Assessment of Environmental and Economic Benefits Associated with Streambank Stabilization and Phosphorus Retention

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PURPOSE: This technical note documents the assessment of potential water quality improvements and economic impacts associated with streambank stabilization and phosphorus retention. Phosphorus (P) comes from both point sources (e.g., sewage effluents and industrial discharge) and nonpoint sources (e.g., urban, agricultural, and forest runoff). Measures to control point source pollution (e.g., constraints on P-based inputs) were implemented with the 1972 U.S. Clean Water Act. Recent environmental management efforts have focused on the control of nonpoint sources of contaminants. Erosion and subsequent transport of sediment-bound phosphorus from streambanks can provide a major source of bioavailable phosphorus to aquatic systems. Reduction in the availability of phosphorous (and sediment, and nitrogen), associated with streambank stabilization provides potential economic benefits through reduced treatment costs and adverse environmental impacts. Recent studies in the Demonstration Erosion Control (DEC) Project in Mississippi have indicated that nationwide, costs for phosphorus removal range from $8.82 to $1113.32 per kg ($4 to $505 per pound) of phosphorus (Watson et al. 2001). This suggests that the potential financial benefit associated with streambank stabilization measures and subsequent phosphorus retention could be significant.

BACKGROUND: Harland Creek was selected as the study site and is part of Black Creek watershed, located near Howard, MS. The study reach is known as Harland Creek, Site 23, and is part of the DEC Project. The DEC Project was initiated by the U.S. Government in 1984 and seeks to develop and demonstrate a watershed systems approach to address problems associated with watershed instability: erosion, sedimentation, flooding, and environmental degradation.

STUDY SITE: The location of the study site can be seen in Figure 1, and extends from just downstream of Eulogy Road to just upstream of Hebron Road. The study site is 2,876 m (9,435 ft) in total length as measured from the 1991 aerial photograph and has been divided into 14 reaches.

Geomorphic Status of Harland Creek Pre-stabilization. Harland Creek is an actively meandering sinuous channel with defined pools, large sandy gravel point bars, and riffles between bends. The 2-year discharge calculated for Site 23 is 21.2 m^3/s (750 cfs), reach slope is 0.00084, and drainage area is 104.4 km^2 (40.3 mi^2) (Watson et al. 1996). Bank heights range from 1.5 to 13.4 m (5 to 44 ft), averaging 3.0 to 6.1 m (10 to 20 ft) (Raphelt et al. 1995). The bed material ranges from silts and clays to gravel (Raphelt et al. 1995), with an average d_{50} of 0.5 mm with gravel up to 4 cm (Pokrefke et al. 1996).

