	Land Use Coverage	Soil Coverage	Forested Area (%)	Urban Area (%)	Impervious Area (%)
1	11006	Garrett	4.5	1970s USGS	SSURGO	68.7	0.7	0.3
2	11027	Garrett	2.9	1970s USGS	SSURGO	44.3	0.0	0.1
3	11010	Garrett	7.2	1970s USGS	SSURGO	55.7	0.0	2.0
4	11045	Garrett	5.5	1970s USGS	SSURGO	55.5	0.0	2.2
5	1018 (Barton 1)	Allegany	2.2	2002 MD/DE	STATSGO	45.6	1.8	1.5
6	11023	Garrett	12.9	1970s USGS	SSURGO	41.6	0.0	0.0
7	Utility Crossing (Barton 2)	Allegany	55.3	2002 MD/DE	STATSGO	72.4	8.4	4.3
8	11009	Garrett	3.1	1970s USGS	SSURGO	54.9	0.2	0.1
9	1006	Allegany	14.2	1970s USGS	SSURGO	80.9	6.8	3.4
10	Private driveway	Allegany	14.3	2002 MD/DE	STATSGO	71.9	12.3	4.4
11	Proenty	Allegany	36.2	1970s USGS	SSURGO	83.6	3.3	1.6
12	Mt Savage US	Allegany	5.3	2002 MD/DE	STATSGO	78.2	6.6	2.3
13	Mt Savage DS	Allegany	13.0	2002 MD/DE	STATSGO	74.8	12.1	4.2
14	G-13	Garrett	4.9	2002 MD/DE	STATSGO	28.7	13.1	3.7
15	RR culvert at Water Station Run	Allegany	2.1	2002 MD/DE	STATSGO	72.4	4.2	3.1
16	11/07	Washington	13.1	2002 MD/DE	STATSGO	58.0	14.1	3.7
17	07/19	Washington	1.5	2002 MD/DE	STATSGO	57.1	15.9	4.1
18	07/11	Washington	1.6	2002 MD/DE	STATSGO	58.4	15.9	4.1
19	21072	Washington	2.3	2002 MD/DE	STATSGO	45.9	12.2	3.3
20	21032	Washington	6.7	2002 MD/DE	STATSGO	45.7	28.0	9.7
21	1068	Allegany	2.0	2002 MD/DE	STATSGO	54.2	2.8	1.0
22	W-6061C (Dog Creek)	Washington	2.7	2002 MD/DE	STATSGO	65.0	6.1	1.6
23	1003	Allegany	37.9	1970s USGS	SSURGO	83.1	3.7	1.8
24	1004	Allegany	37.7	1970s USGS	SSURGO	83.1	3.6	1.7
25	21024	Washington	29.6	2002 MD/DE	STATSGO	1.7	2.8	1.4
26	21070	Washington	1.7	2002 MD/DE	STATSGO	70.9	7.3	1.8

* Forested, urban, and impervious areas were obtained from GIS Hydro [3].

Physiographic Province and Watershed Size

Data for the Appalachian Plateau indicate an increase in the observed LTBD for increases in watershed area (Figure 8). The data from the other two physiographic regions, however, indicate an opposite trend. The dataset for each region is too small to draw a reliable conclusion about a relationship between LTBD and watershed area.

