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Sediment Management at the Watershed Level

by James R. Leech and David Biedenharn

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) is an approach to analyze and manage sediment at the watershed level. Sediment management can be a localized problem that requires a holistic approach. This Technical Note introduces considerations in the quest to manage sediment at COE flood control reservoirs.

INTRODUCTION: Channel instability is a serious problem throughout the United States (U.S.). The magnitude of this problem is illustrated in the Corps of Engineers' final report to Congress for the Streambank Erosion Control Evaluation and Demonstration Program, which reported that the U.S. contains over one-half million (574,000) miles of eroding bank lines (USACE 1981). Dams, levees, diversion structures, and the straightening, widening, deepening, and clearing of channel systems are common methods used to provide flood control, navigation, water supply, sediment management, irrigation, recreation, and hydropower. The cumulative impacts of these types of activities, combined with watershed changes such as de-forestation and urbanization, have significantly disrupted the dynamic equilibrium of stream systems and the related ecosystems. The sediments generated by these disturbances clog flood-control channels, destroy wetlands and lakes, adversely impact fish and wildlife habitats, degrade the water quality of streams, adversely impact infrastructure, and initiate accelerated stream instabilities. The accelerated sediment yields associated with these watershed instabilities are particularly a problem with respect to sedimentation in reservoirs.

As water-resource projects become more and more complex, there is a growing emphasis on the ability to implement effective watershed sediment management. A common goal of many watershed sediment management projects is the reduction of sediment loading from the watershed. This is usually accomplished by rehabilitation features such as grade control, bank stabilization, drop pipes, and land treatments. While these features are often implemented with the stated purpose of reducing sediment yields to downstream reservoirs, flood-control channels, or wetlands, the spatial and temporal impacts of these features with respect to downstream sediment loads are complex, and often result in unanticipated morphologic adjustments and degradation of riverine habitats and ecosystems. This complexity has led some engineers to conclude that treatment of sediment sources at the watershed level will have little or no impact on downstream sediment delivery. This assumption has been supported by the studies of Trimble (1983) and others who found little correlation between watershed sediment sources and downstream sediment loads. However, there are many stream systems throughout the U.S. where the channels are efficient conveyors of sediment and the sediment delivery processes are much different than those studied by Trimble and others. Therefore, effective watershed sediment management lies in identifying the sediment sources and sediment sinks in the watershed sediment system and understanding the processes responsible for transferring sediment along the

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pathways that link sediment sources and sinks at the reach and watershed scales. Consider two types of watersheds, which for this discussion we will simply refer to as a source dominated system and a pathway dominated system. The Trimble (1983) investigation of Coon Creek is an example of the source dominated system in which the disturbance is in the upper portions of the watershed, primarily consisting of agricultural disturbance, and the channels are relatively inefficient conveyors of sediment. The Yazoo Basin of Mississippi is an example of the pathway dominated system in which streams have been disrupted by channelization, flow diversions, and other activities to enhance sediment and water conveyance. In this type of stream system (pathway dominated), many streams are incised channels, and the delivery of sediment from upstream sources to downstream locations may be very efficient. Additionally, in these incised stream systems, the channels are often the major source of sediment.

Treatment of upstream sediment sources in a source dominated type of system may be ineffective in reducing downstream sediment yield because the stream channels do not have the capability to transport the upstream eroded sediment. For a pathway dominated type of system, the eroded sediment is transported downstream directly, and watershed and channel erosion treatments can be an effective watershed sediment management approach. Thus, there is no "one size fits all" answer to complex watershed sediment management, particularly when sediment transport is involved. Each system must be analyzed specifically to establish the relationships between the sediment sources, pathways and sinks.

WATERSHED SEDIMENT DELIVERY

Watersheds vary considerably with respect to sediment delivery and various treatment measures. Upstream erosion control measures that have been successful in reducing downstream sediment delivery in one watershed may be ineffective in another. This section provides a brief literature review of sediment delivery for two distinctly different types of watersheds: (1) watersheds where the sediment delivery ratio is low due to considerable storage of sediments in the channels and valleys (source dominated systems); and (2) watersheds where the channels are efficient conveyors of sediment and the sediment delivery ratios are high (pathway dominated systems).