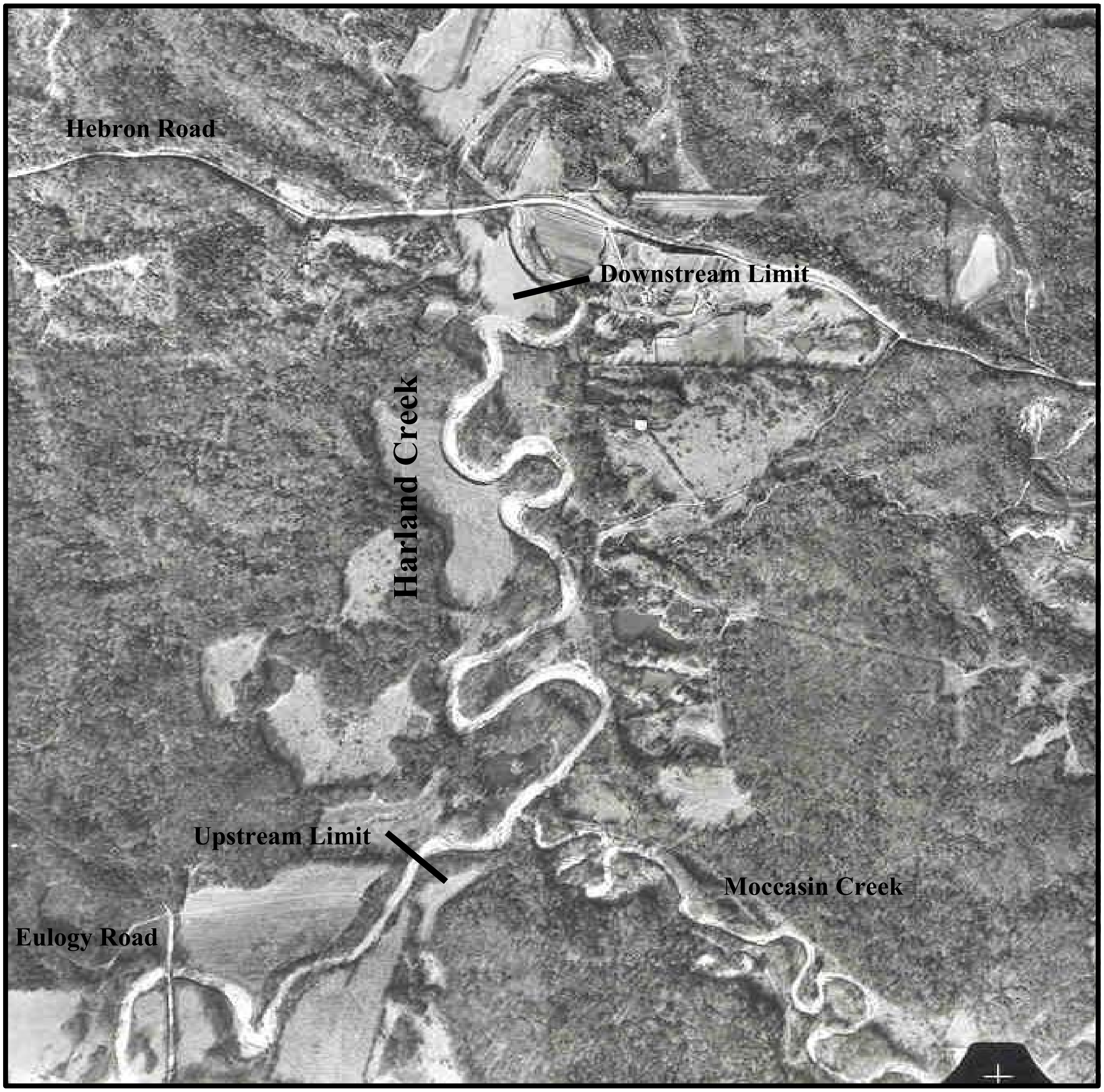

Figure 1. Location of project study site, Site 23 on Harland Creek (1991 aerial photograph)

Historically, lateral migration has been the dominant instability in the reach, occurring over 70 percent of the channel, with the level of activity described as severe (Northwest Hydraulic Consultants, Inc. (NHC) 1987). NHC reported an average meander migration rate of 1.8 m per year (6 ft per year) for a reach of Harland Creek that included Site 23 (NHC 1987). These figures were based on analysis of aerial photographs from 1955 and 1986. Pokrefke et al. (1996) reported a much higher bank migration rate for Site 23 of 4.3 m per year (14 ft per year) after analyzing four sets of aerial photographs from 1955 to 1991. An annual migration rate of this magnitude means that the river moves a full channel width in less than 7 years (Pokrefke et al. 1996).

Harland Creek Bank Stabilization. Bendway weirs were tested as bank protection on nine reaches of Harland Creek, Site 23. Construction of the bendway weirs started in 1993. A bendway weir is located in the channel and angled from 10 to 30 deg upstream of a line drawn perpendicular to the bank line at the bank end of the weir. Raphelt et al. (1995) point out that the 54 bendway weirs used in this small stream are different from those used in navigable channels. The Harland Creek bendway weirs are sloped, fairly short (between 5.2 to 12.3 m (17 to 60 ft)) in length, and emergent except at very high flows (Raphelt et al. 1995). Willow posts were also tested as bank protection on Harland Creek and during 1994 over 9000 willow posts were planted in selected bends (Raphelt et al. 1995). Additional analysis showed that at some locations the bendway weir and willow post designs would need to be supplemented with traditional longitudinal peaked stone toe dikes with tiebacks. Figure 2 shows the general design for Harland Creek and Table 1 lists the bank stabilization treatment for each reach. The total cost is given as $303,660, with a per-linear foot cost of $25.94 (Raphelt et al. 1995). For a more detailed discussion on the design methodology of bendway weirs and willow posts as bank protection, and the bank stabilization design for Harland Creek itself, please see Raphelt et al. (1995) and Watson et al. (2001).

