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THE EFFECT OF CHANNELIZATION ON FLOODPLAIN SEDIMENT DEPOSITION AND SUBSIDENCE ALONG THE POCOMOKE RIVER, MARYLAND[1]

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ABSTRACT: The nontidal Pocomoke River was intensively ditched and channelized by the mid-1900s. In response to channelization; channel incision, head-cut erosion, and spoil bank perforation have occurred in this previously nonalluvial system. Six sites were selected for study of floodplain sediment dynamics in relation to channel condition. Short- and long-term sediment deposition/subsidence rates and composition were determined. Short-term rates (four years) ranged from 0.6 to 3.6 mm/year. Long-term rates (15-100+ years) ranged from −11.9 to 1.7 mm/year. ^{137}Cs rates (43 years) indicate rates of 0.24 to 7.4 mm/year depending on channel condition. Channelization has limited contact between streamflow and the floodplain, resulting in little or no sediment retention in channelized reaches. Along unchannelized reaches, extended contact and depth of river water on the floodplain resulted in high deposition rates. Drainage of floodplains exposed organic sediments to oxygen resulting in subsidence and releasing stored carbon. Channelization increased sediment deposition in downstream reaches relative to the presettlement system. The sediment storage function of this river has been dramatically altered by channelization. Results indicate that perforation of spoil banks along channelized reaches may help to alleviate some of these issues.

(KEY TERMS: channelization; subsidence; sedimentation; floodplain isolation; radioisotopes; dendrogeomorphology; fluvial processes; geomorphology.)

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INTRODUCTION

Background

Channelization, a common although controversial engineering practice aimed at controlling flooding and draining wetlands, occurred along approximately 300,000 km of streams in the United States (U.S.) (Schoof, 1980) much of which was in the Coastal Plain physiographic province. Following settlement by Europeans, the promise of fertile land for agriculture and lumber resulted in the wide-scale ditching of wetlands and channelization of streams in order to facilitate agriculture. This drainage has had far reaching impacts on the hydrologic functioning of these systems (Hupp, 1999).

Generally, this change has resulted in decreased nutrient and sediment retention along channelized reaches (Noe and Hupp, 2005) and accelerated storage

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of sediment and nutrients downstream of channelization (Darby and Thornes, 1992; Shankman and Smith, 2004; Noe and Hupp, 2005). Channelization increases drainage by increasing stream gradient and stream power, typically resulting in further channel incision (Darby and Thornes, 1992; Hupp, 1992). The increased channel cross-sectional area following channelization and incision increases floodplain drainage and decreases floodplain inundation. Additionally spoil banks (the material excavated from the channel and deposited along the side of the stream) decrease water volume interchanges between the sediment laden main channel flow and relatively sediment poor flows across the floodplain (Pizzuto, 1987), resulting in decreased sediment storage on the floodplain.

Sediment storage in alluvial wetlands is well known, but poorly understood (Trimble, 1977; Walling, 1983; Phillips, 1991; Hupp *et al.*, 1993). Geomorphic analyses (Leopold *et al.*, 1964; Jacobson and Coleman, 1986) verify that riparian retention of sediment is a common and important fluvial process, yet remobilization time of sediment may be the most poorly understood, generally unquantified aspect of sediment budgets (Hupp, 2000; R. B. Jacobson, USGS, 2004, written communication). Sediment deposition rates have been reported for forested wetlands in western Tennessee, eastern Arkansas, South Carolina, North Carolina, and along tributaries to the Chesapeake Bay in Maryland and Virginia (Kleiss, 1996; Hupp, 2000). Radio isotopic tracers have allowed researchers to make significant progress in identifying sources of sediment and storage rates (Walling *et al.*, 2002; Foster *et al.*, 2003).

The sediment-trapping function of forested wetlands is widely recognized as critical for downstream water quality (Kleiss *et al.*, 1989; Hupp *et al.*, 1993; Ross *et al.*, 2004). This function in Coastal Plain fluvial systems is especially important because these floodplain surfaces are the last areas for sediment storage and biogeochemical cycling before rivers enter estuaries and critical nursery areas for marine biological production. Analyses of upland erosion and delivery of sediment to coastal waters suggest that large percentages of sediment eroded from uplands is cycled for decades to millennia in alluvial systems before reaching saltwater (Meade *et al.*, 1990). Thus, human activities that limit the contact of streamflow with the riparian zone, such as channelization, change the sediment-trapping function of the system. In some settings, channelization may change the water balance within the floodplain, possibly resulting in accelerated subsidence.

Subsidence is the net loss of surficial elevation that occurs when sediments loose volume over time, for example, by dewatering and biotic consumption of organic components. The presence of recent sediment deposition does not preclude the existence of subsidence. Sediment deposition must exceed the internal processes of compaction and decomposition within the soil column in order for a net increase in surface elevation to occur (Kaye and Barghoorn, 1964). Blackwater stream systems (Hupp, 2000) typically store large amounts of carbon as partially decomposed organic matter. In these systems, the highly organic floodplain sediments are preserved by the anoxic conditions (absence of oxygen) maintained by near constant saturation and/or inundation, similar to processes that facilitate organic carbon storage in peat bogs. If channelization increases the channel depth, by design or as a consequence, then portions of the floodplain may be drained of surface and groundwater, resulting in decreased durations of soil saturation and anoxia. Increased oxygen availability aids organic decomposition, and thus increases the rate of subsidence (Moore and Knowles, 1989; Glenn *et al.*, 1993; Laine *et al.*, 1994). Subsidence may be further exacerbated by reduced sediment deposition as a result of decreased floodplain inundation by overbank flow.

All measurements of floodplain sediment deposition are estimates of the true deposition rate in an area of floodplain. It is impossible to determine the true rate of deposition beyond measured points that are inevitably affected in some measure by bioturbation. Every study measuring floodplain sediment deposition contains these errors and the measurement methods utilized in this study offer a range of accuracy. In order to control the built-in errors, it is important to have enough samples to be representative of the area, and repetitive for different landforms. The researcher must assume that minor bioturbation is consistent through the studied system and that bioturbation is minimal compared with the deposition. Measurement points where major disturbance has occurred must be discarded.

This paper assesses the net effects of channelization on sediment deposition, storage, and subsidence along a typical Coastal Plain stream of the southeastern U.S. as channel form changes from channelized to unchannelized and finally to tidal reaches (Figure 1). Riparian floodplains along many Coastal Plain streams often store high concentrations of organic matter in the deposited sediments. Oxidation of organic floodplain sediments following channelization may represent a large loss of carbon storage in humid regions worldwide.

