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# Understanding Sediment Sources, Pathways, and Sinks in Regional Sediment Management: Application of Wash Load and Bed-Material Load Concept

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**PURPOSE:** This System-Wide Water Resources Program (SWWRP) technical note describes how the concept of wash load and bed-material load can be applied to sediment transfer through the fluvial system for sediments derived from various bed, bank, gully, and catchment sources thereby providing a reliable analytical foundation for effective regional sediment management. The utility of this concept is demonstrated for Hickahala Creek, where erosion control features in the upper watershed were shown to have the potential to reduce sediment delivery to the downstream channel improvement project (Biedenharn et al. 2006).

**BACKGROUND:** Hickahala is one of 16 watersheds included in the U.S. Army Corps of Engineers (USACE) Mississippi Delta Headwaters Project (DHP) (formally the Demonstration Erosion Control Project (DEC)). It is located in northwestern Mississippi, approximately 48.3 km (30 miles) south of Memphis, TN (Figure 1). Hickahala Creek is a tributary of the Coldwater River that drains an area of approximately 595.7 km$^2$ (230 square miles) and confluences with the mainstream just upstream of Arkabutla Reservoir. The lower course of Hickahala Creek has, for decades, been plagued by severe aggradation and related flooding problems in the vicinity of the Arkabutla Reservoir. Early attempts to improve the situation through dredging failed as the channel silted again almost immediately following completion of the work due to the excessive sediment loads supplied from the watershed and upstream fluvial system. This may be illustrated by reference to the minimum monthly stages in Hickahala Creek, which show short-lived stage lowering following dredging between the 1960s and the early 1980s (Figure 2).

On implementation of the DEC/DHP in 1985, a comprehensive investigative program was initiated to support a watershed-wide sediment-management project. The goal of these efforts was not only to improve the lower course of the creek with respect to flood control, but also to lengthen the effective life of the improvement measures by reducing sediment loads supplied to downstream reaches prior to the proposed channel improvement works being performed. The sediment management project and channel-improvement works were completed in 1994. Gauge records and field investigations from that time through the fall of 2003 reveal that the stage lowering accomplished by the works has persisted, with no renewed aggradational trends or maintenance dredging required (Figure 2). Thus, it appears that the project goals to reduce upstream erosion have been successful in prolonging the life of the channel-improvement works.

Application of the wash load and bed-material load concept within the context of successful regional sediment management in Hickahala Creek is illustrated here following an overview of the concept.

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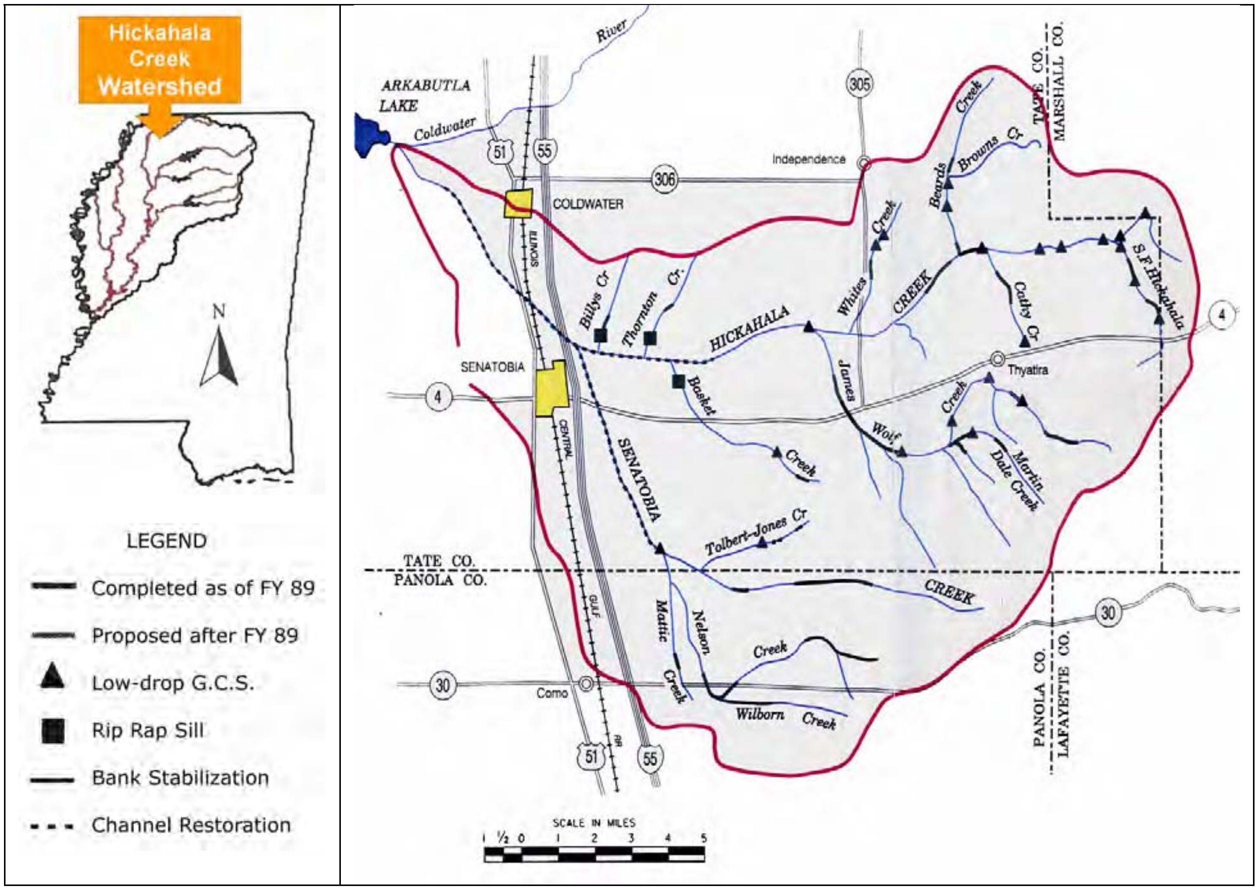