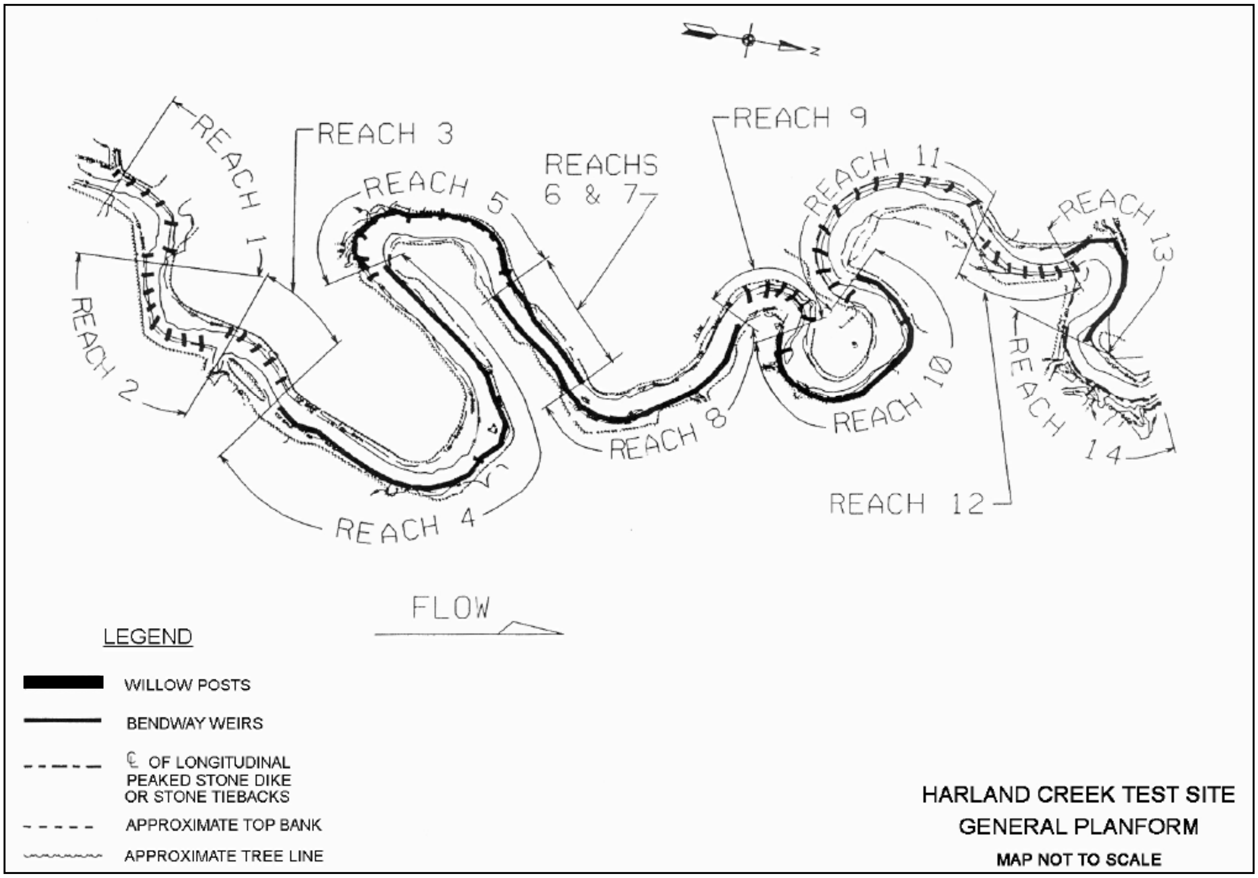

Figure 2. General site map for Harland Creek, Site 23 (Raphelt et al. 1995)

Table 1
Bank Stabilization Treatment by Reach for Harland Creek, Site 23 (Raphelt et al. 1995)

Reaches	Centerline Reach Length (m)	Bendway Weirs	Willow Posts	Longitudinal Peaked Stone Toe
Reach 1	165	6		
Reach 2	128	8		
Reach 3	185	5		
Reach 4	496	1	3 and 5 rows (Approx. 2583 willow posts)	
Reach 5	282	6	2 rows	Along entire length
Reach 6 & 7	146		3 rows (Approx. 1206 willow posts)	
Reach 8	248		5 rows (Approx. 1630 willow posts)	
Reach 9	203	7		Repaired with longitudinal stone toe
Reach 10	282	2	5 rows (Approx. 1805 willow posted)	
Reach 11	231	12		
Reach 12	129	7		
Reach 13	189		4 and 5 rows (Approx. 1005 willow posted)	Repaired with longitudinal stone toe
Reach 14	191		2 rows (Approx. 469 willow posts)	Majority of length

Note: Center-line reach lengths were measured from the 1991 aerial photograph.

Geomorphic Status of Harland Creek Post Stabilization. After nine years, the bendway weir and longitudinal peaked stone toe sites viewed during the field investigation seemed to be performing adequately with minimal bank erosion. Figure 3 shows an example of the stable banks with vegetation successfully colonizing and maturing. There are a few sites where raw banks were visible directly next to bendway weirs, as seen in Figure 4. However the majority of the raw banks appear to coincide with the willow post sites, an example of which is seen in Figure 5. The raw banks at the willow post sites may be due in part to the low survival rates of the willow posts. According to Pokrefke et al. (1996), survival at the willow post sites was at 80 percent in spring of 1994 but dropped to 42 percent by October. By 2002 there is almost 100-percent mortality of the willow posts. Although some of the banks are raw, they have not retreated much as remnants of the willow posts are still visible. Field observation at these sites revealed that there has been erosion at the toe (1 to 2 ft). This is supported by a numerical model study conducted in 1999 that found the added roughness of the willow posts increases stress on the toe (Watson et al. 2001). While it is possible that the willow post remnants may be contributing to the stability of the banks, it is more likely that the historical erosion rates in these bends were lower due to the presence of resistant bank material and the longer radius of curvature bends.

Figure 3. Reach 11, bendway weir site

Figure 4. Reach 11, bank sample location next to bendway weir

In 1994, only 2 percent of the banks were determined to be at risk of failure with current amounts of degradation, the reach slope was near stability, and bank erosion was due to local hydraulic forces (Pokrefke et al. 1996). Watson et al. (2001) described the same bank and bed conditions along

Harland Creek Site 23 as seen in 2002, suggesting that little change is occurring within this section at the present time and that the site is relatively stable.

