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Hydrology, geomorphology, and vegetation of Coastal Plain rivers in the southeastern United States

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Abstract:

Rivers of the Coastal Plain of the southeastern United States are characteristically low-gradient meandering systems that develop broad floodplains subjected to frequent and prolonged flooding. These floodplains support a relatively unique forested wetland (Bottomland Hardwoods), which have received considerable ecological study, but distinctly less hydrogeomorphic study. The hydroperiod, or annual period of inundation, largely controls the development of characteristic fluvial landforms, sediment deposition, and vegetation distribution patterns. Order of magnitude differences in wetted perimeter, width/depth, suspended sediment load, and hydraulic roughness may exist between "dry" in-channel seasons and the hydroperiod. Substantial sediment (and adsorbed contaminants) retention and storage through lateral and vertical accretion is common (where not heavily impacted by flow regulation) along these Coastal Plain rivers. The present chapter summarizes our current understanding of the hydrology, fluvial geomorphology, general and local sedimentation patterns, and related plant ecological patterns of these Coastal Plain bottomlands.

KEY WORDS: Coastal Plain, meandering rivers, fluvial geomorphology, fluvial landforms, sediment deposition, woody vegetation

INTRODUCTION

The Coastal Plain Physiographic Province of the United States (Fig. 1) lies almost entirely in the southeast. It covers an area of about 1.2 million square kilometers (slightly larger than the combined area of Belgium, France, Germany, and the United Kingdom). This topographically distinct lowland is bounded on the east and south by the Atlantic Ocean and the Gulf of Mexico, respectively, and landward on the west and north, at some places less distinctly, by the Piedmont and Ozark Highlands (Fig, 1). Bottomlands typically are broad, alluvial features with low gradients, meandering streams, most of which terminate downstream in tidal estuaries. These Coastal Plain river systems have received noticeably less hydrologic study than higher gradient Piedmont and montane river systems, where such concepts as bankfull discharge and flood-return interval were developed (Leopold et al. 1964). The flood plains of Coastal Plain rivers are typically inundated every year for prolonged (months in some cases) periods. The forests (Bottomland Hardwood systems including southern Deep-Water Swamps), however, have received considerable ecological study, yet the linkages between the fluvial geomorphic processes and forest ecology remain poorly understood.

Fluvial geomorphology refers to study of the surficial landscape, geomorphic forms, and physical processes developed or mediated by the action of flowing water, most typically in the form of streamflow. Most geomorphic work in fluvial systems involves the erosion, entrainment, transport, deposition, and storage of sediment. At least ninety percent of all sediment eroded 'from uplands is trapped in alluvial systems before reaching saltwater (Meade et al. 1990). Detailed spatial and historical analyses of sediment trapping, storage, and retention time, at both large and small scales, generally are lacking, possibly with the exception of the lower Mississippi Valley (Saucier 1994). Alluvial processes create and maintain a variety of landforms, including flood plains that supports Bottomland Hardwood (BLH) Forest ecosystems in the southeastern United States. These forests interact with hydrologic and fluvial geomorphic processes and forms (including binding alluvium through root development and enhancing deposition by increasing stream roughness) such that the intrinsic character of each is at least partly the result 'of the other. The purpose of the present paper is to provide an overview of our current understanding of the form and process linkage between lowland meandering streams on the Coastal Plain of the southeastern U.S. and their characteristic BLH forests.

Several definitions of BLH have been published recently (Wharton et al. 1982, Mitsch and Gosselink 1993, Sharitz and Mitsch 1993, Shepard et al. 1998). All definitions confine BLH to the riparian zone, thus associating BLH systems with the bottomland adjacent to streams. The riparian zone can be defined as that part of the landscape supported by and including recent fluvial landforms and inundated or saturated by the bankfull discharge (Hupp and Osterkamp 1996). Although this definition is not as inclusive of bottomland features as others (e.g., Malanson 1993) it is quantitative in that the bankfull discharge typically occurs at least once every 1 to 3 years (Leopold et al. 1964). BLH systems are usually considered forested wetlands; many definitions also require inundation or saturation of the soil at least once annually during the growing season (Mitsch and Gosselink 1993). The riparian zone, in particular the flood plain, reaches its greatest development in the U.S. along the many low-gradient rivers originating on or flowing across the Coastal Plain physiographic province. Thus, BLH systems are, in large part, an extensive and characteristic feature of southeastern rivers (Fig. 1). Here and throughout the text the term vegetation refers to the woody vegetation of BLH systems; it is beyond the scope of the present paper to discuss herbaceous vegetation, although many of the interpretations would apply as well.

Since the late 1970's there has been considerable focus on the function and value of wetlands (Greeson et al. 1979, Carter 1986, 1996, Landin 1992), summarized recently, Brinson and Rheinhardt (1998). Riparian wetlands (including BLH) have been cited to be of particular value for several reasons. Biologically, the riparian zone is the ecosystem with the greatest biodiversity in most regions of the world (Nilsson 1992, Naiman et al. 1993). Riparian areas also provide critical habitat for many plants and game and non-game species of fish and wildlife. Environmentally, these wetlands function as an important, if not critical, natural element in the maintenance of water quality. Properly functioning BLH systems annually trap and store enormous amounts of sediment, nutrients, and contaminants (Kleiss 1996, Hupp et al. 1993).

Unfortunately, BLH systems have decreased tremendously in area1 extent, principally through conversion to agriculture (Mitsch and Gosselink 1993, Kress et al. 1996) following World War II. Missouri, Arkansas, and Louisiana alone lost 21,000, 57,000, and 24,000 hectares, respectively, between 1960 and 1975 (Turner et al. 1981). Their continuing rapid loss is of imminent concern because of concomitant losses of water-quality and habitat functions (Sharitz and Mitsch 1998). In addition, the majority of remaining BLH forests have been modified as a result of lumbering or agricultural usage and/or more recent activities such as highway construction and channelization (Bazemore et al. 1991, Hupp 1992, Lockaby and Walbridge 1998). Many of these forests particularly those near the Fall Line (Fig. 1) along the Atlantic Coastal Plain experienced substantial aggradation in the 18th and 19th centuries following deforestation and poor agricultural practices by European settlement (Wolman 1967, Costa 1975, Jacobson and Coleman 1986). Subsequent reforestation and better agricultural practices substantially reduced sediment loads which has led to channel incision leaving flood plains and terraces relatively "high and dry" along many East Coast streams. Heightened post-settlement deposition has been documented on at least two Coastal Plain streams, namely along the Congaree River in South Carolina (Patterson et al. 1985) and along the Roanoke River in North Carolina (Hupp et al. 1999a). The lower Roanoke river aggraded by as much as 4 meters near the Fall Line; this deposit attenuates downstream toward the estuary but nevertheless affects channel depths, point bar development, levee formation, and vegetation patterns (Hupp et al. 1999b).

GEOLOGIC CONTROLS

The Coastal Plain (including the subaqueous Continental Shelf) from the Chesapeake Bay to eastern Texas (Fig. 1) is largely the result of sediment deposition, both alluvial and marine, from the adjacent eroding mountains and Piedmont since at least the Cretaceous Period. This broad plain has been sculpted by hydrologic and fluvial geomorphic processes that vary in their effect in response to changes in sea level and climate. During oceanic regressions (sea-level retreat to a low stand) streams on the Coastal Plain and adjacent Piedmont tended to entrench into their valley (degradation) owing to higher stream gradients. Oceanic transgressions (sea-level rise to a high stand) with lower stream gradients typically led to valley filling and widening (aggradation). Coupling this rather simple conceptual model with concomitant variation in climate and tectonics has led to a deceptively complex modern landscape. For instance, many of the rivers on Atlantic Coastal Plain are under-fit, that is, the present channel does not carry sufficient discharge or sediment to have created the broad alluvial flood plain within which the river now flows. This underfit condition may result from stream capture (loss of drainage area), or perhaps more typically, from a reduction in rainfall. Rainfall during a pluvial period 18 to 10 thousand years ago may have been 18 times greater than at present (Dury 1977). Melting continental glaciers undoubtedly increased discharge and sediment load on some of the larger rivers. Further, Pleistocene frost action and variation in plant cover probably made available considerable amounts of sediment for transport and deposition.

