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Effectiveness of grade-control structures in reducing erosion along incised river channels: the case of Hotophia Creek, Mississippi

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Abstract

Herein, we undertake a geomorphological analysis in which spatial and temporal trends of bed and bank erosion along an 18-km length of Hotophia Creek, Mississippi, are estimated for the period between 1961 and 2050. The evaluation was undertaken for two scenarios of channel response to channelization during 1961–1963. One scenario represents the 'actual' response of the channel and includes the effects of installing a series of grade-control structures (GCS) between 1980 and 1996, while the other represents a hypothetical scenario in which the channel is left to adjust naturally. This allows the effectiveness of GCS in reducing in-channel erosion to be assessed. The analysis relies on the availability of channel survey data to develop empirical bed and bank response models for each adjustment scenario, supplemented by bank stability modelling to predict future rates of bank erosion. Results indicate that channel erosion rates decline nonlinearly with respect to time since 1961, for both adjustment scenarios. However, by the year 2050, the "with" GCS adjustment scenario results in the cumulative removal of some 663,000 (9%) extra tonnes of sediment relative to the "without" GCS scenario. Most (63%) of this excess is derived from enhanced bed erosion during 1976–1985 and 1985–1992, with the remainder derived from increased bank erosion during 1985–1992. Detailed analysis of the patterns of erosion and deposition, and their association with the GCS, provides evidence to support the view that GCS installed along Hotophia Creek have, for the most part, been ineffective in reducing channel erosion rates. This is because the GCS were installed too late to prevent bed degradation, caused by the 1961–1963 channelization, migrating upstream. In addition, some structures have disrupted the downstream transmission of bed material from eroded reaches upstream, exacerbating bed degradation and bank erosion in incised reaches downstream. Published by Elsevier Science B.V.

Keywords: Hotophia Creek; Grade-control structures; Sediment yield; Erosion control; Applied geomorphology

1. Introduction

Incised river channels are ubiquitous features of disturbed landscapes. Whether incision results from natural causes or as the result of human activities,

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incised channels are found wherever and whenever there is an excess of flow energy (sediment-transporting capacity) relative to the amount of sediment supplied to the stream (Simon and Darby, 1999). The precise causes of sediment supply–transport imbalances that lead to incision have been intensively researched (Cooke and Reeves, 1976; Galay, 1983; Graf, 1983; Schumm et al., 1984). This research has shown that numerous factors (including changes in climate, land cover, tectonics, the role of animals, as well as a range of human activities) are responsible for initiating channel incision (Schumm, 1999).

While the causes of incision are many and varied, incised channels in different environments pass through a consistent sequence of channel forms with time (Ireland et al., 1939; Daniels, 1960; Elliott, 1979; Schumm et al., 1984; Simon and Hupp, 1986; Simon, 1989). These observations form the basis of empirical–conceptual models of incised channel evolution, such as the Simon and Hupp (1986) model shown in Fig. 1. This model, together with others like it

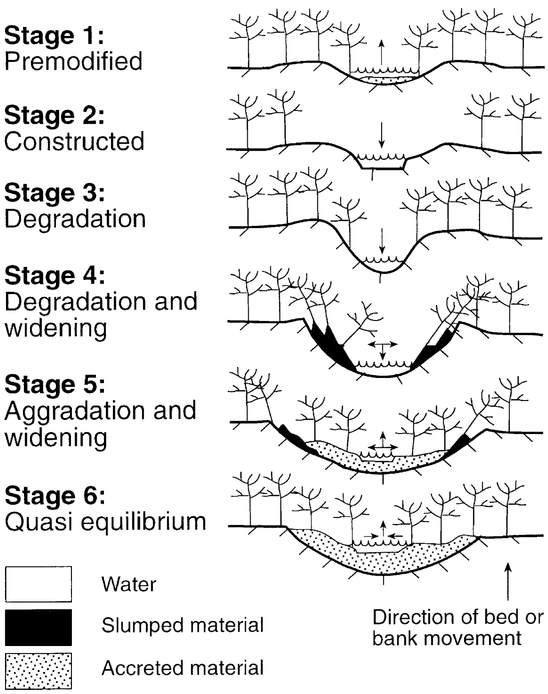


Fig. 1. Stages of channel adjustment in the conceptual channel evolution model by Simon and Hupp (1986).

(Schumm et al., 1984), has been used widely as a framework for evaluating the sequence of adjustment following incision (e.g., Rinaldi and Simon, 1998; Simon and Darby, 1999; Thorne, 1999). In the Simon–Hupp model, the equilibrium channel is initially considered as a predisturbed stage (I) of channel evolution subsequently disrupted by channelization (stage II). Rapid bed degradation then ensues as the channel begins to adjust (stage III). Degradation flattens channel gradient and thus reduces the available stream power for given discharges. Concurrently, bank heights are increased and bank angles are steepened by fluvial undercutting. Thus, the degradation stage (III) is related to destabilization of the channel banks and leads to channel widening by mass-wasting (stage IV). As degradation migrates upstream, aggradation (stage V) becomes the dominant trend in previously degraded downstream sites because the flatter gradient cannot transport increased sediment loads emanating from upstream. Attainment of a new dynamic equilibrium (stage VI), therefore, takes place through (i) bank widening and the consequent flattening of bank slopes, and (ii) gradient reduction by meander extension and elongation.

Evolution towards a new channel configuration involves processes of accelerated erosion and deposition that are significant in terms of their magnitude, extent, and duration. Hence, incision is a major concern because it causes erosion of adjacent lands, threatens river-crossing infrastructure, and produces sediment that causes further problems downstream (Cooke and Reeves, 1976; Graf, 1983; Schumm et al., 1984). Incised rivers also represent disturbed ecosystems in which "...habitat diversity and niche potential are reduced, and...the quality and functions of the species occupying the system are changed" (Brookes, 1988, p. 111). The environmental and socio-economic problems associated with channel incision are, therefore, numerous and have been comprehensively reviewed by Bravard et al. (1999), who identify three main approaches to the management of incised rivers.

(i) Restoration and rehabilitation (Brookes and Shields, 1996; Shields et al., 1999) focus on addressing the causes of incision. Such projects involve changing management practices to increase sediment or reduce runoff supplied from the catchment upstream (e.g., Chaney et al., 1990; Piégay et al., 1997). Alternatively, restoration might involve reconstructing a channelized river to a more stable meandering planform (e.g., Haltiner et al., 1996).

(ii) A variety of measures are used to control or prevent incision, dissipate flow energy, or trap sediment. Such measures often involve the use of "hard" engineering structures such as weirs, spurs, or drop structures (e.g., Peiry et al., 1994; Mendrop and Little, 1997; Klingeman et al., 1998), but vegetative treatments are also common (Chaney et al., 1990).

(iii) Various methods are used to mitigate the worst impacts of incision. Examples of such approaches include flood plain excavation to improve connectivity between ground water and ecological units (e.g., Kern, 1992; Petersen et al., 1992), or introducing artificial features on the bed of the channel to enhance physical habitat diversity (Cooper et al., 1997).

In seeking solutions that may involve one, or combinations, of the above elements, incised channels pose a challenge to engineers and planners because they are so dynamic. Flows that would otherwise be dissipated during over-bank flooding are constricted, so they become erosive. Hence, this often requires implementation of structural grade-control measures as a component of remedial schemes. However, despite their significance, few studies have been undertaken that seek to assess the effectiveness of such structures and consequently improve their design.

In 1984, the United States Congress directed the initiation of the Demonstration Erosion Control (DEC) project. The DEC project is an initiative pursued by a consortium of state and federal agencies to develop and implement basin-wide approaches to channel stabilization and management within the Yazoo Basin of north Mississippi (US Government Printing Office, 1996). The DEC project involves 16 watersheds covering a drainage area exceeding 6800 km^2, with over 2300 grade-control measures (drop pipes and drop structures), 72 flood-water retarding structures, 200 debris basins, and 500 km of bank stabilization (Hudson, 1997). Within each watershed, monitoring of system response to the installed structures is conducted, with the aim of feeding the results back into the design and construction of project features to enhance their performance.

Research on grade-control structures (GCS hereafter) has been a particularly important component of the DEC project, as they are an important means of arresting the headward migration of knickpoints. A

Fig. 2. A typical low-drop grade-control structure on Hotophia Creek, Mississippi.

wide range of different GCS are available, and comprehensive reviews are provided by Neilson et al. (1991) and Watson and Biedenharn (1999). The main focus in this study is on high-drop and low-drop GCS (Fig. 2). These are in-channel structures designed to prevent the upstream passage of knickpoints greater than (high-drop) or less than (low-drop) 2 m in height. In terms of these specific GCS, previous research has focused on two main issues, namely their engineering design (Little and Murphey, 1982; Neilson et al., 1991; Rice and Kadavy, 1998; Robinson et al., 1998; Gu et al., 1999; Watson and Biedenharn, 1999) and their environmental impact. The latter topic has been addressed in terms of channel erosion and sedimentation (e.g., Bormann and Julien, 1991; Raphelt et al., 1995; Watson and Biedenharn, 1999) and in terms of the diversity of degraded aquatic habitats (e.g., Cooper and Knight, 1987; Shields et al., 1995, 1998). However, most of this research effort has been focused on relatively short time scales and over spatial scales restricted to the immediate vicinity (≤ 500 m) of the structures.

2. Objectives

The aim of this investigation is to evaluate the effectiveness of GCS in mitigating channel erosion over time and space scales relevant to the management of incised river systems. This will be achieved by using geomorphological analysis to evaluate and predict the response of the lower 18 km of Hotophia Creek (see next section) during 1961–2050 for two scenarios: one with and the other without grade-control structures. In each case, the following will be evaluated and compared:

(i) erosion and deposition of bed materials via adjustment of the longitudinal profile;
(ii) erosion of bank materials by mass-wasting processes;
(iii) gross rates of channel erosion derived from the bed and banks of the main channel.