Figure 5. Reaches 6 and 7, willow post site, bank sample location

The field investigation revealed that the study site has a bed material of fine gravel, with an average d_{50} of 7.6 mm. This is much coarser than the d_{50} value of 0.5 mm and the presence of 4-cm gravel reported by Pokrefke et al. (1996). Stabilizing the banks did not cut off the supply of fines to the bed, as the bank material is very fine and would act as washload. The driving factors behind the coarsening of the post-stabilization bed are beyond the scope of this study but there are several possible explanations. It is possible that the coarsening of the bed is due to the flow being concentrated more into the channel resulting in more of the fines being transported out of the bed. Other explanations may be a coarser supply of sediment from upstream or the bed sample taken in 1996 was taken after the deposition of fines following a high flow event.

METHODS: By comparing the bank line positions for different dates, it was possible to obtain the area of sediment eroded by Harland Creek and the rate of bank retreat between those dates. Four sets of aerial photographs were available for the site (1955, 1973, 1980, and 1991). Using digitized bank lines from these aerials, the area of sediment eroded from the banks was determined for three time periods (1955 to 1973, 1973 to 1980, and 1980 to 1991). The rate of bank retreat in a reach was obtained by dividing the area of sediment eroded in a reach by the length of erosion along the reach.

Reach average maximum bank heights for right and left banks were obtained from a series of 22 cross sections surveyed along the reach in 1993 as part of the DEC Project. The maximum bank height is defined here as the top bank elevation minus the thalweg elevation. While maximum bank heights range from 2.6 to 11.7 m (8.6 to 38.5 ft), the majority of banks fall between 3.0 to 5.2 m (10 and 17 ft).

The volume of sediment eroded from the banks can be calculated using the area of eroded sediment and the average maximum bank height. For each reach, the areas of sediment removed from the right and left banks were multiplied by the relevant reach average maximum bank height before being combined to obtain a reach value of volume of sediment eroded.

Phosphorus samples were collected and analyzed by Colorado State University (CSU) for total phosphorus (TP) and bioavailable phosphorus (BP). The sampling scheme outlined by Bledsoe et al. (2000) was used. The scheme yielded six samples at each site, one from the bed, one from the bank toe, two samples evenly spaced between the toe and top bank, and two samples from on top of the bank. CSU sampled five sites along Harland Creek, one from Site 23 and four from Site 1. Site 1 is located approximately 4.38 km (2.7 RM) upstream from Site 23 at the next county road bridge and is 1219.20 m (4000 ft) in length.

Total phosphorus analysis was conducted using a microwave digestion method developed by CEM Corporation that utilizes alkaline potassium persulfate solution for oxidation. Samples were heated in a microwave digester for 40 min to a maximum pressure of 135 psig and a maximum temperature of approximately 170 ˚C (Littau and Engelhart 1990). The Mehlich 3 soil test (Mehlich 1984) was selected in order to estimate bioavailable phosphorus. The Mehlich 3 soil test extracts Al-P, Ca-P, and a portion of Fe-P. It has been shown that Mehlich phosphorus is well correlated to plant phosphorus needs (Wolf et al. 1985). A Mehlich 3 value of 45-50 mg/kg in soils is generally considered to be optimum for plant growth (Sims 2000).

Total and bioavailable phosphorus concentrations were statistically analyzed using a General Linear Model and the Waller-Duncan K-ratio t Test (SAS Institute, Cary, NC). Data for total phosphorus were normally distributed and data for the bioavailable phosphorus were normalized with a log base 10 transformation prior to statistical analysis.

RESULTS AND DISCUSSION

Total Phosphorus and Bioavailable Phosphorus Analysis. Analysis of samples collected for total phosphorus and bioavailable phosphorus taken from Harland Creek Site 23 show generally similar values as those obtained from further upstream at Harland Creek Site 1 (Table 2). Thus, Site 23 concentrations are adequate to describe the concentrations in the study reach. As the focus of this study is erosion along the bank and the total phosphorus concentrations for the bank are varied, the average of the five bank samples was used to represent the amount of total phosphorus per kg of sediment. The average total phosphorus concentration calculated for Site 23 was 196.55 mg/kg (0.48 lb/ton).

The bed total phosphorus values range from 39.20 to 62.92 mg/kg (0.08 to 0.13 lb/ton) and are significantly ($\alpha = 0.05$) lower than the toe and all bank site values that range from 91.32 to 301.65 mg/kg (0.18 to 0.60 lbs/ton). Figure 6 displays the total phosphorus concentrations graphically. A trend of greater concentrations of total phosphorus in bank sediments (417 mg/kg, 0.8 lbs/ton) compared to concentrations in bed sediments (281 mg/kg, 0.6 lbs/ton) has also been observed in an agricultural watershed in Pennsylvania (McDowell and Sharpley 2001). The same trend has also been reported on one of two Mississippi streams studied by Bledsoe et al. (2000). The concentrations reported from the two Mississippi streams are very similar to the Harland Creek values. A detailed assessment of the phosphorus release function of the two sediment sources led McDowell and

Sharpley (2001) to conclude that bank sediments in the stream system should be a sink for phosphorus when compared with resuspension of bed sediments. However, bank sediments may be a potentially large source of bioavailable phosphorus when eroded and transported to downstream reservoirs or lakes where conditions would favor solubilization (e.g., remobilization associated with anoxic conditions).