Figure 1. Hickahala Creek watershed, northern Mississippi

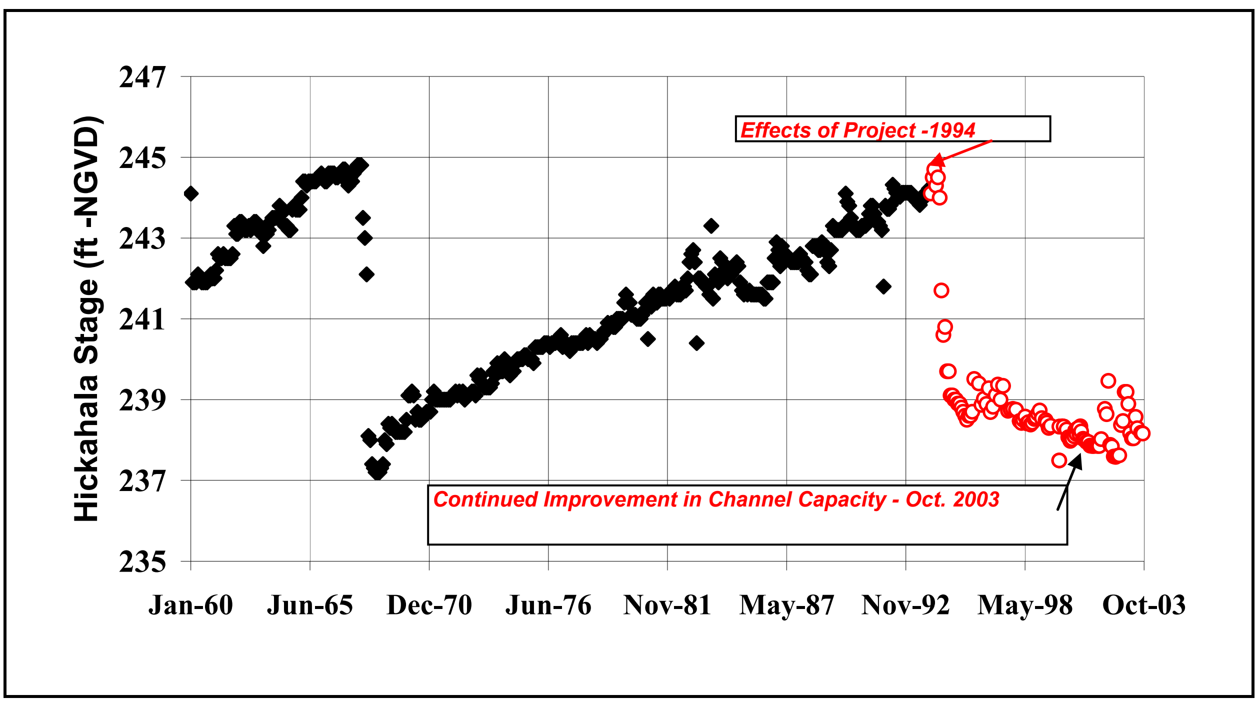


Figure 2. Minimum monthly stages at Hickahala Creek

**WASH LOAD AND BED-MATERIAL LOAD CONCEPT:** There is no universally accepted definition of wash load, so the distinction between bed-material-load and wash-load components of the total load adopted here, is that wash load is not found in appreciable quantities in the bed of the channel. The numerical value assigned is that suggested by Einstein (1950), who defined wash load as the grain size of which 10 percent of the bed mixture is finer. While the value assigned to wash load is not universally accepted, the wider concept that sediment in transport that is finer than that making up the bed of the channel behaves differently and plays a different role in the sediment transfer system, is widely perceived to have merit and has often proven useful in river-engineering studies (Einstein 1950). A detailed description of the wash load and bed-material load concept is found in the companion technical note by Biedenharn et al. (2006).

**APPLICATION OF WASH LOAD AND BED-MATERIAL LOAD CONCEPT:** The aim of the proposed sediment management measures in the Hickahala Creek watershed was to: (a) reduce the sediment loading supplied to the lower courses of the stream from upstream and watershed erosion involving bank caving, channel headcutting, stream side gully development; and (b) provide erosion control using appropriate bank stabilization works, grade control structures, drop pipes, and land treatment measures. This was to be accomplished by stabilizing seriously eroding sediment source areas within the watershed, thereby reducing sediment loads supplied to downstream reaches, and extending the life of the channel-improvement works. It was, however, recognized that the relative contributions of individual eroding features to sediment loadings in the lower reaches varies considerably and that an understanding of sediment dynamics and pathways would be required to support effective sediment management at the system scale.

To assess how stabilizing individual erosional sources would impact sediment balances in intermediate reaches and reduce sedimentation rates in the downstream reaches, it was necessary to evaluate sediment source-pathway-sink linkages in the Hickahala Creek drainage network. It was in this context that the wash load and bed-material load concept was applied. The principles adopted were as follows:

*a.* Sediment load in each reach of the drainage system can be separated into wash- load and bed-material-load components based on a threshold grain size equivalent to the $D_{10}$ for the bed material in that reach.

*b.* Sediments supplied to a reach from each erosion source can be expressed as contributions to the bed-material load and wash load in that reach based on the $D_{10}$ for the bed material in that reach.

*c.* As the $D_{10}$ for the bed material decreases in the downstream direction, the threshold grain size separating bed-material load and wash load is adjusted as necessary. Hence, sediment entering each reach is reclassified as wash load or bed-material load in that reach.

