Available online at www.sciencedirect.com

SCIENCE DIRECT®

Geomorphology 70 (2005) 85–96

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Sediment storage and yield in an urbanized karst watershed

Evan A. Hart[a,*], Stephen G. Schurger[b]

[a]*Department of Earth Sciences, Tennessee Technological University, Cookeville, TN 38505, USA*
[b]*Department of Geology, University of Kansas, Lawrence, KS 66045-7613, USA*

Received 17 May 2004; received in revised form 18 April 2005; accepted 19 April 2005
Available online 23 June 2005

Abstract

In karst watersheds, sinkholes and other drainage features control the temporal and spatial pattern of sediment storage across the landscape. However, studies dealing with sedimentation in karst watersheds are scarce and the sediment storage function of sinkholes and caves has not been investigated using a sediment budget approach. In this study, we use estimates of channel erosion, sinkhole sedimentation, and suspended sediment yield to examine changes in sediment storage in the 9 km^2 Upper Pigeon Roost Creek fluviokarst watershed near Cookeville, TN. The study watershed has undergone urbanization over the last ~50 years, and sinkholes and caves in the area show signs of recent sedimentation (buried tree roots, buried cultural artifacts, etc.). While sinkholes are generally considered to be sediment sinks, sinkholes examined in this study are shown to cycle between periods of net sediment storage and net sediment loss. Using copyright dates on trash items buried in sinkhole deposits, we estimated the residence time of sinkhole-stored sediment to range from 6 to 10 years. However, other evidence indicates that some sinkholes may store sediment for several centuries. We propose that sediment storage within sinkholes is controlled by several factors including sinkhole drainage area, sinkhole morphology, and basin sediment yield. In addition, changes in sediment storage in karst watersheds are contingent upon random events such as sinkhole collapses. Annual sediment yield was estimated to be 111 Mg km^{-2} year^{-1} for the entire study watershed and ranged from 11 to 128 Mg km^{-2} year^{-1} for 3 sub-watersheds. Sediment eroded from the watershed, perhaps during historic settlement of the area, is stored within a large cave system underlying the city. However, the results of a partial sediment budget indicate that the cave is presently a net sediment source. Overall, the findings indicate that the sediment storage function of caves and sinkholes varies spatially and temporally, and that these changes need to be incorporated into sediment budgets for karst watersheds.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Sediment budget; Karst; Sinkholes

1. Introduction

Sediment storage and remobilization are essential components of drainage basin sediment budgets (Trimble, 1983). Sediment storage sites may include hillslope hollows, toeslopes, alluvial fans, active

---

* Corresponding author.
E-mail address: ehart@tntech.edu (E.A. Hart).

0169-555X/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2005.04.002

stream channels, and floodplains. Under equilibrium conditions, net change in sediment storage may be considered minimal (i.e., the amount of sediment moving into storage is equal to the amount leaving storage) (Trimble, 1995). However, changes in basin land use, regional climate, and base level can trigger periods of net gain or loss of sediment from storage reservoirs (Schumm and Lichty, 1963; Trimble, 1983; Knox, 1987; Phillips, 1991). One geomorphic setting in which studies of historic and modern sedimentation are scarce is the karst watershed.

Despite the importance of solutional processes in landscape evolution, karst areas are replete with topographic features, particularly sinkholes and caves, that influence suspended sediment storage. Despite their sediment storage potential, only a few studies have examined rates or patterns of sedimentation in sinkholes. Hall (1976) showed that terra rosa soils within sinkholes of southern Indiana, widely thought to be residual in origin, consisted predominantly of transported material. Oh (1992) used radiocarbon dating to reconstruct Holocene deposition in sinkholes in Wisconsin's Driftless Area. Sinkhole sedimentation rates were shown to be one order of magnitude greater than floodplain aggradation rates in the same region. A greater rate of sedimentation in sinkholes than on floodplains is the expected result of greater trap efficiency by sinkholes. Turnage et al. (1997) used ^{137}Cs, the RUSLE method, and evidence from buried soils to estimate historic sedimentation rates in three small sinkholes in east Tennessee. Other studies have linked sinkhole sedimentation levels with past hydrologic regimes or to cave collapses (Knez, 1997; Stepisnik, 2004). Since very few studies have focused on sedimentation in karst areas, we submit that sinkholes are an underutilized and potentially valuable landscape unit for the study of sedimentation rates in karst watersheds. Knowledge of sediment dynamics in caves and sinkholes also has implications for cave fauna, which may be adversely affected by pollutants carried by suspended sediment (Brown and Graening, 2000).

In addition to sinkholes, caves represent another potential sediment storage site in karst areas. However, limited accessibility to and maneuverability within caves complicates the use of traditional methods (i.e., trenching, coring, etc.) to investigate fluvial deposits in caves. Also, a considerable amount of sediment may be stored in cave passages and conduits that are too small to access or too numerous to sample adequately. For these reasons studies assessing sediment storage in caves may benefit from the use of indirect methods, including sediment budgets.

This paper presents a preliminary assessment of fluvial sediment storage and yield in an urbanized, karst watershed. As few studies have sought to examine sediment dynamics in karst watersheds, this paper aims to identify and quantify the function of caves and sinkholes within the context of a sediment budget. With this aim in mind, the research has three specific objectives: (i) to investigate the function (source or sink) of sinkholes with respect to sediment transport; (ii) to demonstrate how sinkhole sedimentation rates can be used as an indicator of basin sediment yield from some sinkhole drainage basins; and (iii) to determine the relative contribution of a major cave system to a preliminary sediment budget for a karst watershed.