The modern Coastal Plain bottomlands of most southeastern rivers are largely a result of fluvial processes during the last low stand (about 14,000 to 18,000 years ago) and the subsequent oceanic transgression toward a new high stand. The lower Mississippi River incised into its bottomlands (the largest contiguous area of BLH), during the last low stand, upstream to about the vicinity of Vicksburg, Mississippi. This relatively short distance is probably due, in part, to a concomitant lengthening of the channel (Saucier 1994). With rising sea level over the past several thousand years, the bottomlands rapidly filled, widened, and formed large anabranches associated with deltaic processes, forming the aggrading Atchafalaya Basin. Smaller rivers of the Gulf Coastal Plain probably did not incise deeply due to a high sediment load and relatively low discharges during the past low stand (Saucier 1994). Many of these streams, like those on the Atlantic Coastal Plain, are now underfit following a pluvial period (18 to 10 thousand years ago, Dury 1977) and subsequent oceanic transgression and aggradation. Additionally, several stream captures may have occurred, including the Cache River, AR, (Bennett and Saucier 1988) that contributed to the commonly under-fit nature of many BLH systems. Similar processes affected streams of the Atlantic Coastal Plain, excepting major tributaries of the Chesapeake Bay. All large tributaries of the Chesapeake Bay that arise in the Appalachian Mountains incised to the Fall Line and remain in an embayed condition today, possibly due largely to the Bay's principal tributary, the Susquehanna River. The extremely high discharge and ocean proximity of the Susquehanna River may have lowered the regional base level to such a degree during the last glacial retreat that aggradation in the other major Bay tributaries has not kept pace with rising sea level. However, streams of the region that arise on the Piedmont and Coastal Plain with substantially less discharge and erosive capacity than the Susquehanna River did not incise like the major tributaries during the last low stand and now support BLH systems on relatively broad bottomlands.

HYDROLOGIC PROCESSES

Water is of singular importance in BLH systems, as in all wetland systems, as the medium for biogeochemical processes (in living and physical systems), as an ecological limiting factor, and as the force that controls the movement and storage of sediment and associated material. All wetland functions can be described entirely or in part by hydrologic processes (Nestler and Long 1994) and agreement on the primary influence of hydrology in wetland ecosystems is pervasive in wetland hydrologic literature (Carter 1986, 1996, Walton et al. 1996). Yet our basic understanding of most hydrologic processes remains somewhat tenuous due in part to the relatively recent emergence of hydrology as a science and because most hydrologic processes are subject to the vagaries of precipitation and climate. Slight hydrologic changes may result in only loosely predictable, yet often substantial, wetland responses (Mitsch and Gosselink 1993). Defining the relation among hydrologic processes and other wetland phenomena in BLH systems is further hampered by the lack of more than a few rigorous studies in this wetland type (Walton et al. 1996).

A strong seasonal variation in discharge occurs along most medium and large streams on the southeastern Coastal Plain (Fig. 2). Annual variation in evapotranspiration and rainfall produce two distinctly different hydrologic seasons; a low-flow season from about June through October, when streamflow is largely confined to a meandering main channel and a high-flow season from about November through May, when large parts of the wooded bottomland may be inundated. This period of inundation is referred to as the hydroperiod (Fig. 2). Order of magnitude differences in wetted perimeter, width-depth ratio, and roughness may occur seasonally along the same reach. This bimodal hydrology leaves an indelible signature on the biotic and abiotic landscape (Fig. 3, A and B) and complicates environmental interpretations.

Two major types of streams, classified according to suspended-sediment load, form the bottomlands that support BLH systems. They are: 1, alluvial rivers that arise in uplands (typically mountainous areas or the Piedmont) and transport substantial amounts of eroded mineral sediment; and 2, blackwater rivers that arise on the Coastal Plain typically with low gradients that transport relatively little mineral fines (Table 1). Alluvial rivers can be subdivided further into brown-water systems and red-water systems. The former are usually large systems with initially high gradients arising in the mountains, whereas the latter tend to be smaller, lower-gradient systems that arise in the Piedmont and derive their red color from iron oxides that characterize the Piedmont residuum. Blackwater systems tend to be smaller than either brown- or red-water systems principally due to their limited potential to develop large watersheds. Water in blackwater systems, with little gradient, flows relatively slowly and has limited ability to erode sediment. This slow moving water leaches tannins from the typically highly organic bottomlands or riparian wetlands, which stains the water and lowers the pH (from 7 to 6, Wharton et al. 1982) relative to alluvial systems. However, drainage may affect the mineral content of blackwater streams such that better-drained systems develop soils with a relatively high mineral content. The origin of streams flowing on the Coastal Plain also affects the dissolved load (chemical characteristics). Alluvial rivers have relatively high concentrations of inorganic ions including several macronutrients, and relatively low concentrations of total organic carbon (Table 1); the converse is true for most blackwater rivers (Wharton and Brinson 1979). Thus, pH, hardness, and specific conductance tend to be higher in alluvial rivers than in blackwater streams.

Alluvial rivers develop a fairly abrupt reduction in gradient after crossing the Fall Line and contacting the relatively flat Coastal Plain. Coincident with reduction in gradient are greater frequencies of over-bank flows, a flatter hydrograph, and longer periods of inundation. These tendencies are partly due to the relict nature of the Coastal Plain and the stream-regime shift, without a reduction in discharge, from high energy, at least partly bedrock-controlled, relatively straight upland reaches to low-energy meandering reaches. The broad bottomlands of the Coastal Plain often do not fit empirical hydrologic concepts such as bankfull discharge (Leopold et al. 1964), developed for upland streams. These flood plains tend to be flooded much more frequently than every year and a half and for much longer durations. During leaf-off seasons with high discharges and little transpiration some BLH systems are regularly inundated for months each year, effectively increasing channel width as much as an order of magnitude during the hydroperiod. Streamflow during the hydroperiod is less meandering and in intimate contact with the riparian zone that supports BLH forests. Many functional attributes of BLH systems including sediment and associated-material trapping (Fig. 3), are most prominent during the hydroperiod. Unfortunately anthropogenic features such as 19th century agricultural levees may reduce the effective flood plain surface area and reduce residence time of out-of-bank flow by increasing velocities.

GEOMORPHIC FEATURES

Fluvial geomorphic processes create a variety of widely recognized landforms, from small channel bedforms to extensive flood plains. The latter typically support BLH

Table 1. Summary of suspended sediment (susp. sed), total and dissolved (Diss.) Nitrogen (N) and Phosphorus (P) for selected southeastern U.S. streams monitored by the U.S. Geological Survey, National Stream Quality Accounting Network (NASQUAN). Table adapted from Alexander (1998). Streams listed in order of ascending suspended sediment concentration; first five streams are blackwater systems, others are alluvial Values are averages over the period of record.