*d.* Transport of wash load in each reach is supply-limited, meaning that the wash load supplied to the next reach downstream is simply the sum of wash-load sized materials input from upstream plus that derived from all the erosive sources in that reach. Consequently, wash load moves through the reach but does not reside there.

*e.* Transport of bed-material load in each reach is transport-limited, meaning that the bed-material load supplied to the next reach downstream is equal to the transport capacity for that reach. If the input of bed-material load from upstream, plus that derived from erosive sources in the reach exceed the transport capacity, then the excess is stored within the reach, defining the reach as a sediment sink. If the inputs are less than the transport capacity, the deficit is made up through scour within the reach, defining the reach as a sediment source.

*f.* Morphological responses are expected in reaches where the supply of bed-material load does not match the transport capacity, with the nature of the response dependent on the sense of the imbalance.

Based on these principles, it was recognized that the reductions in sediment loads supplied to the lower reaches that were expected to occur following implementation of erosion-control measures would occur over two distinct time scales. Short-term impacts would occur within months or a few years, reflecting reductions in the sediment loading associated with decreases in the quantity of material delivered to the project reach as wash load. Longer-term impacts would occur over years and decades due to morphological response to reductions in bed-material load in the intermediate reaches situated between the source control sites and the project reach.

**FIELDWORK AND SEDIMENT SAMPLING:** The first step in the sediment study was a geomorphic assessment of the entire watershed. A key component of the geomorphic assessment was a detailed field investigation to identify sediment sources, sinks, and the general morphological character of the channel system. The next step in the sediment study was a bed and bank material sampling campaign. Bank samples were collected to establish the particle size distribution of material being supplied by streambank erosion and extension of streamside gullies. Visual inspection was used to identify stratigraphic layers in the banks, with multiple samples taken from each layer. The overall bank height and thickness of each layer were recorded. Gradation curves were developed for each layer, and then combined into a weighted-average gradation curve for the entire bank. Figure 3 shows the bank gradation curves for selected sample sites on streambanks along Hickahala Creek. It is clear that the gradation of sediment derived from erosion of the banks varies widely, with some sources yielding almost exclusively fine-grained sediment, while other sources input a considerable proportion of coarser material.