Study Area

The Pocomoke River Swamp was once considered to be an impenetrable wilderness, with conditions

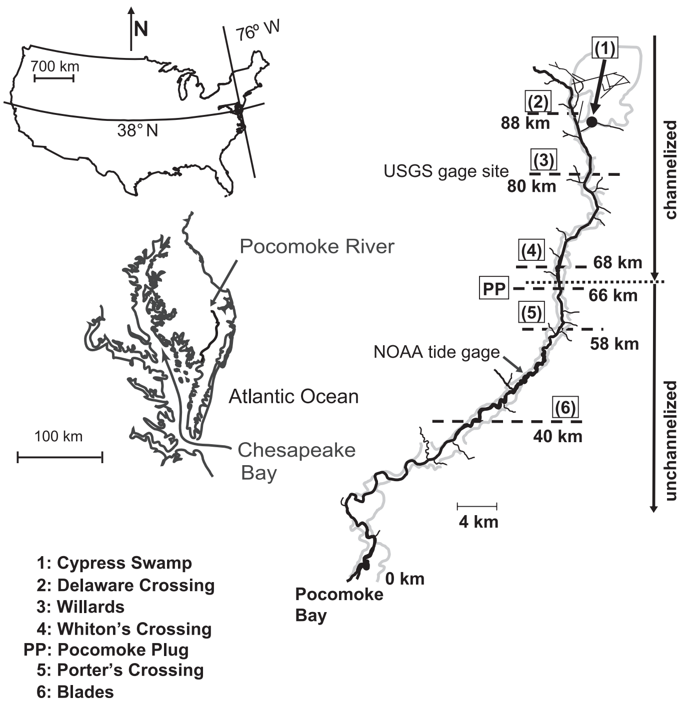

FIGURE 1. The Pocomoke River Study Area. Location, names, and numbers of study sites along and near the Pocomoke River. Distances are in kilometers from the mouth of the Pocomoke River. Areas between gray lines are riparian zones and (or) swamps.

strongly resembling the Dismal Swamp of North Carolina and Virginia. The original width of the forested wetland, as evidenced by black organic soils, extended far beyond the floodplain edge along the upper reaches of the river, perhaps two to three times the width of the present day swamp (Beaven and Oosting, 1939; Kroes *et al.*, 2007).

Typical of blackwater systems, the Pocomoke River has a very low gradient (0.15 m/km), wide floodplains (0.35-3.6 km), and long hydroperiods with backswamp portions of the floodplain often inundated more than 255 days/year (Kroes *et al.*, 2007). Although streams like the Pocomoke generally have blackwater at base flows, high iron content in discharging groundwater imparts a rust color to the Pocomoke and reduces clarity (O.P. Bricker, USGS, 2002, personal communication).

The Pocomoke River is a minor, fourth-order tributary to the Chesapeake Bay (Figure 1) with a drainage area of approximately 1,300 km^2. In an average year, the drainage basin receives 1.14 m of total precipitation, has an average air temperature of 12.6°C, and a growing season of 198 days. Under historical, natural conditions, the nontidal Pocomoke River sequestered organic material for a period of time sufficient to develop 1-2 m of peat deposits at upstream sites. Floodplain sediments in the past ranged from sapric-Histosols (an organic soil in which the original plant parts are not recognizable) in the headwaters and upper reaches (Beaven and Oosting, 1939) to sandy and silty loams in the lower nontidal reaches (Perkins and Bacon, 1928; Kroes *et al.*, 2007).

The majority of the Pocomoke River drainage basin was ditched (channel created where no channel occurred prior to excavation) and channelized (natural channel modified to hasten drainage) prior to 1938 (Beaven and Oosting, 1939). The channelization of the upper 40 km of the Pocomoke began in November 1940 and was dedicated on September 25, 1946 (M. P. Sigrist, USDA, 2002, personal communication). Ditching increased the drainage density of the basin by nearly 300%. Channelization and incision made floodplain inundation rare and drained surficial groundwater from large portions of the floodplain. This channelization left only the lower 64 km of the Pocomoke River main stem (58 km of which is tidal) and a few small tributaries unchannelized (Kroes *et al.*, 2007).

Agricultural fields constitute 37% (Maryland Department of Planning, 2002) of the drainage basin, which has been heavily farmed since circa mid-1600s. Many tributaries to this low-gradient river are ditches originating in subdrainage basins that are agriculture fields and ditched presettlement wetlands. This once blackwater system now (2010) carries enough mineral sediment to be classified as a brownwater alluvial system (Kroes *et al.*, 2007). Radio isotopic signatures of transported sediments in the main river channel indicate ditch erosion as the primary source of suspended sediment during most storms. Erosion from fields is generally limited by low topographic gradients. However, during exceptionally heavy rain, agricultural fields contribute high concentrations of sediment (Gellis *et al.*, 2009).

METHODS

Study Sites

Field reconnaissance and inspection of topographic maps were used to select specific study sites from the headwaters to tidal portions of the river (Figure 1). Sites were selected based on channel conditions (channelized, unchannelized) and hydrologic regime (rare to frequent inundation, tidally influenced or not). The Cypress Swamp (1) area has no defined channel and was selected to determine autochthonous (organic) deposition rates. The channel at Delaware Crossing (2) and Willards (3) has been channelized and is now deeply incised to a depth of 3 to 4 m (Figure 2). A U.S. Geological Survey streamflow-gaging station

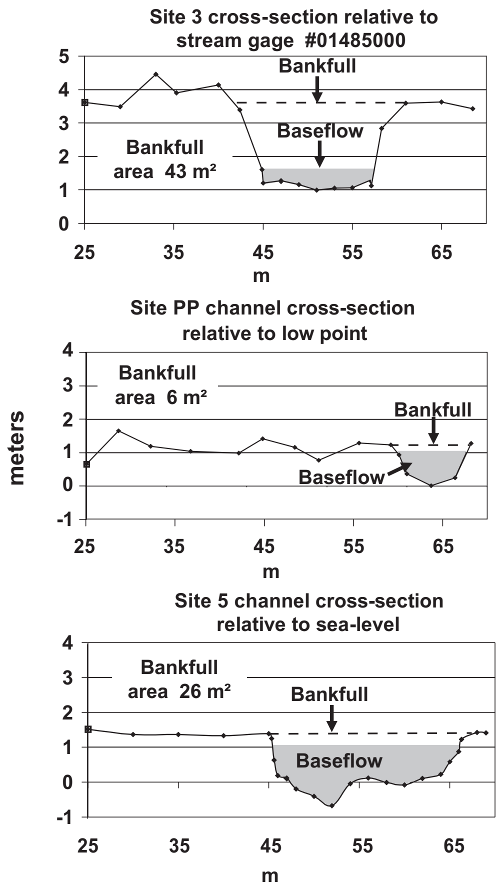

FIGURE 2. Representative Channel Cross-Sections Are Given for Channelized, Unchannelized Sites, and the Junction Reach (Site PP) With Bankfull Cross-Sectional Area. The stage of normal baseflow conditions are indicated by shading on the two representative cross-sections. Bankfull stage is based on geomorphic features.

(01485000) near Willards, Maryland (1949 to September 2004, October 2006 to present), located 80-river km upstream from the mouth has recorded a mean daily discharge of 2.0 m^3/s. This gaging station is approximately 0.5 km downstream of Site 3 and is the only gage on the Pocomoke River. At Sites 2 and 3, this gage recorded water levels that inundated the floodplain 100 days during the 54-year record, and 1 day during 1998-2004.

Whiton's Crossing, Site 4, is approximately 1.6 km upstream of the limit of channelization and the floodplain is inundated by streamflow and groundwater discharge. During the study period, Site 4 had standing water continuously in the backswamp except during the 2002 drought (near record). The original channel at Site 4 is still present (2009) and carries water. Although the flow regime may have changed, the hydroperiod at Site 4 has probably not decreased due to channelization. Sediment exchange between the main channel and the floodplain at Site 4 may be reduced by the presence of highly perforated spoil banks. Porter's Crossing, Site 5, has a natural channel with a daily tidal range of 13 cm (stilling well data, installed 2001). No tidal signature was present during overbank stream stages (well data). Blades, Site 6, is the most tidally influenced site with a daily tidal range of approximately 60 cm (NOAA tide station 8571359). Windblown tides can inundate the entire floodplain at Site 6; normal tidal action and streamflow inundate portions daily. Flows across the floodplain at Site 6 are in effect backwater and have only minor velocity (Kroes *et al.*, 2007).