River	Location of Station	Period of Record	Instantaneous streamflow Value	Susp. Sed. (mg/L)	Susp.Sed. % less than 0.062mm	Diss. N (mg/L)	Total N (mg/L)	Diss. P (mg/L)	Total P (mg/L)	Organic Carbon Total (mg/L)	organic Carbon Suspended (mg/L)
Aucilla	near Scanlon FL	1/78 to5194	539	4.83	44.80	0.57	0.75	0.04	0.06	18.38	0.20
Coosawhatchie	near Hampton SC	10/74 to 8/86	204	5.38	88.22	0.82	0.78	0.08	0.10	13.10	0.63
Edisto	near Givhans SC	10/74 to 9/95	2506	7.25	87.47	0.51	0.67	0.05	0.44	8.51	0.54
suwannee	near Branford FL	1/73 to 10/94	7727	9.01	53.90	0.97	1.03	0.21	0.24	14.36	0.31
Blackwater	near Franklin VA	10/74 to 1/95	702	9.85	88.77	0.69	0.85	0.02	0.04	11.02	0.78
Santee	near Pineville SC	1/74 to 9/77	1846	12.20	96.87		0.47		0.03	7.04	
Apalachacola	at Chattahoochee FL	1/73 to 9/95	3 1552	15.57	84.97	0.54	0.71	0.01	0.04	5.16	0.61
Satilla	at Atkinson GA	2/73 to 2/94	2 9 3 6	16.62	79.41	0.74	0.90	0.07	0.10	19.43	0.82
Roanoke	near Scotland Neck NC	3/73 to 12/76	9039	17.47	90.91	0.55	0.53	0.03	0.04	6.26	
Savannah	near Clyo GA	2/73 to 7/95	12329	17.90	93.43	0.77	0.69	0.06	0.09	5.62	0.73
Yellow	at Mulligan FL	2/73 to 9/93	1269	19.05	61.51	0.36	0.51	0.01	0.03	5.42	0.59
Flint	at Newton GA	1/73 to 8/95	13375	21.49	81.13	0.45	0.91	0.04	0.08	4.26	1.38
Meherrin	at Emporia VA	1/73 to 9/93	657	23.02	92.83	0.35	0.62	0.02	0.05	7.87	0.80
PeeDee	at Peedee SC	10/77 to 9/95	10507	27.34	93.32	0.72	0.98	0.04	0.09	5.70	1.24
Contentnea	at Hookerton NC	9/75 to 6/95	982	27.58	72.10	1.80	1.91	0.22	0.31	10.12	0.79
CapeFear	near Kelly NC	1/73 to 8/95	5907	30.79	84.91	1.17	1.31	0.14	0.20	9.28	0.76
Escambia	near Century FL	2/73 to 9/94	693 1	31.36	59.86	0.38	0.56	0.01	0.04	6.55	0.60
Alabama	near Montgomery AL	1/73 to 1/93	59949	34.98	92.98	0.47	0.59	0.02	0.05	5.87	0.49
Altamaha	at Doctortown GA	1/73 to 10/79	16238	38.34	89.33		0.66	0.05	0.07	7.72	
Wolf	near Landon MS	1/78 to 7/86	538	49.16	68.07	0.48	0.45	0.01	0.04	6.20	0.96
BogueChitto	near Bush LA	1/73 to 8/95	2415	57.82	81.46	0.87	0.82	0.03	0.07	4.82	1.06
Congaree	at Columbia SC	10/77 to 9/78	9640	63.58	100.00		0.73	0.02	0.08	6.82	0.93
Pearl	near Bogalusa LA	1/73 to 8194	14494	83.61	89.38	1.10	0.93	0.04	0.10	6.55	1.81
Pascagoula	near Benndale MS	2/73 to 6/95	14494	106.12	85.20	0.62	0.83	0.03	0.08	7.77	2.23

systems in the southeastern Coastal Plain. Flood plains, like most fluvial landforms are dynamic features almost constantly eroding in some places while aggrading in others. Meandering channel dynamics (typical of most streams in BLH systems) provide the energy necessary to erode and transport flood-plain sediments. Meanders typically extend, eroding accreted sediments until they are cut off by an avulsion (channel cutoff) leaving an ox bow lake and a new channel (Fig. 4). Entire meander loops, additionally, tend to migrate downstream. Thus, over geomorphic time, nearly all alluvium in BLH systems is in a state of flux, even though the transport distance for eroded alluvium may not extend much past one meander loop downstream (Saucier 1994).

Flood plains on the Coastal Plain tend to have net sediment storage during periods of high or rising sea level such as the conditions over the past several thousand years. Flood plains aggrade in two ways. First, by lateral accretion or point-bar extension, where coarse (sand) material is deposited on the inside bank of channel bends; a corresponding volume is typically eroded on the opposite, or cut bank (Fig. 4). Second, by the vertical accretion of suspended sediment (typically fines) over the flood plain during overbank flows. Lateral accretion is an episodic process that occurs during high flows, building the point bar into a typically crescent-shaped ridge. Over time, a series of high-flow events produce the ridge and swale topography (Fig. 4) associated with meander scrolls. The establishment of ruderal woody vegetation during intervening low-flow periods on fresh scroll surfaces creates bands of increasingly younger vegetation toward the main channel (McKenney et al. 1995). These bands of vegetation may accentuate the ridge and swale topography by creating distinct micro-depositional environments during subsequent high flows, but the hydraulics necessary to produce meander scroll topography and the role of vegetation in its development are poorly understood (Nanson 1980, 198 1)

Fine-sediment deposition is facilitated by the typically striking reduction in flow velocity as water leaves the main channel and enters the hydraulically rough flood-plain environment (Fig. 5). As rising flood waters overtop the bank the coarse (or heavy) sediment is deposited first and relatively rapidly creating natural levees along the flood-plain margin. Levees tend to be most pronounced along relatively straight reaches between meanders and are often the highest ground on the flood plain. Levees are sometimes breached by streamflow resulting in a crevasse splay that may insert coarse material deep into the otherwise fine-grained floodplain (Fig. 5). Levee development and the breaches that form are poorly documented in the literature, yet are critical in the understanding of the surface-water hydrology of most Coastal Plain bottomlands. Levee height and breaches strongly affect the hydroperiod (and thus, sedimentation dynamics) in systems dominated by surface-water flow (Patterson et al. 1985). The levee surface usually djps gently away from the channel into the bottomland where the surface may be extremely flat. Superimposed on this flat bottom are internal drainage networks, overflow channels, and abandoned main channels or oxbows that remain wet after the hydroperiod and support the more hydric BLH species. Slight differences in elevation associated with the above flood-plain geomorphic features and large woody debris (LWD) create a complex pattern of microsite velocity regimes during the hydroperiod that ultimately affect intra-site sedimentation regimes. Also highly correlated with these variations in elevation are the distributional patterns of many BLH plant species (Wharton et al. 1982, Sharitz and Mitsch 1993).

WATER QUALITY

Sediment Trapping

Suspended sediment may be the most important water-quality concern in the United States today (US EPA, 1994). Increases in suspended sediment, directly affects aquatic biota by coating vegetation and clogging gills of invertebrates and fishes. Indirectly, increased suspended sediment changes the habitat from more coarsely grained aquatic environments to highly silted environments. Further, increased suspended sediment may lead to high sediment-deposition rates in critical riparian areas thus damaging living resources through burial and suffocation. Perhaps most importantly, suspended sediment is the transport medium for hydrophobic forms of nutrients and pesticides, and most trace elements (Horowitz 199 1). Mean values of suspended sediment, percent of suspended sediment finer than 0.062 mm (sand-silt/clay break), and dissolved and total phosphorus, nitrogen, and carbon are provided in Table 1 for a selected set of Coastal Plain streams that support BLH systems along their lower reaches (Alexander et al. 1998).

Deposits of fine sediment typically contain large concentrations of adsorbed, associated contaminants (particularly nutrients, trace elements and hydrophobic pesticides) from agriculture and urban areas (Johnston et al. 1984, White and Tittlebaum 1985, Phillips 1989a, Puckett et al. 1993). This sediment and contaminant trapping function of wetlands is commonly acknowledged (Kadlec and Kadlec 1979, Lowrance et al. 1984, Phillips 1989b, Brinson 1993, Hupp et al. 1993, Lowrance et al. 1995, Brinson et al. 1995, Kleiss 1996), despite limited understanding of the transport and deposition of sediment and associated contaminants and the lack of consistent mass-balance studies (Boto and Patrick 1979, Winter 1981, Carter 1986, Labaugh 1986, Mitsch and Gosselink 1993). Biogeochemical cycles within forested wetlands are particularly complex and difficult to study (Walbridge and Lockaby 1994, Lockaby and Walbridge 1998). Although alluvial material may be considered in transit over geomorphic time, most bottomlands, especially those on the Coastal Plain, exhibit net aggradation through sediment deposition from two initially distinct sources: (1) runoff from adjacent uplands (riparian buffer) and (2) streamflow during inundation of bottomlands (riparian retention). Although the former has received some study (Brockway 1977, Karr and Schlosser 1978, Peterjohn and Correll 1984, Correll 1986, Johnston et al. 1984, Lowrance et al. 1984, 1986, 1998) the latter has received far less (Kleiss et al. 1989, Hupp and Morris 1990, Hupp and Bazemore 1993, Hupp et al. 1993, Kleiss 1996).

