DRAINAGE DITCHES AS SEDIMENT SINKS ON THE COASTAL PLAIN OF NORTH CAROLINA

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Abstract: This paper examines the role that slope-channel linkages and seasonal variations in vegetation play in explaining spatial and temporal variations in sediment flux through agricultural drainage ditches in eastern North Carolina. We used biannual cross-sectional surveys of drainage ditches to assess erosion/deposition during a five-year period in the headwaters of a small agricultural watershed. Although net accumulations of sediment were observed in three-fourths of the cross sections surveyed, the rate of sedimentation varied considerably from ditch to ditch and cross section to cross section. The ditches were sediment sinks during the growing season in summer and autumn when they became choked with dense vegetation growth, and more hydraulically efficient after removal of vegetation in December during annual maintenance operations. The ditches experienced erosion or modest deposition while the vegetation was dormant during the late winter/early spring. Sediment was delivered to the ditches from isolated gullies that linked the primary source of sediment, soil eroded on agricultural fields, to the channels. Except for these isolated linkages, ditches and fields are largely decoupled. [Key words: drainage ditches, sedimentation, Coastal Plain, North Carolina.]

INTRODUCTION

Quantifying the components of sediment budgets provides a useful framework for understanding the effects of human disturbance in fluvial systems and formulating watershed management strategies. Although it is widely recognized that human impacts on natural vegetation cover have produced large increases in historical rates of erosion (e.g., Knox, 1977), much remains to be learned about the transport, storage, and redistribution of the eroded soil (Phillips et al., 1993). Many studies have documented that only a small proportion of the sediment flux from upland source areas is transported to the outlets of larger basins (>100–200 km^2) where sediment delivery ratios are typically less than 10% (e.g., Trimble, 1977; Meade, 1982; Walling, 1983; Phillips, 1991, 1995). This implies extensive colluvial and alluvial storage within watersheds. The spatial and temporal complexity of this storage makes it difficult to quantify (e.g., Phillips, 1986, 1991; Walling et al., 2002), which has led many investigators to compute storage terms in sediment budgets as residuals (Kondolf and Matthews, 1991).

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The sandy soils, gentle slopes, and dense vegetation of the Atlantic Coastal Plain lead to the perception that soil erosion, and therefore sediment transport and storage, is relatively insignificant in the region (Markewich et al., 1990). Most attention concerning the effects of human impacts on sediment dynamics has been focused on the Piedmont, with its steeper slopes and clay-rich soils (e.g., Trimble, 1974). Although research during the last several decades has shown that rates of soil loss in the Coastal Plain are much greater than previously assumed (Beasley, 1979; Dendy, 1981; Lowrance et al., 1986, 1988; Cooper et al., 1987; Sheridan and Hubbard, 1987; Hubbard et al., 1990; Phillips, 1993; Phillips et al., 1993; Slattery et al., 1998, 2002; Phillips, Golden et al., 1999a; Phillips, Slattery et al., 1999), few studies have quantified the storage of this sediment in great detail. Slattery et al. (2002) suggested that little of the eroded soil even reaches streams in small watersheds. Instead, most of the soil may be redistributed within individual fields or stored very near the source in headwater portions of the drainage network. In agricultural landscapes on the Coastal Plain, these headwater networks consist of drainage ditches and canals whose roles as sediment sinks remains poorly understood (Phillips, 1997; Moore et al., 2001; Cooper et al., 2002).

Previous research has identified a number of factors that influence sedimentation patterns in drainage systems, including vegetation and the efficiency of linkages between hillslopes and stream channels. Although several recent studies have promoted the use of vegetated drainage ditches as buffers to improve water quality by trapping sediment and other agricultural pollutants (Moore et al., 2001; Cooper et al., 2002, 2004), the geomorphological effects of in-channel vegetation growth have largely been ignored in the literature (Watson, 1987; Clarke, 2002; Cooper et al., 2004). Nevertheless, Watson (1987) showed that seasonal increases in the growth of aquatic macrophytes could increase hydraulic roughness by an order of magnitude, which can have a dramatic effect on sediment trap efficiencies. Stanley (1996) argued that sediment storage in drainage and irrigation ditches, which is more important than the Aswan High Dam in reducing the sediment supply to the Nile Delta, is partly due to the rapid spread of water hyacinth and algae. Several studies in eastern North Carolina have shown that, if not maintained on a regular basis, drainage ditches in wetlands deteriorate quickly through the invasion of vegetation and sedimentation (Swicegood and Kriz, 1973; Lilly, 1981; Stephenson and Steila, 1982; Phillips, 1988; Belk and Phillips, 1993). Swicegood and Kriz (1973) reported that even with annual mowing the conveyance capacities of drainage ditches require re-excavation every 10–15 years. Stephenson and Steila (1982) showed that 70% of the conveyance capacity of one artificial drainage ditch near Myock, North Carolina was lost just two years after excavation. In reporting that interviews with farmers suggested that artificial drainage channels had to be rehabilitated every 2–10 years, Phillips (1988) concluded that many (if not all) artificial drainage channels in eastern North Carolina would eventually lose conveyance capacity if not maintained. Although similar investigations of abandoned drainage ditches in agricultural areas have not been conducted (Slattery et al., 2002), observations of sedimentation in actively maintained ditches are common (Slattery et al., 1997, 1998).