In early 2006, after most field work was finished, an additional site (PP) was identified and established approximately 2 km downstream of Site 4. Site PP is located immediately downstream of where the engineered channel and the natural channel meet. This site exhibits past and current evidence of rapid sediment deposition, and water velocities relative to the other sites; including channel avulsion, sand splays across the floodplain, high-density slough formations, and rapid water velocity in the main channel. The fluvial dynamics at this site are analogous to those described for valley plugs (Pierce and King, 2007b).

Measurement of Sediment Deposition Rates

Sediment deposition rates were determined using three methods over three time spans; clay pads (1998-2002), dendrogeomorphic (1898-1998), and radio isotopic (1963-1964 till 2006). Short-term measurement of clay marker horizons (pads) is the most accurate measurement of deposition due to the high density of spatial distribution and measurement. Short-term (four years) net sediment deposition rates (hereafter deposition rates) were measured along transects at each site (except Site PP). Two to three transects were established per site in 1998 on the floodplain perpendicular to streamflow (Table 1). The transect design allowed local deposition rates to be related to elevation, distance from channel, inundation hydraulics, and discrete fluvial landform (e.g., levee, backswamp, slough). Transect length ranged from 150 to 250 m. Powdered white feldspar clay pads were placed onto an area cleared of leaves and vegetation (0.5 × 0.5 m) to a thickness of 1 to 2 cm at intervals of 50 m along the transects or at a change in landform. This clay pad becomes a fixed marker horizon after absorption of soil moisture (Bauman *et al.*, 1984; Kleiss *et al.*, 1989). All clay pads along the Pocomoke River were in place for four years (1998-2002). Clay pads were checked annually or after a flooding event for cumulative deposition above the marker layer by carefully cutting a plug through the deposited layer to the marker and measuring the

TABLE 1. The Experimental Design, Numbers of Sampling Points (*N*) for Sediment Deposition and Subsidence.

Site	Transects	Pads	Trees Sampled	Radio Isotope Cores	SETs
1. Cypress Swamp	3	15	7	-	-
2. Delaware Crossing	2	7	14	-	-
3. Willards	3	13	60	1	3
4. Whiton's Crossing	3	16	78	-	-
PP. Pocomoke Plug	-	-	-	1	-
5. Porter's Crossing	3	15	54	1	3
6. Blades	2	11	24	-	-

Note: SET, surface elevation table.

depth in three locations; after measurement the plug was replaced. Reported deposition rates were cumulative over the four-year period.

Where no other long-term (15-100+ years) measurements exist, dating of deposition on tree roots as compared with tree age (dendrogeomorphic technique) may give the best estimate when sampled at high density. The most accurate use of this method is where trees grow on mineral sediments; the least reliable use is in hummock and hollow organic sediment settings. Long-term (1898-1998), net rates of deposition on bottomland surfaces were measured using tree-ring (dendrogeomorphic) techniques (see Hupp and Bazemore, 1993, for method details). Along transects, tree roots were excavated to determine the depth of sediment deposited above roots; in nondepositional areas major tree roots are normally just below the soil surface. Tree age was determined by taking an increment core from near the base for tree-ring analysis. Average annual net deposition was then determined by dividing the depth of root burial by the tree age (Sigafoos, 1964; Everitt, 1968; Hupp, 1988). Trees were sampled along transects in proximity to individual clay pads. Between 14 and 78 trees were sampled per site, except for Site 1 where only 8 representative trees were sampled because no channels existed and all elevations were similar (Table 1). A total of 237 trees were sampled for deposition rates. All increment cores were returned to the laboratory for microscopic analysis and cross-dating (Phipps, 1985). These long-term root burial rates were then compared with the short-term data.

The least representative measurement of deposition used in this study is cesium-137 and lead-210 isotopic dating, not because of bioturbation or movement of the peak isotope deposition, but because of cost and time constraints there are typically only a few samples representing an entire reach of floodplain. Any number of incidences could make that measurement inaccurate; one must assume that the floodplain is perfectly homogenous and stable over time, which is rare on active floodplains. Radio isotopic analyses (^{137}Cs) were used to determine the depth of the 1963-64 peak occurrence of bomb produced fallout in order to estimate the rate of sediment deposition (Craft and Casey, 2000; Stokes and Walling, 2003). Cores were collected from Sites 3, 5, and PP in 2006 (Table 1). Cores were collected at locations representative of mid-levee conditions using a 5-cm tube with a sharpened lip. Cores were cut in 1 cm sections, dried, ground, wood removed, and placed in sample containers. ^{137}Cs activity was determined by placing samples (5-20 g) in a flat aluminum can and then placed on the flat surface of a J-type intrinsic high-purity germanium semiconductor detector of 25% relative efficiency enclosed in a 7.5-cm thick lead shield for counting.

Measurement of Subsidence

Subsidence was measured for two time periods with two methods: dendrogeomorphically from trees predating channelization (1940-1946) and surface elevation tables (SETs) (2003-2007). Dendrogeomorphic measurement of subsidence has inherent errors (compaction of sediments beneath the tree) but trees stand as witnesses of the past conditions where no other data exist. Sites 2 and 3 exhibited extensive tree-root exposures that were inconsistent with erosional processes, such as lack of erosion of clay pads, lack of sediment splays, lack of differential flow paths (i.e., consistent surficial loss regardless of topography), and subsurface cavities within the sediment column. Estimates of net soil loss (subsidence) were determined at sites that showed subsidence (2 and 3) by surveying root and soil surfaces. Representative areas of 50 × 70 m at Site 2 and 70 × 100 m at Site 3 were selected for micro-topographic analysis. A total station was used to survey the topography (0.25 m lateral resolution within 2 m of trees, 2 m at all other points; 2 mm vertical resolution) and to relate the level of the soil surface to the elevations of primary root surface (top of exposed roots immediately distal to the base flare curvature). Fourteen and sixty trees that predated channelization were surveyed at Sites 2 and 3, respectively, in 2002. The elevational difference between the primary root surfaces and the surrounding sediment surfaces were then calculated (Figure 3 and Table 1). The date of channelization was used to determine the postchannelization rate of subsidence. The ground surface was assumed to be level with root surfaces prior to channelization.

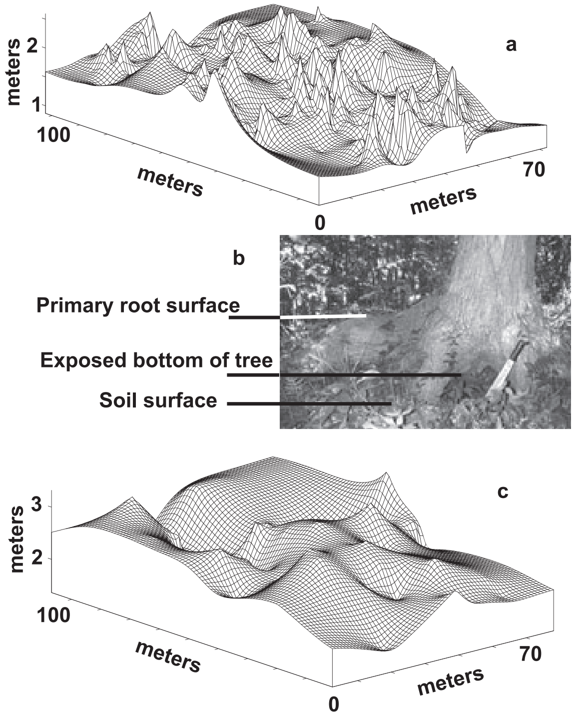

FIGURE 3. An Illustration of the Magnitude of Conditions Observed at the Willards Study Site. (a) A surface plot of primary root surfaces (spikes in plot) in comparison with the sediment surface as surveyed in 2002. (b) An example of typical root exposure at this site, machete is 75 cm long. (c) A recreation of the prechannelization surface based on the primary root surfaces of trees assuming that soil surfaces were level with initial root development at the time of germination. These conditions are common along much of the channelized Pocomoke.