The bioavailable phosphorus concentrations found at the bed display the same trend as the total phosphorus bed concentrations, having lower values than the bank. Bioavailable phosphorus values for the bed range from 6.74 to 19.88 mg/kg (0.01 to 0.04 lb/ton), and were significantly lower ($\alpha = 0.05$) than bank and on top bank concentrations that ranged from 15.68 to 67.04 mg/kg (0.03 to 0.13 lb/ton). The bioavailable phosphorus concentrations generally show similar values over the entire bank height, with maximum values most often observed at Site B, Figure 7.

Overall the percentage of bioavailable phosphorus ranged between 7 and 37 percent with higher values generally occurring in the bed sediments (Table 2). Toe, bank, and on top bank samples were not statistically different ($\alpha = 0.05$) and concentrations were highly variable, particularly for the on top bank samples. Observations of higher percentages of bioavailable phosphorus in the bed sediments are consistent with the results of McDowell and Sharpley (2001).

To determine the amount of total phosphorus eroded from the bank in each of the 14 reaches, it is necessary to multiply the volume of sediment eroded from the banks by the specific weight and the amount of total phosphorus per kilogram of sediment. It is difficult to assign a specific weight value to a sediment sample as it has been shown that specific weight varies with the mechanical composition, environment and time (ASCE Task Committee, 1977). Using the grain size information collected from Harland Creek and the summary of specific weights given in ASCE Task Committee (1977), a range of values from 10,995 to 14,608 kN/m^3 (70 to 93 lb/ft^3) were applicable to the Harland Creek, Site 23 sediment. As the values listed in the ASCE Task Committee publication were for sediments that had been deposited for 1 year or less, and as specific weight increases with time, a value of 14,137 kN/m^3 (90 lb/ft^3) was deemed appropriate. For each reach, Table 3 lists the rate of bank retreat, volume of sediment eroded, and the total phosphorus eroded for three time periods.

Table 4 lists the rate of bank retreat, volume of sediment eroded, and total phosphorus eroded for three time periods and the overall values for the 36-year period. The Site 23 values of bank retreat for each time period were found by averaging the 14 reach values. The Site 23 values of volume of sediment eroded and total phosphorus eroded for each time period were found by summing the 14 reach values. For the entire period (1955 to 1991) a more accurate determination of the average rate of bank retreat, volume of sediment eroded and amount of total phosphorous eroded from the entire site was obtained by averaging the values from the three time periods.

Table 2
Total Phosphorus and Bioavailable Phosphorus Concentrations, and Percent Bioavailable for Harland Creek, Site 23 and Site 1

Site & Location	Sample Position	Numeric Code	Bioavailable P. (mg/kg)	Total P. (mg/kg)	Bioavailable (percent)	Bank Average Total P. (mg/kg)
Site 23 Location E Reach 13 Left Outer Bank	Bed	01-2-10-9-1-1	6.74	46.79	14.40	
	Toe	01-2-10-9-2-1	32.27	145.13	22.24	196.55
	Lower Bank	01-2-10-9-2-2	32.69	236.22	13.84	
	Upper Bank	01-2-10-9-2-3	23.60	169.96	13.89	
	On Top Bank	01-2-10-9-2-4	19.72	180.26	10.94	
	Further Back On Top Bank	01-2-10-9-2-5	47.09	251.20	18.75	
Site 1 Location A Dst Bridge Right Outer Bank	Bed	01-2-6-9-1-1	10.38	57.19	18.15	
	Toe	01-2-6-9-2-1	22.15	241.31	9.18	210.16
	Lower Bank	01-2-6-9-2-2	29.37	194.93	15.07	
	Upper Bank	01-2-6-9-2-3	34.89	158.53	22.01	
	On Top Bank	01-2-6-9-2-4	25.12	176.20	14.26	
	Further Back On Top Bank	01-2-6-9-2-5	34.92	279.85	12.48	
Site 1 Location B 182.88 m Dst Left Outer Bank	Bed	01-2-7-9-1-1	19.88	62.92	31.59	
	Toe	01-2-7-9-2-1	47.88	209.40	22.87	168.07
	Lower Bank	01-2-7-9-2-2	44.23	229.05	19.31	
	Upper Bank	01-2-7-9-2-3	67.04	183.21	36.59	
	On Top Bank	01-2-7-9-2-4	15.68	91.32	17.17	
	Further Back On Top Bank	01-2-7-9-2-5	21.94	127.40	17.22	
Site 1 Location C 304.80 m Dst Left Outer Bank	Bed	01-2-8-9-1-1	16.61	51.57	32.21	
	Toe	01-2-8-9-2-1	24.29	235.07	10.33	190.11
	Lower Bank	01-2-8-9-2-2	16.96	100.91	16.81	
	Upper Bank	01-2-8-9-2-3	32.09	193.28	16.60	
	On Top Bank	01-2-8-9-2-4	31.80	217.34	14.63	
	Further Back On Top Bank	01-2-8-9-2-5	22.39	203.94	10.98	
Site 1 Location D 670.56 m Dst Right Outer Bank	Bed	01-2-9-9-1-1	6.95	39.20	17.73	
	Toe	01-2-9-9-2-1	27.61	220.45	12.52	237.14
	Lower Bank	01-2-9-9-2-2	37.00	222.91	16.60	
	Upper Bank	01-2-9-9-2-3	22.50	150.73	14.93	
	On Top Bank	01-2-9-9-2-4	20.89	289.96	7.20	
	Further Back On Top Bank	01-2-9-9-2-5	25.13	301.65	8.33	