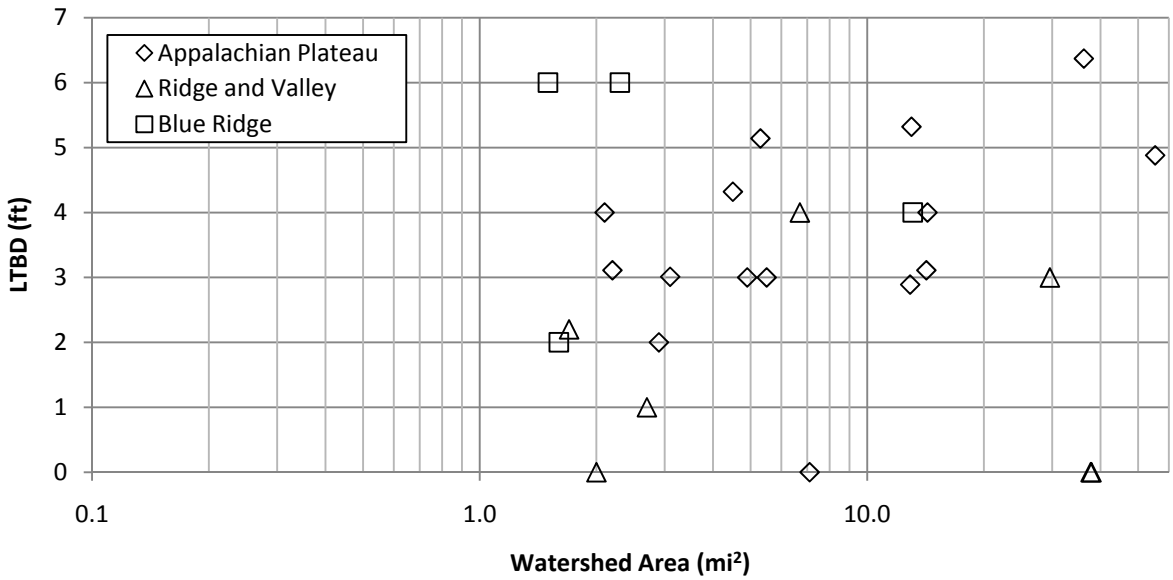

Figure 8. Variation of LTBD with watershed area for each physiographic province.

Valley Slope

The data from the Appalachian Plateau and the Ridge and Valley (Figure 9) indicate that the LTBD was limited to about 3 ft for valley slope of less than 0.01 ft/ft and rapidly increases from 3.1 ft to 6.4 ft in the range of slopes between 0.01 and 0.027 ft/ft. Although measured LTBD remained at or below 6 ft for the three sites where valley slopes were greater than 0.027 ft/ft, the dataset for slopes above 0.027 ft/ft is too small to be conclusive.

A conservative upper limit curve that describes the observed LTBD as a function of valley slope (S_v) based on the data from all three provinces is

$$\text{LTBD (ft)} = 3 \text{ ft for } S_v < 0.01 \text{ ft/ft} \quad (1)$$

$$\text{LTBD (ft)} = -11300\,(S_v)^2 + 615\,(S_v) - 2.0 \text{ for } 0.01 \text{ ft/ft} < S_v < 0.027 \text{ ft/ft} \quad (2)$$

LTBD measurements are inadequate to predict LTBD for valley slope greater than 0.027 ft/ft.