2. Study area

The study area is located on the East Highland Rim, bordering the west edge of the Cumberland Plateau in north-central Tennessee. Study sites are situated within the 9-km^2 Upper Pigeon Roost Creek watershed (Fig. 1) (Cookeville East USGS 7.5' Quadrangle), the boundaries of which coincide closely with the city limits of Cookeville, TN (pop. 26,000). The terrain of the area is best described as fluviokarst (White, 1988) with most surface streams flowing through blind valleys before disappearing into sinkholes eroded into Mississippian limestone. Exposed tree roots and bank slumping along many surface streams indicate severe erosion and channel enlargement likely related to increased peak discharges from impervious surfaces. Present land use in the watershed is mainly residential and commercial with impervious surfaces covering between 10% and 40% of subbasins. Sinkhole flooding and sinkhole collapse have threatened several residential areas within the city (Mills et al., 1991).

The Upper Pigeon Roost Creek watershed consists of four main tributaries, which enter the subsurface through sinkholes, combine within Capshaw Cave, and return to the surface as one stream at the Canal (Fig. 1) (Faulkerson et al., 1981). The sinkholes into which Terry and Waterfall Creeks flow are sufficiently

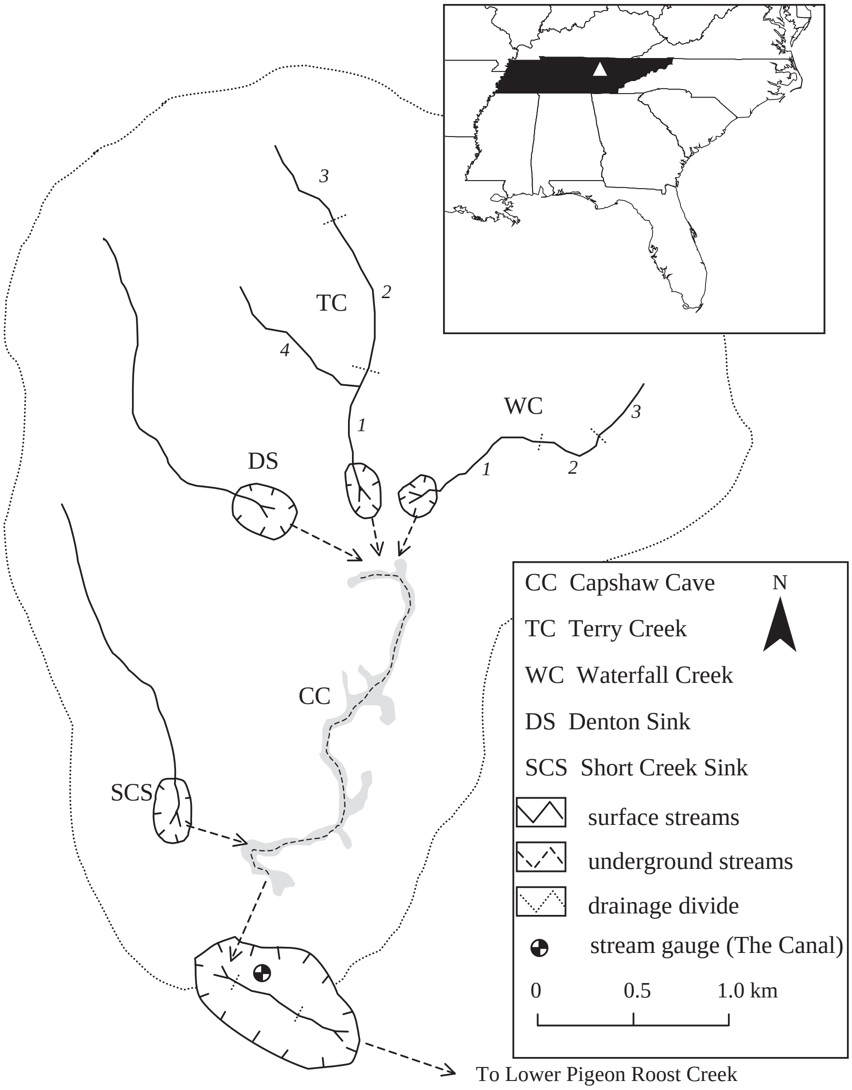

Fig. 1. Generalized diagram of the Upper Pigeon Roost Creek watershed showing numbered stream reaches referred to in Table 1. Capshaw Cave is shown in gray shading.

large to convey flood discharges and back-up flooding is not typically observed at these locations. In contrast, sinkhole outlets for Denton and Short Creeks are covered with sediment and debris that impedes drainage resulting in frequent back-up flooding.

3. Methods

Herein we estimate the relative contribution of Capshaw Cave to the sediment yield of the Upper Pigeon Roost Creek watershed (Fig. 1). To do this we computed the difference between the volume of sediment entering and leaving the cave. We determined the volume of sediment leaving the cave by gauging suspended sediment load at the Canal, a resurgence of the stream in Capshaw Cave (Fig. 1). Due to differences in channel type and sinkhole morphology, two different methods were used to estimate sediment delivery to the cave. Rates of sediment entering the cave from Terry and Waterfall Creeks (Fig. 1) were based on channel erosion rates, as these channels are predominantly earthen-lined. Denton and Short Creeks are predominantly concrete-lined channels, with only a few areas of soil exposed along channel banks. For this reason, the average rate of sediment delivery to Capshaw Cave from Denton and Short Creeks is based on estimates of sinkhole sedimentation rates.

