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Spatial distribution of pipe collapses in Goodwin Creek Watershed, Mississippi

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Abstract:

The internal erosion of soil pipes can induce pipe collapses that affect soil erosion processes and landform evolution. The objective of this study was to determine the spatial distribution of pipe collapses in agricultural fields of Goodwin Creek watershed. Ground survey was carried out to detect pipe collapses, and the location, size and surface elevation was measured with differential GPS. A total of 143 of the 145 pipe collapses were found in cropland, and the density was approximately 0.58 collapses per hectare. The spatial distribution of pipe collapses was not uniform as pipe collapses were concentrated in the flat alluvial plains where the land use was dominated by cropland. One of the four parcels had 90% of the pipe collapses with a density of 7.7 collapses per hectare. The mean depth, area and volume of these pipe collapses were 0.12 m, 0.34 m^2 and 0.02 m^3, respectively, and all these properties exhibited a skewed distribution. The drainage area–slope gradient equation, which has been widely used for erosion phenomenon prediction, did not represent pipe collapses in this study as the coefficient of determination was <0.01. This is clear evidence that subsurface flow is not represented by surface topographic characteristics. The pipe collapses were found to intercept runoff, thereby reducing the slope length factor by 6% and the drainage area by 7%. Both of these factors can reduce the sheet and rill erosion; however, the increased subsurface flow could enhance ephemeral gully erosion. Published 2012. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS pipe flow; collapse; erosion; topography; drainage area; slope

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INTRODUCTION

Numerous studies have established the significance of soil pipe flow to catchment hydrology (Jones, 2010), hillslope stability (Uchida *et al.*, 2001), embankment failures (Richards and Reddy, 2007) and erosion of classic and ephemeral gullies (Wilson, 2011). Terajima *et al.* (2000) proposed that understanding soil pipe flow was predicated upon first describing the morphology of soil pipes (shapes, sizes, lengths, networking and tortuosity). It is clear from the reviews by Uchida *et al.* (2001) of such studies in peaty pedosol and hillslopes and by Chappell (2010) for humid tropics that a substantial body of work exists on soil pipe morphology. Such descriptions are not static properties because the very nature of these 'water-sculptured' pores, as described by Jones (2010), is that their morphology is dynamic because of internal erosion.

The internal erosion of soil pipes can result in tunnel collapse that leaves depressions on the land surface. These pipe collapses are evidence of soil loss that was occurring undetected before collapse. They can appear suddenly as mature gullies (Swanson *et al.*, 1989; Ziemer, 1992) or as isolated depressions like mini sinkholes (Verachtert *et al.*, 2010). Compared with morphologic descriptions of soil pipes, few studies have described pipe collapses. Chappell (2010) noted that the measurement of the upslope extent of soil pipes is rare in humid tropics due to the difficulty in identifying their beginning point. Using pipe collapses as evidence of an upper extent, Chappell (2010) showed a figure of soil pipes that, assuming a connected path, extended around 25 m at one location and more than 60 m at another location. They also quoted Sayer *et al.* (2006) and Baillie (1975) as reporting soil pipes that extended 90 m. Holden and Burt (2002) measured pipe lengths in upland blanket peats of Northern England of up to 150 m by identifying pipe collapses upslope from outlets, but they did not describe the pipe collapses. Wilson (2011) noted that pipe collapses observed in laboratory experiments resembled those observed at Goodwin Creek watershed in Northern Mississippi but did not describe their morphology or distribution.

The most extensive investigation of pipe collapses to date was by Verachtert *et al.* (2010) in a 236-km^2 area of Belgium. They identified 560 pipe collapses and noted that 97% occurred in pastures. They used aerial photographs, landowner surveys and personal field checks to identify pipe collapses. They categorized these according

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to their morphology into sinkholes (300 cases), closed depressions (195 cases) and filled-in collapses (65 cases). The mean diameters of the sinkholes and closed depressions were 1.1 and 1.3 m, respectively. They also used LiDAR data to determine the relationship between the slope gradient (S) at the collapse and the upslope contributing area (A). The relationship between A and S to predict where channels begin in response to overland flow is often attributed to Montgomery and Dietrich (1988) but was presented earlier by Patton and Schumm (1975). Researchers (Jones, 1987, 2010; Holden and Burt, 2002) have noted problems by applying A–S relationships to areas where pipe flow is prevalent; namely, that the contributing area is based on surface topography, whereas the contributing area of pipes may extend beyond surface divides.

Regardless of their shape or size, pipe collapses can change the spatial pattern of runoff as well as the governing process from surface flow to enhanced subsurface flow. Depending on the soil and the hydrologic conditions, the resulting water erosion from the affected parcel of land can be increased or decreased. Soil erosion is often classified as sheet, rill, ephemeral gully erosion and gully erosion. Depressions from pipe collapses can affect all of these erosion types. Pipe collapses affect sheet and rill erosion by breaking the hillslope into smaller segments, thereby reducing the slope length factor and changing the drainage area. Slope length factor is one of the key factors in sheet and rill erosion prediction models, such as USLE and RUSLE (Renard *et al*., 1997). Generally, longer slope length results in more soil erosion. The existence of pipe collapses can act as sinkholes, in which surface runoff is diverted into subsurface pipe flow pathways. Although this can reduce sheet and rill erosion, the potential for ephemeral gully erosion by subsurface flow processes increases. Several physically based ephemeral gully erosion models have been developed (Knisel, 1980; Gordon *et al*., 2007). The key factor in these models is runoff prediction, which is dependent on the calculation of drainage area based on surface topography and as previously discussed can be strongly affected by pipe collapses.