In order to accurately determine current subsidence, elevation and deposition must be measured around a rod, pole, or post driven to refusal. Measured rates of subsidence are valid only for the depth of the measuring device. Three, rod SETs (mechanism utilizing a benchmark rod driven to refusal as its central point designed to repeatedly measure the surface elevation around the rod) (Boumans and Day, 1993; Cahoon *et al.*, 2002) were installed at Sites 3 and 5 in 2003 (Table 1). SETs were placed 60-100 m from the channel at Site 3 and 20-80 m from the channel at Site 5, representing levee, mid-levee, and backswamp features. SET rods were driven to refusal (3 to 5 m). All measurements were made at a stream stage of 1.4 m (USGS stream-gaging station 01485000) in order to minimize measurement error caused by possible shrinkage or swelling of the fluvial aquifer sediments caused by fluctuating water content. Measurements were made at approximately the same time of year (late summer, 2003-2007) by the same person. Additionally, leaf litter interference was avoided by taking measurements at the end of summer (late August, early September). A clay pad was placed at each SET in order to determine sediment deposition rates at each SET. Using these data, sediment deposition, surface elevation change, and actual subsidence were determined.

Sediment Analysis

A surface sediment sample was collected near each clay pad at fluvial sites for textural analysis. These samples were oven-dried and sieved with a sonic sifter. Sediment composition was determined by fractional separation and reported as a coarseness index (CI) using a weighted average of the size classes representing phi units 1-4 (Krumbein, 1936). The scale was inverted so that the weight fraction of sediments larger than 0.5 mm (coarse sand) was multiplied by 5, sediments between 0.5 mm and 0.25 mm (sand) by 4, 0.25 mm and 0.125 mm (fine sand) by 3, 0.125 mm and 0.062 mm (very fine sand) by 2, and smaller than 0.062 mm (silt and clay) by 1. These numbers were totaled to yield a number between 1 and 5, with larger numbers representing larger grained sediment.

Sediment samples were analyzed for organic matter content by loss-on-ignition (LOI) (Nelson and Sommers, 1996). Bulk density samples were collected using a section of 5-cm inner diameter metal tubing with a sharpened edge. Bulk density samples were dried for 24 hours at 100°C, weighed, and divided by the volume of the sample. Estimates of the rate of sediment storage, reported as g/m^2/year, were based on bulk density multiplied by the average volume of deposition per year on clay pads at each site. Storage per kilometer of reach was extrapolated from the site average deposition weight/m^2 multiplied by the riparian area 500 m upstream and downstream from the center of the site. Areas were determined using GIS software and USGS Digital Raster Graphic 1:24,000 topographic sheets (ESRI, Redlands, California).

Data Analysis

Soil texture and composition were analyzed in relation to the independent factors of distance from the river mouth, distance from the river edge, and pad elevation to determine important factors in sediment deposition (short- and long-term). Distance from the river mouth was determined by measurement of aerial photography and (1:100,000) topographic maps (1983) from the point where the Pocomoke River enters the Pocomoke Bay using GIS software.

Three pads that were bioturbated, eroded, or otherwise could not be found were removed from analysis (1 pad at Site 2, and 2 pads at Site 6).

Within-site long- and short-term depositional data were compared using independent t-tests. Significance of difference between headwater, channelized incised, and natural hydroperiod were determined using ANOVA for depositional data from individual pads and trees. Multiple regression analyses were conducted on elevation, distance from the river, deposition rates, and distance from the mouth with depositional data. Simple correlations were carried out to determine correlation coefficients. Within-site comparisons were of averages of similar pad stationing between transects. Average deposition rates of the headwater site (1) and the unincised and (or) unchannelized Sites 4 and 5 were graphed in relation to distance (stream km) upstream. Short-term subsidence data from the SETs between sites were analyzed using a two-sample t-test and comparisons over time were made using a repeated measures design under the split-plot framework (Cahoon *et al.*, 1995). ANOVAs were conducted on short- and long-term deposition, sediment CI, and organic sediment concentration data comparing the significance of differences of all data at all sites in relation to relative elevation, channelization, distance from the channel, and distance from the mouth.

RESULTS

Deposition

Headwater Site. The headwater site (1) had significantly less short-term deposition than the natural hydroperiod sites (sig < 0.00). Long-term rates were not significantly different from natural hydroperiod sites (sig = 0.26). No within site difference was found between the long- and short-term rates (Table 2). Sediment samples taken from Site 1 were highly organic, likely composed of autochthonous litter with some sand grains, possibly from bioturbation. The percentage LOI increased with decreasing elevation ($\beta = -0.91$, $p = 0.03$) (Table 3).

Channelized and Incised River Sites. Channelized and incised Sites 2 and 3 had lower short- and long-term deposition (Table 2) than both the headwater (sig = 0.06, sig < 0.00) and natural hydroperiod (sig < 0.00, sig < 0.00) river sites. Short-term deposition rates between Sites 2 and 3 were similar (sig = 0.62). The pads farthest from the channel had the highest amount of deposition. At Site 3, the lowest elevation pads had greater deposition ($\beta = -0.64$, $p = 0.09$). Analysis of ^{137}Cs activity in the core taken from Site 3 indicates peak deposition (1964) at a depth of 10-20 mm (Figure 4). Sediment texture did not vary significantly with distance from the channel (Figures 5a and 5b, Table 3).

Unincised River Sites. Short- and long-term deposition rates at Site 4 were not significantly different than Sites 5 and 6 with natural hydrology (sig=0.23, sig=0.65). Sites 4, 5, and 6 had short-term deposition rates that were significantly ($p = 0.01$, $p = 0.02$, $p = 0.01$) higher than the long-term rate (Figure 6). Distance from the channel was an important factor at Sites 4 and 5 with high deposition rates behind the natural levee, decreasing, and then increasing at the transect end (Figures 5c and 5d). Analysis of ^{137}Cs activity in the core taken from Site PP indicates peak deposition at a minimum depth of 300-310 mm. In comparison, Site 5 indicated peak deposition at a depth of 30-40 mm (Figure 4).

The coarsest sediment was deposited within about 25 m from the channel with fining away from the river (Figures 5c, 5d, and 5e). At Site 5, coarse sediment was carried into the backswamp by a slough. Deposition at Sites 4 and 5 was composed primarily

TABLE 2. Deposition Rates, Percent Loss-On-Ignition (LOI), and Bulk Density for Pocomoke Floodplain Sites.