3.1. Sediment delivery to Capshaw Cave—Terry and Waterfall Creeks

In order to estimate channel erosion rates for Terry and Waterfall Creeks, we measured bankfull channel area along these streams and then compared these measurements to the presumed pre-urban bankfull channel area. Cross sections were measured every 20 channel widths and channels were divided into reaches of similar channel area. The average bankfull area of each reach was computed as the average channel area of all cross sections along the reach. We assumed that the channel area (A_C) of the pre-urban, "natural" stream was related to drainage area (A_D) by the regression equation $A_C = 1.2A_D^{0.66}$ (Hammer, 1972), where A_C is the pre-urban bankfull channel area (m^2) and A_D is the drainage area (km^2). The volume of sediment derived from channel erosion along each reach was found by subtracting the area of the assumed pre-urban natural channel from the present channel area that we measured in the field. This difference in channel area was then multiplied by reach length to obtain the volume of sediment derived from channel erosion (Fig. 2). We estimated the average rate of channel erosion by dividing the total volume by 50 years, which is the approximate time since impervious surfaces became dominant in the watershed, as indicated by air photos.

Runoff from off-stream sites was observed during storm events, however, very little sediment was found entering streams in the form of wash or sheet erosion because most streams are de-coupled from upland areas. This de-coupling appears to take place because: 1) channels are buffered by forest and grass areas limiting sediment delivery to channels via overland flow; and 2) numerous broad, soil-mantled sinkholes (not shown in Fig. 1) trap sediment before it reaches stream channels. Based on these observations, and for the purpose of a sediment budget, we assume that bank erosion is the dominant process contributing sediment to streams. While upland sediment production in the Terry and Waterfall Creek watersheds does undoubtedly occur in some areas, the amounts are low compared with bank erosion because the streams are generally de-coupled from upland areas with respect to sediment.

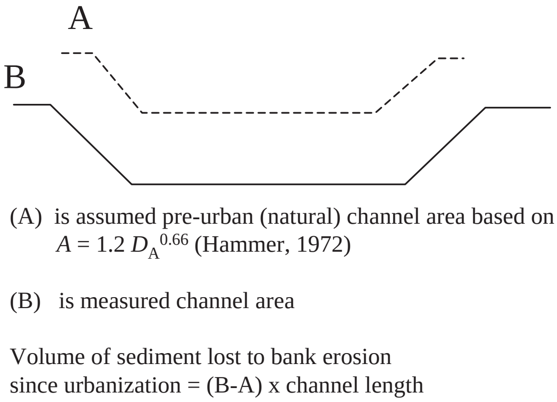

Fig. 2. Diagram shows the method used to estimate channel erosion rates since urbanization. The method assumes that the pre-urban "natural" bankfull channel area is related to drainage area by the regression equation: $A = 1.2D_A^{0.66}$ (Hammer, 1972). Present channel area along study streams was measured along reaches indicated in Fig. 1 and Table 1.

3.2. Sediment delivery to Capshaw Cave—Denton and Short Creeks

The residence time of historic sediment within a drainage basin has been estimated using radiometric methods (e.g., ^{137}Cs, ^{210}Pb) (Walling, 1998) and through the use of dendrogeomorphic evidence (Hupp, 1988). More recently, Phillips and Marion (2001) estimated relative ages for floodplain alluvium based on soil color. While the use of cultural artifacts has been suggested as a possible method for estimating sedimentation rates (Trimble, 1998), few applications of the method are found in the literature. We used recent cultural artifacts buried in alluvium within sinkholes to estimate residence times of stored sediment and thereby infer basin sediment yield. Sediment inputs to Capshaw Cave from the Short and Denton Sink watersheds (Fig. 1) were determined using this method. These sinkholes show signs of recent alluviation, including buried trash and leaf layers and tree bases buried in alluvium.

In order to estimate sedimentation rates for these sinkholes, we measured sediment volume by augering and digging soil pits, and we used buried cultural artifacts as time indicators. Our method involved searching through sinkhole alluvium to find refuse (mainly cans, bottles, and plastic packaging materials) with preserved age indicators. The main age indicators that we found still preserved on refuse were printed copyright dates. Other age indicators, such as product expiration dates on packages of perishable items (e.g., milk bottles), may have given a more recent origin date for refuse. However, such indicators had already deteriorated and were no longer legible, thus the more durable copyright dates were used. The most recent copyright date among refuse from a single layer was used as an age marker for that layer. Because refuse buried in the sinkhole could not have been deposited before its copyright date, its presence in a certain layer indicates the maximum residence time of sediment above that layer. The maximum residence time was then used to determine the minimum rate of sediment yield from the watershed during the period since the refuse was buried.

3.3. Sediment yield downstream from Capshaw Cave

Sediment yield downstream from Capshaw Cave was estimated based on measurements of suspended sediment at The Canal. Discharge was monitored continuously for 18 months using an automatic stage recorder and a discharge rating curve. Suspended sediment samples were collected over a range of discharges and a suspended sediment rating curve was developed (Fig. 3). Using this curve we calculated the average annual sediment yield for the watershed contributing flow to the Canal. We were then able to estimate the contribution of the cave system to basin sediment yield by comparing sediment input (channel erosion along Terry Creek and Waterfall Creek and inputs from Denton and Short Creek Sinks) with suspended sediment yield measured at The Canal.