Headwater drainages are often considered significant sediment sources for areas downstream because of the strong coupling between slopes and channels and the lack of (i.e., relative to larger watersheds) significant sediment sinks such as wide floodplains (Gomi et al., 2002, 2004; Walling et al., 2002; Yeager et al., 2002, 2005). Several studies, however, have shown that this strong linkage does not necessarily exist and that slopes and channels may be effectively decoupled, leading to extensive storage close to the source (Fryirs and Brierley, 1999; Slattery et al., 2002; Lecce et al., 2006). The purpose of this paper is to examine such storage in the headwater portions of a small agricultural watershed on the Coastal Plain of North Carolina. In particular, we focus on the influence that slope-channel linkages and seasonal variations in vegetation have in explaining spatial and temporal variations in sediment flux through agricultural drainage ditches and canals.

STUDY AREA

The study site at Littlefield consists of a small agricultural basin (7.7 km^2) in the headwaters of Swift Creek, a major tributary to the Neuse River. It is situated on the Pleistocene Wicomico marine terrace in southern Pitt County (Fig. 1). The maximum relief in the basin is 7 m and typical slope gradients range from 0.001 to 0.004 m/m. Land cover consists of a mixture of woodlands and crops in rotation between tobacco, soybeans, cotton, corn, and pasture. Spring planting generally begins in mid-April to mid-May, with tobacco as the first crop planted and the first harvested (August). All crops are generally harvested by mid-November. The climate is humid subtropical and the annual rainfall total averages about 127 cm, with the summer months receiving about twice as much rainfall as winter months. The soils are Ultisols, belonging to two general groups: Udults with sandy surficial horizons overlying argillic horizons on uplands and gentle hillslopes, and darker, finer-grained Aquults along valley bottoms (for details, see Phillips, Golden, et al., 1999).

Most watersheds in the region are artificially drained by subsurface tile drains and surface ditches and canals. Tributary drainage ditches often lack significant flow during the summer and fall when they become choked with dense vegetation growth (Fig. 2). Perennial flow in the Main Ditch limits most of the tall grasses and brush to the channel banks, but aquatic macrophytes become large and abundant during the growing season. Farmers begin annual maintenance of the ditches when crops have been harvested and vegetation growth slows in late November or early December. This maintenance consists of the mowing of vegetation from ditch banks and bottoms. The ditches are re-excavated periodically (every 2–10 years) to remove accumulated sediments, with the excavated material placed above channel banks along field edges. The last such excavation occurred in 1998/1999, prior to this study. Some of the material from excavation is redistributed within the fields by tillage (Swicegood and Kriz, 1973; Belk and Phillips, 1993; Lange et al., 2000). Grassed maintenance roads along field edges are also elevated by the accumulation of the excavated sediment, providing a barrier separating fields from the ditches.

METHODS

The data used to quantify the sediment flux were obtained from biannual surveys of drainage-ditch cross-sections conducted from February 2000 to February 2005.