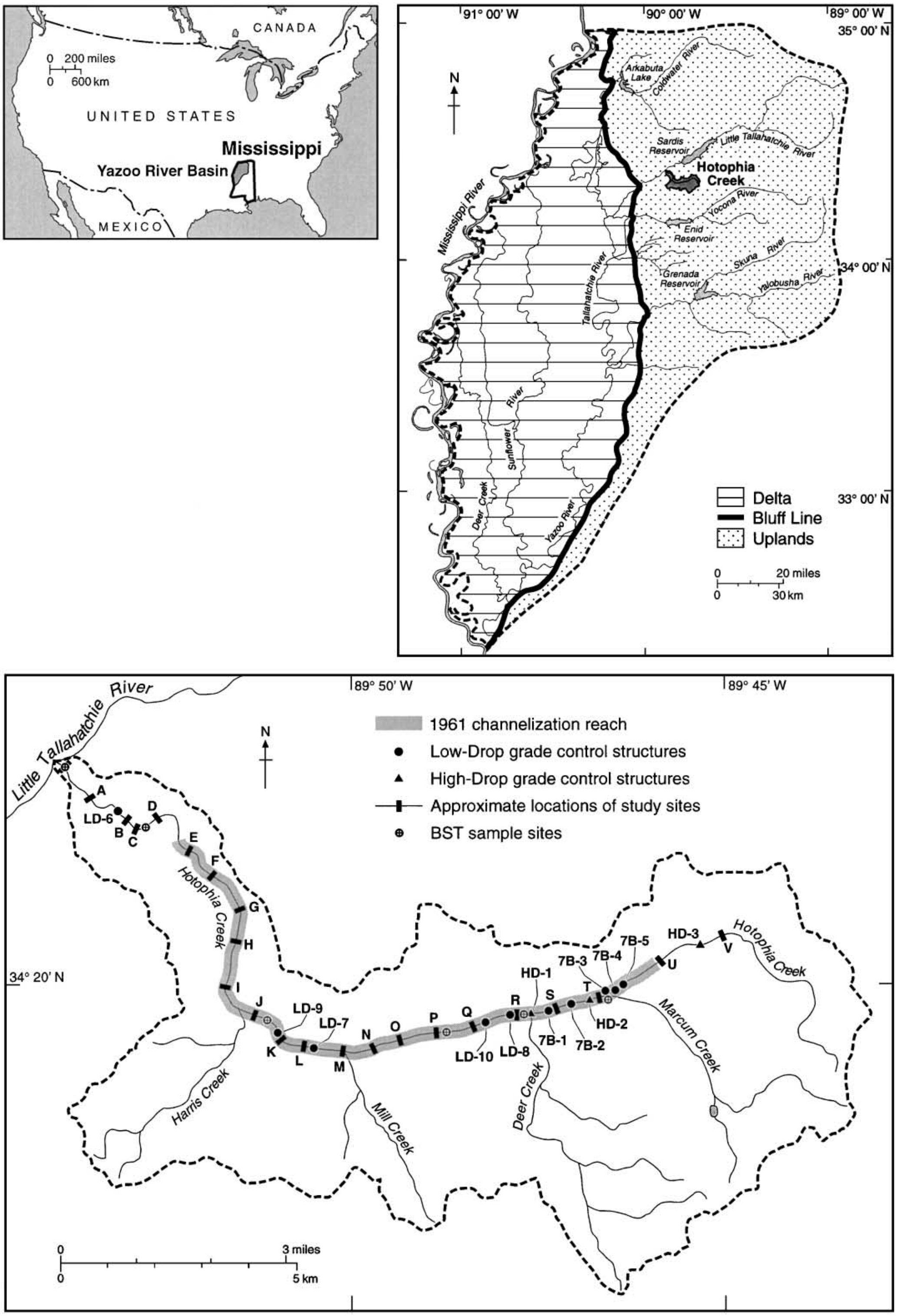
3. Methods and results

3.1. Study area

Hotophia Creek (85 km^2) is a sand-bedded alluvial channel located in the loess hills region of the Yazoo Basin in northern Mississippi (Fig. 3). Watershed topography ranges from small alluvial valleys along the major channels to moderately hilly uplands, with land surface elevation varying between about 60 and 130 m above sea level. Land use is mainly agricultural, with cultivated land (mostly cotton and soybeans) in the valley bottoms and pasture and forest in the uplands. The climate is humid, with hot summer temperatures and mild winters. During 1982–1990, mean annual precipitation in the adjacent Goodwin Creek watershed was 1471 mm, with the majority of large runoff events occurring after intense convective precipitation during winter and spring months (Blackmarr, 1995). Hotophia Creek is broadly representative of catchments throughout the loess belt of the midwestern United States, both in terms of its physiographic characteristics and its history of river management and engineering.

Over the last 170 years, channels within the Hotophia Creek watershed have been severely perturbed by a series of human activities (Simon and Darby, 1997a). Following European settlement of the region during the 1830s, deforestation led to severe upland channel erosion and problems of sedimentation downstream, particularly on the Mississippi alluvial plain, known locally as the ‘Delta’ (Fig. 3). To improve drainage, a 16-km length of Hotophia Creek upstream of its confluence with the Little Tallahatchie River was channelized at the start of the twentieth century (Water Engineering and Technology, 1986). The increase in available stream power and erosive energy that this caused was compounded when sediment supply from eroding upland areas was reduced after a reforestation program implemented during the 1930s. The watershed was further perturbed when construction of Sardis Dam on the Little Tallahatchie River upstream of Hoto-

Fig. 3. Map of the Hotophia Creek study reach showing the extent of the 1961 channelization reach and locations of study cross-sections and BST sample sites. The map also shows the low- and high-drop grade-control structures installed on the main stem of Hotophia Creek during 1980–1996.


CANADA
0 200 miles
0 600 km
UNITED STATES
Mississippi
Yazoo River Basin
MEXICO
91° 00' W
90° 00' W
89° 00' W
35° 00' N
34° 00' N
33° 00' N
N
Arkabuta Lake
Coldwater River
Sardis Reservoir
Little Tallahatchie River
Hotophia Creek
Yocona River
Enid Reservoir
Skuna River
Grenada Reservoir
Yalobusha River
Mississippi River
Tallahatchie River
Sunflower River
Deer Creek
Yazoo River
Delta
Bluff Line
Uplands
0 20 miles
0 30 km
89° 50' W
89° 45' W
34° 20' N
Little Tallahatchie River
1961 channelization reach
Low-Drop grade control structures
High-Drop grade control structures
Approximate locations of study sites
BST sample sites
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
LD-6
LD-7
LD-8
LD-9
LD-10
HD-1
HD-2
HD-3
7B-1
7B-2
7B-3
7B-4
7B-5
Hotophia Creek
Harris Creek
Mill Creek
Deer Creek
Marcum Creek
0 3 miles
0 5 km

phia Creek was completed in 1940. This reduced the water surface elevation of the Little Tallahatchie downstream of the dam by around 0.9 m (Biedenharn, 1983), thereby increasing the energy slope of floodwaters associated with storm runoff generated within the Hotophia Creek watershed. Much of the Hotophia Creek main stem was again channelized during 1961–1963 (Fig. 3), and base level was further lowered after dredging on the Little Tallahatchie River in 1981.

As a result of these disturbances, channels within the catchment responded through rapid and extensive incision. In an effort to mitigate some of the undesirable impacts of channel erosion and sedimentation in the 'Delta' downstream, and as part of the DEC project, three high-drop and 10 low-drop GCS were installed during 1980–1996 (Table 1; Fig. 3). Additional low-drop GCS were installed near the mouths of major tributaries between 1990 and 1992. Hotophia Creek therefore represents an ideal site to investigate the effectiveness of GCS in mitigating accelerated bed and bank erosion along incised channels. Furthermore, Hotophia Creek is broadly representative of similar channels across the loess belt of the midwestern United States. Similar problems of incised channel evolution have also been documented in other parts of the New World where rivers have been perturbed after European settlement (Wasson et al., 1998; Brierley and Fryirs, 1999; Fryirs and Brierley, 1999). This case study may, therefore, have relevance over a wide geographical area.

Table 1
Summary data for grade-control structures installed on the main stem of Hotophia Creek during 1980–1996

Structure	Type	Location (distance upstream from mouth, km)	Installed	Invert elevation (m)
7B-1	Low drop	15.15	1980	79.55
7B-2	Low drop	15.59	1980	81.07
7B-3	Low drop	16.25	1980	82.60
7B-4	Low drop	16.57	1980	84.12
7B-5	Low drop	16.76	1980	85.34
LD-6	Low drop	1.68	1983	60.65
LD-7	Low drop	9.93	1987	71.93
LD-8	Low drop	14.34	1987	78.33
HD-2	High drop	15.91	1991	85.64
HD-3	High drop	17.74	1993	91.13
HD-1	High drop	14.67	1993	81.07
LD-10	Low drop	13.96	1995	76.50
LD-9	Low drop	9.11	1996	68.58

3.2. Geomorphic evaluation

A series of geomorphic techniques was used to reconstruct channel erosion rates for two specific channel adjustment scenarios.

- Case 1 (without GCS) represents the natural recovery of Hotophia Creek after the 1961–1963 channelization and is, therefore, a hypothetical scenario in which post-1980 GCS have not been implemented. This scenario includes the effects of high-flow years observed during 1973–1975.
- Case 2 (with GCS) represents a two-phased channel response. The first phase is identical to Case 1, involving adjustment to the 1961–1963 channelization and the 1973–1975 high-flow years. However, the second phase involves a rejuvenation of Hotophia Creek by renewed incision starting in the mid-1980s. Case 2 represents the actual response of Hotophia Creek and includes the effects of the 1961–1963 channelization, dredging of the Little Tallahatchie in 1981, the high-flow years of 1973–1975 and 1989–1991, as well as the effects of main stem and tributary GCS installed from the early 1980s onwards.

For the purposes of this study, it is convenient to use the simplifications "with GCS" and "without GCS" when referring to the Case 2 and Case 1 scenarios, respectively. While these terms are adopted to promote clarity, it is important to recognise that the Case 2 and Case 1 scenarios do not simply compare channel response with and without GCS because dredging of the Little Tallahatchie River introduces an additional element into the comparison between the two scenarios. However, our methodology does involve analyses to account for the noise introduced by the effects of the 1981 dredging. For both scenarios, predictions of channel adjustment are extrapolated to the year 2050 to account for the influence of GCS on channel adjustment over their full design lifetime.

3.2.1. Bed-level response model

The net contribution of sediment derived from bed erosion and deposition during a specific time interval can be estimated by comparing successive thalweg profiles. For Case 2 (with GCS), historical channel surveys gathered as part of the DEC project (see Raphelt et al., 1995) from 1961 (construction plans), 1976, 1985, 1992, and 1996 were used for this purpose. Empirical bed-level response models, which have worked well in a wide range of environments (Simon, 1992; Simon and Hupp, 1992; Rinaldi and Simon, 1998), were used to predict bed elevations for the hypothetical Case 1 (without GCS) scenario. In this way, bed-level data for the Case 1 scenario were obtained for the time period 1961–1996, enabling the necessary comparisons to be made with the (Case 2) survey data. Each model of bed-level change at an individual site was based on a normalized exponential equation (Simon, 1992):

$$Z/Z_0 = a + b\exp^{-kt} \tag{1}$$

where Z is the elevation of the bed (m) at time t, Z_0 is the initial elevation (m) of the channel bed, and t is the time (in years) elapsed since the year prior to the start of the adjustment process (so that $t_0 = 1$). The dimensionless coefficients a, b, and k are determined by regression. The value of a is equal to the normalized bed elevation (Z/Z_0) when the curve becomes asymp-

Table 2
Parameter values used to initialize the Case 2 ("with GCS") scenario bed-level response models at specific study sites within Hotophia Creek

Study site	Distance upstream of the mouth (km)	Start date	Initial elevation (Z_0, m)	Comments
1	0.04	1981	59.82	For the downstream sites 1–6, the Case 2 scenario begins in 1981 to coincide with the dredging of the Little Tallahatchie River. For these sites, the 1981 starting bed elevations are calculated using the Case 1 scenario bed-level response models.
2	0.98	1981	60.11	
3	1.80	1981	60.96	
4	2.38	1981	61.80	
5	3.05	1981	62.43	
6	4.57	1981	64.38	
7	5.18	1988	64.98	Further upstream (sites 7–13), the channel survey data indicates that the Case 2 scenario begins later, between 1985 and 1992 (see Fig. 4). A 1988 starting date is close to the mid-point of this range and is consistent with the 1987 construction of two key structures influencing this reach (LD-7 and LD-8). The 1988 starting bed elevations are calculated using the Case 1 scenario bed-level response models.
8	6.10	1988	65.96	
9	6.83	1988	66.77	
10	7.62	1988	66.93	
11	8.53	1988	68.50	
12	9.14	1988	69.15	
13	9.91	1988	70.75	
14	10.67	N/A	N/A	Insufficient data to derive a Case 2 model
15	11.43	1988	72.32	See comments for sites 7–13
16	12.19	1988	73.49	See comments for sites 7–13
17	13.35	N/A	N/A	Insufficient data to derive a Case 2 model
18	13.72	N/A	N/A	Insufficient data to derive a Case 2 model
19	14.48	1988	78.32	See comments for sites 7–13
20	15.24	1980	79.55	Initial conditions are based on the invert elevation of low-drop structure 7B-1 located at this site and constructed in 1980.
21	16.0	1985	81.99	Channel survey data indicates that the Case 2 scenario begins between 1976 and 1992 at this site (see Fig. 4U). The 1985 starting date is the mid-point of this range. The 1985 starting bed elevation is calculated using the Case 1 scenario bed-level response model.
22	17.53	1988	87.66	See comments for sites 7–13

totic, with $a > 1$ implying net aggradation and $a < 1$ representing net degradation. The value of b equates to the total change in normalized bed elevation (Z/Z_0), with $b>0$ for degradation and $b < 0$ for aggradation. The value of k is simply indicative of the rate of change of bed elevation over time.