Bed-material samples were collected in 2002 at eight locations along Hickahala Creek, starting from the bridge farthest downstream and extending upstream about 35,685 m (117,000 ft). While there was some variability in the gradations, $D_{10}$ values were reasonably consistent. Therefore it was decided to use the overall average $D_{10}$ to set the wash load and bed-material load threshold size for each reach (Table 1).

Spatial trends in the average $D_{10}$ values along Hickahala Creek (Figure 4) show that values are almost uniform upstream of sta 583+00 with a mean value of about 0.26 mm. However, downstream of sta 583+00, the $D_{10}$ values begin a steady decreasing trend, culminating at sta 0+00, where the bed comprises significant amounts of fine sand and silt and has a $D_{10}$ value of about 0.018 mm. Sta 0+00 is located well within the reach normally influenced by backwater effects from Arkabutla Reservoir and where, consequently, it would be expected that the channel bed would include significant amounts of fine-grained sediment.

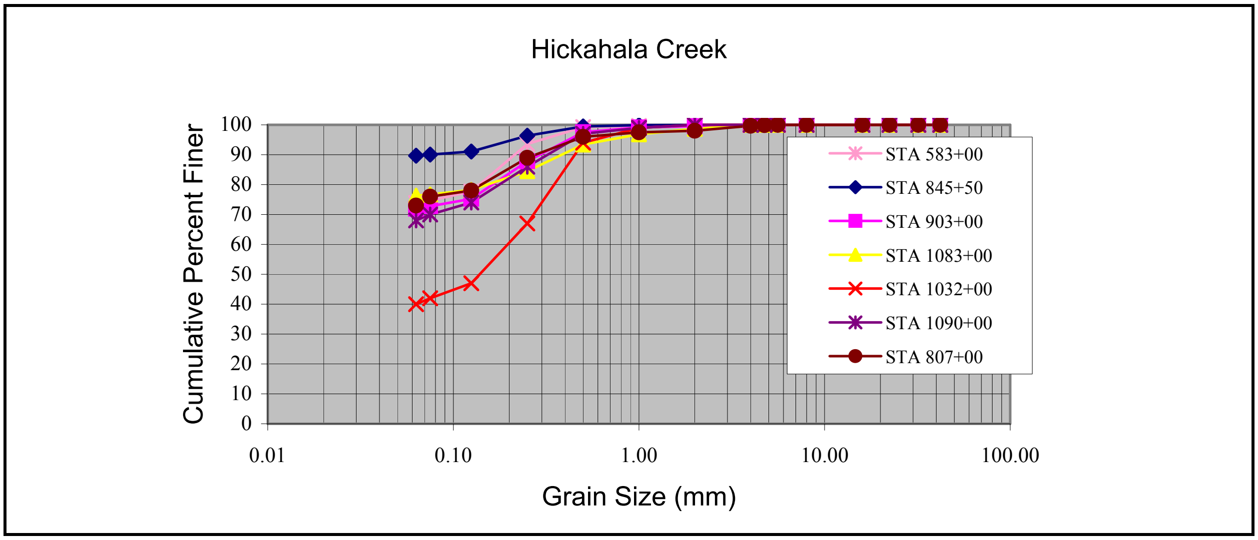


Figure 3. Bank gradations along Hickahala Creek

**Table 1**
**Bed Material $D_{10}$ Values along Hickahala Creek (all sizes are in millimeters)**

| Station (100 ft) | Sample 1 Spring | Sample 2 Spring | Sample 3 Spring | Sample 4 Summer | Sample 5 Summer | Sample 6 Summer | Sample 7 Summer | Sample 6 Summer | Average $D_{10}$ |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.130 | **0.018** |
| 146 | 0.002 | 0.17 | 0.15 | 0.33 | 0.27 | 0.26 | 0.002 | 0.002 | **0.15** |
| 327 | 0.14 | 0.13 | 0.07 | 0.25 | 0.18 | 0.26 | 0.28 | | **0.19** |
| 583 | | | | 0.27 | 0.26 | 0.28 | 0.27 | | **0.27** |
| 903 | | | | 0.18 | 0.23 | 0.27 | 0.25 | 0.26 | **0.24** |
| 989 | | | | 0.26 | 0.27 | 0.26 | 0.27 | | **0.27** |
| 1083 | | | | 0.26 | 0.27 | 0.26 | 0.27 | | **0.26** |
| 1171 | | | | 0.27 | 0.27 | 0.26 | | | **0.27** |