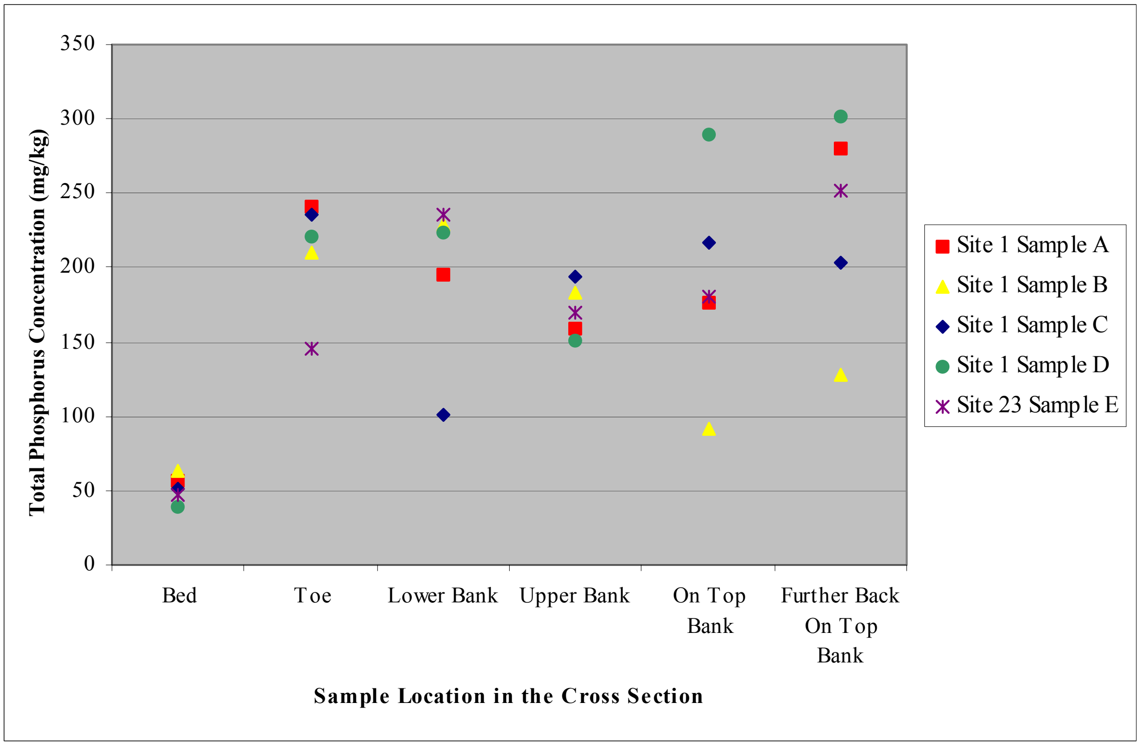

Figure 6. Total phosphorus concentrations for Harland Creek, Site 1 and Site 23

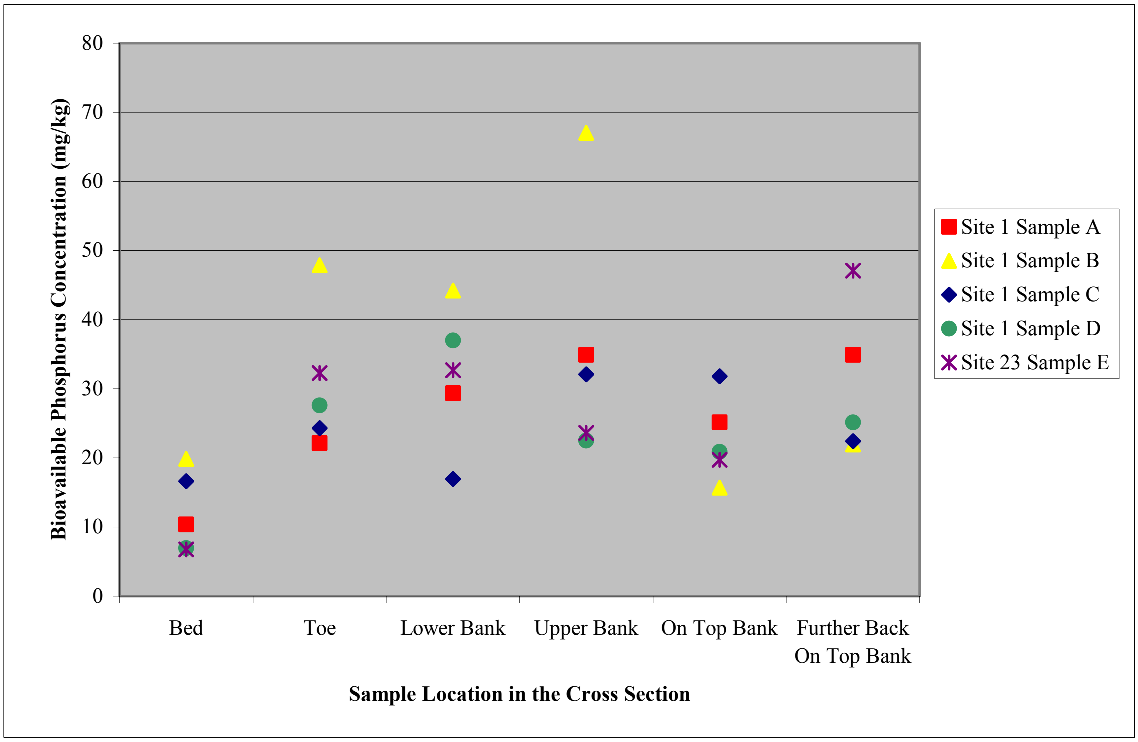

Figure 7. Bioavailable phosphorus concentrations for Harland Creek, Site 1 and Site 23

Table 3
Rate of Bank Retreat, Volume of Sediment Eroded, and Amount of Total Phosphorus Eroded by Each Reach for Three Time Periods

	1955-1973			1973-1980			1980-1991		
Reach No.	Annual Bank Retreat (m/yr)	Annual Volume of Bank Eroded (m3/yr)	Annual Total P Eroded (kg/yr)	Annual Bank Retreat (m/yr)	Annual Volume of Bank Eroded (m3/yr)	Annual Total P Eroded (kg/yr)	Annual Bank Retreat (m/yr)	Annual Volume of Bank Eroded (m3/yr)	Annual Total P Eroded (kg/yr)
Reach 1	1.24	640	181	1.60	757	215	1.29	317	90
Reach 2	0.99	460	130	3.50	1,877	532	4.84	959	272
Reach 3	1.39	1,099	311	2.33	2,123	602	0.61	660	187
Reach 4	1.33	2,272	644	1.26	2,962	839	0.72	1,298	368
Reach 5	0.76	1,053	298	1.69	2,863	811	0.67	986	279
Reaches 6&7	1.14	772	219	1.48	881	250	0.38	164	47
Reach 8	0.63	611	173	2.27	2,656	753	0.85	699	198
Reach 9	1.31	841	238	2.37	2,739	776	2.14	1,726	489
Reach 10	1.76	2,052	581	1.46	2,475	701	0.77	1,052	298
Reach 11	0.43	292	83	1.10	964	273	2.71	2,497	708
Reach 12	0.55	307	87	3.86	2,618	742	1.96	1,120	317
Reach 13	0.67	1,063	301	2.13	2,440	691	1.57	1,266	359
Reach 14	0.65	414	117	2.98	2,239	635	0.62	548	155

Rate of Bank Retreat. Harland Creek Site 23 appears to be a very active channel prior to stabilization, undergoing severe bank erosion. The annual rate of bank retreat varies for each reach and each time period, and can be seen in Table 3. Harland Creek does appear more active between 1973 and 1980, with rates of bank retreat ranging from 1.10 to 3.86 m/yr (3.60 to 12.66 ft/yr), yielding an average rate for that period of 2.16 m/yr (7.09 ft/yr). The highest rate of bank retreat is seen between 1980 and 1991, at 4.84 m/yr (15.89 ft/yr).