4. Results

4.1. Waterfall and Terry Creeks

The ratio of natural channel area to channel area after urbanization was termed the “channel enlargement ratio” by Hammer (1972). Channel enlargement ratios for stream reaches along Terry and Waterfall Creeks ranged from 0.7 to 2.6 (Table 1) and are consistent with data from Hammer (1972), who calculated an average ratio of 2.2 for residential watersheds greater than 4 years old on the Pennsylvania piedmont. Although far removed from the stream considered here, Hammer’s streams are similar in that they are also eroded into clay-

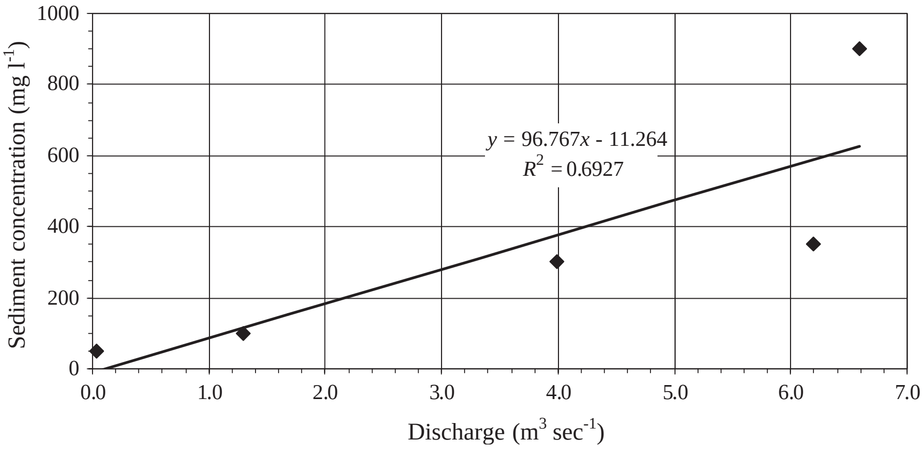

Fig. 3. Sediment rating curve for The Canal at gauging station shown in Fig. 1.

Table 1
Channel erosion rates for Terry and Waterfall Creeks

(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
Stream section[a]	Stream section length (m)	Average bankfull channel area of stream section (m^2)	Drainage area upstream from stream section (km^2)	Expected bankfull channel area of each stream section under natural conditions[b] (m^2)	Channel enlargement ratio (columns C/E)	Estimated channel enlargement since urbanization (columns C–E) (m^2)	Estimated volume of sediment eroded from channels since urbanization (columns B × G) (m^3)
WC-1	876	2.4	1.9	1.9	1.3	0.5	440
WC-2	340	1.6	1.0	1.2	1.3	0.4	140
WC-3	347	1.7	0.8	1.0	1.7	0.7	240
Total							820 m^3 (1230 Mg)[c] (25 Mg year^{-1})[d]
TC-1	191	6.0	2.6	2.3	2.6	3.7	710
TC-2	280	1.5	2.5	2.3	0.7	(−0.8)	(−220)
TC-3	263	2.0	1.5	1.6	1.3	0.4	100
TC-4	356	1.0	0.6	0.8	1.3	0.2	70
Total							660 m^3 (990 Mg)[c] (20 Mg year^{-1})[d]

Estimates are based on the amount of channel enlargement since "natural" pre-urban channel conditions.

[a] WC = Waterfall Creek; TC = Terry Creek; locations shown in Fig. 1.

[b] Expected channel area in m^2 (A_C) under natural conditions at a given drainage area in km^2 (A_D): determined using $A_C = 1.2A_D^{0.66}$ where A_D is value from column D above; original regression equation reported by Hammer (1972) for English units is $A_C = 24.8A_D^{0.66}$.

[c] Assumes a bulk density for sediment of 1.5 g cm^{-3}.

[d] Assumes a ~50-year period since intensive urbanization, based on air photos.

rich, residual soils. This suggests that channel enlargement ratios can be used to make reasonable estimates of channel erosion rates for streams in this study.

All but one surveyed stream reach showed evidence for channel enlargement since urbanization (Table 1). Air photos taken in 1938 indicate little in the way of urbanization and impervious surface coverage in the watershed. However, 1955 air photos show that urbanization had begun in earnest by that time. Based on this evidence, we estimate that widespread urban-induced channel changes began at least 50 years ago in the Upper Pigeon Roost watershed. Channel cross section measurements indicated that ~1480 m^3 of sediment have been eroded from channel banks along Terry and Waterfall Creeks since urbanization (Table 1). Assuming a 50-year period of urbanization and a soil bulk density of 1.5 g cm^{-3}, we compute an average rate of channel erosion of 25 Mg year^{-1} for Waterfall Creek and 20 Mg year^{-1} for Terry Creek (Table 1).

4.2. Denton and Short Creek Sinks

Preliminary observations of Short Creek Sink during 2001 and 2002 indicated that the swallet outlet was effectively blocked with organic debris, resulting in a large accumulation of sediment within the sinkhole and a flat cross-sinkhole profile. In June 2003, flash flooding caused water to rise within Short Creek Sink to an approximate height of 5 m above the sinkhole floor. Under this hydraulic pressure, debris blocking the swallet was apparently flushed out causing the sinkhole to drain rapidly. This event triggered rapid headward erosion, which carved a 1 × 3.5-m outlet channel in the alluvium stored on the sinkhole floor (Fig. 4).

The formation of this outlet channel revealed a complex, yet short depositional history within the sinkhole (Fig. 5). Several buried leaf layers as well as modern cultural artifacts found in the profile attest to the recent origin of this sediment. The deposit is highly stratified and contains abundant coarse mate-

Fig. 4. Short Creek Sink at baseflow in 2003, after the formation of the outlet channel. Eroded channel banks are ~1 m high. Arrow shows direction of flow through the outlet channel toward the terminal swallet.

rial, up to cobble size, reflecting the flashy response of the urbanized watershed. Although no permanent gauging station exists along Short Creek, estimates over a 3-year period indicate that discharge ranges from 0 at baseflow to ~10 m^3 s^{-1} during a typical annual flood. Sediment layers within the sinkhole are separated by sharp boundaries defined by abrupt texture and color changes. Sediment textures of individual layers range from clay loam to very gravelly sand and sediment colors range from 7.5YR 5/8 (strong brown) to 10YR 4/2 (dark grayish brown) (Table 2).