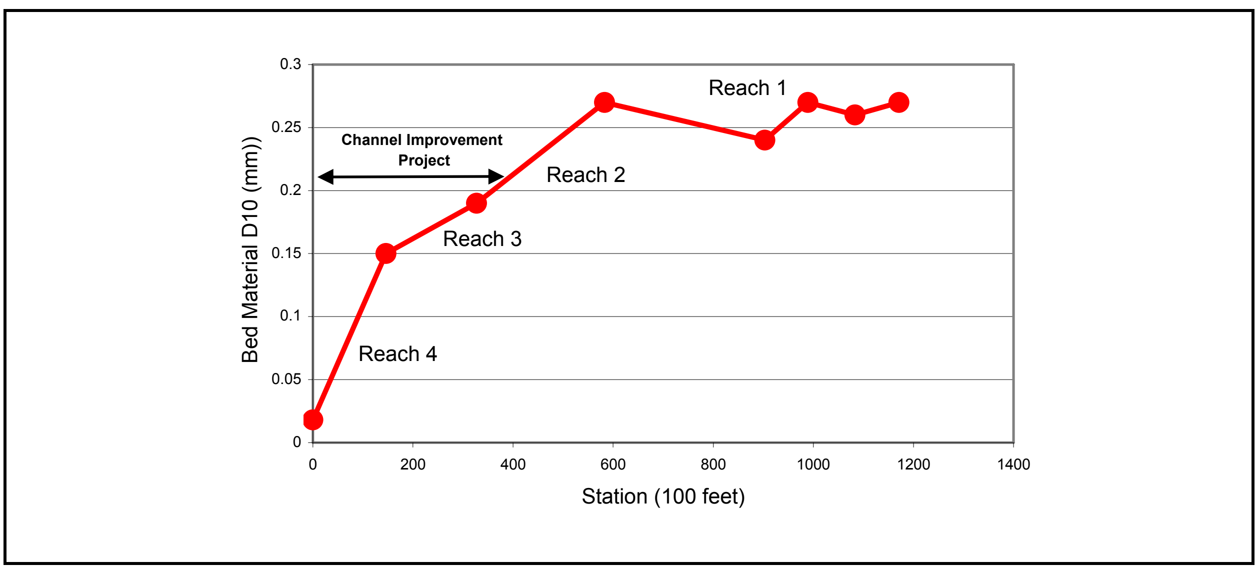


Figure 4. Bed material $D_{10}$ values along Hickahala Creek

**SEDIMENT IMPACT ANALYSIS:** The following discussion uses a limited example drawn from a wider study to illustrate how the wash load and bed-material load concept was used to establish the pathways linking upstream sediment sources with downstream sinks in the Hickahala Creek drainage network and explore how sediment source control would likely affect the adverse morphological impacts associated with deposition of fines in the lower course of the main stem channel. Four sediment reaches are used to support this illustration and discussion:

Reach 1 – Upstream of Station 583+00
Reach 2 – Stations 583+00 to 327+00
Reach 3 – Stations 327+00 to 146+00
Reach 4 – Stations 146+00 to 0+00

The channel-improvement project extends from sta 0+00 upstream to about the lower third of Reach 2.

Due to space limitations, it is not possible to include the complete sediment impact analysis that was performed for Hickahala Creek. Instead, the utility of applying the wash load and bed-material load concept in evaluating sediment source-pathway-sink linkages in the drainage network to establish how stabilizing various erosional sources would impact sediment balances in the reaches downstream is illustrated using the example of two eroding streambanks with similar erosion rates, but contrasting bank material size distributions.

For this discussion, eroding banks at sta 1032+00 and 845+00 were each assumed to be supplying 1,000 kg/year of sediment to the drainage network (Figure 5). However, the bank at sta 1032+00 is composed of relatively coarse-grained sediment, while that at 845+00 is formed in much finer material (Figure 3).

a. Station 1032+00

b. Station 845+00

Figure 5. Eroding banks on Hickahala Creek

**WASH LOAD AND BED-MATERIAL LOAD ANALYSIS:** The first step in the sediment impact analysis is to use a wash load and bed-material load analysis to determine how the sediment supplied by the eroding banks would travel through the Hickahala Creek sediment transfer system.