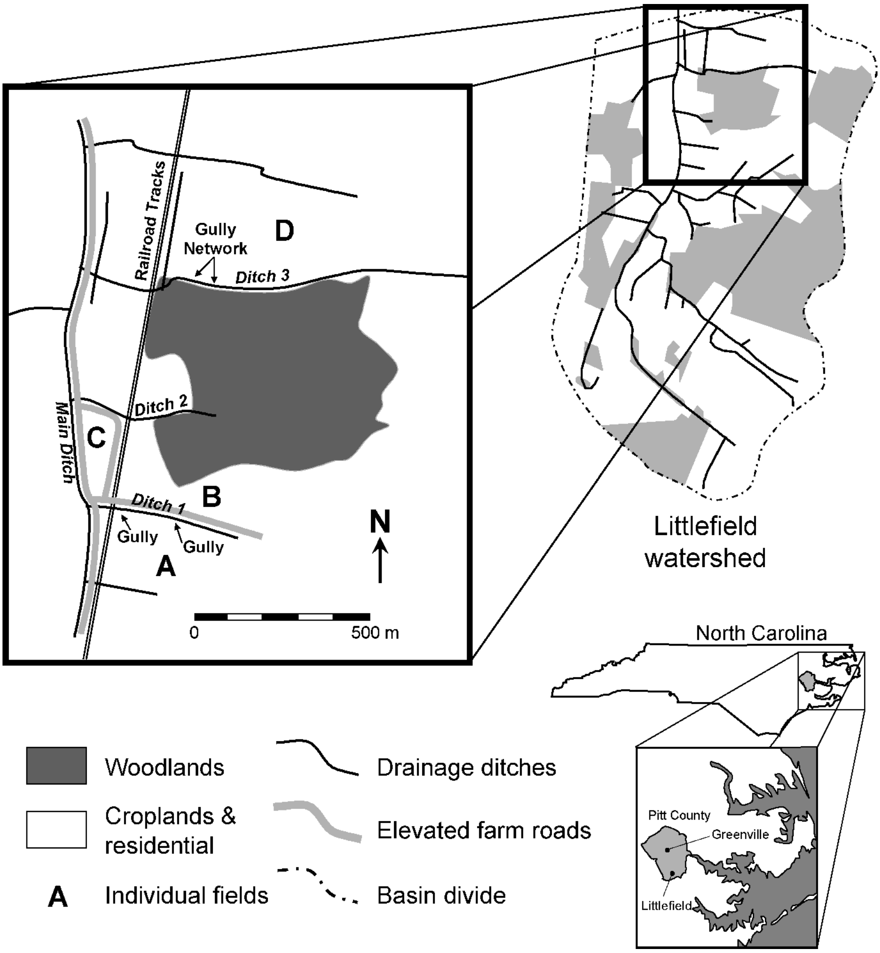

Fig. 1. Location map showing ditches and fields in the northern part of the Littlefield watershed in Pitt County, North Carolina.

Surveys were carried out in January/February after the ditches were mowed and in May before they became choked with dense vegetation (Fig. 2). Elevations for all cross sections were tied to the railroad track crossing on Ditch 1. Metal rods (rebar) driven into the channel bed were used as fixed benchmarks to relocate and overlay cross sections along the Main Ditch. The rods remained undisturbed because perennial flow in the Main Ditch limited vegetation removal to the ditch banks. In contrast, vegetation in the tributary ditches was removed by mowing both the bed and banks, so rods driven into the bed of these ditches in January/February were removed after the May survey and replaced with flexible survey flags that would not damage mowing equipment. Although many of the survey flags were removed or buried by the time of the next January/February survey, we relocated the longitudinal position of each cross section measuring the distance upstream from culverts. The missing flags eliminated cross-channel survey control, but it was relatively easy

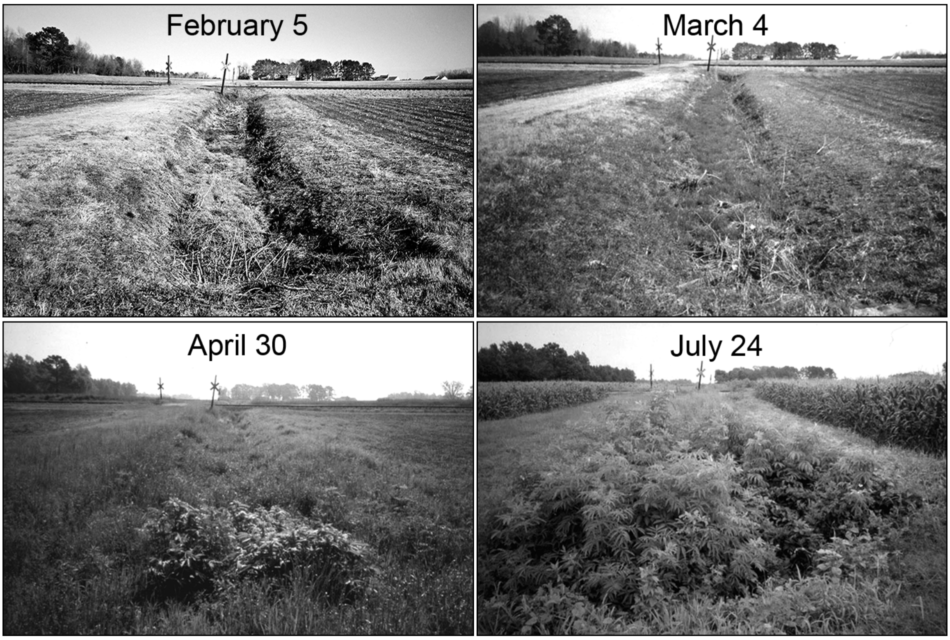

Fig. 2. Seasonal changes in vegetation along the lower portion of Ditch 1.

to overlay successive cross sections because erosion/deposition was largely confined to the channel bed, while the ditch banks were quite stable. The stability of the ditch banks was confirmed by comparing the January/February and May surveys when cross-channel control was maintained with the metal rods. We calculated the cross-sectional area of erosion/deposition between surveys at each cross section and, using measurements of mean bulk density (1.3 g/cm^3), determined a mass flux in Mg/m of channel length. The difference between the 3–4 month winter/spring season and the longer survey interval from May to January was standardized by expressing deposition/erosion in kg/m/yr.