Eq. (1) was parameterized for each of 22 study sites along Hotophia Creek using measured survey data, together with specific values of the initial elevation (Z_0) and starting date (t_0) appropriate for each individual study site and each adjustment scenario. For the Case 1 (without GCS) scenario, an

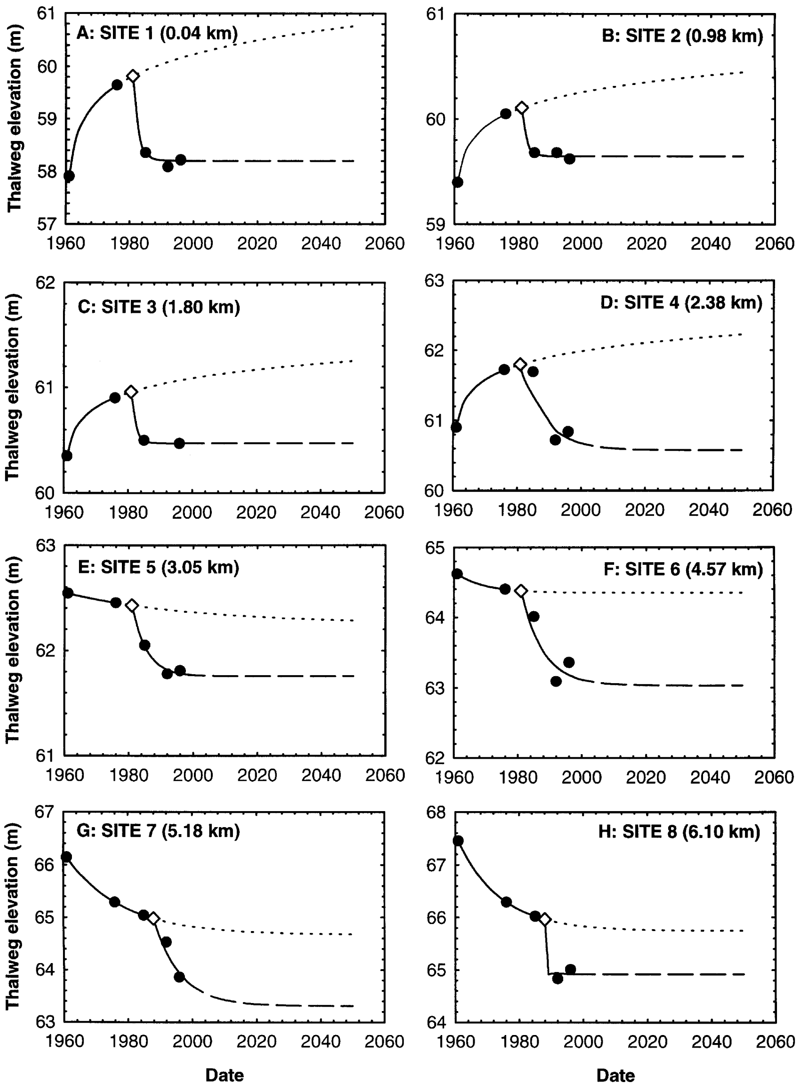


Fig. 4. Empirical bed-level response models developed for various sites along the main stem of Hotophia Creek. The time interval denoted by the ticks on the horizontal axes is 4 years. The solid curves represent the regression models fitted to field survey data, with r^2 values ranging between 0.82 and 1.0. Dotted and dashed lines represent the Case 1 (without GCS) and Case 2 (with GCS) models, respectively, extrapolated beyond the latest available survey date used in the regression. Open diamond symbols indicate the initial elevations for the Case 2 (with GCS) scenario; these are obtained from the respective Case 1 (without GCS) models (see Table 2). Distances shown in each figure indicate the location of the site relative to distance upstream from the mouth of Hotophia Creek.

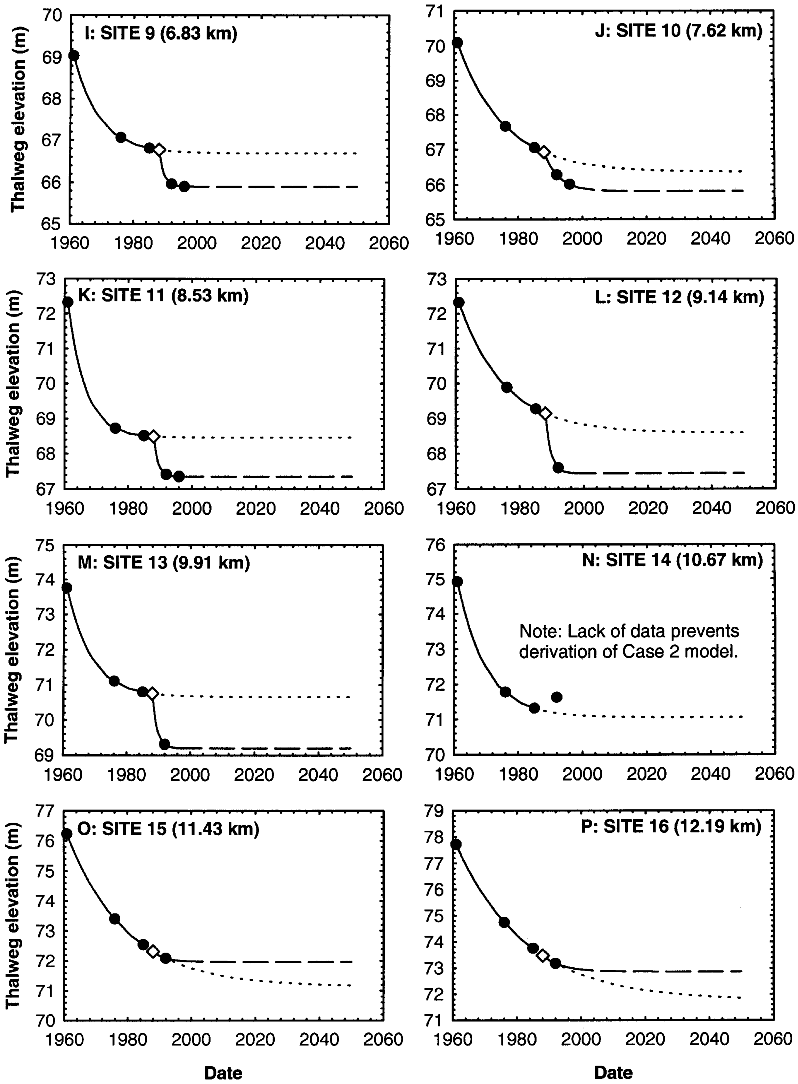


Fig. 4. (*continued*).

initial start date of 1961 was used for all study sites, with initial bed elevations obtained from the 1961 channelization construction plans. The Case 2 (with GCS) scenario is more complex, because the starting dates vary with location along the study reach. The initial conditions for the Case 2 scenario are detailed in Table 2. For both adjustment scenarios, the models have been used primarily to evaluate bed-level changes during the period 1961–1996, but long-term predictions to the year 2050 have also been undertaken. Specific limitations associated with the derivation and application of the bed-level response models are discussed below, but we recognise that extrapolation beyond 1996 (the latest date at which survey data is available) is uncertain. Nevertheless, crude predictions for the distant future are included here for completeness because this time scale is compatible with the design lifetime of the GCS. In any case, it is shown later that uncertainty in the year 2050 predictions has no bearing on the inter-scenario comparison.

Fig. 4 illustrates the derived bed response models for both the Case 1 (without GCS) and Case 2 (with

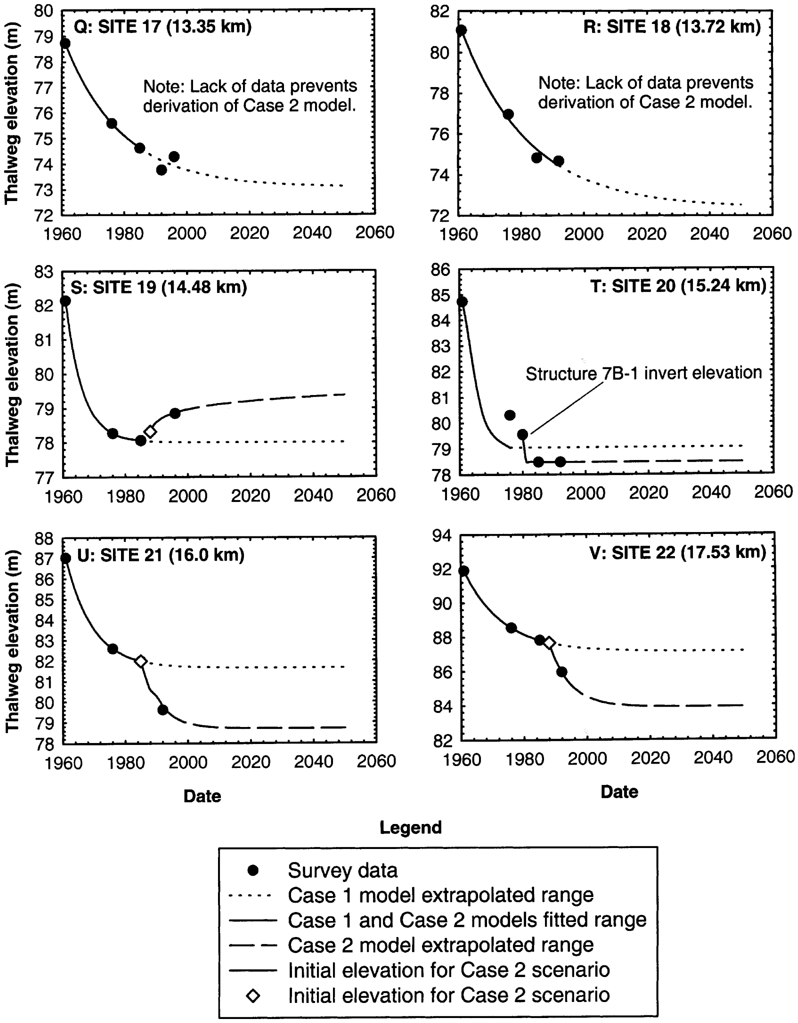


Fig. 4. (*continued*).