Numerous studies have indicated that much of the sediment that is eroded from upland sources is stored in the system and not exported out of the watershed (Meade 1982; Trimble 1983; Phillips 1991; Beach 1994; Renwick et al. 2005). Trimble examined ten river basins (1,000 to 7,500 mi^2) and found that the sediment yield averaged about six percent. He attributed the small percentage of sediment yield in these stream systems to storage in massive deposits in streams and valleys. Some of the deposits were found to be eroding and becoming sources of sediment. In his review of the subject, Knighton (1998) concluded that Trimble (1983) clearly demonstrated the importance of storage and remobilization in controlling sediment yield from the 139 mi^2 Coon Creek watershed in Wisconsin. Trimble prepared sediment budgets for two periods: (1) 1853-1938 and (2) 1938-1975. In the first period, soil erosion was characterized by poor land management and severe soil erosion, especially in the upland portions of the watershed. The later period was marked by application of soil-conservation measures. While those measures reduced upland soil erosion by 26 percent, sediment yield downstream did not change. These two sediment budgets showed that most of the material eroded during the first period had been stored on the lower slopes and in the valley floors, with only a small portion reaching the basin outlet. Material stored in the tributary valley and in the upper part of the main valley was remobilized during the second period to result in an apparent unchanged sediment yield. Knighton (1998) advised that sediment budget analysis, as demonstrated by Trimble, provides a useful framework for investigating the internal dynamics of sediment storage and mobilization. Accurate rates and quantities of sediment movements are difficult for even small watersheds; however, knowledge of the complexities of sediment storage and movement should be carefully considered.

In watersheds with considerable sediment storage and low downstream sediment delivery ratio such as those discussed above, there may be little correlation between upland sediment supply and downstream sediment delivery. In systems such as these, it is doubtful that upstream erosion-control methods would have a significant impact on downstream sediment delivery, particularly in the short term. However, there are many watersheds where the channels are efficient conveyors of sediment and may act as dominant sediment sources rather than sinks. In these types of systems, the sediment delivery ratio may be relatively high. In a study of channelized streams in north Mississippi, Dendy et al. (1979) reported sediment delivery ratios ranging from 72 to 95 percent, and also found that gullies and channels contributed 50 to 60 percent of the sediment while constituting less than two percent of the land area. Based on these findings, Dendy et al. (1979) concluded that effective erosion control of these two major sediment sources could conceivably reduce watershed sediment yields by one-half. This concept has been demonstrated by the U. S. Army Corps of Engineers (USACE) Vicksburg District's Delta Headwaters Project. A brief discussion of some of the Delta Headwaters Project is provided in the next section.

It is important to recognize that the channels of north Mississippi are not unique, and that there are thousands of miles of incised channels throughout the U.S. This interest in incised streams was illustrated by the success of the Conference on Management of Landscapes Disturbed By Channel Incision, which was held in Oxford MS in May 1997. Because of the excellent response to the call for contributions, the conference had to be expanded to accommodate over 180 papers and 250 participants from 25 states in the U.S. and 26 countries overseas.

SEDIMENT MANAGEMENT IN THE DELTA HEADWATERS PROJECT

In this section, the sediment-reduction benefits of the Delta Headwaters Project (DHP) are discussed. However, it is first important to understand the characteristics of the DHP stream systems, and how they may vary from many of the systems studies by Trimble and others discussed in the Section 2. Therefore, this section is divided into two sub-sections. The first sub-section is a brief description of the erosion and sedimentation history of the DHP watersheds. The second sub-section discusses the impacts of the DHP activities on sediment delivery.