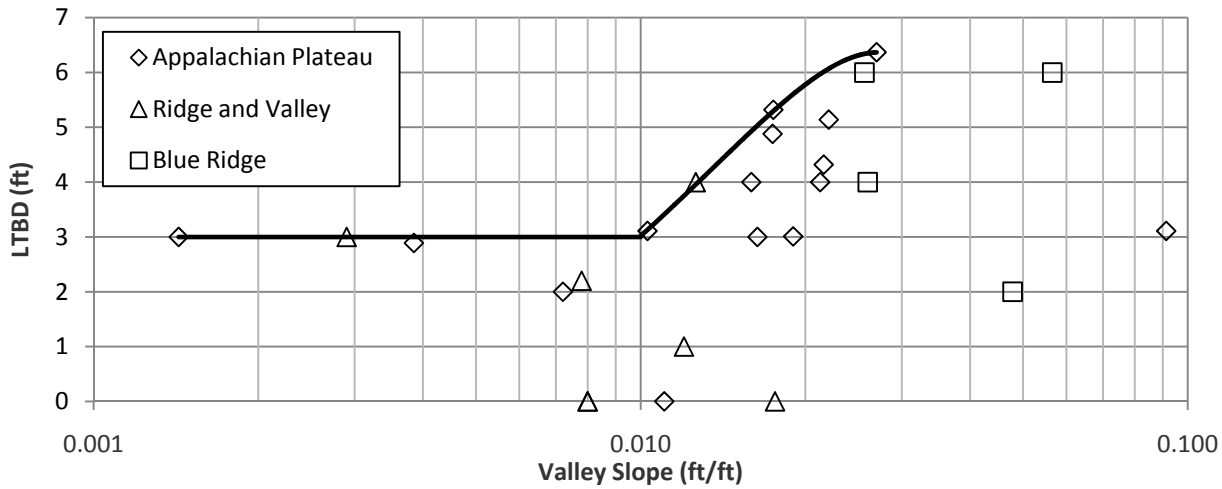

Figure 9. LTBD as a function of valley slope.

LTBD versus Boundary Shear Stress Index

A boundary shear stress index (τ_o) was developed to include the effect of valley slope, valley confinement, and the potential discharge that could be produced by each sample site drainage area for all three provinces. The τ_o (psf) was defined as

$$\tau_o = \gamma\ Y_{100}\ S_v \qquad (3)$$

where γ is unit weight of water (62.4 pcf), S_v is the valley slope (ft/ft), and Y_{100}, flood flow depth (ft), is given by

$$Y_{100} = [(Q_{100}\ n)/(1.49\ W_{fp}\ S_v^{0.5})]^{0.6} \qquad (4)$$

where Q_{100} is the 100-year recurrence interval peak flow obtained from GISHydro [3] using the Fixed Region equations [5], W_{fp} is the effective valley width (ft), and n is the composite Manning n estimated for the effective floodplain width. One value of n representative of the roughness of the effective valley width downstream of the structure was used at each site. The effective valley width was measured using contours available from 7.5-minute USGS topographic maps and an examination of floodplain obstructions and channelization observed during site visits and examination of the most recent aerial photographs obtained from Google Earth. The effective floodplain width, W_{fp}, was determined from the measured minimum width of the floodplain unobstructed by embankments or structures or, where channelization was apparent, from the width of the widened and deepened channel. The valley slope, S_v, was estimated from the two closest contours shown on USGS 7.5-minute topographic maps downstream of the structure: the change in elevation between the two contours was divided by the distance between them as measured on the map.

A conservative upper limit curve (Figure 10) that describes the LTBD as a function of τ_o is

$$\text{LTBD} = 1.87\ \text{Log}_{10}\ (\tau_o) + 4.73 \qquad (5)$$

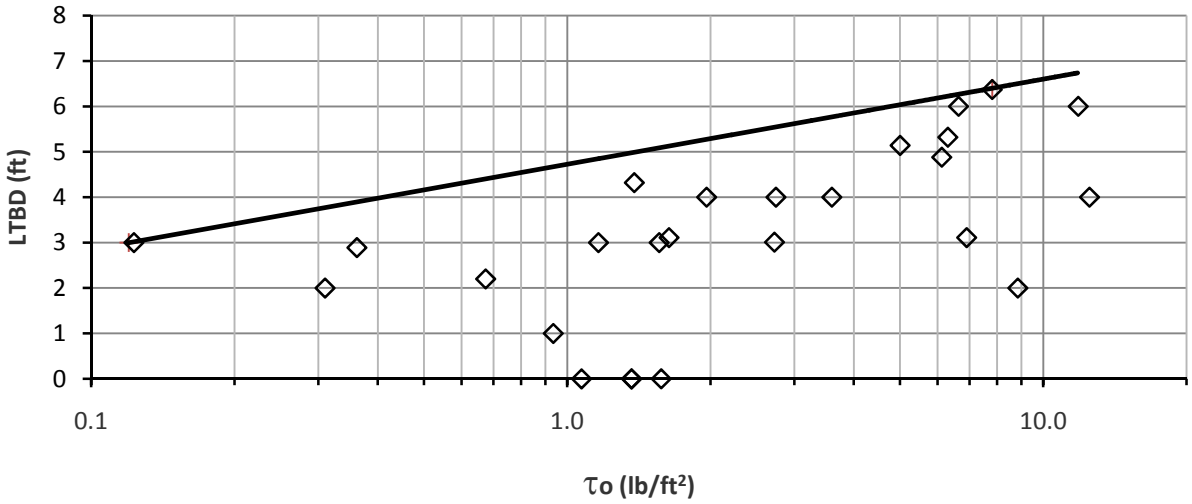

Figure 10. Conservative upper limit of LTBD as a function of τ_o.