GCS) adjustment scenarios. It can be seen that adjustment scenarios involving a general trend of bed degradation characterize most sites in the study reach. Exceptions to this rule include the four most downstream study sites for the Case 1 (without GCS) scenario (where aggradation is dominant), and sites 15–19 for later stages of the Case 2 (with GCS) scenario. While the Case 1 models display smooth trends of channel adjustment, the Case 2 "with GCS" models are characterized by the two-phased response cycle described previously. Accordingly, "with GCS", bed elevations are in general lower than equivalent bed elevations predicted under the Case 1 (without GCS) scenario, with the exception of sites 15–19 in the middle of the study reach.

The bed elevation data obtained from the models illustrated in Fig. 4 can be combined with observed survey data (1961, 1976, and part of 1985 for the "without GCS" scenario, together with 1961, 1976, 1985, 1992, and 1996 for the "with GCS" scenario) to develop Fig. 5. This shows the cumulative impacts of erosion and deposition on thalweg elevations along the study reach for each scenario. Fig. 5A and B shows that while the two channel adjustment scenarios differ in terms of the overall magnitude of response, patterns of response are similar in each case. In both cases, severe degradation (exceeding 5 m in some locations) was experienced in the middle and upstream portions of the study reach, with aggradation restricted to downstream sections close to the confluence with the Little Tallahatchie River. By 1996 (Fig. 5C), Case 1 (without GCS) bed elevations were typically around 1 m higher than their Case 2 (with GCS) counterparts, and locally this difference exceeded 2.5 m. By 2050 (Fig. 5D), the discrepancy is predicted to exceed 3 m in some places. However, in the sub-reach located some 11–15-km upstream of the mouth, bed elevations for the "with GCS" scenario are around 0.5 and 1.0 m higher than the corresponding "without GCS" elevations for the years 1996 and 2050, respectively.

Bed-material yield from the entire reach is estimated by integrating to obtain the area under each thalweg profile and multiplying by the mean bed width for each time interval (Table 3). Volumetric estimates are then converted to mass estimates using an assumed bulk bed-material density of 1430 kg/m^3 (Selby, 1982). More erosion is predicted under the Case 2 (with GCS) scenario than under the Case 1 (without GCS) scenario, with the greatest discrepancy occurring during 1985–1992. In terms of cumulative erosion during 1961–1996, the "with GCS" scenario yields around 418,000 more tonnes (44% extra) of bed material than the "without GCS" scenario. For the period 1961–2050, the discrepancy is smaller but still significant, amounting to some 379,000 tonnes (or 38%) of extra bed-material erosion.

Estimating the precise magnitude of error and uncertainty in the preceding analysis is difficult, but four specific problems can be identified and discussed.

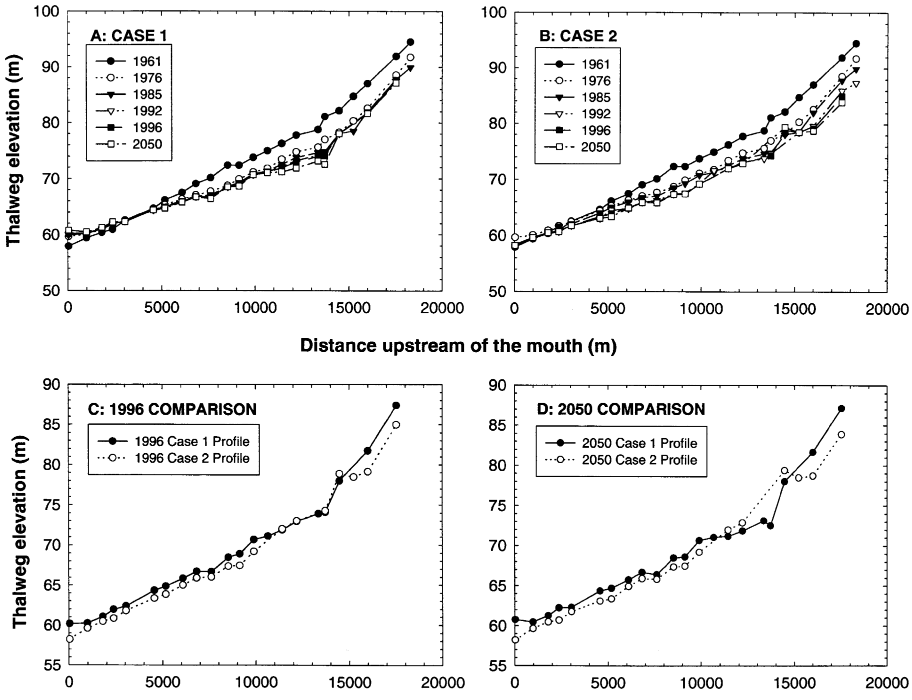


Fig. 5. Thalweg profiles along Hotophia Creek for the period 1961–2050: (A) Case 1 (without GCS) scenario 1961–2050; (B) Case 2 (with GCS) scenario 1961–2050; (C) comparison of Case 1 (without GCS) and Case 2 (with GCS) thalweg elevations in 1996, and (D) comparison of Case 1 (without GCS) and Case 2 (with GCS) thalweg elevations in 2050. Note that the data shown in this figure are a combination of observed survey data (1961–1996 for Case 2 and 1961–1985 for Case 1) and predicted data obtained from the bed response models shown in Fig. 4 (2050 for Case 2 and 1985–2050 for Case 1).

Table 3
Net amounts of bed-material erosion along Hotophia Creek for the period 1961 – 2050

Period	Net amount of eroded bed material (tonnes)	
	Case 1 (without GCS)	Case 2 (with GCS)
1961 – 1976	290,000	290,000
1976 – 1985	151,000	250,000
1985 – 1992	60,000	349,000
1992 – 1996	29,000	59,000
1996 – 2050	94,000	55,000
Subtotal (1961 – 1996)	530,000	948,000
Total (1961 – 2050)	624,000	1,003,000

(i) The survey data used to derive the empirical models may include measurement errors, though these are likely to be minor.

(ii) The bed-level response models for individual sites are sometimes fitted using very few (two or three) data points. While the data are sparse at any one point, the consistency of response over long reaches of the channel indicates that the fitted trends are almost certainly real.

(iii) Predictions of bed elevation obtained by extrapolating statistical models beyond the range of data used in their derivation are subject to uncertainty, though Fig. 4 indicates that the goodness of fit for most of the models is quite high. In extrapolating the bed-level response models, it can also be noted that the curves go asymptotic and show a reduction to almost zero incision by 2050. However, based on conceptual models of channel evolution (e.g., Fig. 1), one would expect aggradation during late stages of channel evolution, as sediment is supplied from eroding reaches upstream. In fact, little late-stage aggradation is anticipated for Hotophia Creek because much of the eroded material is fine-grained material, and coarse-grained material is likely to be trapped by the GCS (see Section 4). Neither of these limitations affect the (survey) data used in analyzing the Case 2 (with GCS) scenario between 1961 and 1996, but the "with GCS" scenario estimates for the year 2050 and Case 1 (without GCS) predictions beyond 1985 are affected.

(iv) In estimating the total sediment yield along the study reach, inherent uncertainties in interpolating between study sites are evident, although a relatively high spatial resolution (22 sites in an 18-km reach) was used here.

3.2.2. Bank response model: channel widening 1961–1996

Similar to the methods used to analyze bed-level changes, the net contribution of sediment derived from bank erosion and deposition during a specific time interval can be estimated by comparing successive profiles of channel-top width along the study reach. For Case 2 (with GCS), the same historical surveys from 1961 (channel construction plans), 1976, 1985, 1992, and 1996 were used for this purpose (Fig. 6). As in the previous section, an alternative method was required to generate top-width profiles for the Case 1 (without GCS) scenario (Fig. 6). Again, the approach employed relied on the use of selected survey data to develop empirical bank response models analogous to the bed-level response models described previously. Hence, for the Case 1 (without GCS) scenario, channel widening during 1961–1996 was estimated using historical channel surveys for the years 1961, 1976, and 1985. These data were then used to develop a simple empirical model of bank response:

$$W = mt^n \quad (2)$$

where W is the predicted channel-top width (m), m and n are coefficients determined by regression, and t is the time in years since the year prior to the start of the adjustment process. Eq. (2) was then used to estimate the (without GCS) channel-top width for the years 1992 and 1996. This type of power law has in the past been shown to be a useful means of predicting channel widening in incised channels destabilized by channelization (Wilson and Turnipseed, 1994).

Modeled and measured widths along the study reach for Case 1 (without GCS) and Case 2 (with GCS) are shown in Fig. 6 for the years 1961, 1976, 1985, 1992, and 1996. This is in contrast with the bed-level response models, which were extrapolated to the year 2050 for each channel adjustment scenario. Such extrapolation was not favored in the case of the bank response model because, unlike the bed response modeling, a simple physically based alternative exists. Bank response during 1996–2050 is discussed in the

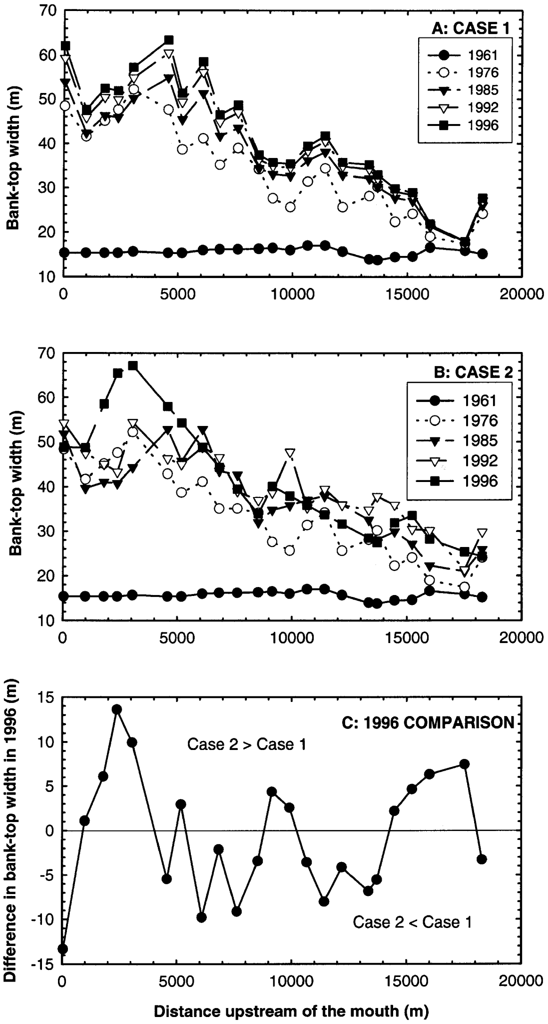


Fig. 6. Bank-top width profiles along Hotophia Creek for the period 1961–1996: (A) Case 1 (without GCS) scenario; (B) Case 2 (with GCS) scenario; and (C) comparison of Case 1 and Case 2 width profiles in 1996. The profiles shown for the Case 2 (with GCS) scenario are all observed survey data, whereas the Case 1 (without GCS) profiles are a combination of survey data (1961, 1976, and 1985) and predictions obtained from Eq. (2) (1992 and 1996).

next section. Estimates of widening during the four intervals between the five dates analyzed herein were converted to net volumes of bank erosion at individual sites by multiplying the estimated net change in width by the corresponding bank height, extracted from the channel survey data. The total volume of eroded bank material was then obtained by integrating these volume estimates along the length of the study reach. Estimates of volumetric bank erosion amounts were then converted to estimates of mass using local values of bank material density obtained from direct field measurements at various sites along Hotophia Creek (Table 5).