History of Erosion and Sedimentation in the DHP Watersheds: The Delta Headwaters Project (DHP), formerly the Demonstration Erosion Control (DEC) Project, has demonstrated a watershed systems approach to address problems associated with watershed instability: erosion, sedimentation, flooding, and environmental degradation. Initiated by the Federal government in 1984, DHP activities targeted sixteen watersheds comprising 2,625 mi^2 within the Yazoo River Basin in the Lower Mississippi Valley (Figures 1 and 2).

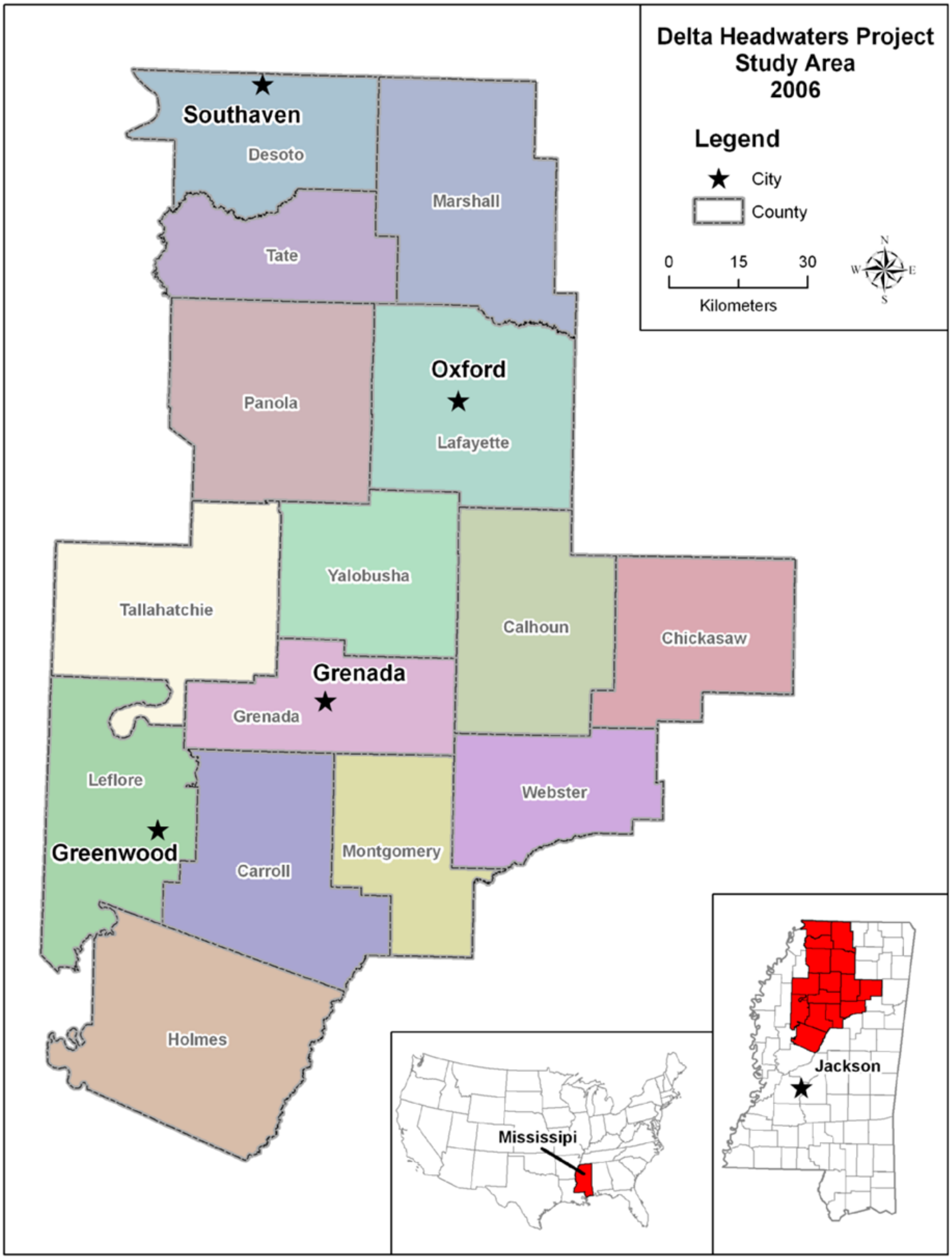

Figure 1. DHP study area.