This equation was developed for 0.12 psf < τ_o < 12 psf. The LTBD measurements are inadequate to predict LTBD for τ_o greater than 12 psf.

Bed Mobility Index versus LTBD

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

$$BMI = \tau_o/\tau_c \quad (6)$$

where τ_c is the boundary shear stress required to mobilize the native bed material and is defined as

$$\tau_c = 0.04\ (S-1)\ \gamma\ D \quad (7)$$

where S is the specific weight of the sediment, γ is unit weight of water (62.4 pcf), and D is the estimated median size of the bed material. Calculation of a BMI for each sample site required an estimate of τ_c from Equation 7 for each site. Therefore, an estimate of the specific weight of the bed material and an estimate of bed material grain size at each site was required. A constant specific weight of 2.65 was used for all bed materials. A median bed material class (Table 4), which excluded placed rock protection, was visually estimated on site or from photographs obtained during site visits. The characteristic size for the median bed material class was assigned according to Table 4 to provide an estimate of D in Equation 7. The BMI for each site was then computed from the estimate of τ_c and an estimate of τ_o from Equation 3.

Table 4. Bed Material Classification

Bed Material Class	Grain Size (mm)
Fine gravel	4
Small gravel	8
Medium gravel	16
Coarse gravel	32
Very coarse gravel	64
Cobble	128

A plot of BMI versus LTBD data is shown in Figure 11. The plot shows a trend of increasing LTBD with increasing BMI for 1.1 < BMI < 9. A conservative upper limit curve that describes the LTBD as a function of BMI is

$$LTBD = 3.68 \log_{10} (BMI) + 2.8 \quad (8)$$

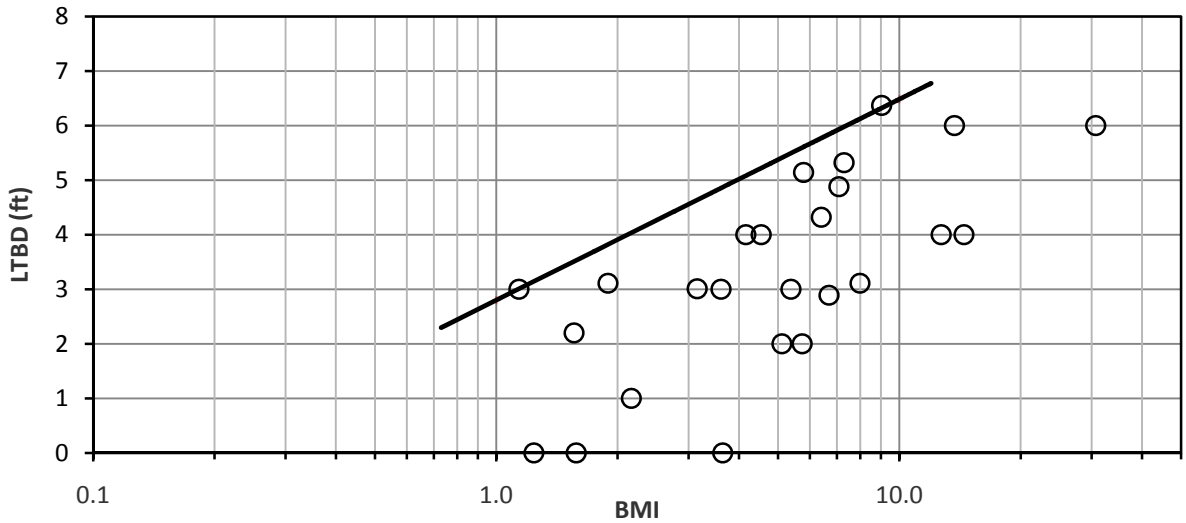

Figure 11. LTBD as a function of the bed mobility index.