Site Name	Site Number	Condition	Long-Term Deposition Rate 50-100+ years, mm/year	Short-Term Deposition Rate 4 years, mm/year	SET Surface Elevation Change 4 years, mm/year	^{137}Cs Rate 42 years, mm/year	LOI%	Bulk Density (g/cm^3)
Cypress Swamp	1	H	1.2 (0.22)	1.2 (0.35)	-	-	80	0.10
Delaware Crossing	2	C, I	−6.9 (0.54)	0.7 (0.19)	-	-	61	0.12
Willards	3	C, I	−11.9 (0.64)	0.6 (0.18)	−6.4	0.24-0.48	50	0.16
Whiton's Crossing	4	C, N	1.4 (0.09)	2.9 (0.35)	-	-	35	0.25
Pocomoke Plug	PP	A, E	-	-	-	7.1-7.4	-	-
Porter's Crossing	5	N	1.7 (0.12)	2.9 (0.44)	−0.37	0.72-0.95	23	0.33
Blades	6	N, T	1.3 (0.14)	3.6 (0.75)	-	-	70	0.10

Notes: A, avulsed; C, channelized; E, extended hydroperiod; H, headwater; I, incised; N, natural hydroperiod; SET, surface elevation table; T, tidal. Standard error is in parenthesis beside the long- and short-term deposition rates.

TABLE 3. Correlation Coefficients (r^2) and p-Values for Short- and Long-Term Deposition, Soil Texture, and Loss-On-Ignition (LOI) in Relation to Distance From River Bank and Elevation.

	m From Flow		**Elevation**			**m From Bank**		**Elevation**	
Site 1	r^2	p	r^2	p	**Site 4**	r^2	p	r^2	p
Short-term	0.36	0.40	0.74	0.14	Short-term	0.21	0.15	0.01	0.90
Long-term	-	-	-	-	Long-term	0.02	0.66	0.14	0.26
Soil texture	-	-	-	-	Soil texture	0.39	0.01	0.03	0.63
LOI	0.39	0.26	0.83	0.03	LOI	0.69	0.01	0.12	0.29
Site 2	**m From Bank**		**Elevation**		**Site 5**	**m From Bank**		**Elevation**	
	r^2	p	r^2	p		r^2	p	r^2	p
Short-term	0.53	0.07	0.04	0.70	Short-term	0.01	0.64	0.10	0.27
Long-term	-	-	-	-	Long-term	0.28	0.06	0.01	0.93
Soil texture	0.12	0.45	0.17	0.02	Soil texture	0.06	0.37	0.01	0.92
LOI	0.04	0.69	0.46	0.13	LOI	0.14	0.19	0.01	0.77
Site 3	**m From Bank**		**Elevation**		**Site 6**	**m From Bank**		**Elevation**	
	r^2	p	r^2	p		r^2	p	r^2	p
Short-term	0.03	0.67	0.40	0.09	Short-term	0.45	0.03	0.20	0.20
Long-term	-	-	-	-	Long-term	0.14	0.83	0.04	0.74
Soil texture	0.04	0.88	0.01	0.88	Soil texture	0.22	0.17	0.09	0.62
LOI	0.01	0.82	0.07	0.53	LOI	0.42	0.03	0.24	0.41

Note: Site 1 has no channel banks, only a zone of concentrated flow during storms.

of mineral sediment, whereas sediment at Site 6 was composed primarily of organic material (cypress needles and tupelo leaves) (Table 2). Short-term deposition rates increased with distance from the river at Site 6 ($\beta = 0.67$, $p = 0.03$) as water levels became unaffected by the tidal cycle and sediment saturation remained constant (Figure 5e, Table 3).

Whole River. Short- and long-term deposition rates along the river as a whole were strongly related to channelization. Relative elevation was also a factor in short-term deposition rates and sediment CI. LOI and CI of the deposited sediments were strongly related to km upstream of the mouth; however, channelization was insignificant as a factor in LOI despite the fact that channelized reaches were upstream (Table 4).

Sediment Storage

Total (mineral and organic) sediment storage along channelized reaches was low, 27,000 kg/km/year at Site 2, and 51,000 kg/km/year at Site 3. The greatest sediment (mineral and organic) storage was at Site 4; where the river begins to reconnect with the floodplain, storing 860,000 kg/km/year, 300,000 kg/km/year of this was organic. Site 5, historically a fluvial site, stored 560,000 kg/km/year of which 130,000 kg/km/year was organic. The area around Site 5 is the furthest downstream reach for significant mineral sediment storage. At Site 6, there was 410,000 kg/km/year of sediment storage, of which 290,000 kg/km/year was organic (Figure 7).

Subsidence

Subsidence was measured using two methods. SETs were set up at Sites 3 and 5 to measure subsidence in relation to surface deposition, and at Sites 2 and 3 dendrogeomorphic techniques were used to determine net subsidence. During the SET deployment period, subsidence at channelized Site 3 (−6.4 mm/year) far exceeded deposition (0.50 mm/year) resulting in a significant ($p < 0.00$) surficial elevation change of −5.9 mm/year. At the unchannelized Site 5, SETs recorded deposition of 0.38 mm/year with a subsidence of −0.66 mm/year resulting in an insignificant ($p = 0.38$) surficial elevation change of −0.28 mm/year (Figure 8). Subsidence differed significantly between these two sites ($p < 0.00$).

Primary root surfaces were consistently above the sediment surface over the floodplain at Sites 2 and 3. On average, primary root surfaces were exposed by 47 cm ($n = 14$) at Site 2 (−6.9 mm/year) and 64 cm ($n = 60$) at Site 3 (−11.9 mm/year) (Figure 3). Site 3 had significantly more subsidence than Site 2 (sig = 0.05). Based on bulk density, percent LOI, and subsidence volume, Site 2 organic loss was

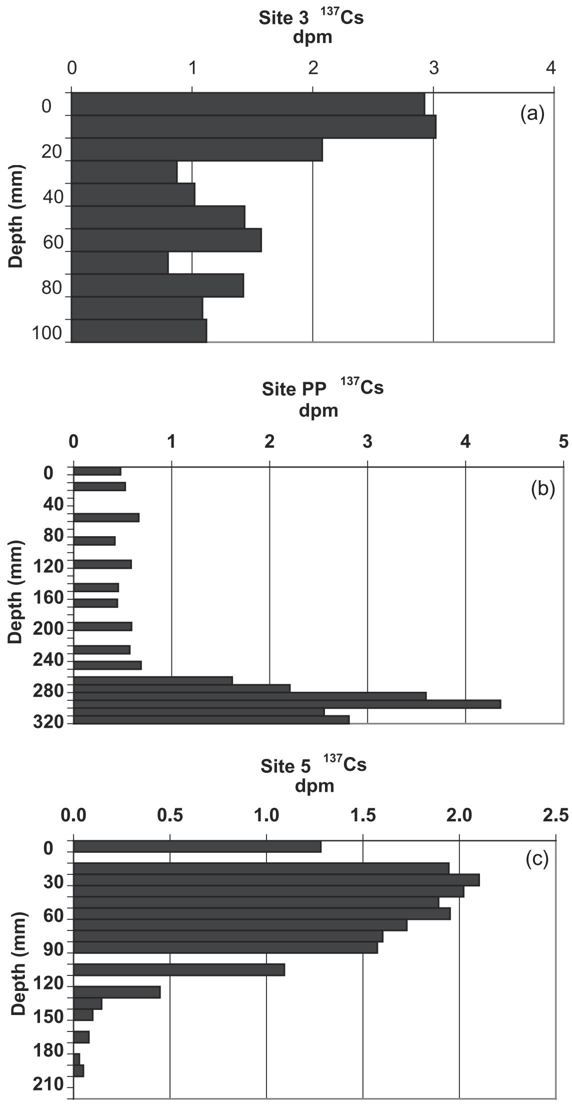

FIGURE 4. Plots of ^{137}Cs Activity in Cores From Sites (a) 3, (b) PP, and (c) 5. The greatest dpm in each chart indicate peak deposition from atomic bomb testing (1963-1964) in comparison with the depth of deposition.