The aim of this study was to characterize the morphology and spatial distribution of collapsed pipes in Goodwin Creek watershed in north Mississippi. The spatial distribution of pipe collapses may help us understand the role of pipe collapse from a holistic soil erosion approach.

MATERIALS AND METHODS

Study area

The study area was a 248-ha area within the 2132-ha Goodwin Creek experimental watershed (GCEW) of North Mississippi (Figure 1). The GCEW was described in detail by Kuhnle *et al.* (2008). The watershed is in the bluff hills physiographic subprovince with an elevation range from 71 to 128 m a.s.l. The upland areas have a thin loess surface that is highly erodible. Historically, the watershed was used extensively for agricultural production from the uplands to

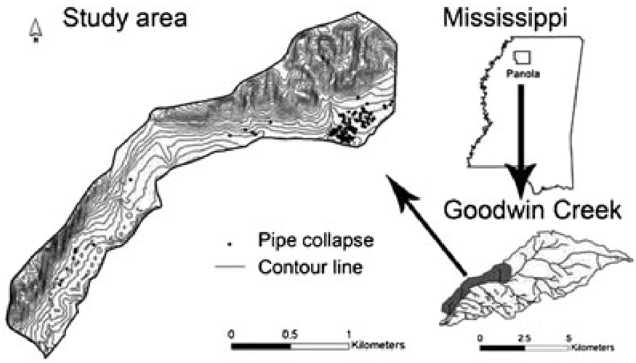

Figure 1. Location of the study area. The contour line interval was 1 m. Locations of pipe collapses are identified as solid dots

the channels. However, cultivated land has decreased since 1982 from 26% to only 8% (Kuhnle *et al*., 2008), with the uplands managed as pasture and forest and present day agriculture limited to the alluvial plains. Goodwin Creek is deeply incised and has an average channel slope of 0.004. Numerous erosion control structures and practices have been established in and along the channels such that most of the channels in GCEW currently have riparian forest buffers. Reaches without vegetation are subject to undercutting by seepage erosion and collapse (Fox *et al*., 2007). The annual precipitation averages 1358 mm, with a fairly uniform monthly precipitation of 127 mm from November through June and 86 mm for July through October.

The current land use is dominated by grassland (pasture), forest and cropland (Figure 2A). The cropland is located on lower, nearly level, alluvial plains of the watershed. Four parcels of cropland were surveyed for pipe collapses (Table I). The two parcels farmed for cotton were managed as no-till but with furrows reestablished every few years. The furrow interval was approximately 0.9 m, and the furrow depth was 10 cm. The two parcels farmed for soybean were managed as flat land no-till. Both management systems have crop residue left on the surface after harvest and no winter cover crop. Thus, the soil surface had not been disturbed by tillage for several years at the time of this study.

The mean slope gradient of the study area within Goodwin Creek was approximately 2.61°. The slope gradients of the upper part of the hillslope were generally larger than 3°, whereas the slope gradients of the lower part were generally less than 2°. The relatively flat (<2% slope) alluvial plains are typically Falaya silt loam (coarse-silty, mixed, active, acid, thermic Aeric Fluvaquent) and Collins silt loam (coarse-silty, mixed, active, acid, thermic Aquic Udifluvent) soil series (Figure 2B). The surrounding hillslopes (2%–8% slope), managed as pasture and forests, are generally Grenada silt loam (fine-silty, mixed, active, thermic Oxyaquic Fraglossudalfs), Loring silt loam (fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs) and Memphis (fine-silty, mixed, active, thermic Typic Hapludalfs) with some gullied land. The transition areas (2%–5% slope), which are in cropland, tend to be either Calloway silt loam (fine-silty, mixed, active, thermic Aquic Fraglossudalfs) or described as gullied land.