The depositional zone within Short Creek Sink covers an area of ~230 m^2 and contained ~220 m^3 of alluvium before the formation of the outlet channel in June 2003. By November 2003, ~78 m^3 (37%) of sediment had been removed from the sinkhole through the outlet channel. Additional observations in February 2004 showed that a total of 95 m^3 (45%) of sediment had been removed from the sinkhole via the outlet channel. These data indicate that the sinkhole experienced a period of aggradation followed by a period of net sediment loss after the formation of the outlet channel.

Refuse was found throughout the sediment profile exposed in Short Creek Sink (Fig. 5). The most recent copyright date among trash articles from a single layer was used to estimate sediment residence time. For example, a layer of refuse with a most recent copyright date of 1997 was found buried in the sinkhole at a depth of 95 cm. Another refuse layer at 46 cm contained a most recent copyright date of 1999. Based on these markers, we estimate a sediment yield of 56 m^3 $year^{-1}$ from 1997 to 1999 and 26 m^3 $year^{-1}$ from 1999 to 2003. This is an average yield of 36 m^3 $year^{-1}$ (54 Mg $year^{-1}$) from 1997–2003. Combining sedimentation rates with recent surveys of the sinkhole, we can summarize changes in sediment storage in Short Creek Sink from 1997 to 2003 by a series of elevation profiles (Fig. 6). The sequence indicates a period of in-filling from 1997 to 2003, followed by formation of the outlet channel in 2003 and its subsequent enlargement since that time.

Within Denton Sink sediment buries the bases of several trees growing on the sinkhole floor. An outlet channel, perhaps formed in a manner similar to the one in Short Creek Sink, has previously been eroded into the alluvium on the sinkhole floor. However, rounded channel banks and established vegetation along the margins suggest that this outlet channel formed earlier than the one in Short Creek Sink and has since stabilized. The upper 47 cm of the sediment stored in Denton Sink consists of 2.5Y 3/1 (very dark

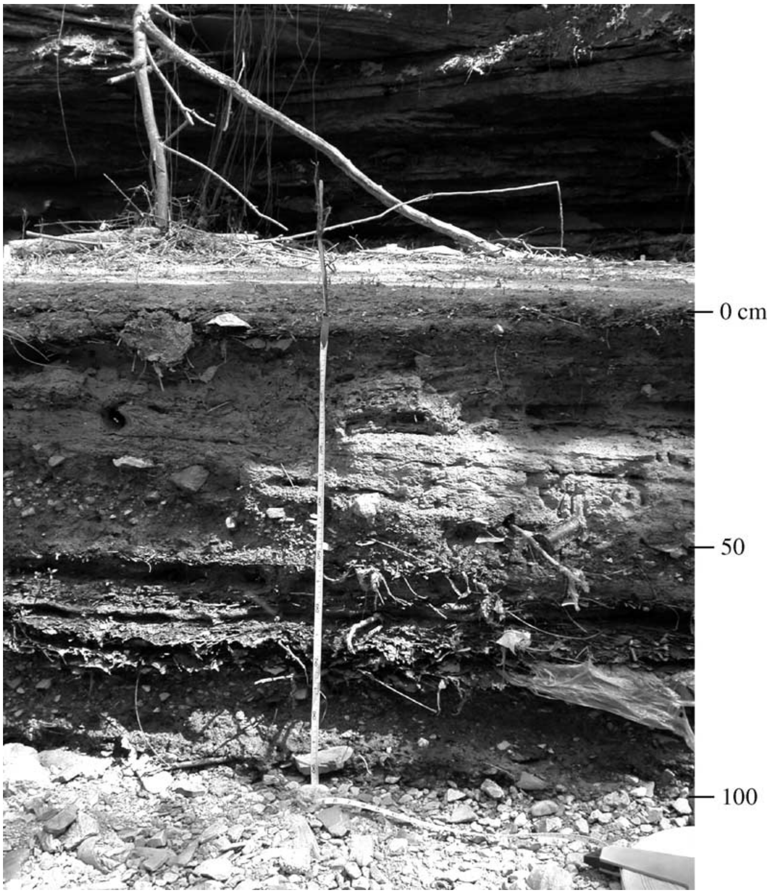

Fig. 5. Layers of sediment within Short Creek Sink exposed by erosion of the outlet channel shown in Fig. 3. Buried leaf layers between 50 and 100 cm are interbedded with trash and other urban debris. Copyright dates on buried trash items were used to estimate a sedimentation rate of 36 m^3 $year^{-1}$ between 1997 and 2003 for this sinkhole. A profile description for this site is given in Table 2.

gray) and 2.5Y 2.5/1 (black) sandy loam (Table 3). From 47 to 65 cm sediment is 2.5YR 4/6 (yellowish-red) very gravelly sandy clay loam. The depositional area within Denton Sink covers ~680 m^2 and contains ~480 m^3 of alluvium. Several refuse items were found in the deposit at a depth of 50 cm. The most recent copyright date from these items was 1993, found on an aluminum can. Assuming that the upper 50 cm of sediment was deposited between 1993 and 2003, we compute a sedimentation rate for that period of 34 m^3 $year^{-1}$ (51 Mg $year^{-1}$) in Denton Sink.