60,000 kg/km/year. At Site 3, this loss of organic material was 120,000 kg/km/year.

DISCUSSION

General Deposition Trends

Short-term deposition rates ranged from 0.6 to 3.6 mm/year (Figure 6b, Table 2). Although these values are within the range of published rates for southeastern U.S. floodplains (DeLaune *et al.*, 1978; Kleiss *et al.*, 1989; Hupp and Morris, 1990; Conner and Day, 1991; Hupp and Bazemore, 1993; Hupp, 2000), our data suggest that the lowest rates at channelized and incised sites were significantly lower than normal for this system. The period of study (1998-2002) was drier than the preceding 10-year period (USGS gaging station data, Willards). This dry period may have lowered short-term deposition rates because of shortened duration of inundation by overbank flow. The lowest short-term rates of deposition occurred along channelized reaches. The isolation of the floodplain from the river along channelized and incised reaches (2 and 3) has resulted in decreased storage of entrained sediment. The short-term deposition rates at the incised sites were half that of the relatively undisturbed headwater site. This low rate suggests that organic deposition (primarily autochthonous) along the incised sites may have been oxidized. In reaches where hydraulic connectivity has been restored (Site 4), sediment deposition is as high or higher than downstream unchannelized sites. Where channelization ends, and river waters with high suspended sediment loads regain unrestricted hydraulic connectivity with the floodplain (Site PP), an order of magnitude increase in deposition has occurred (Table 2).

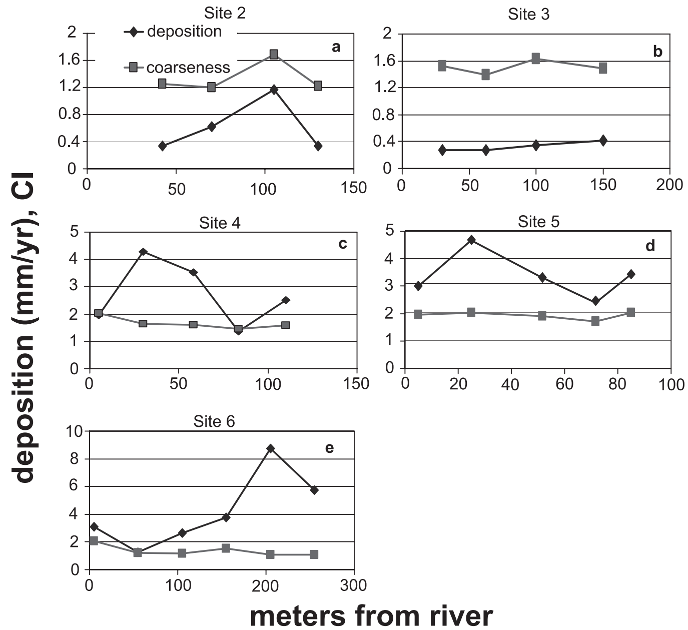

FIGURE 5. Deposition and Sediment Texture (CI) as a Function of the Distance From the Main Channel for Sites (a) 2, (b) 3, (c) 4, (d) 5, and (e) 6.

Variations in deposition rates within each site were affected by several factors. At Cypress Swamp (1) and Willards (3) lower elevations (increased hydroperiod and sediment anoxia) resulted in increased deposition rates. Proximity to upland field erosion was important at Delaware Crossing (2). Sites 2 and

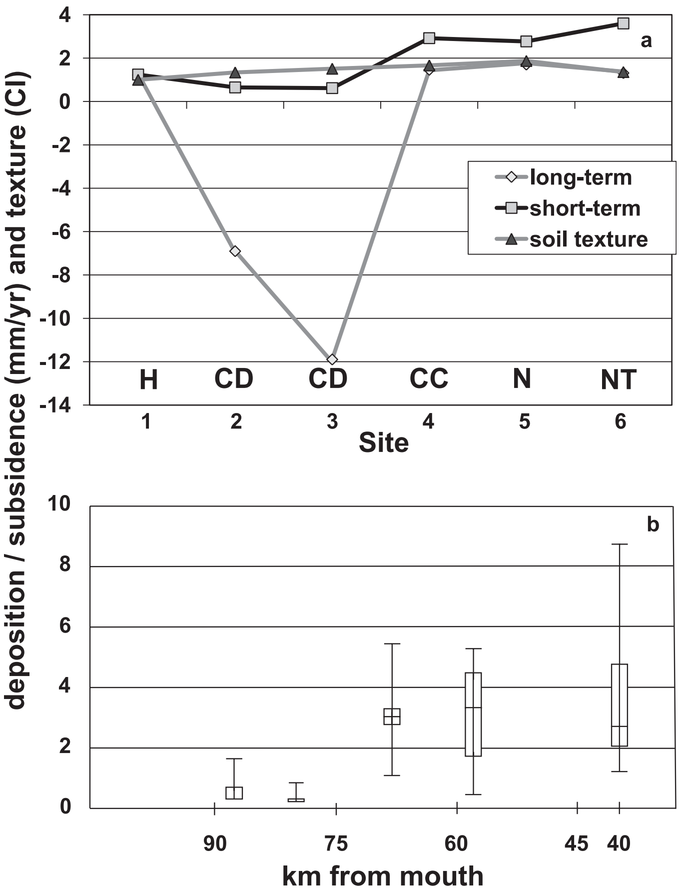

FIGURE 6. Average Long- and Short-Term Deposition and Subsidence Rates, and Sediment Textures (CI) of Study Sites. (a) Total spread of rates −12 to 4 mm/year. (b) Box and whisker plot of observed deposition for Sites 2 to 6. Short-term data are from clay pads, long-term data are from dendrogeomorphology.

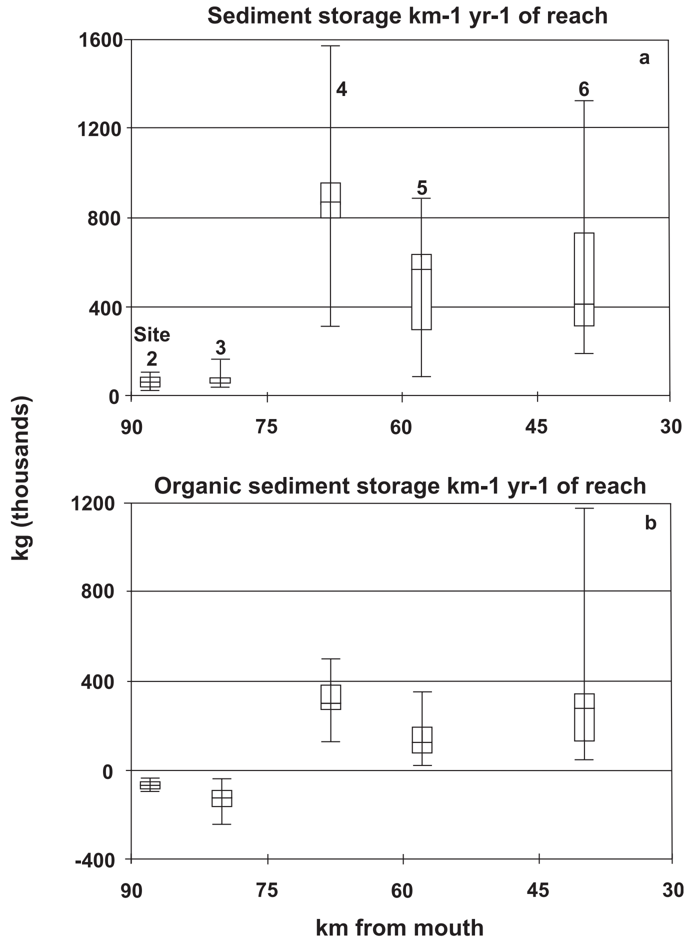

FIGURE 7. Box and Whisker Plots of Calculated Kilograms of Storage/Stream km/Year for (a) Total (mineral and organic) Sediment Storage (thousand kg) and (b) Organic Sediment Storage or Loss (thousand kg).