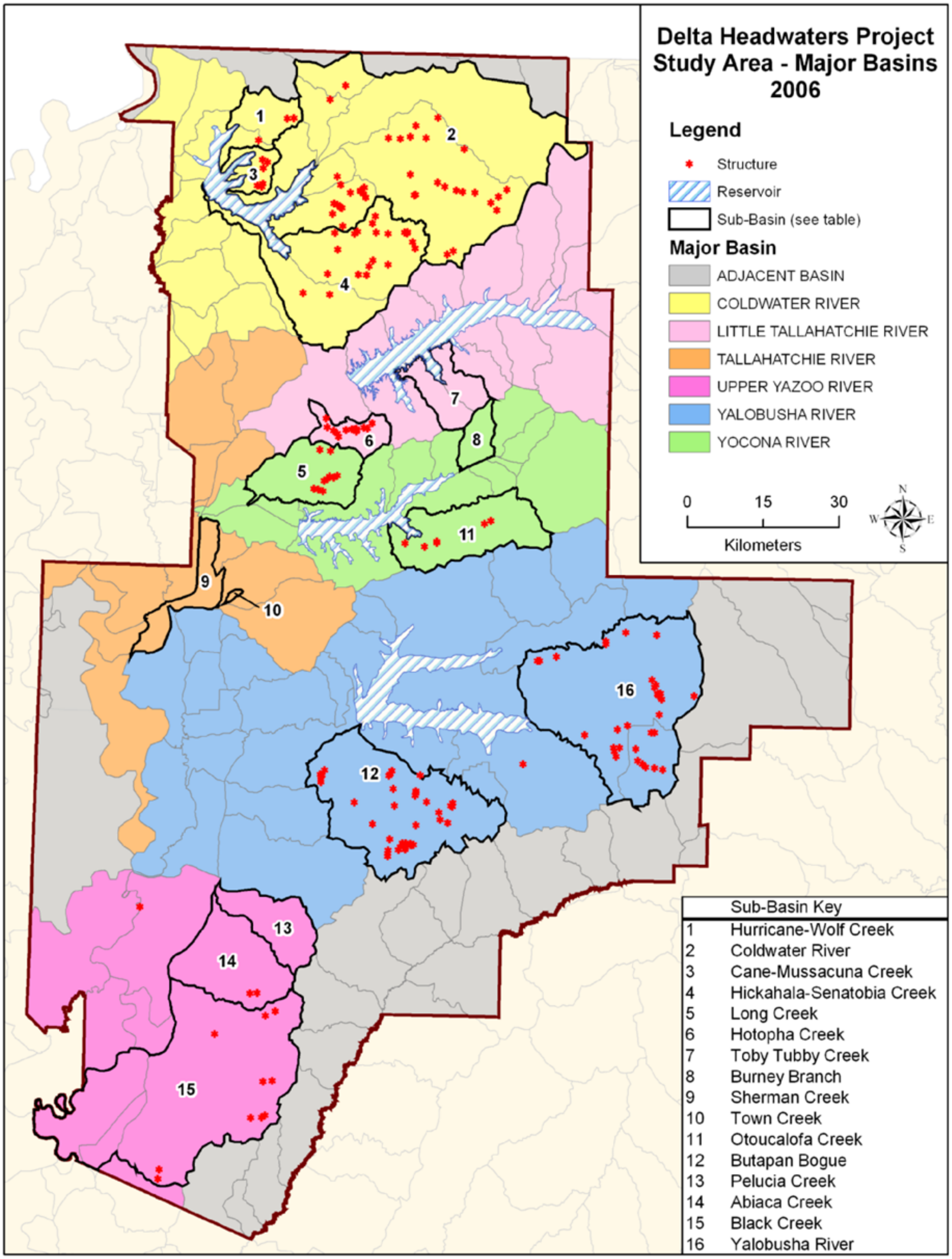

Figure 2. Location of DHP watersheds.