Fig. 6 shows that Hotophia Creek experiences significant widening under both adjustment scenarios. In both cases, widening is triggered by mass-wasting initiated by the 1961 channelization, but the Case 2 (with GCS) adjustment scenario is additionally affected by the 1981 dredging of the Little Tallahatchie River. In each case, widening is greatest in the downstream reaches (up to 40 m of widening during 1961–1996) and diminishes (albeit nonuniformly) in magnitude as one moves upstream. The upstream reaches are still subject to considerable amounts of bank erosion, around 12 and 9 m of widening between 1961 and 1996 for the Case 1 (without GCS) and Case 2 (with GCS) scenarios, respectively. In both cases, the spatial distribution of widening is highly nonuniform. For example, by 1996, the "with GCS" scenario results in a significantly wider channel than the "without GCS" scenario in four specific sub-reaches (Fig. 6C), but there are significant lengths of the study reach where the reverse is true. The overall impression is, therefore, one of a complex spatial and temporal distribution of bank response in which the net difference in bank material yield, taken along the study reach as a whole, is small (Table 4). In fact, by 1996, Case 2 (with GCS) yields only an additional 117,000 tonnes of bank-material erosion, a 2% increase relative to the "without GCS" scenario. This is well within the bounds of any error and uncertainty involved in estimating these totals. Differences in the overall amount of material eroded from the banks for each adjustment scenario are, therefore, essentially indistinguishable.

3.2.3. Bank response model: mass-wasting analysis 1996–2050

A Culmann wedge-type bank stability analysis was employed to estimate net channel widening during 1996–2050. The Culmann analysis was selected for its simplicity and because it is appropriate for steep banks with or without tension cracks that fail along approximately planar failure surfaces. Such conditions are commonly encountered along the study reach. Bank stability is assessed by comparing the bank

Table 4
Net amounts of bank erosion along Hotophia Creek for the period 1961 – 2050; note that bank erosion for the period 1996– 2050 is estimated via mass-wasting analysis

Period	Net amount of eroded bank material (tonnes)	
	Case 1 (without GCS)	Case 2 (with GCS)
1961 – 1976	3,848,000	3,848,000
1976 – 1985	920,000	872,000
1985 – 1992	567,000	790,000
1992 – 1996	285,000	227,000
1996 – 2050	953,000	1,120,000
Subtotal (1961 – 1996)	5,620,000	5,737,000
Total (1961 – 2050)	6,573,000	6,857,000

height at a specific location and time with the critical bank height required to initiate mass failure. The critical bank height is estimated using (Selby, 1982):

$$H_c = \frac{4c' \sin\alpha \cos\phi'}{\gamma(1 - \cos(\alpha - \phi'))} \tag{3}$$

where H_c is the critical bank height required to generate instability with respect to mass failure (m), c' is the effective cohesion of the bank material (kPa), α is the bank angle (°), ϕ' is the effective friction angle of the bank material (°), and γ is the unit weight of the soil (kN/m^3). To account for the presence of tension cracks, the critical bank height is calculated using:

$$H_{cz} = H_c - z \tag{4}$$

where H_{cz} is the critical bank height with a tension crack (m), and z is the tension crack depth (m). The tension crack depth is estimated using (Selby, 1982):

$$z = \frac{2c'}{\gamma} \tan\left(45 + \frac{\phi'}{2}\right) \tag{5}$$

Using Eqs. (3)–(5), stability analyses were undertaken at six representative sites (Fig. 3). At each site, the cohesion and friction angle of the bank materials was measured using an Iowa Borehole Shear Tester (BST). At the same time, density samples were collected in order to characterize the soil unit weight. Luttenegger and Hallberg (1981) and Simon and Hupp (1992) have described the main features and operation of the BST. The key advantage of the BST relative to conventional techniques is that testing is undertaken in situ without the need to remove a sample.

With reliable geotechnical data (Table 5) as the foundation of the analysis, a series of calculations were undertaken to develop a set of stability charts (Fig. 7) summarizing bank stability conditions at each of the six sites. These charts enable assessment of changing stability conditions under "ambient" and "worst-case" soil moisture conditions. In this context, "ambient" refers to values of cohesion, friction angle, and unit weight measured under drained conditions in the field at the time of site visits in summer 1996. In contrast, "worst-case" refers to conditions encountered when the soil is fully saturated. Under these conditions, the soil unit weight is maximized due to high water content, and the cohesion component of shear strength is unchanged, while friction angle values are reduced to account indirectly for the effects of positive pore water pressures. Herein, worst-case

Table 5
Bank-material characteristics for the Hotophia Creek study sites (from Simon and Darby, 1997a); note that these data are composite average values derived by considering the bank properties in discrete stratigraphic units at each of the six study sites

Distance of study site above mouth (km)	Ambient conditions				Worst-case conditions			
	c' (kPa)	ϕ' (°)	γ (kN/m^3)	z (m)	c' (kPa)	ϕ' (°)	γ (kN/m^3)	z (m)
0.04	13.8	31.2	22.9	2.1	13.8	0	25.2	1.1
2.40	15.0	24	22.0	2.1	15.0	0	24.2	1.2
8.71	5.8	30.9	23.5	0.9	5.8	0	25.9	0.4
13.4	6.2	36.3	21.3	1.1	6.2	0	23.4	0.5
14.5	19.6	31.6	23.0	3.0	19.6	0	25.3	1.5
16.2	2.4	34.0	23.0	0.4	2.4	0	25.3	0.2

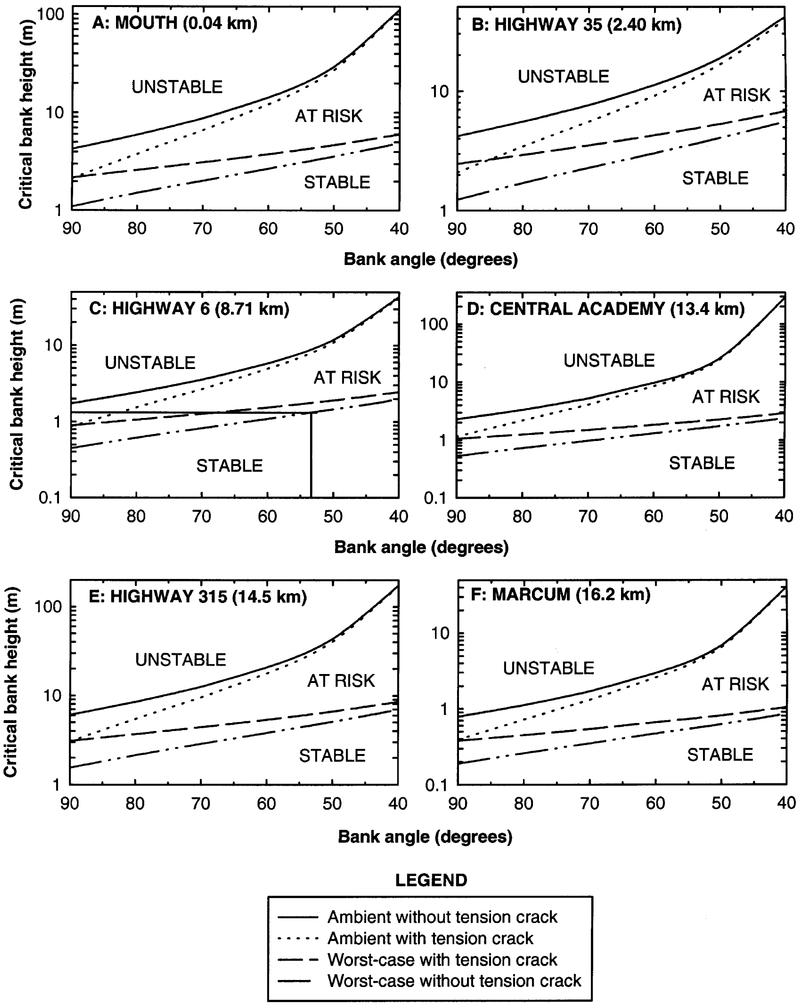


Fig. 7. Simulated bank stability conditions at six representative sites along Hotophia Creek. The distances shown in each figure indicate the location of the site relative to distance upstream from the mouth of Hotophia Creek. An example of the procedure used to estimate the ultimate angle of stability (α_t) is shown in (C) in which a hypothetical bank height of 1.5 m gives a value of α_t of around 54°.

data values were estimated assuming that (i) frictional strength is reduced to zero under saturated conditions, and (ii) saturated soil unit weight values are 10% greater than those recorded under ambient conditions (Simon and Darby, 1997a; Darby et al., 2000).

The analysis proceeds by comparing predicted values of critical bank height (for worst-case conditions) with estimated bank heights for the year 2050. Critical bank heights were obtained from the stability charts (Fig. 7) using bank angle values observed in the field during summer 1996. Predicted critical bank height values were then compared with estimates of "actual" bank heights for the year 2050. The latter were obtained by taking the difference between the flood plain elevation measured from channel surveys and predicted future bed elevations obtained from Fig. 4. For those sites where the actual height exceeded the critical height, the volume of bank material supplied to the channel by mass-wasting was obtained using (Simon and Hupp, 1992):

$$V = H^2(\tan\alpha - \tan\alpha_t) \quad (6)$$

where V is the volume of material per unit length of reach predicted to be susceptible to mass-wasting (m^3/m), and α_t is the ultimate angle of stability (°). The concept of the ultimate angle of stability is based on the notion that bank restabilization will take place once bank heights and angles reach noncritical angles (Carson and Kirkby, 1972; Simon and Hupp, 1992). As bank angles reduce during mass-wasting and bank recession, a threshold is eventually reached where, at a given bank height, the low-angle surface is stable enough to support pioneer woody plants (Hupp and Simon, 1986; Simon and Hupp, 1986). The angle of stability is determined directly from the stability charts developed for each site using the projected (2050) bank height (see Fig. 7).