RESULTS

Total Accumulation

Three-fourths of the cross sections surveyed experienced net accumulations of sediment, ranging from a low of 61% of the cross sections in Ditch 2 to 94% in Ditch 3 (Fig. 3). Although the drainage ditches generally aggraded during the study period, sedimentation occurred at different rates (Table 1). The total sediment accumulation was 6–7 times greater in the Main Ditch and Ditch 3 than it was in Ditch 2. Although the sedimentation rate for the Main Ditch is high, its cross-sectional area is also considerably larger (2–4 times) than the tributary ditches (Table 1). Thus, average sedimentation rates in the Main Ditch (76 kg/m/yr) and Ditch 3 (86 kg/m/yr) are similar, yet sedimentation has only reduced the average cross-sectional capacity of the Main Ditch by 3%, while the average capacity of Ditch 3 has been reduced by 19%.

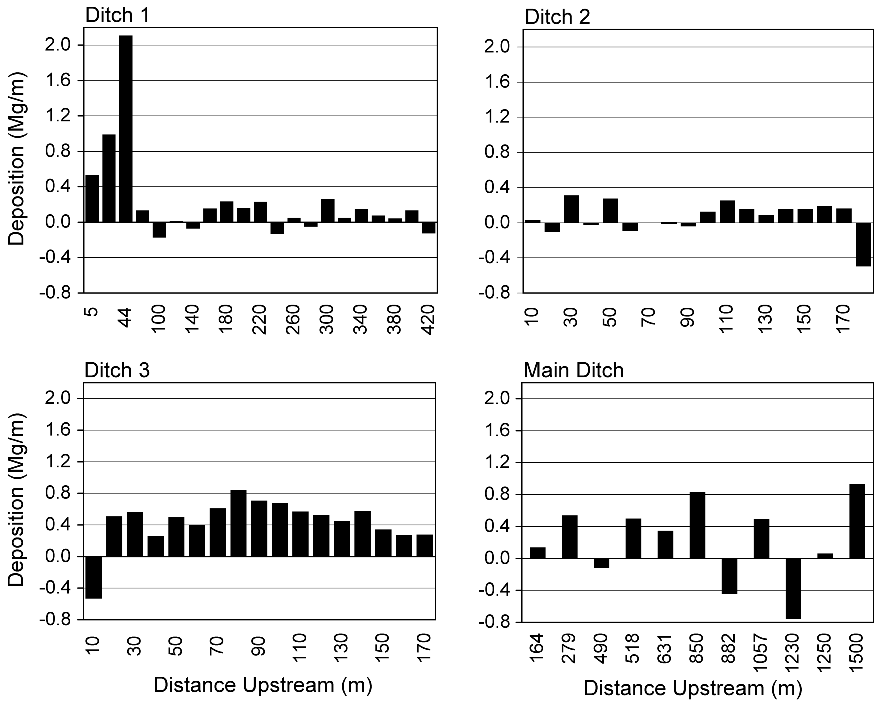

Fig. 3. Cumulative deposition/erosion from February 2000 until February 2005.

Table 1. Sedimentation in Drainage Ditches[a]

	Number of cross-sections	Ditch length (m)	Bankfull cross-sectional area		Total sedimentation (Mg)	Total sedimentation rate (kg/m/yr)[b]
			Average (m^2)	Standard deviation (m^2)		
Ditch 1	21	420	2.1	0.6	76.7	37.0
Ditch 2	18	180	4.2	0.3	11.2	12.5
Ditch 3	17	170	2.4	0.7	74.9	88.8
Main ditch	11	1,600	8.9	1.1	483.2	75.5

[a] Ditches 1–3 were surveyed from February 2000 to February 2005; the Main Ditch was surveyed from January 2001 to February 2005.

[b] Annual rate of sedimentation per unit channel length.