Structure Age versus LTBD

The relationship between the age of the structure and LTBD was examined (Figure 12) 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 could confirm the age of only 15 structures. The data for these structures shows only a weak correlation of LTBD with age, as shown in Figure 12. Given this weak correlation and the small number of observations, the team did not pursue development of a rate relation. The data set is inadequate to develop a reliable rate relationship.

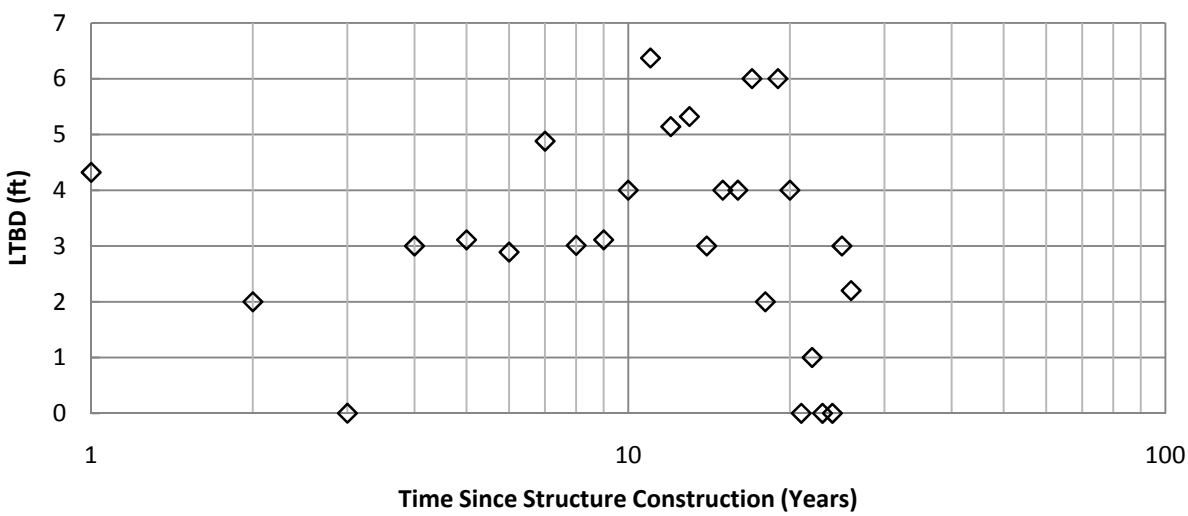

Figure 12. Variation of LTBD with structure's age.

Comparison of LTBD Equations

The observed values of LTBD and corresponding predicted values from Equations 1, 2, 5 and 8 are plotted with a line of perfect agreement in Figure 13. The residuals, difference between predicted and observed, are shown in Figure 14. The predicted and observed values for slope values greater than 0.027 ft/ft were excluded from the plot for Equations 1 and 2 because of the equation limitations stated above. Observed and predicted values for all data are included for Equations 5 and 8. Linear regression was performed on the residuals to compare equations.