The average annual bank retreat rate for the entire 36-year period is 1.54 m/yr (5.05 ft/yr) and can be seen in Table 4. This rate is very similar to the 1.8 m/yr (6ft/yr) between 1955 and 1986 reported by NHC (1987). NHC (1987) used two sets of aerial photographs compared to the more detailed analysis done for this study. Pokrefke et al. (1996) reported a higher rate of bank retreat, 4.3 m/yr (14ft/yr) having used the same four sets of aerial photographs used in this analysis. An explanation for the difference seems to be the way Pokrefke et al. (1996) lined up the downstream bridge in the overlays. From close inspection of the aerial photographs, it appears that the country road and bridge were straightened and rebuilt sometime between 1973 and 1980. The bridge has to be offset in order for the channel to be lined up correctly. Pokrefke et al. (1996) do not seem to have factored this into their calculation, resulting in a greater bank retreat rate.

Table 4
Rate of Bank Retreat, Volume of Sediment Eroded, and Amount of Total Phosphorus Eroded for Harland Creek, Site 23

Time Periods	Average Annual Bank Retreat (m/yr)	Annual Volume of Bank Eroded (m^3/yr)	Annual Total Phosphorus Eroded (kg/yr)
1955-1973	0.99	11,874	3,365
1973-1980	2.16	27,593	7,820
1980-1991	1.47	13,293	3,767
1955-1991	**1.54**	**17,587**	**4,984**

Volume of Sediment and Amount of Total Phosphorus Eroded from the Banks. Prior to bank stabilization, the volume of sediment and amount of total phosphorus eroded annually from the banks varied for each reach and each time period (Table 3). The largest volume of bank sediment eroded annually in a reach occurs between 1973 and 1980, at 2,962 m^3/yr (104,588 ft^3/yr), producing an annual rate of total phosphorus eroded from the bank of 839 kg/yr (1,851 lb/yr). This time period has five reaches with an annual rate of total phosphorus eroded from the banks above 700 kg/yr (1,543 lb/yr), while the time period 1980 to 1991 has only one. The highest annual rate of total phosphorus eroded from the banks in a reach between 1955 and 1973 is a little lower at 644 kg/yr (1,419 lb/yr).