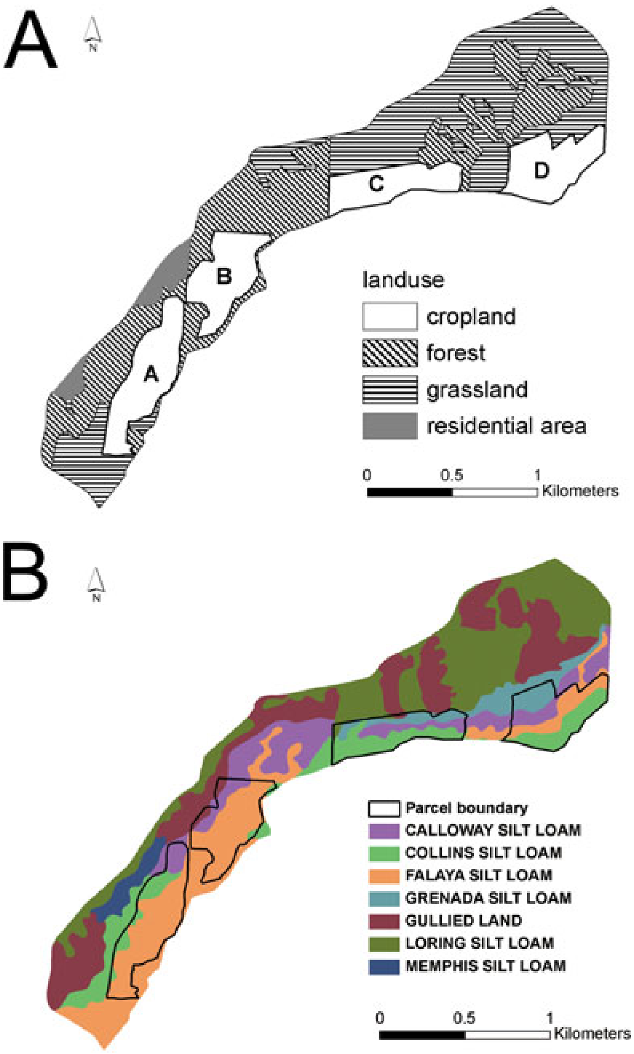

Figure 2. (A) Land use of the study area. (B) Soil map and parcel boundary of the study area. A, B, C and D are parcel identifications

Ground survey

A detailed field inspection was carried out in the cropland and parts of the grassland to detect pipe collapses. Given that Verachtert *et al.* (2010) only observed one pipe collapse in forest, it was assumed that no pipe collapses would be found in the forest areas. The location and the size of each pipe collapse were measured with differential GPS (Topcon GR-3; Figure 3A). The accuracy of this GPS was 1 cm in horizontal direction and 1.5 cm in vertical direction. The surface elevation of cropland and grassland was surveyed with differential GPS by mounting the GPS on an all-terrain vehicle and driving the vehicle down paths spaced 10 m apart and with measurement intervals of 5 m along paths. The surveyed topography was converted into a DEM (10-m resolution) for further analysis. For other areas (forestland, residential area and some of the grassland), the topography was based on the USGS DEM (1/3 arcsecond) that was converted into a DEM (10-m resolution).

Spatial distribution analysis

For each pipe collapse, several points were measured on the upper edge and bottom randomly. To derive the morphology of pipe collapse, two triangulated irregular networks (TINs) were formed, one with only the upper edge points and one with all the measured points. These two TINs were converted into rasters (1 cm in size). Then, the depth subtraction and the volume of the pipe collapse were calculated with the subtraction of these two rasters. The analysis was conducted using ArcGIS 9.3 (www.esri.com).

Topographic analysis

To calculate the slope gradient, S, of pipe collapses, the measured surface elevation was converted into a TIN and converted into a DEM (10 m in size). The slope gradient was computed for each raster.

Rainfall rarely exceeds the infiltration capacity of forest soils (Wilson and Luxmoore, 1988); therefore, to calculate the surface drainage area, it was assumed that the forested areas would not contribute overland flow to the drainage area. This assumption was verified by observations made during intense rain storms. It has been observed in the study area that runoff, for most events, follows the furrow direction into pipe collapses (Figure 3B). However, during a ground survey after a major rain storm on 28 February 2011, some furrows were overtopped by runoff, in which case the surface topography will determine the surface drainage area. The amount and intensity of the rainfall that produced overtopping of furrows was 17.3 mm and 4.5 mm/h, respectively. Therefore, the surface drainage area, A, of pipe collapse was calculated for two cases. For the field topography dominated case, the software of TOPAZ (Garbrecht and Martz, 1999) was used to calculate surface

Table I. Characteristics of each parcel

Parcel ID	A	B	C	D
Total area (ha)	19.6	16.4	14.6	16.8
Mean slope (°)	0.46	0.72	1.17	0.64
Crop	Soybean	Soybean	Cotton	Cotton
Soil series and area percentage in the parcel	Fa (72%) Co (18%) Ca (10%)	Fa (76%) Ca(16%) Gu (6%) Co (2%)	Co (50%) Gr (23%) Ca (22%) Lo (4%) Gu (1%)	Co (36%) Fa (29%) Gr (19%) Ca (16%)
Tillage	No till without furrow	No till without furrow	No till with furrow	No till with furrow

Fa, Falaya silt loam; Ca, Calloway silt loam; Lo, Loring silt loam; Co, Collins silt loam; Gr, Grenada silt loam; Gu, Gullied land.