The spatial distribution of wash load and bed-material load through Hickahala Creek input by bank erosion at sta 1032+00 is listed in Table 2 Examination of Figure 3 indicates that about 70 percent of the material supplied by the eroding streambank at sta 2+00 would move as wash load in this reach based on the fact that the $D_{10}$ value in the vicinity of sta 2+00 is about 0.26 mm (Figure 4). It follows that the 700 kg/year of material finer than 0.26 mm, moving as wash load, would immediately be transferred downstream, to enter Reach 2 at sta +00, while the 300 kg/year of material coarser than 0.26 mm would be added to the bed material in Reach 1, available for transfer downstream as transport-limited, bed-material load.

**Table 2**
**Downstream Distribution of Sediment Supplied to Drainage Network by 1,000 Kg/Year of Streambank Erosion at Sta 1032+00**

| Reach | Upper Size Limit of Wash Load, mm | Bank-Derived Sediment Defined as Wash Load, percent | Wash Load Supplied to Next Reach Downstream, kg/year | Bed Material Supplies to Reach, kg/year |
|---|---|---|---|---|
| 1 | 0.26 | 70 | 700 | 300 |
| 2 | 0.19 | 60 | 600 | 100 |
| 3 | 0.15 | 52 | 520 | 80 |
| 4 | 0.018 | 20 | 200 | 320 |

In Reach 2, the $D_{10}$ value for the bed material decreases from 0.26 mm to 0.19 mm (Figure 4 and Table 2). While 70 percent of the eroded bank material was finer than 0.26 mm, only 60 percent of it was finer than 0.19 mm. Consequently, 10 percent (100 kg/year) of the eroded bank material that was input from Reach 1 as wash load becomes bed-material load in Reach 2. It follows that 100 kg/year of material between 0.19 mm and 0.26 mm is added to the bed material in Reach 2, while the remaining 600 kg/year of sediment transported as wash load is transferred immediately to Reach 3.

In Reach 3, the $D_{10}$ value for the bed material decreases further, from 0.19 mm to 0.15 mm (Figure 4 and Table 2). Figure 3 indicates that the percent finer values for 0.19 mm and 0.15 mm are 60 percent and 52 percent, respectively. Hence, 8 percent (80 kg/year) of the sediment load supplied by the eroding bank at sta 1032+00 becomes bed material in Reach 3, and 320 kg/year passes quickly through to Reach 4, as wash load.

As the $D_{10}$ value for the bed material at sta 0+00 is 0.018 mm (Figure 4 and Table 2), the sediment load input to Reach 4 with sizes between 0.15 mm and 0.018 mm will be added to the bed material in that reach. Hydrometer analysis for one streambank in Reach 1 showed that about 20 percent of the bank material was finer than 0.018 mm. Applying this value to the eroding bank at sta 1032+00 suggests that about 200 kg/year would quickly be transferred past sta 0+00 and out of Reach 4 as wash load, while the remaining 320 kg/year of sediment input from Reach 3 is delivered to Reach 4 as bed material.

The downstream distribution of wash load and bed material delivery from an eroding streambank at sta 845+00 can be established by applying the same source-pathway-sink analysis as for sta 1032+00. The results are listed in Table 3. As shown in Figure 3, the bank material at sta 845+00 is much finer than that at sta 1032+00, and this affects the downstream distribution of eroded sediment, as shown in Table 3.

**Table 3**
**Downstream Distribution of Sediment Supplied to Drainage Network by 1,000 kg/year of Streambank Erosion at sta 845+00**

| Reach | Upper Size Limit of Wash Load, mm | Bank-Derived Sediment Defined as Wash Load, percent | Wash Load Supplied to Next Reach Downstream, kg/year | Bed Material Supplied to Reach, kg/year |
|---|---|---|---|---|
| 1 | 0.26 | 97 | 970 | 30 |
| 2 | 0.19 | 94 | 940 | 30 |
| 3 | 0.15 | 91 | 910 | 30 |
| 4 | 0.018 | 20 | 200 | 710 |

**LOCAL AND DOWNSTREAM SEDIMENT IMPACTS OF BANK STABILIZATION:** The second step in the analysis is to determine the local and downstream impacts on sediment dynamics in Hickahala Creek that would result from stabilizing the eroding banks at stations 1032+00 and 845+00 and, thereby, eliminating two sediment sources of 1,000 kg/year with the size distributions indicated in Figure 3. The results of this step in the impact analysis in terms of reductions in the supply of bed material sized sediment to each of the four sediment reaches along Hickahala Creek are summarized in Table 4. These findings clearly illustrate that the local and downstream sediment impacts of bank stabilization vary significantly, depending on the gradation of the material supplied by the erosional source.