Overall, sediment yield estimates were made using three different methods: (i) estimation of channel erosion since urbanization; (ii) the use of a suspended sediment rating curve; and (iii) sinkhole sedimentation rates as inferred from dates on cultural artifacts. Sediment yield rates for the three different methods ranged from 8 to 128 Mg km^{-2} $year^{-1}$ (Table 4).

Table 2
Profile description for sediment stored in Short Creek Sink

Depth interval (cm)	Matrix color	Texture
0–10	10YR 4/2 (dark grayish brown)	Loamy sand
10–25	7.5YR 5/8 (strong brown)	Gravelly sandy loam
25–28	–	(Buried leaf layer)
28–35	10YR 4/2 (dark grayish brown)	Clay loam
35–45	10YR 4/3 (brown)	Very gravelly sand
45–65	2.5Y 4/2 (dark grayish brown)	Loamy sand
65–68	–	(Buried leaf layer)
68–100	10YR 4/3 (brown)	Very gravelly sand

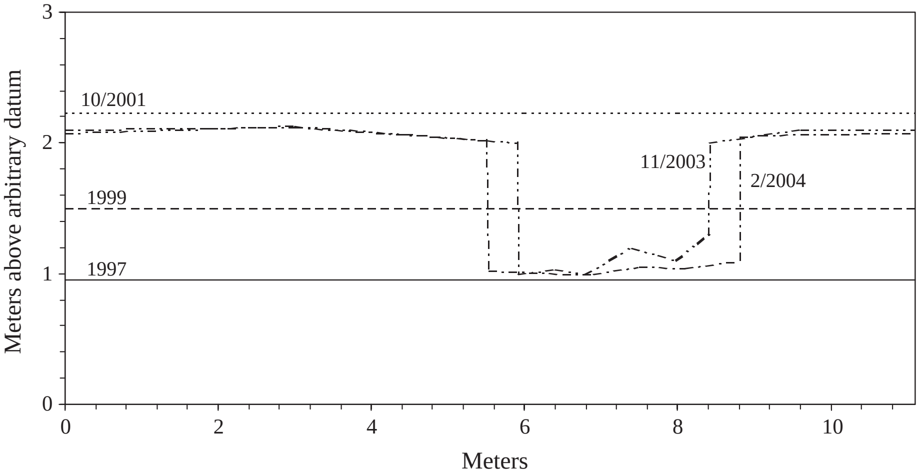

Fig. 6. Cross-sinkhole profiles showing changes in sediment storage within Short Creek Sink between 1997 and 2004 (compare with Fig. 4). Profile elevations in 1997 and 1999 were determined from the copyright dates on buried refuse. All other profiles were surveyed in the field. Sediment storage increased from 1997 until 2003 and has been followed by a period of sediment removal from the sinkhole.

4.3. Sediment budget

By combining our estimates of channel erosion, sinkhole sedimentation, and suspended sediment yield, we can outline a partial sediment budget for the Upper Pigeon Roost Creek watershed (Fig. 7). Channel erosion rates were estimated for Waterfall Creek (25 Mg year^{-1}) and Terry Creek (20 Mg year^{-1}). Average sediment yields from the Denton and Short Creek Sink watersheds, based on sinkhole sedimentation rates, were 51 and 54 Mg year^{-1}, respectively. Sediment yield measured downstream from Capshaw Cave, based on the sediment rating curve, was ~1000 Mg year^{-1}. These results suggest that Capshaw Cave is an important sediment source, perhaps contributing several hundred tons of sediment per year to the Upper Pigeon Roost Creek watershed. While upland sediment production is unknown, it is probably insignificant because of reasons explained in Section 3.1.

Table 3
Profile description for sediment stored in Denton Sink

Depth interval (cm)	Matrix color	Texture
0–40	2.5Y 3/1 (very dark gray)	Sandy loam
40–47	2.5Y 2.5/1 (black)	Sandy loam
47–65	2.5YR 4/6 (yellowish-red)	Very gravelly sandy clay loam

5. Discussion

5.1. Sinkhole sedimentation and the character of sinkhole deposits

Differences in sediment color and texture between Denton and Short Creek Sinks are probably the result of varying land use within these two watersheds (Tables 3 and 4). The upper layers of sediment stored in Denton Sink are darker, suggesting higher organic matter, and lack the coarse fragments found in Short Creek Sink. Perhaps this is due to the land use patterns within the watershed. Denton Sink drains an older residential area where landscaped lawns are likely to contribute sediment having a high organic matter content (from yard mulch, for example). Subsurface soil exposed at construction sites in this region is typically silty or sandy clay with a reddish hue. The lack of reddish colored soils in the upper 47 cm of Denton Sink suggest that few construction sites have been active in this watershed in the last decade. However, the coarse-fragmented, yellowish-red layer found from 47 to 65 cm was possibly deposited during an earlier phase of construction.

Table 4
Sediment yield estimates for sub-watersheds using three different methods

Location	Drainage basin area (km^2)	Sediment yield (Mg km^{-2} year^{-1})	Method of estimation	Land use type
Terry Creek	2.6	8	Channel enlargement ratio	Residential
Waterfall Creek	1.9	13	Channel enlargement ratio	Residential
Short Creek Sink	0.8	68	Sinkhole sedimentation	Commercial
Denton Sink	0.4	128	Sinkhole sedimentation	Residential
Upper Pigeon Roost Creek	9.0	111	Suspended sediment sampling	Residential/commercial

In contrast to Denton Sink, sediment in Short Creek Sink contains abundant coarse material (up to cobble size), as well as several abrupt color changes ranging from strong brown to dark grayish brown (Fig. 5). The coarse texture of these deposits is possibly related to the flashy urban stream and to the presence of several large gravel parking lots within the watershed. The color changes down through the profile suggest frequent changes in the source of basin sediment production or land use change.