TABLE 4. Results of ANOVA for the River as a Whole.

Whole River	m From Bank		Relative Elevation		km Upstream		Channelization	
	F	Sig	*F*	Sig	*F*	Sig	*F*	Sig
Short-term	1.1	0.42	10.5	0.02	8.6	<0.00	12.2	<0.00
Long-term	-	-	-	-	92.2	<0.00	182.7	<0.00
CI	1.8	0.07	7.5	0.03	11.8	<0.00	1.4	0.26
LOI	2.5	0.01	4.3	0.13	20.3	<0.00	3.0	0.06

Notes: Significance of variance short- and long-term deposition, sediment texture (CI) and loss-on-ignition (LOI) as a factor of m from the bank, relative elevation, km upstream of mouth, and channelization.

3 had extremely limited fluvial interaction. Pads at Site 3 were completely inundated only 100 days from 1949 till 2002, and only 1 day during 1998-2004 to depths ranging from 0.02 to 0.6 m (gage data). In comparison, Site 5 was inundated 45 days during 2002 (record drought year, well data). Soil coring at the lowest pads of Sites 2 and 3 at a stream stage of 1.35 m showed the water table to be approximately 1 m below the surface, with sand at 0.6 m below the surface.

A highly perforated or gapped spoil bank at Whiton's Crossing (4), with the floodplain at almost the same elevation as median discharge, maintains site inundation for most of the year, through both overbank flow and presumably groundwater. The extended contact of river water (rich in sediment) with the floodplain allows for high deposition rates of fine mineral and organic sediments on the swamp side of the spoil bank resulting in the greatest short-term (clay pads) storage of sediment annually (kg/km/year). On the channel side of the spoil bank, short-term deposition rates were lower. This low deposition rate may be a result of resuspension of sediment by higher velocity flows. The connectivity of the floodplain to sediment laden flood flow through

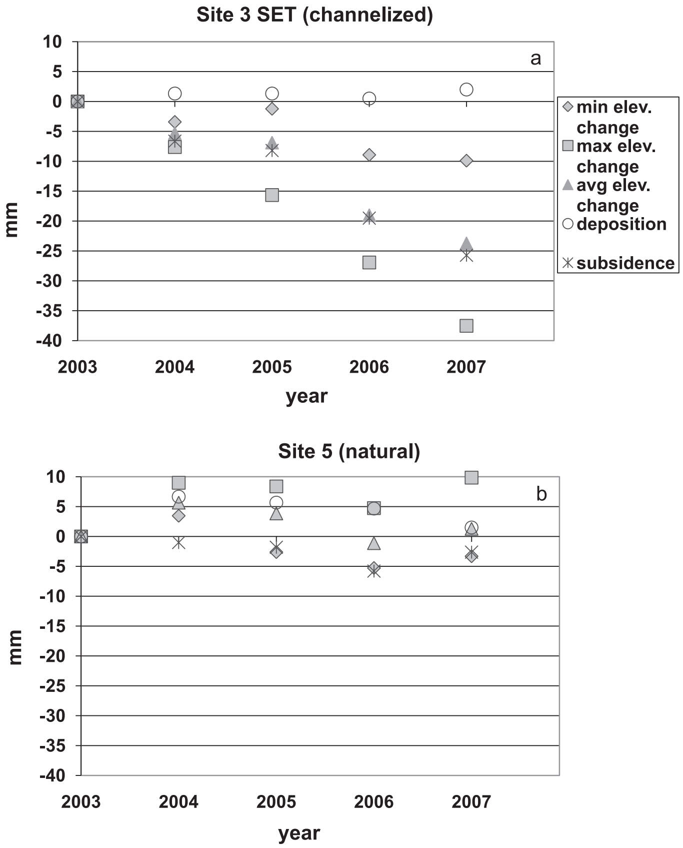

FIGURE 8. Plots of Site Average Data Derived From SETs, Deposition, Subsidence, and Minimum, Maximum, and Average Surface Elevation Change From Sites (a) 3 and (b) 5.

crevasses in levees and spoil banks has been shown to be a prime factor in overall and local sediment trapping (Patterson *et al.*, 1985; Pizzuto, 1987; Hupp, 2000; Ross *et al.*, 2004). Although deposition rates are high in the vicinity of the breaks they are relatively low within the normal range of healthy swamp forests (Pierce and King, 2007a; Hupp *et al.*, 2008).

Sediment storage in the area where the channelized reach reconnects with the natural channel (Site PP) has occurred at a rate that is an order of magnitude higher than other sites on this river since 1963-1964 (Figure 4). Late identification of this site prevented collection of short-term sediment deposition data, however all conditions necessary to maintain a high deposition rate are still in place. Much of the discharge is forced over the floodplain as a result of a reduction of channel cross-section from 27 m^2 upstream (100 m) of Site PP to 6 m^2 at the site; consistent with processes associated with valley plugs (Pierce and King, 2007b). High-density slough formations distribute water across the floodplain. At the current bed level (0.7 m below back swamp), the channel is at risk of further avulsions as sloughs gain competency and capture discharge (Figures 2 and 9). The condition of the stream channel and its hydraulic connectivity to the floodplain may be the most important determinant of sediment deposition along the river system.

Sites 5 and 6 appear to have been minimally affected by channelization. Natural channels and distance below the limit of channelization appear to ameliorate high sediment loads. Site 5 is perhaps the most typical (among study sites) of southeastern Coastal Plain floodplains in terms of fluvial landforms and sedimentary processes (Hupp, 2000). Flow velocities across the flood plain at Site 6 were slow and tidally influenced, lacking the competence to move coarse mineral sediments. Prechannelization deposition may have been very similar to the current deposition. Nutrient ratios in another study indicate that stored sediment at Site 6 does not originate from the watershed (Kroes *et al.*, 2007). Site 6 maintained a high level of floodplain connectivity with overbank flow during the four-year study period. The high organic storage rate at Site 6 may be related to the decreased flow velocities from tidal effects along this reach. Floodplains similar to that at Site 6 maintain almost constant saturation resulting in high deposition rates (unconsolidated coarse organic material) and storage due to anoxic sediment conditions.

Downstream coarsening of sediment texture was observed (Figures 5 and 6, Table 4) and might logically be expected when a channel forms in a blackwater system based in fine organic sediments on top of sand (a natural channel was active) and the stream power increases downstream. The sand component of the sediment was probably not mobilized by the natural channel except during extreme events. This can be shown by the fine texture of the sediment farthest away from the man-made channel and on the bank of the natural channel at Site 4 (Figure 5c). The sediment texture of this farthest pad from the river at Site 4 was still coarser than what was found at the upstream sites although textures across the floodplain were probably influenced by the channelization.