**Table 4**
**Reductions in Bed Material Sized Sediment Supplied to Each Reach Due to Stabilization of Banks at Stations 1032+00 and 845+00. (Channel improvement project extends from lower part of Reach 2 to end of Reach 4)**

| Station | Reach 1 – in the Vicinity of Stabilization Measures, kg/year | Reach 2, kg/year | Reach 3, kg/year | Reach 4, kg/year |
|---|---|---|---|---|
| Station 1032+00 | 300 | 100 | 80 | 320 |
| Station 845+00 | 30 | 30 | 30 | 710 |

According to the sediment transfer analysis outlined in Step 1, Reach 2 would experience a reduction in the supply of bed material sized sediment supplied by Reach 1 of about 100 kg/year. This impact would occur almost immediately following stabilization of the eroding bank at sta 1032+00 because this material would have been transported through Reach 1 as wash load and would, therefore, have been quickly delivered to Reach 2. By the same logic, Reaches 3 and 4 would experience immediate reductions in their inputs of bed-material sized sediment of 80 kg/year and 320 kg/year, respectively, because in both cases the sediment involved would have been transferred to the reach in question as wash load.

At sta 845+00, 97 percent of the bank material is finer than 0.26 mm and, consequently, bank stabilization would result in only a reduction of about 30 kg/year in the supply of bed material sized sediment to Reach 1 (Table 4). Similarly, the reductions in bed material sized sediment transported through intermediate reaches as wash load and then supplied to Reaches 2 and 3 would, in each case, be only 30 kg/year. However, the supply of bed material sized sediment to Reach 4 would experience a much larger reduction of 710 kg/year.

In summary, this analysis suggests that sediment impacts due to stabilization of the coarse-grained, eroding bank at sta 1032+00 would be marked in Reaches 1 and 4, but much less important in Reaches 2 and 3 (Table 4). In contrast, sediment impacts due to stabilization of the fine-grained, eroding bank at sta 845+00 would be concentrated in Reach 4, and negligible in Reaches 1, 2, and 3 (Table 4).

**LOCAL AND DOWNSTREAM MORPHOLOGICAL RESPONSES:** The third step in the sediment impact analysis is to consider the morphological responses likely to be triggered by the changes to local and downstream bed-material loads that result from the bank stabilization efforts at stations 1032+00 and 845+00.

With respect to local morphologic responses in the vicinity of the stabilization measures, it can be seen that of the two sites, stabilization of the bank at sta 1032+00 has the greater potential to drive significant adjustments. Stabilizing this eroding bank would generate a reduction of 700 kg/year in the supply of sediment finer than 0.26 mm (Table 2), but this would have no significant morphologic impact in Reach 1 because this material constitutes wash load, which is not found in significant quantities in the bed and the movement of which is supply rather than transport-limited. However, the removal of 300 kg/year of material coarser than 0.26 mm (Table 2) would be expected to trigger a morphologic adjustment in Reach 1, as this would significantly reduce the supply of bed-material load.

The nature of the morphological response in Reach 1 would depend on the local balance between supply and transport capacity for bed-material load. If local supply and transport capacity were balanced prior to stabilization of the eroding bank, a reduction in supply would promote degradation. If transport capacity exceeded supply, an existing degradational tendency would be worsened. However, if supply exceeded transport capacity then the tendency for the channel to aggrade would be ameliorated. As sta 1032+00 is actually located within Reach 1, the local morphological response to this reduction in bed-material load would be relatively rapid and any morphological response should be discernible within a few months or years.

In contrast to stabilization of the eroding bank at sta 1032+00, morphological response to bank stabilization at sta 845+00 would probably be minimal given the much smaller reduction in the supply of the bed material sized sediment from that bank (Table 4).

The significance of morphological responses in Reaches 2 and 3 would be similar to those in Reach 1. The immediate reductions in the supply of bed material sized sediment associated with stabilization of the bank at sta 1032+00 are smaller than in Reach 1, but are probably not negligible and might be expected to generate short-term morphological responses (Table 4). Conversely, the bed-material load reductions resulting from stabilization of the bank at sta 845+00 appear to be too small to generate any discernible morphological response. In the longer term, the local morphological responses in Reach 1 referred to in the previous paragraph would also affect the supply of bed-material load entering Reaches 2 and 3. However, given the much longer time taken for bed-material load to travel downstream through the drainage network, it would be several years or decades before these longer-term morphological responses became evident.