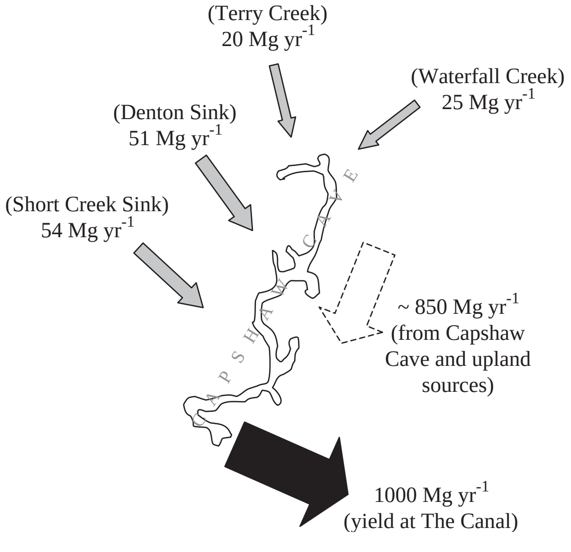

Fig. 7. A partial sediment budget for the Upper Pigeon Roost Creek watershed. Gray shaded arrows show estimates of sediment production from Terry and Waterfall Creeks (based on channel erosion rates, see Table 1) and from Denton and Short Creek Sinks (based on sinkhole sedimentation rates). Black arrow shows measured suspended sediment yield at The Canal during 2002 and 2003. Open arrow represents estimated contributions of Capshaw Cave and upland erosion to basin sediment yield. However, upland erosion is considered to be a minor contributor to basin sediment yield because streams are largely de-coupled from upland areas with respect to sediment, thus the cave is a significant sediment source.

5.2. Use of recent cultural artifacts to estimate sinkhole sedimentation rates

This study has demonstrated that under certain conditions cultural artifacts may be useful in determining sedimentation rates. However, this approach has several limitations. First, the origin date of trash items is often difficult to ascertain. Plastic labels on bottles and printed on ink labels quickly fade making copyright dates difficult to read. In our analysis, numerous trash items were present in sinkhole sediments; however, <10% of these contained discernible copyright dates. Another limitation of this method is that it allows only a minimum estimate of the sedimentation rate, since trash was likely discarded and entered the sinkhole at some point after its copyright date. Another limitation of using cultural artifacts is that their occurrence is dependent upon the presence of human activity in a watershed. This fact, however, makes the method attractive for studies in urban areas.

5.3. Sediment budget

A partial sediment budget (Fig. 7) indicates that Capshaw Cave is a net sediment source within the Upper Pigeon Roost Creek watershed. This conclusion is supported by observations of sediments within the cave itself. For much of its course the cave stream flows through a channel with actively eroding clay-silt banks. This subterranean stream bank erosion appears similar in process to that which is occurring along surface streams upstream from the cave. Also, cave sediment showed lamination but lacked the buried trash layers found in sinkhole deposits, suggesting that little recent deposition has occurred in the cave and that perhaps the cave sediment is of an earlier (pre-urban) vintage than sediment stored in sinkholes.

We are hopeful that further study involving ^{137}Cs analysis will be helpful in distinguishing between pre- and post-1950s cave sedimentation.

5.4. Sediment storage in sinkholes

Results from this study indicate that sediment residence times within Denton and Short Creek Sinks are on the order of 6 to 10 years. However, other sinkholes clearly store sediment for much shorter or longer periods, depending on land use change or changes in sinkhole morphology. Based on a visual inspection of over 30 additional sinkholes, we categorized sinkholes into three groups based on their apparent sediment storage function:

(i) *Total storage sinkholes*: Sediment entering these sinkholes remains in storage for long time periods. These sinkholes are shallow, broad depressions with soil mantles that prevent the direct delivery of sediment to underground streams via a swallet. This category also includes sinkholes in urban environments that have been paved over or filled in. Because of surficial conditions and the absence of a swallet, sinkholes of this type are virtually impervious with respect to sediment. However, sediment may be transported out of such sinkholes if flooding overtops the adjacent drainage divides or in the event of sinkhole collapse. Sinkholes in this category tend to have small drainage areas and insufficient discharge to form a swallet or to keep a swallet free from debris.

(ii) *Variable storage sinkholes*: The sediment storage function of sinkholes in this category varies temporally, mainly from the periodic blockage of swallets by debris. The blockage of swallets is affected by basin sediment supply, which changes depending on land use. Although swallets may become blocked, hydraulic pressure created by sinkhole flooding may flush debris through swallets and lead to a period of net sediment loss from the sinkhole. In this paper, both Short Creek and Denton Sinks appear to have experienced shifts in sediment storage and are thus examples of variable storage sinkholes.

(iii) *Sinkholes with little or no sediment storage*: These sinkholes are not generally important storage sites for sediment because of the presence of large swallets that permit rapid infiltration thereby reducing ponding and sediment storage. Morphologically, such sinkholes may have steep side slopes and lack a suitable flat bottom location for sediment storage. Preliminary analysis indicates that sinkholes of this type have relatively large drainage basin areas, suggesting that sufficient discharge may act to keep swallets free from debris.

Examination of soil profiles around some swallets indicates that sinkholes may, over long time periods, transition between any of the three situations (i–iii) described above. For example, an organic soil horizon (^{14}C-dated at 500 ± 50 BP) was found at a depth of 1.5 m on the floodplain surrounding the Terry Creek Sink swallet. The organic layer is buried by recent alluvium and is interpreted to be the pre-settlement surface A-horizon. The age of the buried organic layer suggests that the sinkhole previously trapped much more of the sediment supplied to it than it does presently. At some point, probably as urbanization came to dominate the contributing watershed, the channel began to down cut into the surrounding floodplain, becoming entrenched and stranding the floodplain above the level of inundation. Thus the present channel is now eroding the old alluvium within the sinkhole floodplain and, due to entrenchment, overbank deposition is rare.