Geomorphic analyses (Leopold et al. 1964, Jacobson and Coleman 1986) verify that riparian retention of sediment is a common and important fluvial process, yet retention time of sediment may be the most poorly understood, generally unquantified aspect of sediment budgets (R.B. Jacobson, written communication, 1996). As of the early 1990's, only four published accounts of vertical accretion rates or mass accumulation for mineral fines in the United States could be located by Johnston (1991) for any type of wetland. Since then, vertical accretion rates have been reported for BLH systems in West Tennessee, eastern Arkansas, South Carolina, North Carolina, and along tributaries to the Chesapeake Bay in Maryland and Virginia (Table 2). In a rare, fairly exhaustive, BLH sediment retention study, Kleiss (1996) reported that the Cache River,

Table 2. Mean sediment deposition rates (mm/yr) for Coastal Plain rivers; data from dendrogeomorphic analyses. The Cache River was investigated twice in different studies and locations.

River	Type	Rate	Authorship	Date
Hatchie, TN	Alluvial	5.4	Bazemore et al.	1991
Forked Deer, TN	Alluvial	3.5	Bazemore et al.	1991
Chicahominy, VA	Alluvial	3.0	Hupp et al.	1993
Obion, TN	Alluvial	3.0	Bazemore et al.	1991
Patuxent, MD	Alluvial	2.9	Schening et al.	1999
Cache, AR	Alluvial	2.7	Hupp and Schening	1997
Roanoke, NC	Alluvial	2.3	Hupp et al.	1999
Cache, AR	Alluvial	1.8	Hupp and Morris	1990
Wolf, TN	Alluvial	1.8	Bazemore et al.	1991
Mattaponi/Pamunkey, VA	Alluvial	1.7	Schening et al.	1999
Coosawhatchie, SC	Blackwater	1.6	Hupp and Schening	1997
Choptank, MD	Blackwater	1.5	Schening et al.	1999
Pocomoke, MD	Blackwater	1.5	Hupp et al.	1999

Arkansas carries more than 90 percent of its total annual sediment load during the high-flow period and that more than 14 percent (about 800 $g/m^2/yr$) of the load is trapped along a 2-3 km wide, 49 river km long reach. The results of the Cache River study (Kleiss 1996) support current efforts to rehabilitate/restore BLH forests. In addition to sediment trapping, restored systems also improve the water quality of adjacent river reaches and reduce the sediment burden on existing downstream BLH systems (Kleiss 1996). The sediment and contaminant trapping function in Coastal Plain fluvial systems is especially important because these flood-plain surfaces are the last areas for sediment storage (and biogeochemical cycling) before entering estuaries and their critical nurseries for marine biological production.

Some of the highest concentrations of suspended sediment occur in the Mississippi Embayment because of channel instability, highly erodible uplands (fine alluvium and loess), and extensive agriculture (Trimble and Carey 1984, Simon and Hupp 1987). Many streams of this region, particularly in West Tennessee, southeastern Missouri, and northern Mississippi, have been channelized, which has led to severe upstream channel incision with concomitant channel erosion (Simon and Hupp 1987, Simon et al. 1996). Channel incision facilitates runoff and peak flows, which reduce the hydroperiod and trapping function in BLH systems that have been channelized (Hupp 1999), ironically in a region where the payoff in water quality benefits of intact, functioning BLH systems would be great. A comparison between the unchannelized Hatchie River and the channelized Big Sandy River in West Tennessee (Hupp and Bazemore 1993) showed that sediment deposition rates were significantly higher on the unchannelized stream as far back as the time of initial channelization (Fig. 6), particularly after large expanses of the basins and bottomlands were cleared for agriculture after World War II (Fig. 6).

Like intensive agricultural areas, urbanizing areas tend to generate high suspended sediment and contaminant loads, particularly trace elements (White and Tittlebaum 1985). Both deposited and suspended sediments contain significantly higher concentrations of most trace elements and hydrophobic contaminants than are dissolved in water (Horowitz 1991). Thus, patterns of sediment transport and deposition largely control the fluvial deposition of most trace elements and many contaminants. Water-quality concerns in southeastern Virginia along the Chickahominy River, which arises in the urbanizing Richmond area, are high because the river is the source of a water-supply reservoir for the densely populated Hampton Roads area. A study of sediment and trace-element trapping along Coastal Plain reaches of the Chickahominy (Hupp et al. 1993) has shown that large amounts of sediment and associated trace elements are trapped in the adjacent BLH system (Table 3). Additionally, changes in the gradient of the river, from relatively steep straight-channel reaches to low-gradient anastomozing reaches, strongly control deposition rates of both sediment (0.7 and 5.7 mm/yr, respectively) and associated trace elements; low stream gradients facilitate the development of broad bottomlands and long hydroperiods, which, in turn, enhance sediment trapping.

Local Sediment Deposition

It may be intuitive that as sediment-laden flow leaves the main channel and enters a forested wetland, velocities slow due to the hydraulically rough nature of a forested

Table 3. Summary of estimated amounts (kilograms) of sediment and trace elements deposited annually at 8 sites along the Coastal Plain reaches of the Chickahominy River between Richmond, Virginia and Providence Forge, Virginia; site number ascends downstream. Area at each site is calculated from forested wetlands delineated from a two kilometer reach centered at the site. Site 3 (greatest amount of sediment) is located near the confluence of several tributaries draining urbanizing areas around Richmond; Site 4 has the highest stream gradient of the study reaches and nearly the least amounts of sediment and trace elements.

Site	Sediment	Zn	Cu	Ni	Pb	Cd	Cr	Sn
1	670,000	118	6	8	43	<1	23	<1
2	1,400,000	205	33	17	155	1	60	2
3	7,600,000	1,269	76	76	426	2	274	4
4	840,000	235	8	12	41	<1	26	1
5	2,200,000	446	29	33	130	1	110	2
6	1,600,000	125	5	10	37	<1	42	<1
7	2,000,000	259	14	17	54	1	51	1
8	860,000	68	5	7	25	<1	28	<1
Total	17,170,000	2,725	176	180	911	5	614	9

bottom (also a dramatic increase in wetted'perimeter) and subsequently sediment deposition occurs (Kleiss 1996). Yet, as previously stated, until quite recently only a handful of attempts have been made to quantify sediment deposition in any wetland system. Thus, it should not be surprising that there are even fewer published accounts and interpretations of factors affecting local variation in deposition rate (Hupp and Schening 1997). The amount of suspended fines available rather obviously, pervasively affects deposition potential. Variation in local elevation (Fig. 7) across a bottomland and correlated length of hydroperiod also have been cited as important factors affecting deposition rate (Hupp and Morris 1990, Hupp and Bazemore 1993, Kleiss 1993, 1996). Several other factors, distinct and correlated, may play an important role in local sediment deposition, including: flow velocity, distance in line of flow from main channel, hydraulic connection to main channel, internal flow paths, ponding (typically in backswamps or behind levees), roughness from standing vegetation and LWD, and beaver activity.

The U.S. Geological Survey, in association with the U.S. Forest Service and several universities, is conducting research on the functioning of BLH through the Southern Forested Wetlands Initiative (Burke and Eisenbies 1999). Two sites chosen for this initiative are the Coosawhatchie River, SC, a blackwater stream, and the Cache River, AR, an alluvial stream, have been intensely sampled to investigate several factors that may affect local sediment deposition (Hupp and Schening 1997, Hupp et al. 1999b). The Coosawhatchie and Cache Rivers annually trap substantial amounts of sediment, 24.5 kg/ha/yr and 187.6 kg/ha/yr, respectively, reinforcing the water-quality functions of both blackwater and alluvial forested wetlands. Deposition rates were estimated along multiple transects, normal to the downvalley axis, using dendrogeomorphic (tree ring) techniques and clay-pad marker horizons. These rates were then related to several physical parameters including velocity, elevation, LWD, and hydraulic connectivity at each sampling station and to dominant woody vegetation. The transects were closely spaced so that the sampling points were arrayed in a grid-like fashion, permitting a three dimensional analysis of data. Many of the following observations could not have been made using widely spaced transects (essentially two-dimensional analysis).