Using the above procedures, volumes of material emanating from mass-wasting at each of the six study sites were estimated for each scenario. In calculating these volumes, we also assumed that mass-wasting processes operate equally on both banks at a cross-section, which is reasonable along deeply incised channels like Hotophia Creek. The total volume of mass-wasting during 1996–2050 was then estimated by integrating along the length of the study reach (Table 4). In interpreting these estimates, it should be recognised that while the techniques for estimating "actual" bank heights for 2050 are reasonable, the critical bank heights may be reached at an earlier date than 2050. This is because the degrading bed is predicted to reach maximum incision anywhere between 1990 and 2020 (Fig. 4). The total volume of sediment derived from mass-wasting in the period 1996–2050 will not be affected by this problem, though the projected rates of bank-material delivery to the channel (see next section) will be. Hence, it is likely that near-term (up to around 2020) rates of bank collapse will be higher than suggested by simply averaging over the 1996–2050 interval, while longer-term sediment inputs from bank collapse will be smaller. As with the bed-level response models mentioned previously, we have made predictions up to the year 2050 in the full knowledge that these predictions are uncertain simply for the sake of completeness. Furthermore, 2050 is an appropriate date for analysis because it is sufficiently far into the future to ensure incision is complete at all the study sites, thereby capturing all the potential future mass-wasting driven by bed degradation at each site within the study reach.

While recognising these problems, altering the dates over which erosion is predicted to occur does not change any of the results relevant to the specific objectives of this paper. Specifically, the mass-wasting analysis is consistent with the general conclusions of the bank response analysis for the period 1961–1996. Thus, Case 2 (with GCS) mass-wasting during 1996–2050 is predicted to yield 167,000 tonnes of extra bank material erosion above the Case 1 (without GCS) scenario. This extra amount is not sufficient to have any marked impact on cumulative loads over the period 1961–2050. By 2050, the Case 2 (with GCS) adjustment scenario leads to an extra input of 284,000 tonnes of sediment, only a 4% increase relative to the Case 1 (without GCS) scenario.

3.3. Channel erosion rates

The results obtained from the bed-level and bank response models developed in the preceding sections can be combined to determine overall rates of in-channel erosion along the 18-km study reach during 1961–2050, for each adjustment scenario (Fig. 8; Table 6). In interpreting these results, it should be noted that data used for this study include neither the sediment derived from in-channel erosion along tributary channels and the main stem upstream of the limits of the study reach, nor the wash load component of the total sediment yield. We also assume that all the eroded material is rapidly exported from the drainage basin. In reality, much failed bank material is likely to be stored in deposits at the toe of the bank (Simon and Darby, 1997b; Simon et al., 1999). Despite these limitations, the study data should be broadly indicative of trends of sediment yield emanating from the drainage basin for each scenario for the following reasons. First, although the 18-km study reach comprises only 35% of the total channel length within the drainage basin, most of the in-channel sediment supply zones within the watershed are located within this reach. This is supported by reconnaissance studies that indicate the limited extent of bank erosion along tributary and headwater channels (Grissinger et al., 1990). This is probably because more resistant boundary materials (clay) outcrop along headwater channels, especially Harris and Marcum Creeks and Hotophia Creek upstream of the study reach (Grissinger et al., 1990). Second, wash

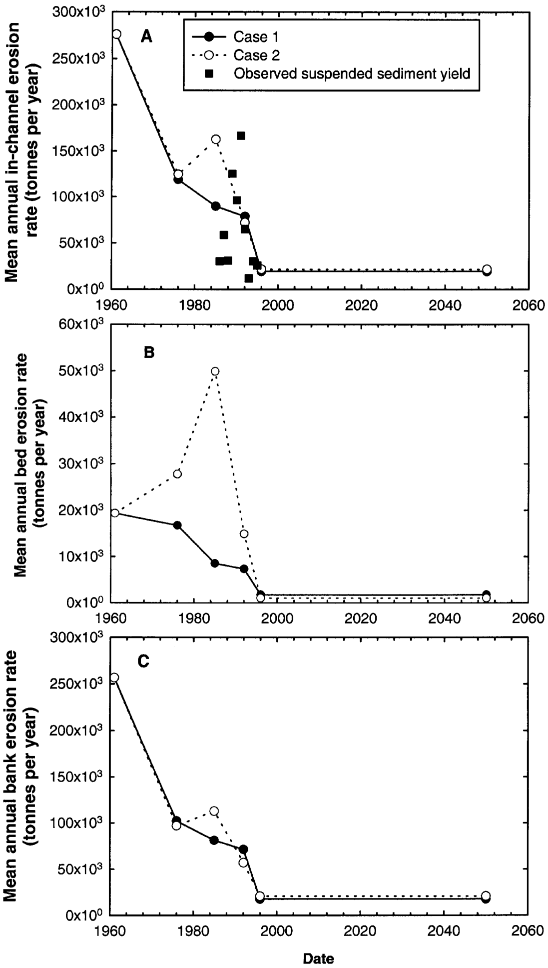


Fig. 8. Annual rates of channel erosion along Hotophia Creek for Case 1 (without GCS) and Case 2 (with GCS) adjustment scenarios during 1961–2050: (A) total in-channel erosion rates and observed suspended sediment yield; (B) bed-material erosion rates; and (C) bank-material erosion rates.

load is known to be a relatively small (<20%) component of the total sediment yield emanating from incised systems in Mississippi (Simon and Darby, 1997b; Thorne, 1999). Finally, the failed bank material debris is fine-grained and is readily reworked by the flow. Thus, the residence time of bank material stored at the toe is probably quite short (Simon and Darby, 1997b; Simon et al., 1999).

As discussed previously, uncertainty in the rates of channel erosion shown in Fig. 8 increase with time beyond 1996. Specifically, it is likely that near-term (up to around 2020) rates of bank collapse may be higher than suggested by averaging over the 1996–2050 interval (Table 6), while longer-term sediment inputs from bank collapse will probably be significantly smaller. However, Fig. 8 shows that for most of the period between 1961 and 2050, differences in annual in-channel erosion rates between each of the two adjustment scenarios fall well within the bounds of any error and uncertainty. However, during 1985–1992 (shown as 1985 on the graph), annual rates of in-channel erosion are significantly higher under the Case 2 (with GCS) scenario than under the Case 1 (without GCS) scenario. Table 6 and Fig. 8 also highlight the nonlinear decline of in-channel erosion rates over time since 1961, consistent with results obtained from other studies of disturbed channels (Simon, 1992; Rinaldi and Simon, 1998). Averaging this variation over the period 1961–2050 gives mean in-channel erosion rates of around 81,000 and 88,000 tonnes/year for the Case 1 (without GCS) and Case 2 (with GCS) scenarios, respectively. In terms of the cumulative effects of these differences, Table 6 shows that by the year 2050, the "with GCS" adjustment scenario results in the erosion of some 663,000 additional tonnes (9%) of sediment over and above the "without GCS" scenario. The majority (63%) of this excess is derived from bed erosion, especially during 1976–1985 and 1985–1992 (Fig. 8B; Table 6). The remainder comes from increased bank erosion during 1985–1992 (Fig. 8C; Table 6).

The validity of our methods can be crudely assessed by comparing erosion rates predicted for the Case 2 scenario (the "actual" adjustment scenario) with observations of sediment load obtained from USGS gauging station 07273100, located 2.4-km upstream of the outlet of Hotophia Creek. Analysis of suspended sediment records for the 10-year period between 1986 and 1995 shows that annual yields vary considerably, with values ranging between 14,000 (1993) and 194,000 tonnes (1991). Averaging over this 10-year period, the observed suspended sediment yield is 75,000 tonnes/year. This compares with predicted mean in-channel erosion rates of 130,000 tonnes/year during 1985–1996 for the Case 2 scenario (Table 6). This discrepancy may be indicative of limitations in the methodology used. Alternatively, two other factors may explain the apparent over-estimate of sediment yield. First, the suspended load measured at the gauge

Table 6
Estimated erosion of channel materials along Hotophia Creek for the period 1961–2050

Scenario	Case 1 (without GCS)						Case 2 (with GCS)					
Source	Bed		Bank		Total		Bed		Bank		Total	
Period	tonnes	tonnes/year	tonnes	tonnes/year	tonnes	tonnes/year	tonnes	tonnes/year	tonnes	tonnes/year	tonnes	tonnes/year
1961–1976	290,000	19,400	3,848,000	257,000	4,138,000	275,900	290,000	19,400	3,848,000	257,000	4,138,000	275,900
1976–1985	151,000	16,800	920,000	102,200	1,071,000	119,000	250,000	27,800	872,000	96,900	1,122,000	124,700
1985–1992	60,000	8600	567,000	81,000	627,000	89,600	349,000	49,900	790,000	112,900	1,139,000	162,700
1992–1996	29,000	7300	285,000	71,300	314,000	78,500	59,000	14,800	227,000	56,800	286,000	71,500
1996–2050	94,000	1700	953,000	17,600	1,047,000	19,400	55,000	1000	1,120,000	20,700	1,175,000	21,800
Subtotal (1961–1996)	530,000	15,100	5,620,000	160,600	6,150,000	175,700	949,000	27,100	5,737,000	163,900	6,685,000	191,000
Total (1961–2050)	624,000	7000	6,573,000	73,900	7,197,000	80,900	1,003,000	11,300	6,857,000	77,000	7,860,000	88,300

does not include the fraction of material transported as bed load, which can be significant in sand-bed rivers such as Hotophia Creek. Second, up to 42% (based on the difference between predicted and measured yields) of the material eroded from channel boundaries during 1985–1996 may have remained in storage. This suggests that the sediment delivery ratio for this reach of Hotophia Creek is about 58%. This is a reasonable upper-limit value for an 85-km^2 catchment in which within-stream coupling (Phillips, 1995) is quite well developed and with limited opportunities for long-term storage of eroded material (American Society of Civil Engineers, 1975; Richards, 1993; Fryirs and Brierley, 1999).

4. Effectiveness of grade-control structures

The results obtained so far are unexpected in that they indicate Case 2 (with GCS) in-channel erosion rates are higher than those associated with the "without GCS" scenario. However, a direct link between the installation of GCS and increased erosion rates has not yet been established. Before firm conclusions about the effectiveness of GCS can be drawn, additional causative evidence is required. Two factors, in particular, complicate the way in which the preceding results can be interpreted. First, the results are based on a temporal analysis of variations in erosion rates at the scale of the reach as a whole, while neglecting small-scale erosion and deposition around structures. Previous research (e.g., Thorne, 1999; Watson and Biedenharn, 1999) has indicated that GCS are effective in reducing erosion at smaller spatial scales. Second, the Case 2 "with GCS" adjustment scenario includes both the influence of GCS and the effects of the rejuvenation of Hotophia Creek after dredging the Little Tallahatchie River in 1981. The possibility exists, therefore, that noise introduced into the analysis by the effects of the 1981 dredging may mask any signal in terms of the effects of GCS on erosion rates. Thus, the next step is to undertake an analysis of spatial and temporal patterns of difference between erosion rates for the Case 1 (without GCS) and Case 2 (with GCS) adjustment scenarios in an effort to link differences to the location and timing of GCS construction along Hotophia Creek.