Sinkhole collapse is another contingency that may lead to changes in sediment supply in karst watersheds. For example, in 1995 a collapse sinkhole formed in a new subdivision dumping ~500 Mg of sediment directly into another cave stream in Cookeville. Ongoing construction in the subdivision has led to even more sediment delivery to the cave stream via the sinkhole. Although sinkhole collapses are rare, if they intersect major cave passages, they may introduce sediment to cave streams from surface areas that were previously disconnected from stream channels.

6. Summary and conclusions

Sediment storage within sinkholes is likely controlled by basin sediment supply, sinkhole drainage area, changes in peak discharge, and sinkhole morphology. Increased sediment supply can clog swallets, leading to a period of net sediment storage within the sinkhole. By contrast, increased peak discharges may excavate swallets previously buried by sediment, pushing the sinkhole into a phase of net sediment loss. Examples presented in this paper demonstrate that the residence time of sediment within sinkholes varies from centuries (in the case of Terry Creek Sink) to decades (Short Creek and Denton Sinks). However, changes in sediment storage are also contingent upon instantaneous events such as sinkhole collapse. The sediment budget presented in this study suggests that a local cave system currently functions as a net sediment source within a small, urbanized watershed. Both sinkholes and caves affect the spatial and temporal patterns of sediment storage on the landscape. If sediment budgets are to be computed for karst watersheds an accounting needs to be made of the effects of sinkholes and caves on sediment residence times.

Acknowledgements

This research was supported, in part, by a grant from the Tennessee Department of Environmental Conservation and by the Department of Earth Sciences, Tennessee Tech University.

References

Brown, A.V., Graening, G.O., 2000. Trajectories of water quality parameters and endangered biota in Cave Springs Cave, Arkansas. Abstracts with Programs-Geological Society of America South-Central Section 32, 5.

Faulkerson, J., Burden, D., Burden, K., Edwards, C., Kinley, T., Lee, T., Sparks, V., Starnes, D., Walls, E., Webster, S., 1981. Karst Hydrology, Morphology, and Water Quality in the Vicinity of Cookeville, TN. Unpublished report for the City of Cookeville, TN, Tennessee Technological University, 67 pp.

Hall, R.D., 1976. Stratigraphy and origin of surficial deposits in sinkholes in south-central Indiana. Geology 4, 507–509.

Hammer, T., 1972. Stream channel enlargement due to urbanization. Water Resources Research 8, 1530–1540.

Hupp, C.R., 1988. Plant ecological aspects of flood geomorphology and paleoflood history. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, pp. 335–356.

Knez, M., 1997. Phreatic channels in Velika dolina collapse doline. Proceedings of the 12th International Congress of Speleology, vol. 12, p. 156.

Knox, J.C., 1987. Historical valley flood sedimentation in the Upper Mississippi valley. Annals of the Association of American Geographers 77, 224–244.

Mills, H.H., George, D.B., Taylor, H.N., Ogden, A.E., Robinet-Clark, Y., Forde, R., 1991. Predicting sinkhole flooding in Cookeville, Tennessee, using SWMM and GIS. In: Kastning, E.H., Kastning, K.M. (Eds.), Appalachian Karst: Proceedings of the Appalachian Karst Symposium. National Speleological Society, Huntsville, AL, pp. 159–167.

Oh, J., 1992. Sinkhole sediments in the Wisconsin Driftless Area Karst. PhD Dissertation, University of Wisconsin-Milwaukee, 213 pp.

Phillips, J.D., 1991. Fluvial sediment budgets in the North Carolina Piedmont. Geomorphology 4, 231–241.

Phillips, J.D., Marion, D.A., 2001. Residence times of alluvium in an east Texas stream as indicated by sediment color. Catena 45, 49–71.

Schumm, S.A., Lichty, R.W., 1963. Channel widening and floodplain construction along Cimarron River in south-western Kansas. U.S. Geological Survey Professional Paper, vol. 352D. United States Government Printing Office, Washington, DC, pp. 71–88.

Stepisnik, U., 2004. The origin of cave sediments inside collapse dolines of Postojna karst (Slovenia). Acta Carsologica 33, 237–244.

Trimble, S.W., 1983. A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853–1977. American Journal of Science 283, 454–474.

Trimble, S.W., 1995. Catchment sediment budgets and change. In: Gurnell, A., Petts, G. (Eds.), Changing River Channels. Wiley, New York, pp. 201–215.

Trimble, S.W., 1998. Dating fluvial processes from historical data and artifacts. Catena 31, 283–304.

Turnage, K.M., Lee, S.Y., Foss, J.E., Kim, K.H., Larsen, I.L., 1997. Comparison of soil erosion and deposition rates using radiocesium, RUSLE, and buried soils in dolines in east Tennessee. Environmental Geology 29, 1–10.

\Walling, D.E., 1998. The use of 137Cs and other fallout radionuclides in soil erosion investigations: progress, problems and prospects. Use of 137 Cs in the Study of Soil Erosion and Sedimentation. International Atomic Energy Agency Publication IAEA-TECDOC-1028. IAEA, Vienna, pp. 39–62.

White, W.B., 1988. Geomorphology and Hydrology of Karst Terrains. Oxford University Press, Oxford, UK. 464 pp.