The history of the Yazoo Basin tributaries, since about 1830, is interwoven with a consistent tragedy of soil erosion and improper management of sediment. The period from about 1830 to 1910 was one of aggressive expansion of agricultural, without consideration for proper soil-conservation, practices. The net result of this period of massive land-use change, from virgin forest with very little cultivation to aggressive cultivation of the hills, was erosion of the soil from the cultivated hills into the floodplain and channels of the valleys. Drainage in the valleys was inadequate and valley croplands were buried with sand and debris (Watson et al. 1997). At this point in time, these channel systems would have exhibited characteristics of the source dominated systems described in Section 1. As a result of the massive sedimentation and flooding problems, drainage districts were formed and the streams were channelized to improve flood capacity. This channelization led to massive channel degradation and widening throughout the watersheds. Degradation of channel beds of 10 to 20 feet and width increases well in excess of 100 percent were not uncommon. These channels had now transitioned from the source dominated to pathway dominated systems. By the mid-1950s, watershed planning was underway by the U.S. Department of Agriculture (USDA), Soil Conservation Service (SCS). The two primary differences in the Federal agency planning, as compared to the previous local drainage district's lack of planning, was: (1) that planning was made on a total watershed basis without restriction by County boundaries and (2) that effective upland soil-conservation practices were designed to reduce sediment supply. Component measures included: conservation cropping practices, revegetation of critical areas, field waterways, terracing, desilting basins, pipe drop structures, floodwater retarding structures, stream-bank stabilization, stream clearing and snagging, and new stream excavation and cutoffs. Upland soil-conservation measures were generally successful and reduced sediment yield. However, the balance of the sediment supply and sediment transport, which had been imbalanced for over 100 yrs by excessive sediment, was now thrown toward increased sediment transport capacity. The result was that stream incision became the main source of sediment (Dendy et al. 1979; Watson et al. 1997).

By 1985, the DHP was in place. The DHP provides for the development of a system for control of sediment, erosion, and flooding in the hill areas of the Yazoo Basin, Mississippi. Features that are being utilized to achieve the project goals include grade control structures, reservoirs, and bank-stabilization measures. In addition, pipe drop structures are being constructed to prevent gullying of the stream banks. Other features being employed in the DHP are: levees, pumping plants, and land treatments.

There are several primary differences between the DHP approach and the prior watershed plans. The DHP is a comprehensive and intensive program, in which a very significant part of the construction is for grade stabilization in the streams and in stream-side gullies; whereas, previous efforts were generally focused on upland soil conservation. The DHP also includes long-term monitoring of the performance of constructed facilities and overall system response of stream rehabilitation.

The DHP had made significant advances in the state-of-the-knowledge with respect to river engineering, channel restoration, watershed sediment management, and watershed rehabilitation. A detailed description of the accomplishments of the DHP with respect to sediment-reduction benefits, advances in technology developed through the DHP, performance of structural features, and the transfer of the DHP technologies to others is provided by Biedenharn and Watson (2011).

A description of the sediment-reduction accomplishments in the DHP is discussed in the next section.

Impacts of the DHP on Sediment Delivery and Soil Loss: Within the DHP, the changes in sediment delivery have been evaluated using either *direct* analysis of measured suspended sediment data and other U. S. Geological Survey (USGS) published data, or by *indirect* methods that involve comparative survey and analytical and modeling techniques.