4.1. Patterns of erosion and sedimentation

Differences between the net amount of material eroded from individual locations along the channel boundary of Hotophia Creek during the period 1961–2050, for each of the two adjustment scenarios, are shown in Fig. 9. In this and subsequent figures, data values greater than zero indicate that the Case 2 (with GCS) scenario results in less cumulative erosion than predicted for the Case 1 scenario. Fig. 9 shows that reaches where there is a reduction in bed-material erosion for the Case 2 (with GCS) scenario are limited in extent and are located between about 11- and 14-km upstream of the mouth (Fig. 9A). This zone is bounded by the low-drop structures LD-7 (9.93 km) and LD-8 (14.34 km), both of which were installed in 1987 (Table 1). Despite a total of nine additional GCS upstream of this sub-reach and two GCS downstream, Case 2 bed-material erosion in these reaches is greater than that predicted for the Case 1 (without GCS) scenario. This pattern is repeated in the predicted trends of bank material erosion along the study reach (Fig. 9B). When combining the bed- and bank-material erosion data, with the exception of a 6-km reach stretching upstream from a starting point approximately 11-km upstream of the mouth (Fig. 9C), there are no locations where the Case 2 (with GCS) scenario is associated with a beneficial impact in terms of reducing in-channel erosion. This raises the question that the GCS may have actually exacerbated problems of erosion along Hotophia Creek.

This question can be addressed by seeking evidence for correspondence between trends of channel response in relation to the timing, as well as location, of specific GCS installed along Hotophia Creek. For this reason, it is necessary to move away from assessment of cumulative impacts highlighted in the preceding analysis and focus on channel response across specific intervals of both time and space (Figs. 10 and 11). The relevant periods of time are 1976–1985, 1985–1992, 1992–1996, and (to a lesser extent) 1996–2050. The assessment of response is not necessary during 1961–1976 because the Case 1 (without GCS) and Case 2 (with GCS) scenarios are identical during this period and the first GCS on Hotophia Creek were not installed until 1980 (Table 1). Although data are presented for each of these four

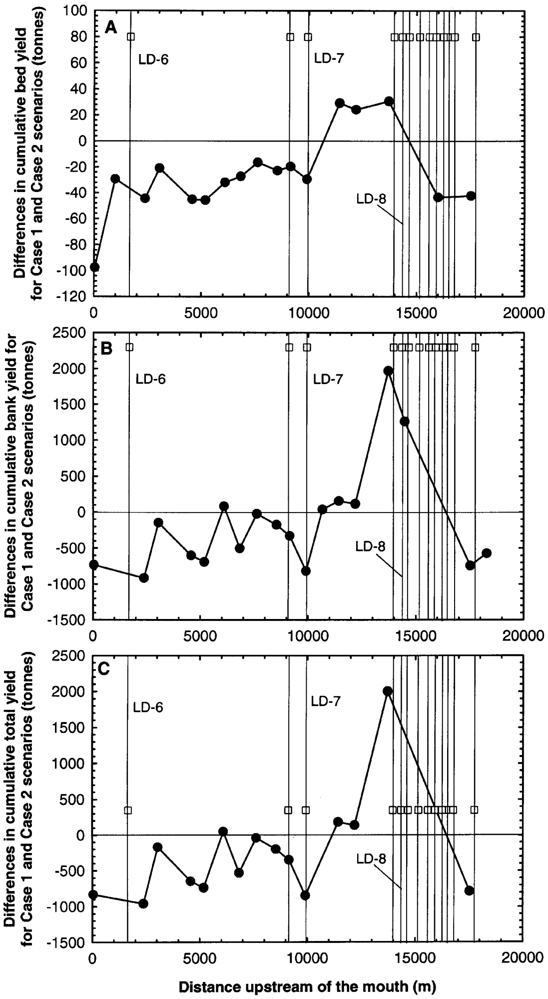


Fig. 9. Differences in cumulative (1961–2050) amounts of channel erosion between the Case 1 (without GCS) and Case 2 (with GCS) adjustment scenarios plotted in relation to the location of grade-control structures installed along Hotophia Creek: (A) bed-material erosion; (B) bank-material erosion; and (C) total in-channel erosion. Vertical lines through open square symbols denote the locations of the grade-control structures. Values greater than zero indicate that the Case 2 (with GCS) scenario results in less cumulative erosion than predicted for the Case 1 (without GCS) scenario (i.e., a beneficial impact).

time intervals, detailed discussion is reserved only for the periods 1976–1985 and 1985–1992. This is because we have already shown that most of the excess material associated with the Case 2 (with GCS) scenario is derived from bed and bank erosion during these intervals.

Fig. 10A clearly shows that for reaches located more than 5-km upstream of the mouth, there is no difference in bed-material erosion predicted for the Case 1 (without GCS) and Case 2 (with GCS) scenarios during 1976–1985. Hence, the five GCS that were installed in the upper portions of the study reach during 1980 appear to have had no discernible impact on channel response during this time interval. However, over a 5-km sub-reach along the downstream part of the study reach, the Case 2 (with GCS) bed sediment yield is greater than that predicted for the "without GCS" scenario. This is probably related to the effects of the 1981 dredging of the Little Tallahatchie River, rather than the direct impacts of LD-6, which was built some 1.68-km upstream of the mouth in 1983. Support for this idea is provided by analysis of this reach during 1985–1992 (Fig. 10B). During this time, the zone of accelerated Case 2 (with GCS) bed-material erosion associated with the 1981 dredging is seen to expand across some 10-km upstream of the mouth, despite the presence of LD-6. Hence, LD-6 was ineffective in preventing the upstream migration of bed erosion caused by rejuvenation of Hotophia Creek following the 1981 dredging. This was probably because knickpoints associated with this phase of erosion had already migrated upstream of LD-6's location prior to its installation in 1983 (see below). By contrast, the transition in Case 1 (without GCS) versus Case 2 (with GCS) response upstream and downstream of LD-7, which is located 9.93-km upstream of the mouth and was built in 1987, is evidence that this structure was effective in preventing the passage of these knickpoints further upstream. However, the spatial extent of the beneficial impact is quite small and reaches further than about 14-km upstream of the mouth are associated with excess bed-material erosion under the Case 2 (with GCS) scenario.

This result suggests that the five structures installed in this reach during 1980, along with HD-2 installed in 1991, have been ineffective in reducing bed-material erosion during 1985–1992. This is intriguing because it is difficult to reconcile enhanced Case 2 (with GCS) bed erosion in the upper reaches of Hotophia Creek with the apparent effectiveness of LD-7 in preventing the upstream migration of knickpoints caused by the 1981 base-level lowering. In fact, it is unlikely that any knickpoint had already migrated into these upper reaches prior to the installation of LD-7 in 1987

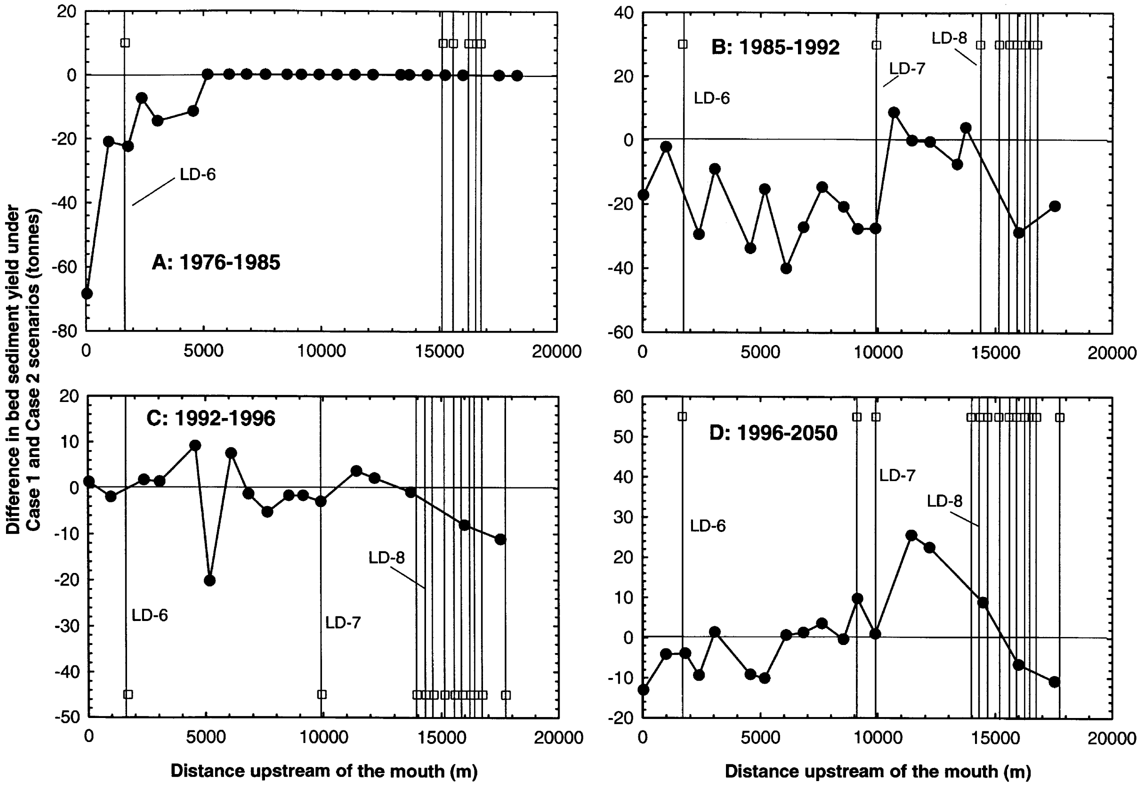


Fig. 10. Differences in bed-material erosion between the Case 1 (without GCS) and Case 2 (with GCS) adjustment scenarios plotted in relation to the location of grade-control structures installed at different times along Hotophia Creek: (A) 1976–1985; (B) 1985–1992; (C) 1992–1996; (D) 1996–2050. Vertical lines through open square symbols denote the locations of the grade-control structures. Values greater than zero indicate that the Case 2 (with GCS) scenario results in less cumulative erosion than predicted for the Case 1 (without GCS) scenario (i.e., a beneficial impact).

because this would require knickpoint migration rates in excess of 1.4 km/year. Therefore, two alternative possibilities offer solutions to this conundrum. First, an interpretation of enhanced bed erosion in the upper reach is based on data from only two individual study sites (Fig. 4U,V). The possibility exists, therefore, that the predicted increased Case 2 erosion at these sites is not real. Fortunately, even if this were true, the spatial extent of this upstream reach is insufficient to undermine the major conclusions drawn from this study. Assuming that enhanced Case 2 bed erosion in the upper reach is real, a second possibility is that the GCS are effective only in reaches with relatively low channel gradients. This idea is supported by the spatial coincidence of the lowest gradient reach within Hotophia Creek (Fig. 5) with the only reach where Case 2 (with GCS) scenario bed erosion is less than Case 1 (without GCS) scenario bed erosion (Fig. 9A). With no additional data available to this study, the true explanation for enhanced Case 2 bed erosion in the upper reaches remains elusive.

Since GCS play less of a direct role in modifying bank erosion rates than they do for bed-material erosion rates, it is not surprising that the trends shown in Fig. 11 are not clear. During 1976–1985, differences in bank erosion rates associated with the Case 1 (without GCS) and Case 2 (with GCS) scenarios are quite small along much of the study reach. The exception to this is the downstream part of the study reach, close to LD-6. This suggests that LD-6, while ineffective in reducing bed-material erosion during this time interval, may have helped reduce bank erosion rates, possibly by trapping material upstream of the structure. Similar to their impact on bed-material erosion rates, GCS in the upstream part of the study reach have had very little effect on bank erosion. However, the possible beneficial role of LD-6 in reducing bank erosion rates in the immediate vicinity upstream is not borne out by the 1985–1992 data (Fig. 11B). In this time interval, two main zones are evident in which Case 2 (with GCS) erosion rates are less than those of Case 1 (without GCS). These are located between 4- to 8- and 10- to 13-km upstream of the mouth and neither coincides with the location of LD-6. On the other hand, the beneficial effect of LD-7 is again evident in this time interval.