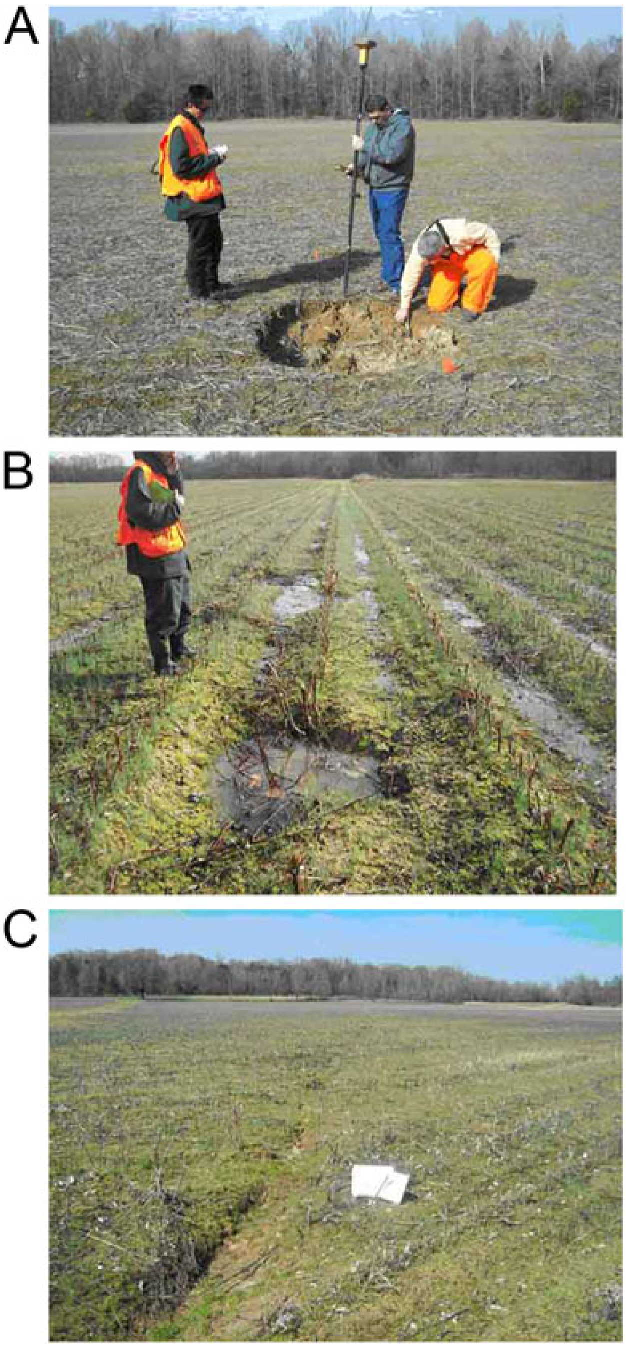

Figure 3. (A) A pipe collapse in parcel A, which does not have furrows, illustrating the morphologic measurements with differential GPS. (B) A pipe collapse in parcel D, illustrating runoff following the furrow direction into the pipe collapse. (C) The ephemeral gully in parcel D used for addressing the effect of runoff interception by pipe collapses on drainage area

drainage area on the basis of the field DEM (10-m resolution). In the tillage roughness dominated case, runoff was assumed to flow along furrows, and the surface drainage area was calculated by measuring the area of each furrow affected by the corresponding pipe collapse. To facilitate this calculation, a detailed survey of flow direction of each furrow was made using visual observations and differential GPS measurements.

A regression equation of slope gradient (S) and surface drainage area (A) at the pipe collapse location was determined by ordinary least squares regression on double logarithmic scale. The equation to illustrate the S–A relationship was in the form of

$$S = aA^b$$

with a and b as coefficients.

Effect of pipe collapse on erosion

Pipe collapses mainly affect sheet and rill erosion by changing the slope length of runoff. The west part of parcel D, where most of the pipe collapses were located, was selected to estimate this effect. The parcel was first divided by furrows, and runoff was assumed to flow along the furrow. Each furrow was further divided into furrow segments by using pipe collapse locations as break points. After dividing, each furrow segment was treated as an individual hillslope with an origin and end point, thereby providing a slope length for all furrow segments with and without pipe collapses.

The interception of runoff by pipe collapse can also affect ephemeral gully erosion by affecting the surface drainage area. An ephemeral gully on the east side of parcel D was selected (Figure 3C) to estimate this effect. The surface drainage area, at different cross sections along the ephemeral gully, was calculated assuming the runoff always flows along the furrows for two cases: with and without pipe collapse. For the case without pipe collapse, the surface drainage area was calculated on the basis of topography alone. For the case with pipe collapse, runoff intercepted by a pipe collapse was assumed to drain into the subsurface, and therefore, this portion of the drainage area was deleted from the surface drainage area calculation for the ephemeral gully.

RESULTS AND DISCUSSION

Spatial distribution

A total of 145 pipe collapses were found. Among these, 143 were found in croplands and only two were found in grasslands (Figures 1 and 2). Among the pipe collapses in croplands, 5 and 130 were found in parcels C and D, respectively (Table II and Figures 1 and 2), where the land was tilled with furrows. It should be noted that 90% of the pipe collapses were located in parcel D, which had

Table II. Pipe collapse numbers of different size (diameter) for each parcel

	Parcel A	Parcel B	Parcel C	Parcel D	All
$D < 0.25$ m	1	–	–	11	12
0.25 m $< D <$ 0.5 m	4	1	1	66	72
0.5 m $< D <$ 1.0 m	1	–	3	39	43
1.0 m $< D <$ 1.5 m	–	–	1	13	14
1.5 m $< D <$ 2.0 m	1	–	–	–	1
$D >$ 2.0 m	–	–	–	1	1
Total	7	1	5	130	143

D is the diameter of the pipe collapse.

a density of 7.7 collapses per hectare. Most pipe collapses in parcel D were located in the lower landscape position near the creek (Figure 1). Aerial photos from 1937 indicate that this area contained an old meandering bend of the creek (Figure 4) and evidence of a different meandering bend in the adjacent field before 1937. The recent alluvial deposits that filled these meandering channels and potentially others over the years were obviously conducive to internal erosion processes that induced pipe collapse.