Direct Analysis of Measured Suspended Sediment Data: The use of measured suspended sediment data to conduct statistical analyses to document pre- and post-project changes in watershed sediment yields is problematic and establishing statistically-significant trends may be difficult, owing to the extreme uncertainty in these data. Several investigators have analyzed the measured sediment data in the DHP in an effort to identify trends. Shields (2008) hypothesized that the DHP erosion-control measures would reduce watershed suspended sediment yield. To test his hypothesis, Shields analyzed fully-integrated samples of depth-integrated, full stream width samples from the Jackson, Mississippi, office of the USGS; the same office responsible for installing and maintaining the DHP gages. Shields (2008) concluded: "*Statistical analyses of flow-adjusted instantaneous measured concentrations data failed to detect significant trends at six of the seven gages*."

Rebich (1993) analyzed the measured suspended sediment data for Hickahala and Peters Creeks for the time period from 1986 to 1991 and found no trends in suspended sediment concentration or discharge that were statistically significant. Hickahala Creek had only six years of data (1986 through 1991) and Peters Creek had five years of data (1987 through 1991). Runner and Rebich (1997) conducted a similar analysis with four additional years at both sites. In their study, they found a statistically-significant increasing trend in the water discharge at both sites. No statistically-significant decreasing trends in suspended sediment concentration or discharge were found at either site. However, they did note that the flow-adjusted sediment discharges for both Hickahala and Peters Creeks appeared to decrease for the latter part of the period.

Biedenharn and Watson (2011) conducted an analysis of the published daily suspended sediment data to determine if any significant trends could be identified. The published daily suspended sediment data were analyzed to determine if any trends existed. Daily data were available for eleven DHP gages. For this analysis, the published daily suspended sediment concentrations (mg/L) and the daily water discharge (cfs) were summed up for each year. A ratio was then calculated as the sum of the suspended sediment concentration for the year divided by the sum of the water discharge for that year. Visual inspection of these graphs indicates apparent downward trends for eight of the gages. However, a statistically-significant downward trend was only indicated at the Hickahala gage. Statistically-inconclusive downward trends were observed at Harland Creek, Hotopha Creek, Otoucalofa Creek, and Topashaw at Derma. The remaining apparent downward trends were statistically insignificant.

In summary, the lack of reported strong statistical trends of decreasing sediment yields using temporally-isolated measured suspended sediment data is not surprising given the large uncertainty associated with this type of data. Limitations that should be considered when using measured suspended sediment data to identify long-term trends in the DHP watersheds include:

- Measured suspended sediment in the DHP is predominantly silts, clays, and very fine sands; which are typically wash load in the DHP streams. The coarser fractions that comprise the channel-bed material are not typically found in appreciable quantities in the sediment samples. Thus, the measured suspended sediment data have limited value as a measure of the bed-material changes in the DHP streams.
- The uncertainty in measured suspended sediment data is large, typically exceeding a log cycle or more; which makes it extremely difficult to identify statistically-significant trends.
- Bunte and McDonald (1999) also suggest that at least 5-to-10 yrs of both pre- and post-project data are necessary to detect trends. In the DHP watersheds, there is little or no pre-project sediment data, and many of the post-project datasets range from about 3-to-14 yrs.
- Spatial-scale issues are particularly important. Bunte and McDonald (1999) suggest that typical annual transport distances can vary significantly for fines (silts and clays), sand, and coarse particles. Consequently, there may be a substantial lag in the occurrence of a sedimentary cumulative watershed effect, depending on the size of sediment in transport. The timing and location of the sedimentary cumulative watershed effect is highly dependent on key factors such as particle size, and the distance and type of stream through which particles are passing. For example, if an upper watershed bank is stabilized that is 15 miles from the gage site and is composed primarily of silt and very fine sand, the effect may be detected at the gage within a short period; whereas, if the bank is primarily medium to coarse sands or gravel, the effect may not be detected for decades or hundreds of years.

Indirect Methods to Estimate Changes in Sediment Yield: Studies that do not rely on measured suspended sediment load, which we refer to as indirect methods, have reported reductions in the annual sediment yields resulting from DHP features. Some studies focused on wash load and others on bed-material loads, but the common theme of all these studies was the identification of a reduced sediment yield. The reported reductions ranged from about 8-to-92 percent. A brief summary of these studies follows.