Mean sediment deposition rates on the blackwater Coosawhatchie River ranged from 0.02 to 0.20 cm/yr and from 0.20 to 0.36 cm/yr on the Cache River. The Cache River carries a suspended load of about 100 to 350 mg/l, whereas the Coosawhatchie River carries about 5 to 25 mg/l. Thus, a greater amount of sediment deposition on the brown-water Cache River was expected and measured. Major sloughs bifurcating through the sites affect both study areas. Hydraulic connectivity (degree of flow-path connections to the main channel) appears to strongly affect sedimentation rates (Fig. 8), with highest deposition occurring near sloughs and their anabranches with a direct flow path to the river. Whereas, relatively low deposition rates occur in stagnant areas poorly connected to the channel or unaffected by sloughs, presumably due to diminished replenishment of suspended sediment during the hydroperiod (Fig. 8); this occurs despite nearly complete inundation during the hydroperiod at both sites. Smaller sloughs associated with crevasse splay areas near the main channels (Fig. 8), similarly experience high deposition rates.

Woody vegetation, including LWD, may also play'an integral part in directing and concentrating flow paths across bottomlands through variation in surface roughness (sloughs tend to be more open). Sedimentation tends to be high on the upstream faces of "ridges" (Fig. 8), areas that also accumulate considerable LWD, whereas adjacent downstream areas tend to have less sediment accumulation. Deposition rates vary inversely with velocity on the Coosawhatchie River but vary directly with velocity on the Cache. Velocities at both sites are relatively low, except in the main channel and major sloughs. Low velocities facilitate deposition of fines, particularly organic material, however relatively moderate velocities may ensure a continuous supply of sediment-laden water, particularly mineral fines. Fines deposited over the clay pads on the Coosawhatchie River contained substantial amounts of organic material with a mean of nearly 40 percent after loss on ignition as opposed to 22 percent on the Cache River. Mineral fines were concentrated largely on the levees and near sloughs.

VEGETATION

The likelihood of a given species vigorously growing on a particular landform, including the various fluvial landforms, is a function of (1) the suitability of the site for germination and establishment (ecesis), and (2) the ambient environmental conditions that permit persistence at least until reproductive age (Hupp and Osterkamp 1996). The distributional pattern may be limited by the tolerance of a species for specific disturbance or stress regimes, as well as by tolerance for other more diffuse interactions including competition. In fluvial systems, the distribution of vegetation across landforms may be driven largely by the tolerance of species to specific geomorphic processes (hydroperiod and sedimentation dynamics in BLH systems) at the severe end of a stress-equilibrium gradient and by competition with other bottomland species at the other end.

Variations in hydroperiod (and, perhaps, to a lesser degree sedimentation/erosion) and plant adaptive strategies largely explain the complex patterns of BLH species distributions (Bedinger 197 1, Leitman and others 1984, Wharton et al. 1982, Mitsch and Gosselink 1993, Sharitz and Mitsch 1993); however, specific patterns of BLH species distribution and their quantitative relations with water level and sediment dynamics remain incompletely understood. For example, streamflow of varying magnitude and duration and sediment deposition/erosion dynamics affect vegetation by creating new areas for establishment such as point bars (lateral accretion), the subsequent ridge and swale topography, and by creating hydroperiod/sediment-size clast gradients (vertical accretion) across the flood plain. Although, these fluvial processes are yet insufficiently understood to allow for reasonably accurate prediction at a specific site, even less understood is the role riparian vegetation plays in affecting fluvial processes (Hupp and Osterkamp 1996). We know that vegetation increases flow resistance (and thus facilitates deposition), increases bank strength, and provides LWD in the form of log jams in channels and as debris piles (rack) across flood plains (Hickin 1984, Hupp 1992, Hupp and Osterkamp 1996). However, separating factors that simultaneously influence both vegetation patterns and geomorphic processes is difficult because most are distinctly interdependent, and consistent definitions of landform and process generally are lacking within the geomorphic sciences, and particularly between the geomorphic and plant-ecological sciences. Where conformity occurs between sciences it is usually in the common belief that hydrologic processes control most aspects of the fluvial BLH ecosystem. Indeed only hydrologic characteristics provide independent parameters consistent on all perennial streams.

Despite the difficulty to demonstrate quantitative relations among hydrology, geomorphology, and vegetation, the striking vegetation zonation across most BLH systems '(Fig. 9) has tempted several researchers to develop a classification of vegetation patterns (Kellison et al. 1998). Small differences in elevation, often measured in centimeters, may lead to pronounced differences in hydroperiod and, thus, to community composition (Mitsch and Gosselink 1993). As a result, most classification systems infer that length of hydroperiod is the most influential factor in controlling species patterns, most probably due to anaerobic conditions associated with flooding (Wharton et al. 1982). Anaerobic respiration within the roots of plants leads to the production of toxic byproducts and limits the uptake of nutrients and water, Plants tolerant of varying degrees of flooding have developed physical and/or metabolic adaptations to withstand inundation and anoxia (Wharton et al. 1982). Presumably the degree to which individual species have adapted to anoxia-related stresses that controls the distinct and striking changes in vegetation composition across very short (meters) lateral distances on many flood plains in this region (Huffman and Forsyth 1981).

A zonal classification system (Fig. 10) of Coastal Plain bottomlands, described by Clark and Benforado (198 1) and adopted by the National Wetland Technical Council, has been the basis for most subsequent BLH vegetation-community classifications. This classification is based largely on hydrologic regime and is highly generalized; much of the geomorphic detail, described earlier, is lacking and of limited use at specific sites, However, this classification serves as a useful framework for interpreting vegetation patterns, as long as the deceptively complex local hydraulic patterns, particularly in plan view (Hupp 1999) are not ignored. With the possible exception of the lower Mississippi (Saucier 1994) hydrogeomorphic patterns across these bottomlands have received far less study than the vegetation.

The species found in BLH systems are remarkably similar throughout the bottomlands of the Coastal Plain (Sharitz and Mitsch 1993). Forty-two tree species occur commonly and 13 of these are ubiquitous (Kellison et al. 1998). A typical pattern of vegetation distribution is shown in Figure 11. Point bars, typically the most recently created surfaces, tend to support shade-intolerant ruderal species such as ***Salix nigra, Betula nigra***, and ***Populus deltoides***. Inward from the channel, levee surfaces and scroll "ridges" frequently stand in considerable relief relative to the rest of the bottomland and tend to be well drained owing the typically sandy substrate. These fluvial features generally support a mixture of older point-bar individuals and other relatively high and dry species such ***as Platanus occidentalis, Quercus laurifolia, Q. phellos, Q. nigra, Fraxinus pennsylvanica***, and ***Liquadambar styraciflua***. The often broad flood plain is a mosiac of flats punctuated by sloughs, oxbows, and swales, which may only be 10's of centimeters (or less) lower than the surrounding flats. These lower and thus wetter features support the most hydric species, such as ***Taxodium distichum*** and ***Nyssa aquatica.*** Just outside these areas are slightly less moist surfaces dominated by ***Quercus Zyrata, Carya aquatica,*** and ***Gleditsia aquatica*** may dominate. The flats support a diverse forest that may include the levee species in addition to ***Quercus michauxii, Q. pagoda, Ulmus americana, Acer negundo, A. rubrum, Celtis Zaevigata, Pinus taeda,*** and ***Fagus*** *grandifolia*. These species display distributional patterns, often in association with other species (Fig. 1 1), along often virtually imperceptible variations in elevation across the flood plain. Along alluvial rivers, the flood plains tend to become increasingly more hydric from the Fall Line to the estuary. Extensive tidal BLH systems near estuaries are rarely flooded relative to other flood plains but are wetted daily during wind and/or lunar high tides; these systems are largely unstudied.

SUMMARY

The Coastal Plain of the southeastern United States is characterized by broad, frequently inundated low-gradient fluvial systems that support a characteristic forest ecosystem, bottomland hardwoods. These systems have received considerable ecological study, but distinctly less hydrogeomorphic study; quantitative process linkages among hydrology, geomorphology and ecology remain largely undocumented. Although heavily impacted by landuse, these flood plains and their bottomland hardwood systems remain a critical landscape element for the maintenance of water quality by trapping and storing large amounts of sediment and associated contaminants.