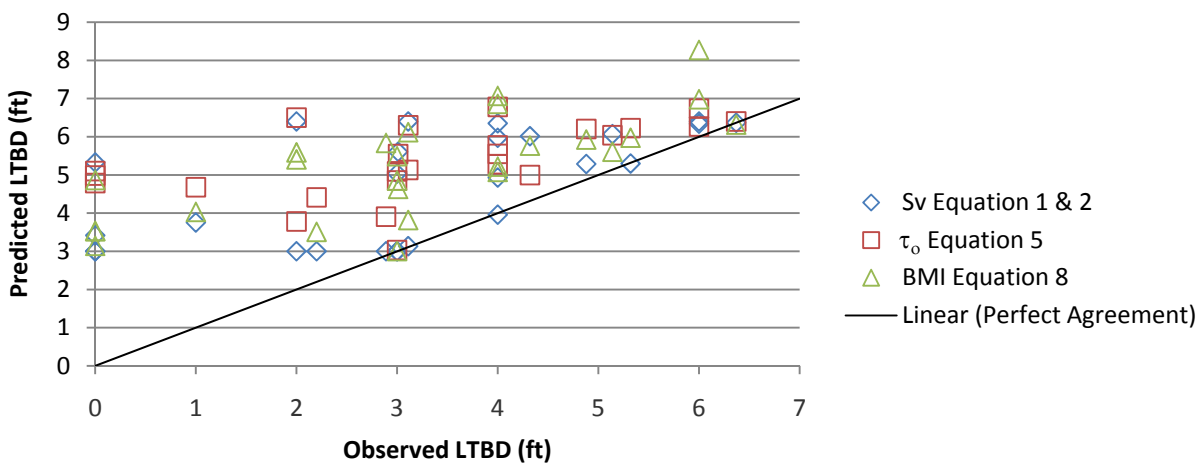

Figure 13. Comparison of predicted LTBD values and observed LTBD.

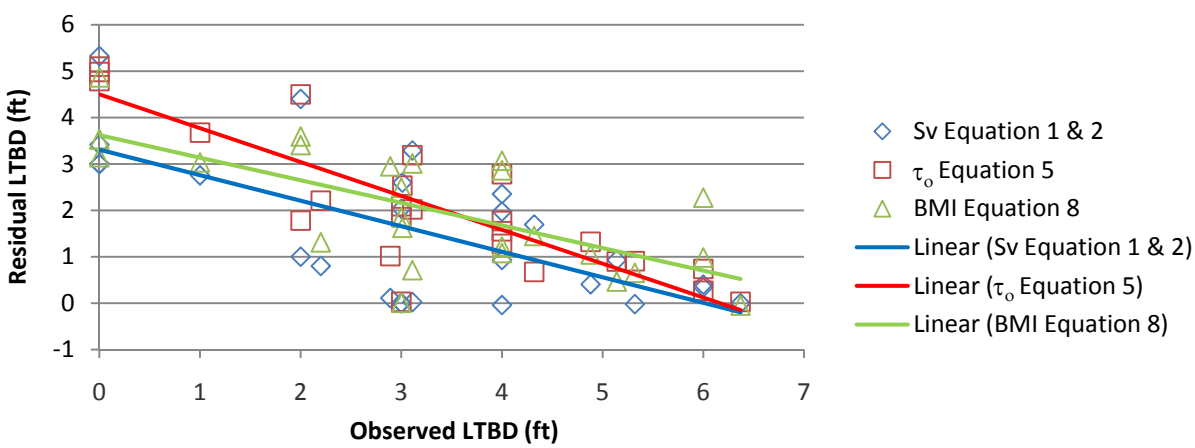

Figure 14. Comparison of residual LTBD values and observed LTBD.

The residuals for all equations show a similar trend of decreasing residual with increased observed LTBD. On average, the combination of Equation 1 and 2 have the lowest residuals for observed values of less than 4 ft. Equation 5 has marginally lower residuals for observed values greater than 4 ft.

Given the simplicity of using valley slope obtained from topographic maps and the lack of improvement in the prediction of observed LTBD values by Equations 5 and 8, Equations 1 and 2 are recommended for use in assessing LTBD on streams with slopes of less than 0.027 ft/ft.

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 Allegany, Garrett, and Washington counties. This includes the entire Appalachian Plateau, the Ridge and Valley Provinces and the part of the Blue Ridge Province contained in Washington County. **Until further study has been completed, however, the research team recommends that use of these equations be limited to non-entrenched channels that have no evidence of existing bed degradation problems**. The team has defined non-entrenched channel to be those that flood their adjacent floodplain for flow events smaller than the 2-year recurrence interval peak flow. The peak flow should be defined by Fixed Region equations [5] as applied in GIS Hydro [3].