In Reach 4, the analysis suggests significant short-term reductions in the supply of bed material sized sediment of 320 and 710 kg/year due to stabilizing the banks at stations 1032+00 and 845+00, respectively. As the bed in this reach is known to be aggrading, the morphological response in Reach 4 would be expected to feature a marked reduction in the rate of bed rise soon after completion of bank stabilization measures in Reach 1.

**IMPACTS IN CHANNEL-IMPROVEMENT REACH:** The fourth and final step in the sediment impact analysis explores how the impacts expected within the channel-improvement project vary depending upon which eroding bank is stabilized.

The upstream limit of the channel-improvement project is located near the downstream end of Reach 2. The results listed in Table 4, therefore, suggest that stabilization of the bank at sta 1032+00 would result in a reduction in the supply of bed material sized sediment to the upper end of the channel-improvement project of 100 kg/year, whereas, stabilization of the bank at sta 845+00 would only reduce the bed-material supply to the upper end of the channel-improvement project by 30 kg/year. Hence, sediment impact analysis reveals that stabilization of the bank at sta 1032+00 would be more than three times more effective in providing benefits to the upper end of the channel-improvement project. The benefits to the middle part of the channel-improvement project would be similar, with stabilization of the bank at sta 1032+00 being more than twice as effective as equivalent measures at sta 845+00. However, with respect to impacts in the lower end of the channel-improvement project, in Reach 4, stabilization of the bank at sta 845+00 would be more than twice as beneficial, reducing the supply of bed-material load by about 710 kg/year as compared to 320 kg/year for sta 1032+00.

This example illustrates the utility of the wash load and bed-material load concept in understanding the local and downstream impacts of sediment source control in the Hickahala watershed. The analysis demonstrates that stabilization of streambanks in the upper reaches will have immediate impacts through reducing bed-material loads in the drainage network and illustrates how those reductions will be distributed between downstream reaches. In the Hickahala Creek watershed, implementation of erosion-control measures throughout the watershed not only provided local channel-stabilization benefits, but also successfully contributed to the longevity of the channel-improvement project downstream.

**SUMMARY:** Effective regional sediment management requires knowledge of the sources, pathways, and sinks of sediment in the watershed. The wash load and bed-material load concept provides a vehicle with which to characterize the sediment transfer system, and therefore, the development of channel and watershed improvements that recognize sediment connectivity in the fluvial system and support the design of schemes that are sustainable in terms of sediment continuity. The utility of applying the concept was demonstrated during the design of a channel-improvement project in Hickahala Creek, where construction of erosion-control measures in the upper watershed was shown to have the potential to significantly reduce the delivery of bed material sized sediments to the downstream channel-improvement project. In the past, efforts to reduce sediment loading through erosion control have resulted in unexpected morphologic responses in the channel system, such as degradation that has increased channel instability outside the project area. Accurate identification of sources, pathways, and sinks is the key to understanding sediment dynamics in the drainage network and selecting erosion-control measures that will produce the desired reductions in bed-material loads supplied to a downstream project reach with the least disruption to the stability of the channel locally and in intermediate reaches.

The sediment impact analysis methodology presented here provides a conceptual basis for developing, designing, and optimizing erosion-control and channel-improvement plans. In the example cited, a simplified application examining just two sources of sediment was used to illustrate the utility of the method. Typically, sources would not be limited to one or two sites of serious bank erosion, but would include agricultural field erosion, hill slopes, gullies, and the bed of the channel. In practice, predicting the magnitude of sediment impacts and the nature of morphological responses to the reductions in sediment inputs would require development of a quantitative sediment budget for the channel system that includes and accounts for all the significant sediment sources in the watershed. To this end, the Sediment Impact Assessment Model (SIAM) is being developed at ERDC, which incorporates the wash load and bed-material load concept discussed herein, and enables rapid assessment of the impacts of upstream changes in sediment input on downstream trends of sedimentation or incision.

**ADDITIONAL INFORMATION:** This technical note was prepared by David S. Biedenharn, research hydraulic engineer, Lisa C. Hubbard, research physical scientist, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Colin R. Thorne, professor, University of Nottingham, School of Geography, Nottingham, England, and Chester C. Watson, professor, Colorado State University, Department of Civil Engineering, Fort Collins, CO. The study was conducted as an activity of the Improved Characterization and Estimates of Sediment Sources Pathways, and Sinks work unit of the System-Wide Water Resources Program (SWWRP). For information on SWWRP, please consult https://swwrp.usace.army.mil/ or contact the program manager, Dr. Steven L. Ashby at Steven.L.Ashby@erdc.usace.army.mil. This technical note should be cited as follows:

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