Alluvial and blackwater fluvial systems within the region typically are flooded annually for prolonged periods, creating two distinct hydrologic seasons. Order of magnitude differences in wetted perimeter, width/depth, suspended sediment load, and hydraulic roughness exist between the in-channel "dry" season and the inundated season or hydroperiod. Vertical sediment accretion rates may be among the highest of any fluvial system. Channel processes and sedimentation dynamics in these low-gradient systems result in the extensive development of levees, point bars and scroll topography, avulsion and associated back channels or sloughs and oxbows, and broad extremely flat flood plains. Variation in hydroperiod, velocity, and suspended sediment may largely control sediment deposition rates. These factors are locally controlled by elevation, levee breaches, amount of large woody debris, and degree of hydraulic connectivity to sediment-laden inundating water. Diverse woody vegetation of this ecosystem has adapted to prolonged inundation (anaerobic conditions) creating unique characteristic riparian vegetation patterns revealed in a mosaic of associations ranging from relatively mesic levee and high flood-plain associations to hydric slough and low flood plain associations. Nearly imperceptible changes in elevation may result in distinct pervasive changes in species composition and zonation, strongly suggesting a rigorous relation between vegetation and hydrogeomorphic processes. These critical fluvial systems and their attendant forests are ripe for future multi-disciplinary research.

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Figure 1. The Coastal Plain of southeastern United States. Potential extent of Bottomland Hardwood Forest is shown along major streams. Note that the BLH forests nearly match the inland extent of the Coastal Plain delineated by the Fall Line.

Figure 2. Mean-monthly discharge (1963 to 1977) for the Cache River near Patterson, Arkansas. The discharge necessary to flood sloughs (8.4 m^3/s) and to inundate the flood plain (52.5 m^3/s) is indicated. Flood plains along this river are typically inundated from late December until mid-April.

Figure 3. (A) Obvious annual high-water mark (darkened tree bases) in a southern deep-water swamp (*Taxodium-Nyssa* forest), Chickahominy River, Virginia. (B) Bottomland Hardwood Forest subjected to high sedimentation rates along the Big Sandy River, Tennessee. Note "buried" tree trunks.

Figure 4. Generalized fluvial landforms on a Coastal Plain bottomland. Note greater levee development along straight reaches and on the downvalley side of the stream.

Figure 5. Transport paths of sediment and associated contaminants for both lateral and vertical accretion.

Figure 6. Sedimentation rates by age class of trees sampled for rate determination along the Hatchie and Big Sandy Rivers, Tennessee. Sedimentation rates are consistently higher along the unchannelized Hatchie River; note sharp increase in deposition beginning around 1950.

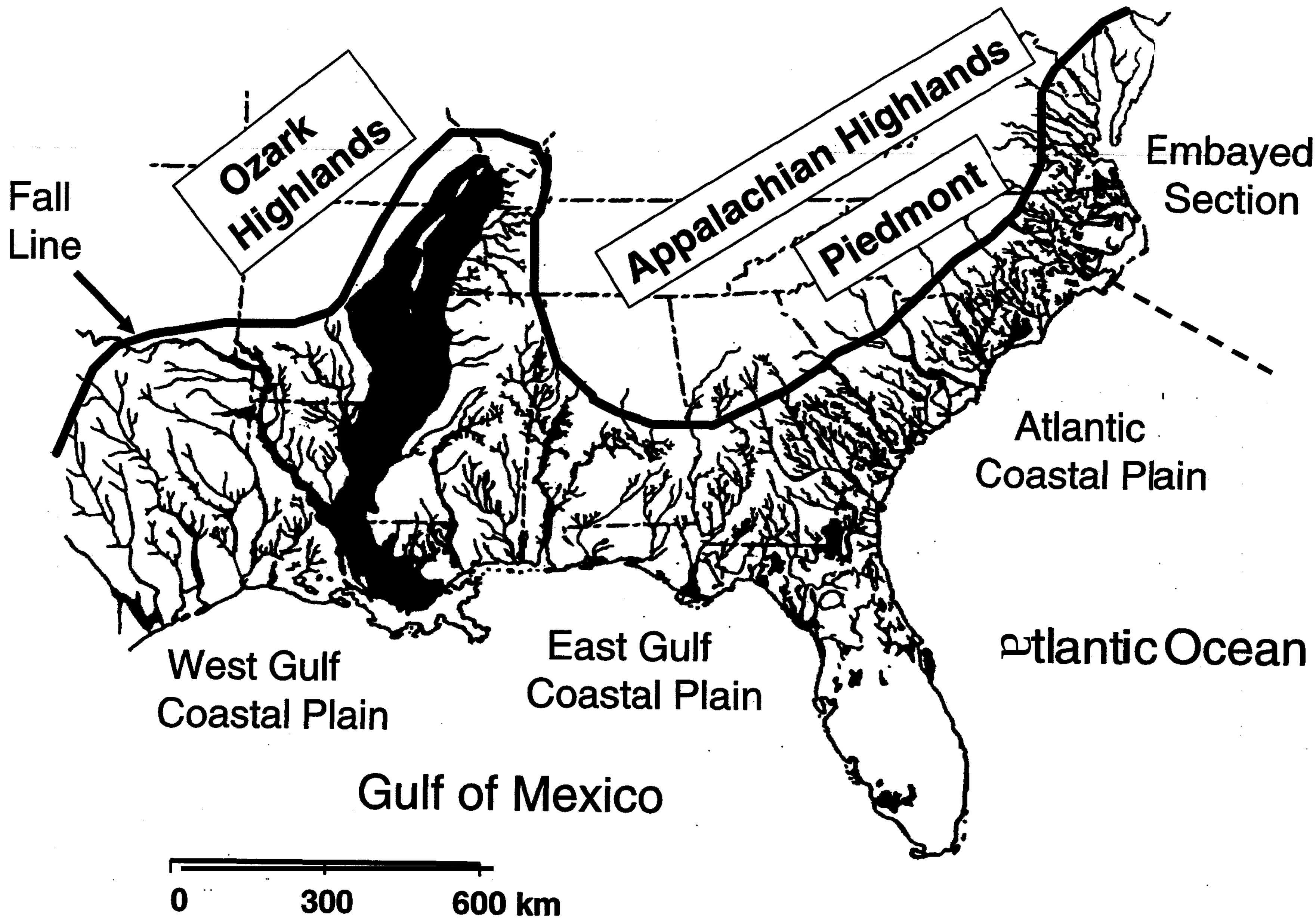
Figure 7. Relation between elevation and sediment deposition along the Cache River, Arkansas. Deposition rates were determined from dendrogeomorphic analyses (tree-ring) and are averages from trees ranging in age from 180 to 25 years.

Figure 8. Sediment deposition patterns across the Cache River, Arkansas bottomland. Data shown along grid lines first through fourth, individual points are separated in straight lines by 250 meters. Deposition rates tend to be greatest along flow paths; (A) indicates area of concentrated large woody debris and relatively high sediment deposition rate. (B) indicates a stagnant area that is poorly, hydraulically connected to sediment-laden river water and has a relatively low sediment deposition rate

Figure 9. (A) High water on the alluvial Cache River, Arkansas. Levee forest is nearly inundated. (B) Slough through a Taxodium forest on the blackwater Coosawhatchie River, South Carolina.

Figure 10. Zonal classification of Bottomland Hardwood forests showing average hydrologic conditions for each zone. (after Sharitz and Mitsch 1993).