The equations in this report should not be used for entrenched channels or those already experiencing channel degradation problems. The value of LTBD may be substantially greater than those given in this study for stream channel networks already experiencing significant LTBD or that have been entrenched through dredging, channelization, or other means. Efforts should be made to determine whether bed degradation problems exist on a stream. Indicators may include perched culverts, exposed utility crossings, exposed bridge foundations, and/or channel head cuts. This evidence may not exist on all streams so the team recommends that all sites be evaluated for entrenchment as well. Entrenched channels are defined here as those that contain a 2-year or greater recurrence peak flow without flooding the adjacent floodplain. For entrenched channels and those with existing channel degradation problems, an LTBD assessment should be completed in accordance with the procedures in Chapter 14 of Maryland's *Hydrology and Hydraulics Manual* [1].

The effects of large impervious areas and other land use modifications associated with urbanization were not examined in this study. The percent impervious was less than 10% in the watersheds contributing flow to the sites selected. Therefore the equations developed in this study should be applied only to streams where less than 10% of the contributing watershed's surface area is impervious.

A channel should be evaluated as follows for signs of degradation and/or entrenchment 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 bed degradation problems.

4. Obtain a cross section downstream and beyond the hydraulic influence of the bridge, and compute the 2-year recurrence interval peak flow from GISHydro. Use HEC-RAS or another simple uniform flow calculator to determine whether the 2-year event is contained within the channel. If the 2-year peak flow is contained within the channel, then the channel is entrenched.

If any of these evaluations indicate that the channel is entrenched and/or degrading, or if the channel slope is greater than 0.027 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 of existing degradation problems in the stream system and is not entrenched, then the LTBD equations may be used as follows:

1. Compute the valley slope, S_v, at the structure from a USGS 7.5-minute quadrangle map. The slope should be computed from the distance along the channel between the nearest two topographic contours that intersect the channel: one upstream and one downstream of the structure. The valley slope should be calculated as

$$S_v = \text{(distance between contours)/(contour inverval)} \tag{9}$$

2. Use Equations 1 and 2 from this study to estimate LTBD.

The LTBD values computed by Equations 1 and 2 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 Equations 1 and 2. Two factors that could be used to reduce the values obtained in Equation 2 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 Equations 1 and 2. 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 Equations 1 and 2. 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 Equations 1 and 2. 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 Equations 1 and 2 and the additional site-specific information.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Field Data Collection

A database of 26 field measurements of LTBD was developed for Allegany, Garrett, and Washington counties. These measurements were adequate for the intended purpose of providing a range of LTBD observed in the three counties. 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 either the top surface of the foundations or 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.

Regional Relation

The possibility of developing regional relations between watershed area and LTBD was evaluated for each physiographic province. The data for the Appalachian Plateau and the Ridge and Valley provinces did not indicate strong trends in the variation of LTBD with watershed area. The data from the Blue Ridge province was inadequate to draw any conclusions. Development of regional relations based solely on watershed area was not pursued in this study.

LTBD Susceptibility Factors

Six factors that may influence a site's risk of LTBD in the three western Maryland provinces were identified. These include the valley slope, the effective valley width, discharge, bed material size, downstream channel entrenchment, and downstream grade controls. Three relations between LTBD and these factors were examined: LTBD and valley slope; LTBD and an index combining Factors 1-3; 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 two 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 0.027 ft/ft.

The analysis and development of indices did not include parameters for the other two factors: downstream channel entrenchment and downstream grade controls. Additional field data would be required to develop parameters and indices that would capture the influence of these factors. The next phase of LTBD research should include some measure of channel entrenchment and the effectiveness of downstream bed controls in limiting degradation.

Rate of LTBD

The analysis of data did indicate a weak correlation between LTBD and the age of the structure; however, the data was insufficient to develop a rate relation. The development of a rate relation should be explored further in the next phase of this research.

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