4.2. Implications for river engineering and management

The apparent failure of the Hotophia Creek GCS to reduce erosion rates below those associated with the natural recovery of the channel highlights the need to develop improved guidance for their installation and engineering design. In this respect, two key points emerge from this study. First, it is necessary to consider the optimal distribution of structures, in terms of both their location and their timing of installation relative to the geomorphological disturbances propagating through the system. GCS are most effective when they are used to prevent headward migrating knickpoints. To achieve this, they must be installed in early stages (stage II or earlier, see Fig. 1) of incised channel evolution, ideally just upstream of observed knickpoints. In the case of Hotophia Creek, the 13 GCS built between 1980 and 1996 appear to have been installed too late in the adjustment sequence. This is because the majority of incision that occurred in response to the 1961–1963 channelization of Hotophia Creek was already complete by 1980 (Fig. 4).

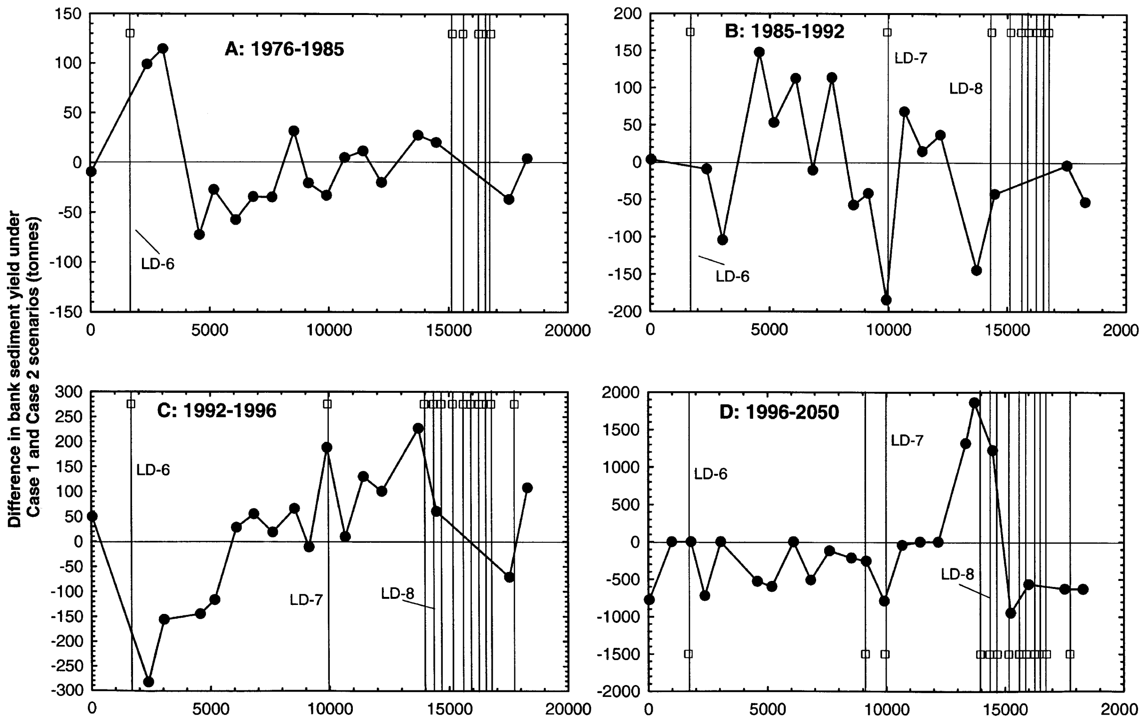


Fig. 11. Differences in bank-material erosion between the Case 1 (without GCS) and Case 2 (with GCS) adjustment scenarios plotted in relation to the location of grade-control structures installed at different times along Hotophia Creek: (A) 1976–1985; (B) 1985–1992; (C) 1992–1996; (D) 1996–2050. Vertical lines through open square symbols denote the locations of the grade-control structures. Values greater than zero indicate that the Case 2 (with GCS) scenario results in less cumulative erosion than predicted for the Case 1 (without GCS) scenario (i.e., a beneficial impact).

Given that the Little Tallahatchie River was dredged in 1981, a second phase of headwards migrating incision could have been anticipated. This second phase of erosion could have been prevented had GCS been installed in the downstream portion of the study reach prior to 1981. In fact, five structures initially installed on Hotophia Creek in 1980 are sited in the upstream portion of the study reach. While LD-6 was later (in 1983) installed 1.68-km upstream of the mouth, the bed-level response models shown in Fig. 4 indicate that this structure was ineffective in preventing erosion during the second phase of channel adjustment. Our observations of streams in north Mississippi indicate that knickpoints can migrate upstream at rates exceeding 1 km/year. Therefore, any knickpoint generated by the 1981 dredging work may have already moved upstream of the location of LD-6 by 1983. In contrast, the Case 2 (with GCS) scenario erosion rates are reduced (relative to the "without GCS" scenario) between LD-7 and LD-8, which were installed further upstream in 1987. Apparently, LD-7 was successful in arresting the headward migration of erosion initiated by the 1981 dredging (see Fig. 10B), albeit at a location some 10-km upstream of the mouth. Given the success of LD-7 in arresting bed erosion in this sub-reach, the installation of three high-drop GCS upstream of this sub-reach in the early 1990s appears unnecessary, likewise the construction (in the mid-1990s) of LD-9 in virtually the same location as LD-7.

The second key point relates to the engineering design of the structures themselves. In comparing the elevations of the inverts of the structures (Table 1) with the elevation of the channel bed at the time of their installation (Fig. 5), the inverts were built above the level of the bed (see Fig. 2). This design feature is intended to promote bed deposition upstream of the structure in order to reduce bank heights and thus help prevent bank erosion upstream (Thorne, 1999). Previous research (Thorne, 1999) has indicated that such a design can be successful in promoting bank recovery upstream of GCS, albeit over a fairly limited (1–2 km) spatial extent.

Unfortunately, in trapping bed material, a raised invert also prevents the transmission of sediment that would otherwise help promote recovery of the bed downstream. In the context of Hotophia Creek, the balance between beneficial upstream impacts versus adverse downstream impacts appears to tip in favor of the latter. A previous study (Simon and Darby, 1997a) highlighted how degradation downstream of LD-7 during 1985–1992 (i.e., the period just after installation of the structure in 1987) was observed over a significant (7 km) spatial extent (Fig. 12). Note that the locus of maximum degradation is observed close to the structure and diminishes in a downstream direction. This suggests that the effect is indeed caused by trapping and is not related to upstream migrating erosion caused by the 1981 dredging of the Little Tallahatchie River. Hence, the design of GCS might be improved by reducing the extent to which the invert is raised above the bed. Furthermore, trapping is likely to be maximized if GCS are installed along previously degraded reaches that are beginning to recover naturally (i.e., stage IV or later reaches in the Simon–Hupp channel evolution model). This serves to reinforce the previous point that the timing of GCS installation is critical if the potential benefits of these structures are to be realized.

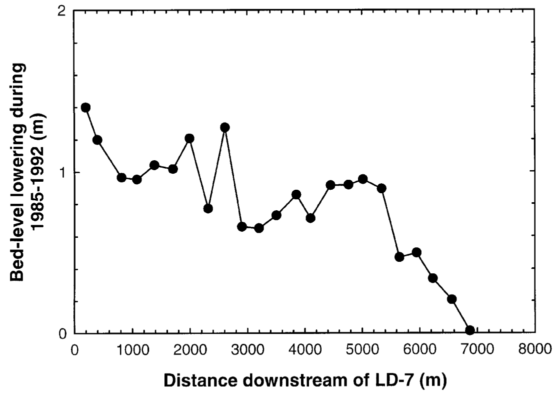


Fig. 12. Channel-bed erosion downstream of low-drop grade-control structure LD-7 between 1985 and 1992 (from Simon and Darby, 1997a).

5. Conclusions

Geomorphological evaluation was used to estimate spatial and temporal trends of bed and bank erosion along an 18-km length of Hotophia Creek, Mississippi. The evaluation was undertaken for two channel adjustment scenarios in response to the 1961–1963 channelization of Hotophia Creek. While the Case 2 scenario represents the "actual" response of the channel and includes the effects of installing a series of GCS, Case 1 (without GCS) represents a hypothetical scenario in which the channel is left to adjust naturally. The geomorphological evaluation relies on the availability of survey data to develop empirical bed and bank response models for each adjustment scenario, together with simple bank stability modeling to predict future rates of bank erosion.

Initially, considering the study reach taken as a whole, the results indicate that channel erosion rates decline nonlinearly with respect to time since 1961 for both adjustment scenarios. However, by the year 2050, the Case 2 (with GCS) adjustment scenario results in the cumulative removal of some 663,000 (9%) extra tonnes of sediment relative to the Case 1 (without GCS) scenario. Most (63%) of this excess is derived from enhanced bed erosion during 1976–1985 and 1985–1992, with the remainder derived from increased bank erosion during 1985–1992. Although the timing of this additional erosion coincides with the main phase of GCS construction along Hotophia Creek, this only provides circumstantial evidence to suggest that the predicted excess erosion is caused by the construction of GCS. This is because the Case 2 (with GCS) scenario also includes the effects of the 1981 dredging of the Little Tallahatchie River.

However, despite the undoubted significance of the 1981 dredging in creating the excess channel erosion associated with the Case 2 (with GCS) adjustment scenario, detailed local-scale analysis provides evidence to support the view that GCS installed along Hotophia Creek have been ineffective in reducing channel erosion rates, for two main reasons. First, the structures were installed between 1980 and 1996, by which time most bed degradation caused by the 1961–1963 channelization had already occurred. Second, by this time, much of Hotophia Creek was moving into later stages of stream channel evolution. As a result, some structures have disrupted the downstream transmission of bed material and hence exacerbated bed degradation downstream.

These results show that, for optimal effectiveness, GCS must be installed in incising channels early in the adjustment cycle. If this is not possible, then great care must be exercised in choosing the location and spacing of structures to optimize the potential for structures to prevent upstream migrating erosion, while minimizing the trapping of coarse material that may promote bed recovery downstream. Overall, when viewed simply in terms of erosion control, a more cost-effective approach to managing Hotophia Creek would have been to allow the channel to undergo a more natural recovery, restricting GCS construction to one or two structures near the mouth of Hotophia Creek. Had they been installed before 1981, these structures could have prevented the rejuvenation of Hotophia Creek that was only eventually stopped 10-km upstream by construction of LD-7 in 1987. However, a more balanced viewpoint would take into account the fact that the Hotophia Creek GCS form part of the multi-objective DEC project. Hence, cost-benefit analysis of the effectiveness of the GCS must account for all relevant elements, including any increased environmental capital known to result from improvements in aquatic habitat quality associated with GCS construction in incised channels of northern Mississippi (e.g., Shields et al., 1995, 1998, 1999). Nevertheless, this study illustrates the need to perform an integrated systems analysis of a watershed to understand the many interactions that can occur and avoid undesirable outcomes.

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