Seasonal Variations

Figure 4 shows that deposition/erosion in the ditches exhibited systematic seasonal variations. The ditches tended to experience net erosion or modest deposition in late winter and early spring when vegetation is dormant. In contrast, the ditches were sediment sinks during the growing season (summer and fall) when the vegetation in the ditches was very dense. Two exceptions to this general pattern occurred: one during the dormant season at the beginning of the study period, and the other

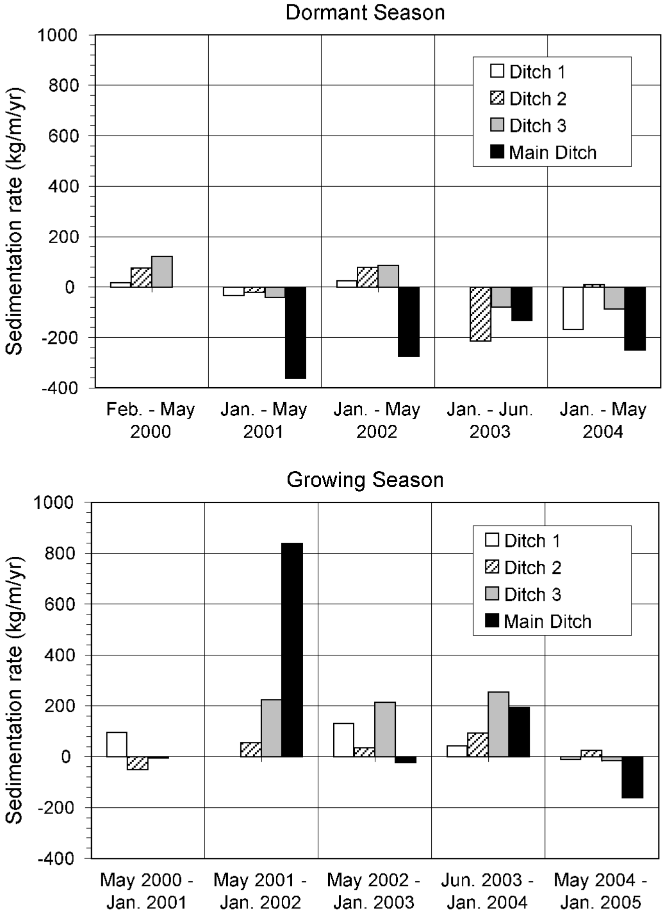

Fig. 4. Seasonal variations in ditch sedimentation rates. Rates were calculated as an average of all cross-sections along each ditch. Note that because we lack survey data in Ditch 1 for January 2002, the small positive sedimentation rate (24 kg/m/yr) reflects accumulation during the entire year (May 2001–May 2002).

during the growing season at the end of the study. Net deposition between February and May 2000 was probably related to a large amount of sediment mobilized during Hurricane Floyd in September 1999. This sediment was clearly evident as sandy bedload throughout all of the ditches. Net erosion between May 2004 and February 2005 may be associated with the filling of a gully network that had been supplying sediment to Ditch 3 (discussed below).

Spatial Variations

In order to compare overall differences between the ditches, Table 1 and Figure 4 treated deposition as average values computed from all of the cross sections surveyed along each ditch. There were, however, substantial variations in deposition/