Table III. Morphologic characteristics of pipe collapses

	Equivalent diameter (m)	Maximum depth (m)	Cross-sectional area (m^2)	Volume (m^3)
Mean	0.56	0.12	0.34	0.02
Median	0.45	0.11	0.16	0.01
Minimum	0.14	0.02	0.02	0.00001
Maximum	2.41	0.41	4.55	0.34
Skewness	4.55	2.02	2.34	4.80
Kurtosis	29.48	5.73	6.47	27.51

Morphologic characteristics

Most of these pipe collapses (~59%) were comparably small (diameter, <0.5 m; Table II). Verachtert *et al.* (2010) observed a mean diameter of 1.1 m for sinkholes and 1.3 m for closed depressions, whereas in this study, only 11% had a diameter greater than 1.0 m. The distribution of collapse diameters was clearly not normally distributed with skewness and kurtosis values, indicating a distribution heavily weighted by small pipe collapses with a long tail of large values (Table III). As a result, the median diameter was smaller than the mean value. The mean depth, area and volume were 0.12 m, 0.34 m^2 and 0.02 m^3, respectively (Table III), and all three properties were heavily skewed. To determine the accuracy of using differential GPS to measure the morphologic characteristics of pipe collapse features, a conical pipe collapse shape was assumed, and the median size collapse dimensions were used to compute the maximum potential error. On the basis of a median diameter of 0.56$\pm$0.01 m and a depth of 0.12$\pm$0.015 m, the maximum potential error was 25%, 7% and 32% for depth, area and volume, respectively. Keep in mind that the actual error would be much less as the probability of error in one direction is equal to the probability of error in the other direction. Thus, on average, these variances in measurement resolution would cancel out with minimal error in the calculated area and volume. The mean, minimum and maximum depths observed were much smaller than those reported by Verachtert *et al.* (2010), which were 0.6, 0.2 and 2.0 m for sinkholes and 0.3, 0.0 and 0.8 m for closed depressions, respectively.

It is possible that some of the smaller depressions observed in this study were the result of animal activity that was misinterpreted as pipe collapses, although great care was taken in visually distinguishing these. Even if as much as 10% of these smaller depressions were misinterpreted, which is unlikely, the results would still be distinctly different from those observed by Verachtert *et al.* (2010) for pasture lands. The difference is more likely timing as these depressions exhibited evidence of recent collapse. Depressed surfaces typically had freshly incised walls (Figure 3A), and the collapses had stalks from the current year's crop (Figure 3B), indicating that they were less than a year old. As such, the erosion rates, based on their collapse volumes without accounting for the soil loss by the internal erosion of the associated soil pipes, were 0.0178, 0.0003, 0.0113 and 0.1315 m^3 ha^{-1} year^{-1} for parcels A, B, C and D, respectively. Verachtert *et al.* (2010) assumed that the depressions they observed

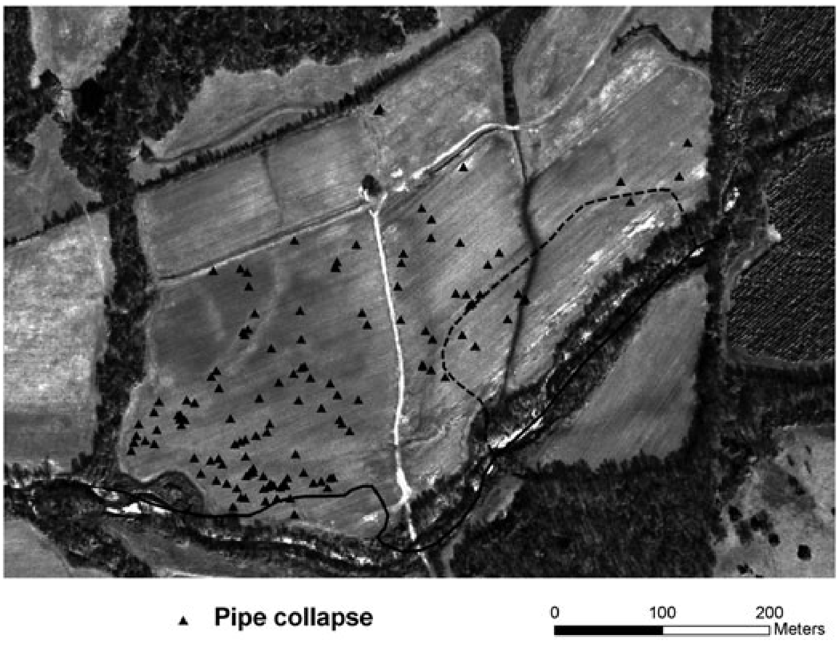

Figure 4. Aerial photograph from 2006 illustrating the location of the current stream channel, the meandering bend of the main channel in 1937 (solid line) and an old meandering bend from before 1937 (dashed line) in parcel D

were 5 to 10 years old. Thus, given time without disturbance, such as would exist in pasture, the collapses observed in this study would be larger.

Relationship to soil series

The most common soils in the study area (Figure 2B) are the Loring (24%) and the Falaya (22%) soils, with an equal proportion (23%) considered gullied lands but their distributions in the cropland area are much different, constituting 1%, 47% and 2%, respectively (Table IV). The Loring, Calloway, Grenada and Memphis soils are loess depositions with prismatic and/or subangular blocky structures in the subsurface layers. The former three are further similar in that they possess a fragipan horizon, typically in the upper meter, that restricts deep percolation, thereby fostering lateral flow. The two main soils in the cropland (Falaya and Collins) are recent alluvial depositions, constituting 90%, 78%, 50% and 65% of parcels A, B, C and D, respectively. These two soils do not contain a fragipan, but the remaining soils in cropland contain a water-restrictive fragipan layer or are mapped as gullied.