The more active bank erosion time period from 1973 to 1980 resulted in an average annual volume of material eroded from the banks of 27,593 m^3/yr (974,309 ft^3/yr) and average annual amount of total phosphorus eroded from the banks of 7,820 kg/yr (17,241 lb/yr). This is more than twice the amount of total phosphorus eroded from the banks for the other two time periods (Table 4).

The variability in the volume of sediment and total phosphorus eroded from the banks over the three time periods was taken into account by averaging the values to yield more representative annual values for the entire time period. The average values of volume of sediment and amount of total phosphorus eroded from the banks for the entire time period (1955 to 1991) are 17,587 m^3/yr (620,997 ft^3/yr) and 4,984 kg/yr (10,988 lb/yr), respectively (Table 4).

Cost of Bank Stabilization Versus Cost of Total Phosphorus Removal. The benefit of bank stabilization can be seen in the estimated cost for not having to remove the total phosphorus that enters the channel. It is possible to estimate the cost for the removal of total phosphorus from an environment. A study by Watson et al. (2001) presented a list of six projects where cost of total phosphorus removal had been published (Table 5). While these figures are not specific to Harland Creek, they can be used to illustrate the process. The wide degree of variability in cost (Table 5) led this study to use the minimum cost of \$8.82/kg-yr (\$4/lbs-yr), maximum cost of \$1113.32/kg-yr (\$505/lbs-yr), and average cost of \$353.18/kg-yr (\$160.20/lbs-yr). Using three different figures for cost provided a more realistic range of expenses for total phosphorus removal than any one figure could report.

Table 5
Cost of Total P Removal (Watson et al. 2001).

Project Site	Nutrient	Minimum Cost for Removal ($/kg-yr)	Maximum Cost for Removal ($/kg-yr)
Tar Pamlico, North Carolina	Total Nitrogen & Total Phosphorus	$141.09	$141.09
Chatfield Basin, Colorado	Total Phosphorus	$88.18	$661.38
Everglades Removal Project, Florida	Total Phosphorus	$233.69	$233.69
Lower Boise River Demonstration Project, Idaho	Total Phosphorus	$8.82	$440.92
Saginaw Basin, Michigan	Total Phosphorus	$8.82	$52.91
Lake Dillon (Copper Mt.), Colorado	Total Phosphorus	$1113.32	$1113.32
	Average	**$353.18**	

If bank erosion had continued on Harland Creek, the anticipated benefits of bank stabilization was on average $1,760,346 annually with respect to total phosphorus retention (Table 6). Compared to the bank stabilization costs of $303,660 (Raphelt et al. 1995), the average cost of total phosphorus removal was nearly six times annually more expensive. The average per linear meter value of total phosphorus removal was $612/m-yr ($187/ft-yr) versus the estimate given by Raphelt et al. (1995) of $85.11/linear meter ($25.94 per linear ft) for bank stabilization. Even when the minimum estimate of total phosphorus removal was considered, the bank stabilization project would only have to stay effective for 7 years before cost benefits would be seen.

Table 6
Estimates for Cost of Total Phosphorus Removal on Harland Creek Site 23

Time Periods	Annual Bank Retreat (m/yr)	Annual Volume of Bank Eroded (m^3/yr)	Annual TP Eroded (kg/yr)	Low Estimate of Unit Cost TP Removal $8.82/kg-yr ($/yr)	High Estimate of Unit Cost TP Removal $1113.32/kg-yr ($/yr)	Average Estimate of Unit Cost TP Removal $353.18/kg-yr ($/yr)
1955-1991	1.54	17,587	4,984	$43,961	$5,549,092	$1,760,346
			$/m-yr	$15	$1,930	$612
			$/km-yr	$15,288	$1,929,700	$612,161

CONCLUSIONS: Historically Harland Creek Site 23 had been an actively meandering channel with an average annual bank retreat rate of 1.54 m/yr (5.05 ft/yr), resulting in 17,587 m^3 or 27,946 tons of bank material eroded annually. Bank stabilization, started in 1993, has greatly reduced erosion of the banks and a large amount of phosphorus has been retained in the banks, resulting in a considerable reduction of phosphorus entering the aquatic system. While bank sediments typically contain higher amounts of total and bioavailable phosphorus, the potential for bioavailability is also a function of sediment transport processes and oxidation and reduction processes in the fluvial system, neither of which can be discarded in assessing the potential for reducing impacts of sediment/bank phosphorus.

This study provides an example of how the benefits of bank stabilization and subsequent phosphorus loading reductions might be quantified using documented cost rates for total phosphorus removal and the potential volumes of sediment eroded from the banks over a period of time. The annual benefits of bank stabilization for Harland Creek Site 23 are $612,161 per km with respect to total phosphorus removal. This type of approach could have application nationwide to show the benefits of bank stabilization.

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