Watson et al. (2001) used empirical relationships developed for the DHP watersheds to predict the potential land losses due to continued erosion with and without DHP grade control structures for four watersheds. A summary of the results follows. As part of the ongoing monitoring efforts, the potential land losses due to continued erosion without grade control structures were calculated for six watersheds (Yalobusha, Batupan Bogue, Hickahala, Long, Hotopha, and Black). This was performed by first calculating a stable slope for each stream in these watersheds, based on extensive geomorphic data and hydraulic analyses. These analyses provide an estimate of the potential degradation necessary for these streams to achieve stable slopes throughout the drainage network. Based on the predicted depths of degradation, new top widths were estimated for all channels; which were used to calculate the quantity of lost land. This procedure was repeated with the DHP grade control structures in place. Grade control structures provide vertical stability and promote a general decrease in the erosion in the streams. Comparing the erosion for the with and without grade control structure scenarios provides a framework to estimate the beneficial impacts of these structures. Table 1 shows the amount of sediment delivered to the channel through erosion for the two scenarios. As indicated in the table, the grade control structures have reduced the amount of sediment delivery from about 28 percent to as high as 84 percent, with an average value of 62 percent. While these may appear to be unreasonably high numbers, the reader only has to look at Figure 3 to get an appreciation of how beneficial grade control structures are. The channel in Figure 3 is Crowder Creek, a DHP stream near Elliott, Mississippi. At the time of this photograph in 1985, the channel degradation had migrated upstream and was halted at the two culverts shown in Figure 3. The culverts are acting as temporary grade control structures. Just a few years prior to this photograph, the severely eroded channel downstream of the culverts looked just like the channel upstream of the culverts. Without these two culverts (grade control structures), the upstream channel would have developed channel dimensions similar to the downstream channel. Therefore, the ability of grade control structures to reduce the sediment delivery to the streams by as much as 62 percent is not unreasonable.

Table 1. Benefits from existing grade control structures.

Watershed	Sediment Delivered to Channel Without Grade Control, (Yds^3)	Sediment Delivered to Channel With Grade Control, (Yds^3)	Percent Reduction Sediment Delivered Due to Grade Control
Yalobusha	86,523,033	34,760,690	60%
Batupan Bogue	119,104,950	43,440,176	64%
Hickahala	45,676,940	7,401,293	84%
Long	83,066,527	21,269,786	74%
Hotopha	8,292,018	3,066,046	63%
Black	87,904,470	62,917,293	28%
Average:			62%

Figure 3. Channel degradation halted by two culverts on Crowder Creek. The culverts are acting as temporary grade control structures.

Watson et al. (2002) used repeat surveys for the years 1993, 1994, 1995, and 1996, to conduct an analysis of the impacts of grade control structures on annual sediment yield for twenty-six DHP monitoring reaches. The computer model SAM was used to compute annual sediment yield based on a computed sediment rating curve and a flow duration relationship. Comparison of the annual yield from the survey reaches indicates that sediment yield has decreased about 36 percent in reaches with grade control structures versus those without grade control structures.

Robeson et al. (2002) analyzed the Yalobusha River, Topashaw Creek, and Hotopha Creek using the one-dimensional sediment transport model HEC-6T. The simulations were run for both the "with DHP" and "without DHP" features for 30 yrs for the Yalobusha River and Topashaw Creek and for 52 yrs for Hotopha Creek. The results were then compared to an analysis using empirical relationships. In summary, the HEC-6T model comparisons result in less change than the empirical models. HEC-6T models are limited to only bed sediment degradation, whereas the empirical models include bed and bank erosion. HEC-6T modeling for with and without DHP grade control structures indicate reductions in sediment yields of 15 percent, 42 percent, and eight percent for the Yalobusha River, Topashaw Creek, and Hotopha Creek, respectively, with an average value of about 22 percent. For the same watersheds, empirical modeling averages 66 percent reduction in sediment yield. Empirical models include the assumption of complete erodibility and time for erosion to completely develop. HEC-6T modeling is for a limited time period and no bank erosion is computed.