No pipe collapses were found in the Loring, Memphis or gullied land, although they occupied 49% of the study area. However, Calloway and Grenada, which contain a fragipan, had 25 and 8 collapses, respectively. Although only occupying 11% of the study area, more pipe collapses (60) were found in the Collins soil than any other soil (Table IV), with the second most (52) being in the Falaya soil. These soils, containing 94% of all pipe collapses, are located in the alluvial plains and are distinctly different from the surrounding loess soils. Both series consist of relatively young, silty alluvial deposits of loess with moderately permeable subsoils and very little horizon development. The main differences between them are that the Collins soil does not exhibit a B horizon, whereas the Falaya soil has a B horizon between 25 and 45 cm deep, and the Collins soil tends to have a higher sand content. Instead, the Collins C horizons have massive structure with horizontal stratification as compared with weak medium platy structure for the Falaya C horizons. In addition, the soils in parcel D where most pipe collapses occur (Figures 1 and 2) are Collins that had very recent alluvial deposits that filled in previous stream channels. It is interesting to note that the greatest concentration of pipe collapses in parcel D occurred where the soils transitioned downslope from the fragipan subsoils to the recent alluvial deposits. These pedologic characteristics explain the propensity of the Collins and Falaya soils to collapse when exposed to internal erosion by lateral flow, although soil pipes are likely generated in the fragipan soil upslope.

Table IV. Area ratio and pipe collapse numbers of different soil series in the study area

	Fa	Ca	Lo	Co	Gr	Me	Gu
AR to study area (%)	22	13	24	11	5	2	23
AR to cropland (%)	47	14	1	26	10	0	2
NPC	52	25	0	60	8	0	0
NCP per hectare	0.95	0.77	0	2.20	0.65	0	0

AR, area ratio expressed as the ratio of the soil series area to the total study area or cropland area; NCP, number of pipe collapses; Fa, Falaya; Ca, Calloway; Lo, Loring; Co, Collins; Gr, Grenada; Me, Memphis; Gu, gullied land.

Pipe length

Hagerty (1991) noted that one of the main difficulties of identifying piping was that direct evidence, such as 'water emerging from a soil face,' is 'rarely encountered'. The stream channel banks were inspected several times during the fall and winter for direct evidence of pipe flow. Pipe openings are prolific; however, no signs of recent hydraulic activity were observed. Therefore, it was not possible to connect pipes collapses to pipe outlets. Assuming a direct path from the pipe collapses to the nearest stream bank, the length of these pipes ranged from 14.6 to 289.4 m, with an average value of 96.6 m. However, a more likely scenario is that the old stream channel indicated in the 1937 photo intercepted the pipe flow and diverted the subsurface flows along the old channel to the current channel. This is substantiated by the fact that the 2006 aerial photo indicates a massive stream bank failure, that is, the edge of field gully (Figure 4) near the entry of the 1937 stream channel with the current channel location. Thus, pipe lengths based on distance from the collapse to the stream may be overestimated.

The likely source area for the water flowing through the alluvial plains subsurface is the surrounding hillslopes, which are managed as forest and pasture. Given that essentially all rainfall in forested areas infiltrates the surface and these forested hillslopes tend to have a fragipan subsurface horizon, and such water restricting layers are commonly associated with facilitating soil pipe flow (Faulkner, 2006), it is reasonable to expect that soil pipes are initiated in the forested hillslopes. Thus, a better representation of the pipe path length may be the distance from the surrounding forested hillslopes to the collapses, which is substantially longer than the estimates made from the collapses to the streams.

Topographic threshold of pipe collapse

Almost all pipe collapses were located in the relatively flat alluvial plains. The slope gradient was less than 1° for 92% of the pipe collapses and less than 2° for 99% (Table V). Soil erosion is often considered a threshold phenomenon, either expressed as a threshold of the shear stress or stream power. Topographic thresholds are often

Table V. Area ratio and pipe collapse density of different slope gradients

Slope (°)	0–1	1–2	2–3	3–4	4–5	>5
Area ratio (%)	22	27	16	12	9	14
NCP per hectare	1.21	1.15	0.05	0	0	0
NPC	131	10	2	0	0	0

NPC is the number of pipe collapses.

used to predict the existence of channels, such as the A–S relationship of Montgomery and Dietrich (1994),

$$SA^b > t$$

where A is the surface drainage area (m^2), S is the slope gradient (m/m), b (dimensionless) is an area exponent and t is a threshold value (area^b). Although this relationship is based on surface topography and thus relates directly to overland flow, some have proposed that positive values for b indicate subsurface flow contributions (Montgomery and Dietrich, 1994; Vanderkerckhove *et al.*, 2000; Morgan and Mngomezulu, 2003). Verachtert *et al.* (2010) applied this method to the prediction of pipe collapse features, although this approach has questionable assumptions for pipe collapses.