Figure 11. Cross section of a Bottomland Hardwood forest showing species distribution relative to a perennial stream and oxbow; (A) is the highest flow elevation, (B) is the mean annual high-water elevation , and C is the mean annual low-water elevation. (after Sharitz and Mitsch 1993).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Coastal Plain
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FIG 1

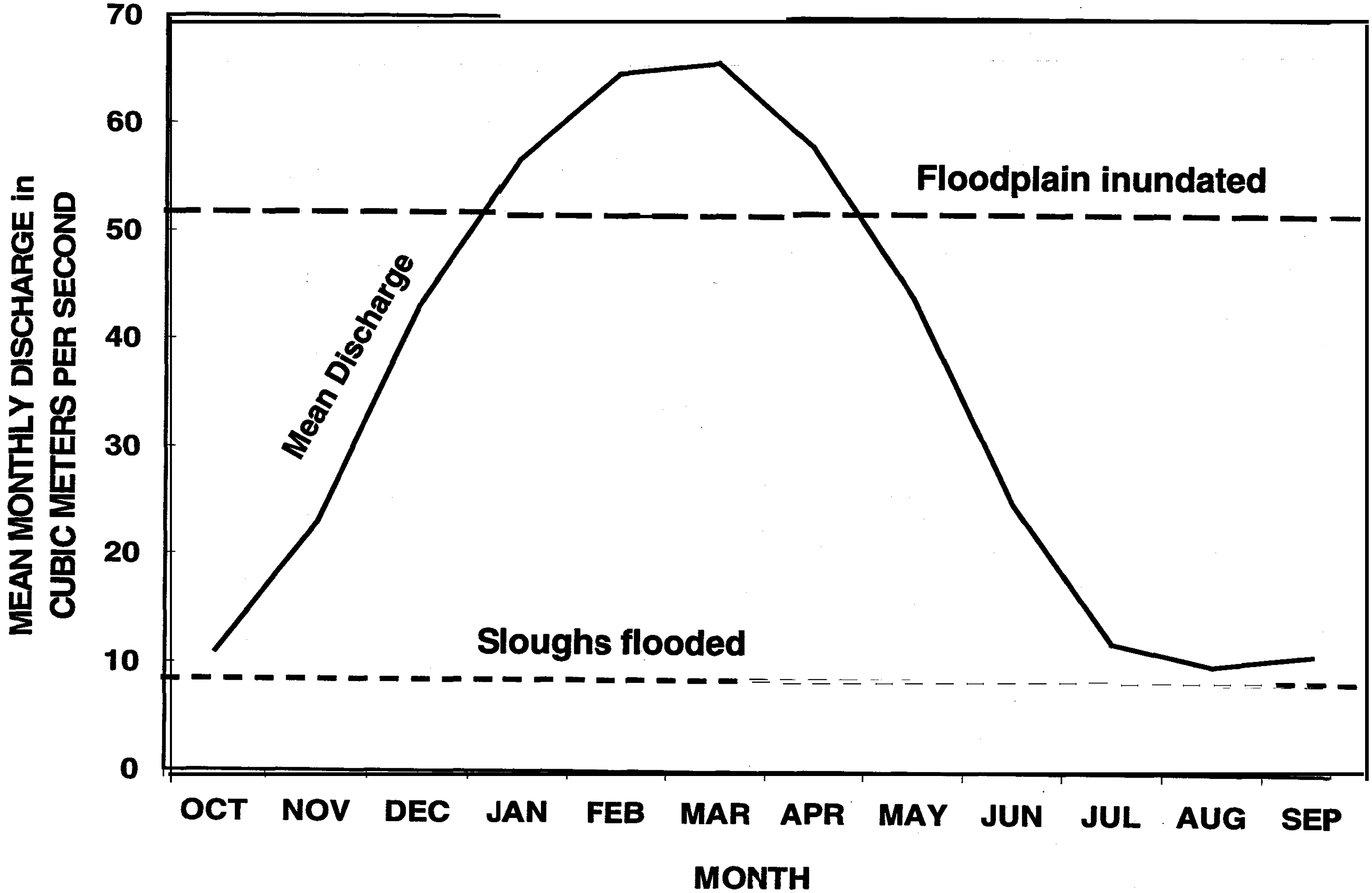

MEAN MONTHLY DISCHARGE in CUBIC METERS PER SECOND
70
60
50
40
30
20
10
0
Floodplain inundated
Mean Discharge
Sloughs flooded
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
MONTH

FIG 2

A

B

FIG 3

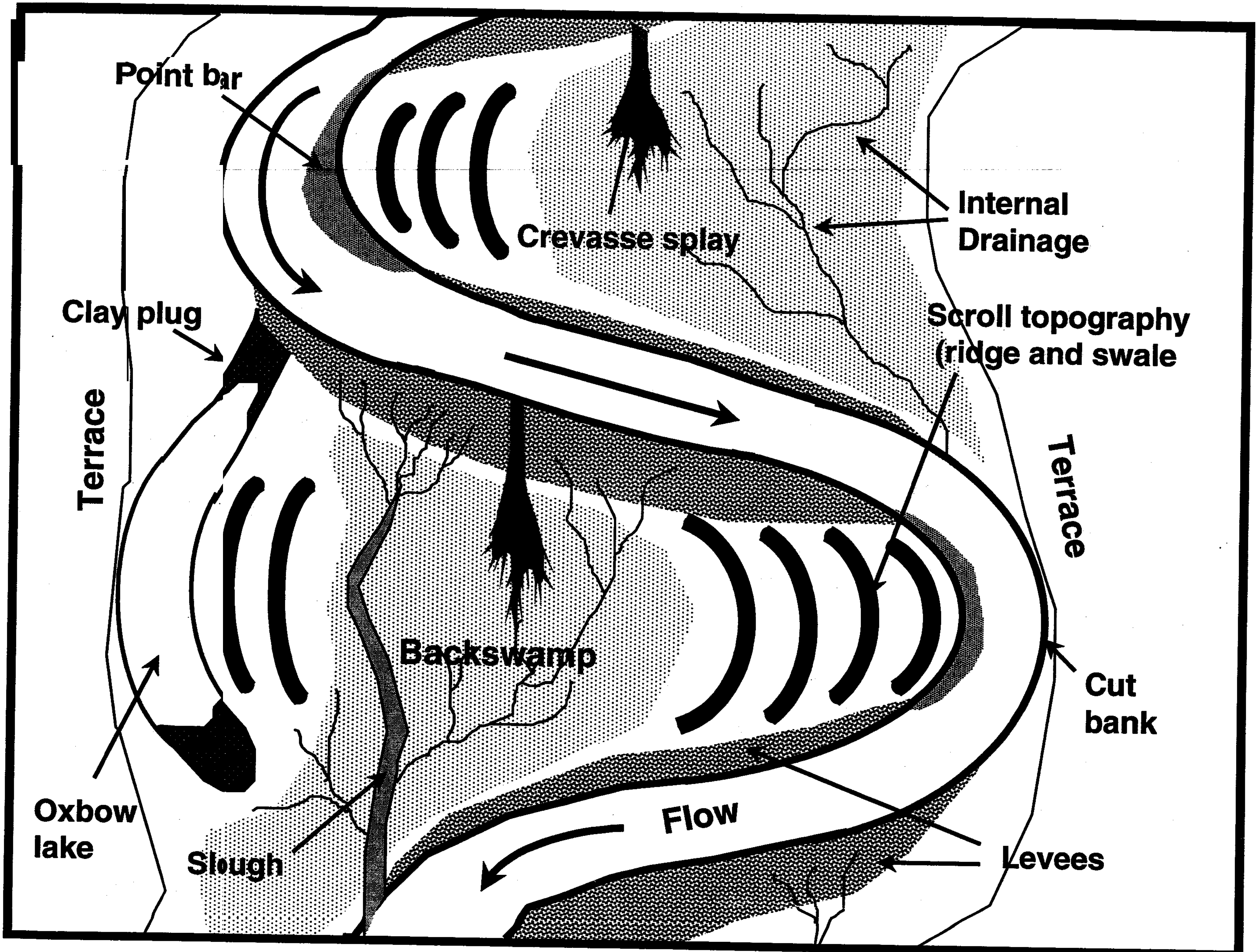

Point bar
Crevasse splay
Internal
Drainage
Clay plug
Scroll topography
(ridge and swale
Terrace
Terrace
Backswamp
Cut
bank
Oxbow
lake
Slough
Flow
Levees