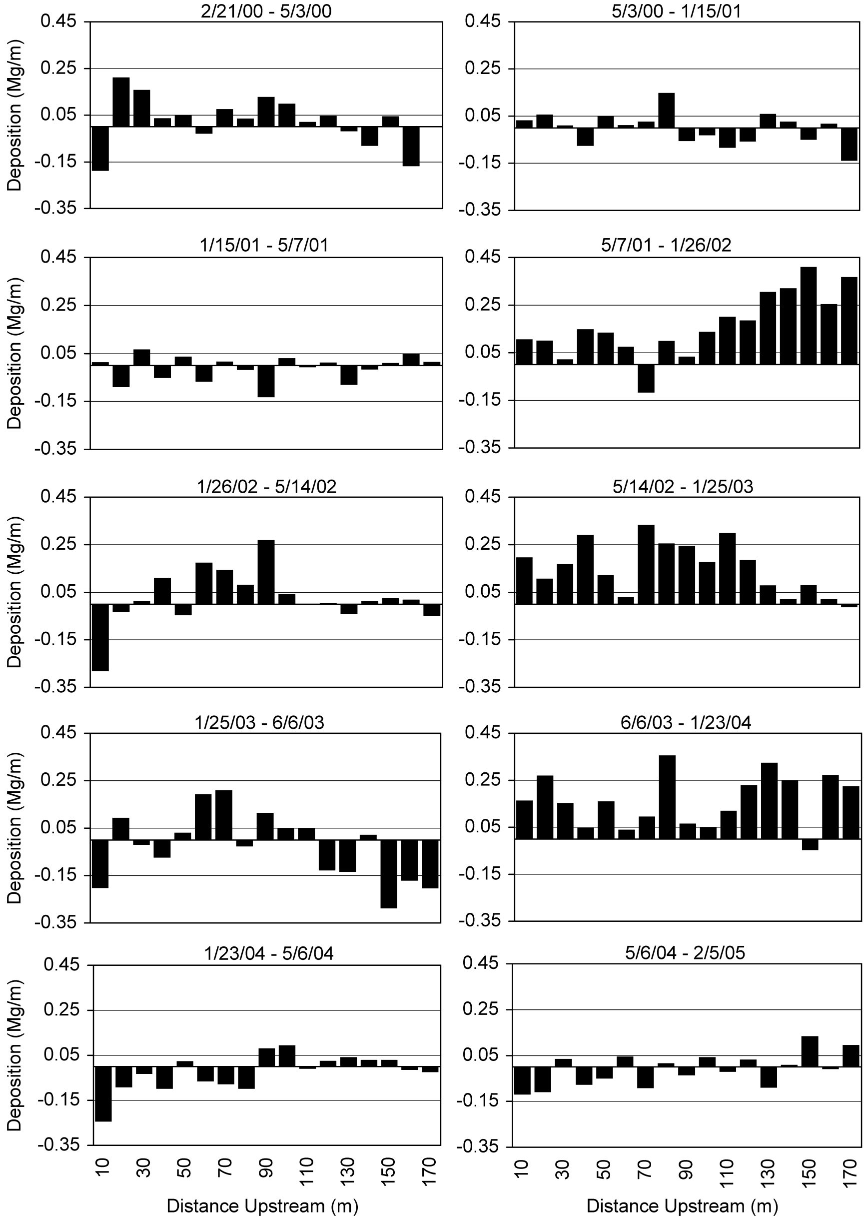

Fig. 5. Spatial variations in deposition/erosion along Ditch 3 computed for each time interval.

erosion between cross sections within each ditch. Most of the change along Ditch 1 (420 m long), for example, was concentrated in the 50 m reach downstream from the railroad tracks where more than 70% (54.6 Mg) of the deposition was located. Although Ditch 3 experienced an overall net aggradation during the study period at 16 of 17 cross sections (Fig. 3), Figure 5 shows that there were considerable

Fig. 6. Pulse of sandy bedload moving through Ditch 3 in February 2003.

differences in deposition/erosion within and between cross-sections. Many of the cross-sections experienced alternating episodes of scour and fill. Little change occurred in the upstream portion of Ditch 3 until the May 2001–January 2002 survey interval, when it aggraded rapidly. From January 2002 until June 2003, more sedimentation took place in the downstream portion of Ditch 3 as the upstream reach incised during the spring of 2003. Although the ditch experienced rapid overall aggradation, pulses of sandy bedload were observed at time scales that varied from seasonal (e.g., Fig. 5) to days or weeks. The movement of these pulses was a common feature in the ditches during the dormant season (Fig. 6). These pulses may be linked to both the migration of coherent bedforms (Gomez et al., 1989) or to longer-term variations associated with discrete inputs of sediment (Nicholas et al., 1995).

DISCUSSION

Explaining the patterns described above is complicated by crop rotations and the timing and magnitude of storm events. Nevertheless, we argue that ditch vegetation, slope-channel linkages, and culverts play a significant role in sediment delivery at Littlefield.

Vegetation

The data from Littlefield suggest that the role that vegetation plays in affecting ditch sedimentation can hardly be overstated. After the ditches are mowed, hydraulic roughness is substantially reduced and the ditches become much more efficient at conveying water and sediment. Values for Manning's roughness coefficient may vary between a minimum value of 0.016 for a uniform, clean, recently excavated earthen channel, to a maximum value of 0.14 for an artificial earthen channel that

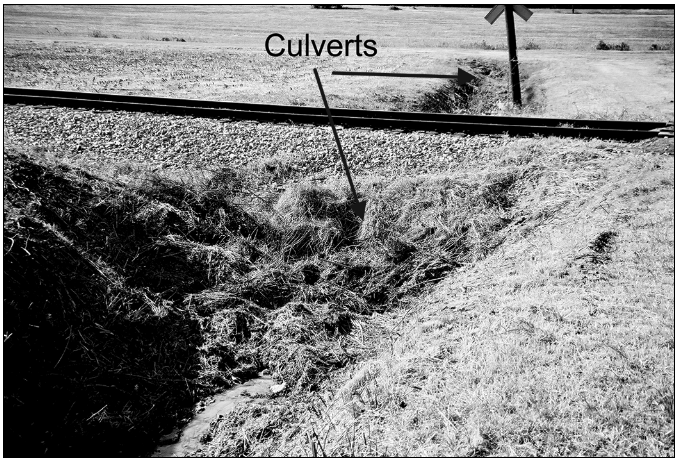

Fig. 7. Culverts along the lower portion of Ditch 1. The culvert under the railroad tracks is blocked by vegetation from mowing.

has not been maintained with dense brush and weeds on the bottom and sides (McCuen, 1998). Following maintenance in December, estimates of minimum values at Littlefield typically range from 0.02 to 0.025. On a seasonal basis, therefore, there can be as much as a five- to seven-fold range in boundary roughness, flow velocity, and discharge within these ditches. Given the density with which these ditches become vegetated and the corresponding decline in flow velocities, it is not surprising that sediment transport is inhibited during the growing season.