For the ‘field topography dominated’ case, the average surface drainage area of pipe collapses was 543.8 m^2. The regression equation between the ‘field topography dominated’ surface drainage area and the slope gradient of the pipe collapses (Figure 5A) was

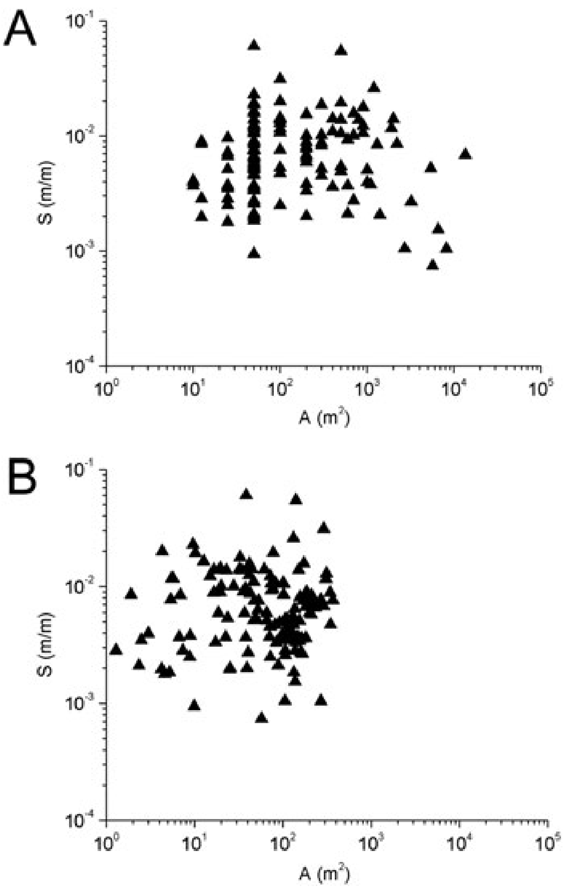

Figure 5. Relation between surface drainage area (A) and slope gradient (S) of the pipe collapse. (A) The ‘topography dominated’ case. (B) The ‘furrow dominated’ case

$$S = 0.006A^{0.011} \quad R^2 = 0.001$$

For the ‘furrow dominated’ case, the average surface drainage area of pipe collapses was 82% smaller than that of the ‘field topography dominated’. The regression equation between the ‘furrow dominated’ surface drainage area and the slope gradient of the pipe collapses (Figure 5B) was

$$S = 0.005A^{0.034} \quad R^2 = 0.003$$

The coefficients of determination for either case were much lower than the value of 0.16 observed by Verachtert *et al.* (2010). This indicates that there was no relation between surface drainage area and slope gradient for the pipe collapse in this study. Internal erosion that induced these pipe collapses is clearly governed by subsurface flow. The slope gradient and surface drainage area may be very different from those of the subsurface flow. This is likely the main reason for the lack of correlation between slope and drainage area. Because the slope gradient of the area with pipe collapses was very small, the runoff route may be influenced by even the smallest of features, such as furrows or ruts, and it is almost impossible to derive the exact surface drainage area. Some authors (Souchere *et al.*, 1998; Takken *et al.*, 2001) have shown the complicated runoff route in croplands with soil roughness, such as furrows.

Effects of pipe collapses on erosion

The existence of pipe collapses reduced the area with slope lengths greater than 200 m and shifted the landscape to a greater proportion of the area containing shorter (<100 m) slope lengths (Table VI). The ratio of areas with slope lengths greater than 250 m dropped from 13% to 8% because of the existence of pipe collapses. The distribution was compensated by an increase of areas with slope lengths between 0 and 50 m and between 50 and 100 m. However, no big changes were found in other classes of slope length.

The pipe collapses reduced the surface drainage area of the study ephemeral gully to some extent (Figures 6 and 7). At the middle point of the ephemeral gully, the surface drainage area was reduced from 1.28 to 1.19 ha. This means a reduction ratio of approximately 7%. At the outlet of the ephemeral gully, the surface drainage area was reduced from 2.21 to 2.05 ha, which is also a reduction of 7%. This result suggests that pipe collapses can reduce ephemeral gully erosion by overland flow but may enhance the contribution of subsurface flow processes. The existence of pipe collapses made the relationship between surface drainage area and runoff for predicting ephemeral gully erosion more complicated (Figure 7).

Table VI. Area ratio (%) of different slope lengths in parcel D

Slope length (m)	0–50	50–100	100–150	150–200	200–250	250–300
Without pipe collapse	12	29	22	12	12	13
With pipe collapse	14	33	22	12	11	8