Subsidence of Organic Rich Sediments

Multiple methods of measuring subsidence at Sites 2 and 3 show significant losses of 6.4-11.9 mm/year (Tables 2 and 4). This subsidence over the period of channelization (54 years) has resulted in root exposures to the extent that tree trunk bases were exposed and perched above the ground. This amount of root exposure might be found in atypically erosive settings, possibly in a slough, eroding bank, or a high-gradient fluvial system following an extreme event, but is not typical (Hupp, 2000) on the entire floodplain of a nearly flat (0.21 m/km) Coastal Plain system (Figure 3). Analyses of tree cores reveal no

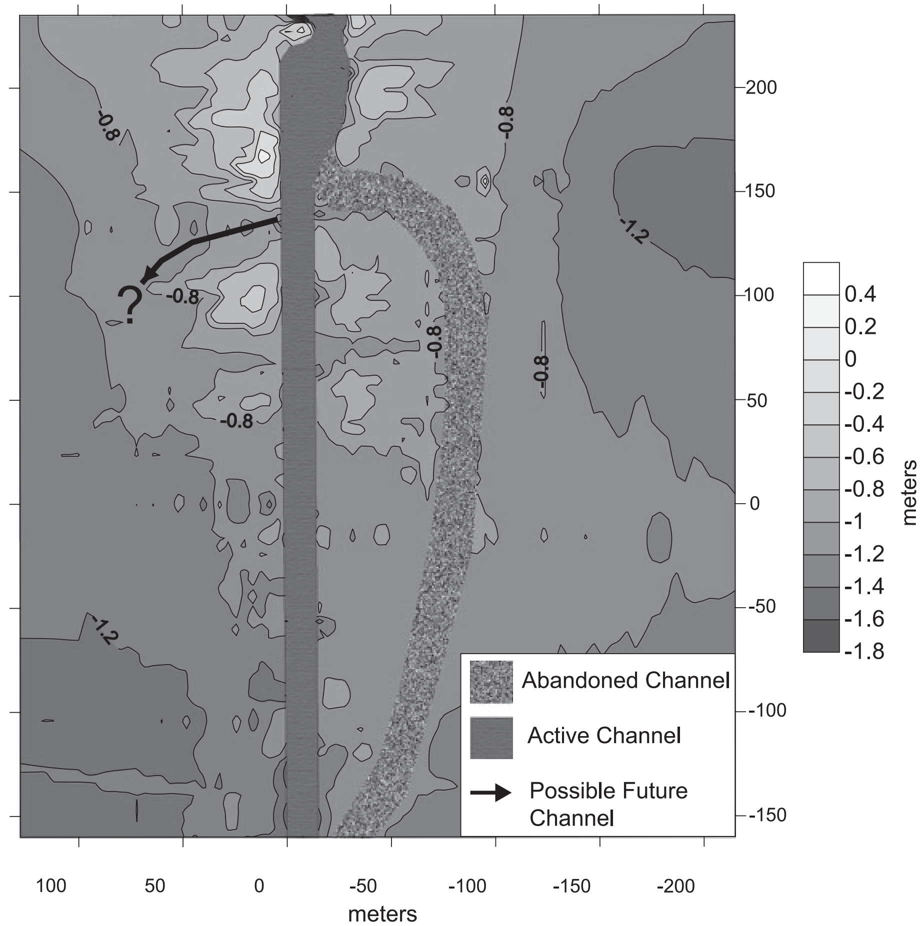

FIGURE 9. A Contour Map of Site PP, the Pocomoke Plug. Distances left and right are based off of the right bank of the current channel for better visualization, giving the appearance of a straight channel, where in the field it is sinuous. The abandoned channel and possible future channel migration are shown.

trace of fire in 131 years of growth. SETs show this to be an internal loss of volume. The observed rates are within the published range for drainage-related subsidence in northern peatlands following drainage (Moore and Knowles, 1989; Glenn *et al.*, 1993; Laine *et al.*, 1994).

These data indicate that the drainage of highly organic sediments in a southeastern U.S. floodplain setting also results in oxidation over time. The highly organic sediment (50-80% LOI) of these sites was effectively drained to the mineral sublayer over much of the floodplain for most of the year. Sapric histosols indicate that the prechannelization condition was almost complete saturation or inundation for most of the year except for drought periods. Drainage allows oxygen to interact with organic sediments deposited and preserved in an anoxic setting. The dried condition allows burrowing organisms that typically do not occupy saturated floodplains (termites, ants, mice, etc.) to introduce oxygen deep into the sediments, resulting in oxidation within the organic sediment rather than just at the surface (Montague, 1982). This condition was observable along channelized reaches where the organic sediments were effectively drained (i.e., not directly underlain by clay). The most feasible explanations for the loss of sediment volume are dewatering and the subsequent oxidation of organic material.

SUMMARY

Channelization has disconnected the floodplain from the majority of the Pocomoke River. The sediment storage function of the entire upper Pocomoke River has been almost eliminated. Along reaches where the spoil banks are gapped, sediment storage is high. The high rate of storage along these reaches suggests that there may be significant water quality benefits in creating gaps in spoil banks along channelized streams to allow some reconnection of the river and floodplain waters. Riverine swamp flora and fauna are adapted and dependent on sediment deposition and fluctuating water levels, isolation of the floodplain from water level fluctuation is detrimental (Kwak, 1988; King and Grant, 1996). Downstream of channelization where streamflow in the Pocomoke totally reconnected with the natural riparian area, deposition rates were increased to the point that sediment filled the river channel resulting in channel abandonment (avulsion); subsequent avulsions can be expected.

The oxidation of organic sediments in the upstream, channelized reaches, has led to substantial subsidence. The ongoing net-subsidence rate of 6.4 mm/year for the affected portion [22 km $\times$ 624 m (average)] of the Pocomoke represents an organic matter loss of 10.5 million kg/year at a bulk density of 0.12 g/cm^3 (bulk densities ranged from 0.12 to 0.16 g/cm^3). This oxidation, in addition to the estimated loss of possible carbon storage along channelized reaches, results in the loss of carbon storage function to the majority of the nontidal reaches of the Pocomoke River. The oxidation of organic sediments will continue until saturated anoxic sediment conditions are restored.

Channelization has occurred on hundreds of thousands of stream kilometers throughout the southeastern U.S. Much of this channelization has been carried out on the Coastal Plain in situations similar to the Pocomoke River (Hupp, 1992); most of these systems have been subsequently logged leaving no trace of where the sediment surface may have once been. In this case, many standing trees are older than the channelization and can be used for rough subsidence-rate estimation. Large-scale channelization efforts have minimized the functions of floodplains by isolating them from streamflow (Ross *et al.*, 2004; Noe and Hupp, 2005). Additionally, the drainage of floodplains by improved channels has resulted in the oxidation of stored organic sediments, resulting in subsidence. The nutrient by-product (nitrates, phosphates) of this subsidence could be a contributor to the eutrophication of downstream water bodies; in this case, the already stressed Chesapeake Bay. A quantification of the subsidence of channelized, blackwater swamp floodplains may be useful to water-resources managers in developing remediation plans. Restoration of hydraulic connectivity to floodplains via check board risers or other means along incised reaches and gapping of the spoil bank may facilitate remediation goals.

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