Most of the ditches in the watershed, and all investigated in this study, have culverts to convey flow under farm roads and railroad tracks. The typical conveyance capacity of the culverts is about half that of the bankfull capacity of the ditches. During higher flows, this difference in conveyance capacity decreases flow velocities and promotes sedimentation upstream. Eventually the culverts fill and become clogged with sediment. Before the most recent ditch re-excavation in 1998/1999 (prior to this study), the culvert under the railroad track on Ditch 1 was not visible and the ditch was almost completely filled in. In the six years since it was cleared, this 0.9 m diameter concrete culvert is now >80% full. As the culverts become filled with sediment, the cut vegetation produced by the annual mowing is not as easily flushed downstream through them. The damming of the upstream sides of the culverts by this vegetation accelerates the rate with which they become clogged. Figure 7 shows the upstream side of the railroad culvert on Ditch 1, which is completely blocked by cut vegetation. Deterioration of this ditch will undoubtedly accelerate, as evidenced recently by the rapid aggradation of the cross-section in Figure 8.

Slope-Channel Linkages

Downstream sediment transfer is influenced by the efficiency with which sediment sources and channels are coupled (Harvey, 1994; Phillips, 1995; Fryirs and

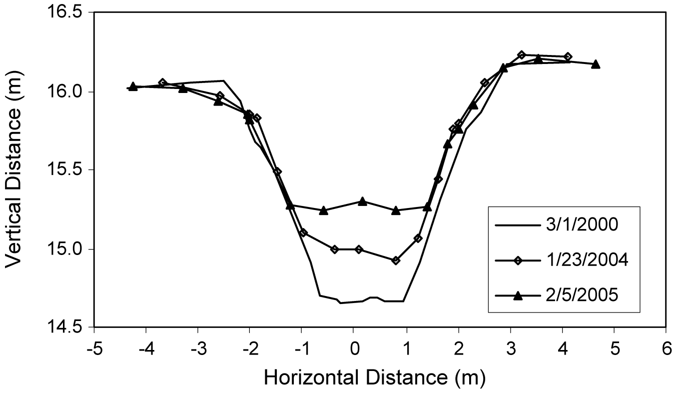

Fig. 8. Cross-section located 5 m downstream from the railroad tracks along Ditch 1. Note that the amount of sediment that accumulated in the last year (2004–2005) was approximately the same as the total aggradation during the previous four years.

Brierley, 1999; Slattery et al., 2002; Swiechowicz, 2002; Gomi et al., 2004). Clearly, the clogging of culverts disrupts the linkage between tributary ditches and the Main Ditch. Drainage ditches are also largely decoupled from the fields due to the presence of the railroad tracks and elevated roads that run along the banks of many of the ditches (Fig. 1). Furthermore, those ditches lacking roads are decoupled from fields by grassed buffer strips that have been shown elsewhere to provide high sediment trapping efficiencies (Van Dijk et al., 1996; Cooper et al., 2000). For example, the east bank of the Main Ditch has elevated grassed buffers (used as access roads for farm machinery) along most of its length, while the wooded west bank reduces runoff and sediment contributions from adjacent fields and discourages the development of gullies. Similarly, Ditch 2 lacks effective linkages between the fields and the channel because the south bank is separated from field C by an elevated, grassed maintenance road. Surveys show that Ditch 2 has remained relatively stable throughout the study period. The 5 m wide grassed road on the north side of Ditch 1 effectively decouples field B from the ditch. In contrast, the south side of Ditch 1 has a very narrow (<0.5 m) grassed buffer that is less effective at preventing runoff and sediment from entering the ditch.

It is likely that the sediment deposited in the ditches was either supplied from within the ditch system or from relatively isolated gullies that linked portions of the fields to the ditches. Gullies linking channels and fields were observed along both Ditch 1 and Ditch 3 (Fig. 1). A large gully that first developed during the rainfall from Hurricane Floyd on the south side of Ditch 1 has led to rapid sedimentation of the culvert under the railroad track and the 50 m reach downstream. Most of the runoff and sediment from field A is directed toward this gully. Two gully networks along the north side of Ditch 3 connected field D (which lacks an effective grassed/elevated buffer) to the ditch. The repair of these gullies (which were present since at least March 2001) during the winter of 2004 may help explain the net erosion that occurred in 2004.