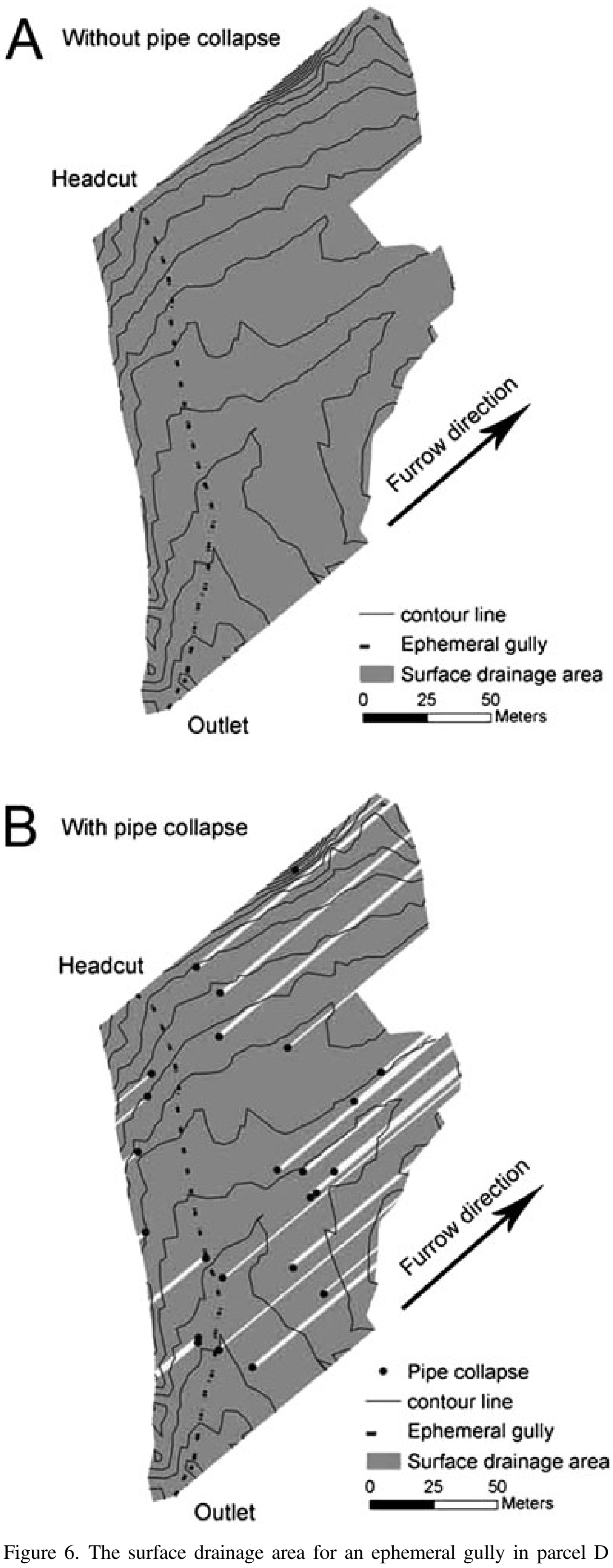

Figure 6. The surface drainage area for an ephemeral gully in parcel D with a contour line interval of 0.1 m. (A) The 'without pipe collapse' case. (B) The 'with pipe collapse' case

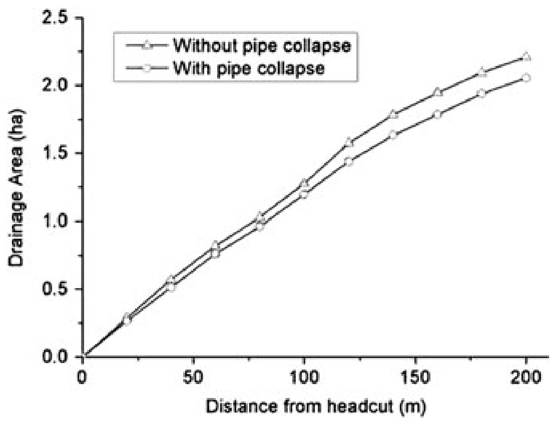

Figure 7. Comparison of surface drainage area along the ephemeral gully channel

CONCLUSION

Research has been performed to quantify the spatial distribution and morphologic characteristics of pipe collapses in a watershed in Mississippi. The sizes of the pipe collapses were much smaller than that reported by Verachtert *et al.* (2010) for a Belgium watershed. The distribution of morphologic characteristics, such as depth, area and volume, were not normally distributed and were weighted by small pipe collapses. The spatial distribution of pipe collapses was located primarily in the flat alluvial plains where the land use was dominated by cropland. Approximately 90% of the pipe collapses were located in a cropland parcel, which only covered 7% of the study area. The pipe collapses were mainly located in the Calloway and Falaya soils, whereas no pipe collapses were found in the Loring and Memphis soils or gullied land.

No relation existed between surface drainage area and slope gradient for the pipe collapses in this study as the coefficients of determination of the A–S (surface drainage area–slope gradient) regression equation were essentially zero, whether based on the DEM alone or roughness of furrows was taken into account. This further demonstrated that pipe collapses were dominated by subsurface flow. Pipe lengths were estimated to be up to 290 m when based on distance to the closest stream outlet. However, these are conservative estimates as the soil pipes likely extend into the alluvial plains from the surrounding hillslopes.

Although the volume of soil loss by subsurface flow, as evidenced by the collapse volume, was estimated to be between 0.0003 and 0.1315 m^3 ha^{-1} $year^{-1}$ for different cropland parcels, this does not include the effect of collapses on sheet, rill and ephemeral gully erosion. Pipe collapses broke the landscape into smaller segments and thus reduced the slope length factor for sheet and rill erosion. The ratio of areas with slope lengths greater than 250 m decreased from 13% to 8% because of the existence of pipe collapses. This decrease was compensated by an increase of areas with slope lengths less than 100 m. This work also demonstrated that the surface drainage area was reduced by 7% by pipe collapses both at the outlet and middle point of an ephemeral gully. However, the effect of this increased subsurface flow on gully erosion is not certain. Future research on soil pipe networks and their hydrologic properties may further illustrate the significance of the spatial distribution of pipe collapses on erosion prediction.

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