Thomas (1995) developed a HEC-6T model for Hotopha Creek to assess the impacts of the DHP grade control structures. He concluded that the DHP grade control structures resulted in a 12 percent decrease in the bed-material sediment discharge on Hotopha Creek. These results are in agreement with Robeson et al. (2002). Robeson et al. (2002) noted that the HEC-6T results are an underestimate, because the model does not include the bank-erosion component of the sediment load. Thomas (1995) also noted that the full impact of the constructed features will not be measured at the mouth of Hotopha Creek for about 13 yrs, suggesting that in small watersheds, stream response to construction is slow and continuing.

Hubbard et al. (2003) conducted an analysis of the effects of bank stabilization along Harland Creek. 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). The study site consisted of fourteen severely eroding meander bends. Based on comparison of aerial photography, the average annual sediment eroded from the stream banks over the period from 1955 to 1991 was determined to be about 23,000 yds^3/yr. These meander bends were stabilized as part of the DHP in 1993. Continued monitoring of this site has indicated that the meander migration of these bends has been terminated. The predominant bank material in this reach is fine sands, silts, and clay, and is, therefore, wash load in this coarse-bed (coarse sands and gravel) system. Consequently, the stabilization of these bends results in an immediate reduction in the delivery of fine sediments to downstream reaches. Harland Creek flows into Black Creek just upstream of its entrance to the Hillside Floodway. Therefore, the DHP bank-stabilization project has resulted in a reduction in sediment delivery to this valuable wetland area of about 23,000 yds^3/yr.

Simon and Darby (2002) analyzed the changes on Hotopha Creek using channel surveys and erosion models. For the period 1985 to 1992, they reported annual sediment yields of 1,580 tons/mi^2. For the period 1992 to 1996, the annual sediment yields were reduced to 467 tons/mi^2, a reduction of about 70 percent.

Kuhnle et al. (1996) reported an approximate 60 percent reduction in sediment concentration for the Goodwin Creek watershed for the period 1982 to 1991. They used measurements and numerical modeling to analyze this watershed.

Summary of Impacts of the DHP on Sediment Yield: In summary, the use of measured suspended sediment data to conduct statistical analyses to document pre- and post-project changes in watershed sediment yields is problematic. In some studies, general trends indicating a reduction in sediment yield have been observed. However, establishing these trends with statistical significance has been difficult, owing to the extreme uncertainty in these data. Indirect methods using empirical relationships, comparative surveys and photography, and numerical modeling have all indicated reductions in the sediment yield that can be attributed to the DHP features. The average reported value for the reduction in sediment yield from the empirical studies was about 60 percent, while the average reported value from the HEC-6T modeling was about 19 percent. This difference is attributable generally to the fact that the HEC-6T models reflect bed-material adjustments and do not take into account bank erosion. Thus, there is strong evidence that the DHP has resulted in significant reductions in sediment yield. The lack of reported statistical trends in sediment yields using the direct analysis of the measured suspended sediment data simply reflects the limitations of the data. Measured suspended sediment data are of value; however, long-term measurements at a single location require years, perhaps decades, to achieve statistically-significant findings. Pre-project and post-project data are desirable. A more appropriate use of the measured suspended sediment data is to identify general trends that can then be used as a complement to the indirect methods.

SUMMARY

The manner in which watersheds respond to different approaches is site specific and can vary significantly, particularly with respect to sediment delivery and morphologic response. No two watersheds are alike and, therefore, features that achieve sediment-reduction goals in one watershed may be completely ineffective in another. The key to optimizing management of sediment dynamics in the fluvial system lies in identifying the sediment sources and sediment sinks in the watershed sediment system and understanding the processes responsible for transferring sediment along the pathways that link sediment sources and sinks at the reach and watershed scales.

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