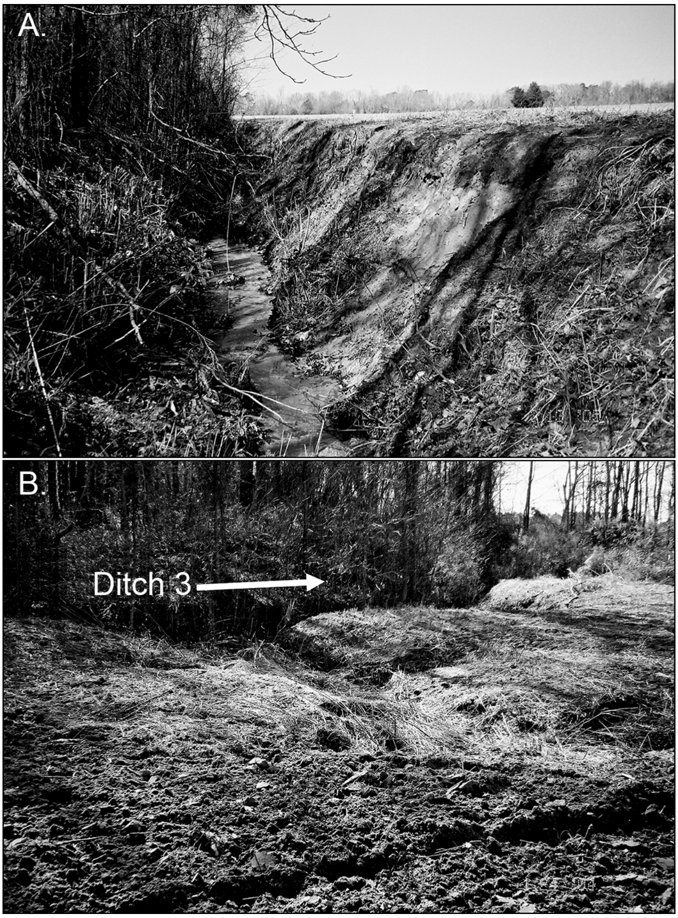

Fig. 9. Ditch 3 upstream from railroad tracks. (A) Erosion of ditch bank. (B) Gully network linking field to ditch.

Other potential sources of the sediment deposited in the ditches may be derived from the sediment excavated from the ditches during maintenance operations and bank failures. Remobilization of the excavated sediment from piles along the ditch banks is not believed to have been a significant source during this study because the last excavation occurred prior to the study period. Such sediment would only be mobile for a short period immediately after excavation before it is stabilized by vegetation and compacted in field-edge maintenance roads. Some of this sediment is also redistributed on fields by tillage. Mass wasting of the channel banks, while not widespread, can be observed in places along the oversteepened sideslopes of Ditch 1 and in several locations along Ditch 3. Most of the upper two-thirds of Ditch 3 flows along the boundary between woods and tilled fields (Fig. 9). Bank erosion from a 200 m section of Ditch 3 was probably the source of some of the sediment deposited in the lower 180 m of the ditch.

Implications

Understanding sediment delivery in small watersheds is important for developing effective sediment control and management strategies for larger river systems because headwater drainages are often considered significant sediment sources for areas downstream (Gomi et al., 2002, 2004). The degree with which sediment sources in headwater drainages are coupled with stream channels, however, is a key control of the importance of such upstream–downstream linkages. Storage in the headwater portions of agricultural basins in North Carolina has important implications. First, the uncertainty associated with whether a strong source-channel coupling exists in urban areas raises concerns about urban and suburban expansion into agricultural areas and its effect on the delivery of sediment and pollutants downstream. The coupling between sediment sources and channels and the connectivity of impervious areas may be greater in urban areas due to traditional stormwater management strategies which seek to remove runoff from the site as quickly as possible (Holman-Dodds et al., 2003). Second, it may suggest that aeolian processes are more effective at actually removing soil from the fields (e.g., Pease et al., 2002).

CONCLUSION

Although the drainage ditches monitored in this study generally acted as sediment sinks, average sedimentation rates along each ditch varied considerably from 12.5 kg/m/yr in Ditch 1 to 88.8 kg/m/yr in Ditch 3. Deposition at individual cross sections also varied both spatially and temporally. Sandy bedload moved through the ditches in pulses, with alternating periods of erosion and deposition superimposed on a longer-term pattern of net aggradation. The ditches experienced net erosion or modest deposition when ditch vegetation was dormant in late winter/early spring, while net deposition was dominant during the growing season in summer and fall. These seasonal patterns of deposition/erosion were influenced by seasonal changes in ditch vegetation. Deposition was dominant during the growing season when the ditches became choked with vegetation. Vegetation density was drastically reduced at the end of the growing season by annual ditch maintenance (mowing). Sediment transport increased during the dormant season while hydraulic roughness was low in the ditches. Fields and ditches are largely decoupled; nevertheless, the ditches that experienced the highest rates of sedimentation were linked to sediment sources on the field by isolated gullies. Ditches that were not linked to sediment sources by gullies experienced minimal net change.

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