FIG 4

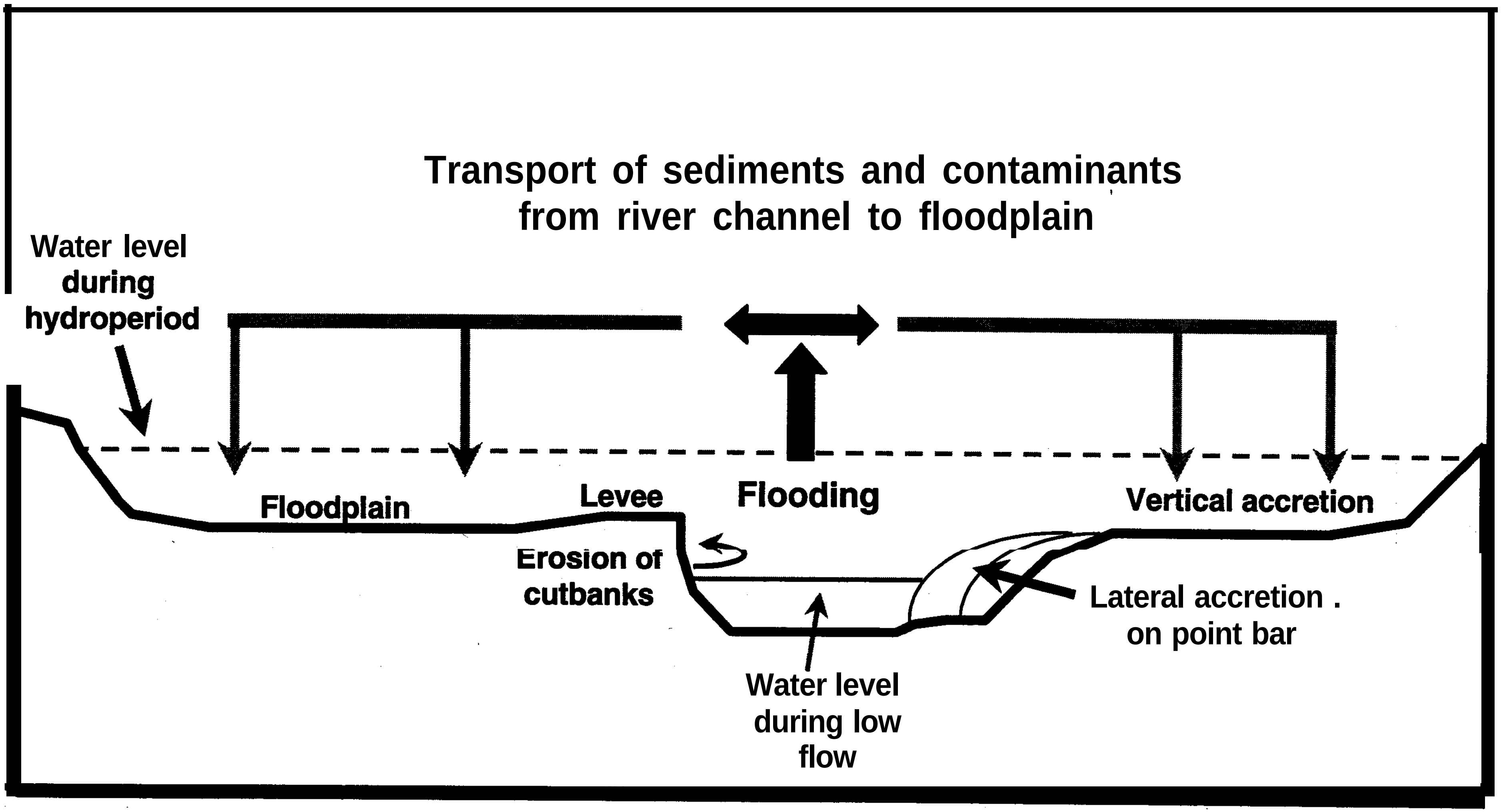

Transport of sediments and contaminants
from river channel to floodplain
Water level
during
hydroperiod
Floodplain
Levee
Flooding
Vertical accretion
Erosion of
cutbanks
Lateral accretion .
on point bar
Water level
during low
flow

FIG. 5

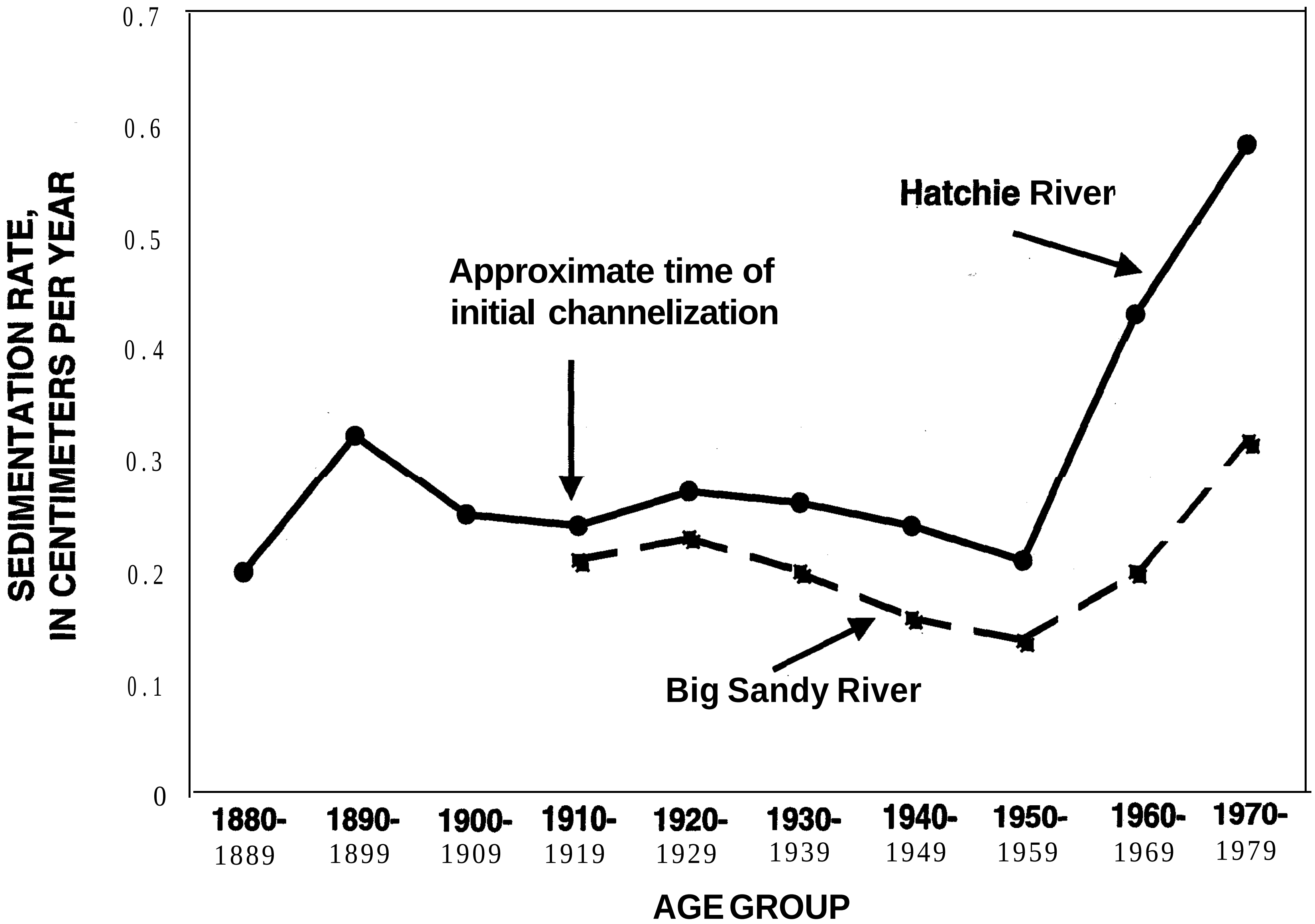

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
SEDIMENTATION RATE, IN CENTIMETERS PER YEAR
Hatchie River
Approximate time of initial channelization
Big Sandy River
1880-1889
1890-1899
1900-1909
1910-1919
1920-1929
1930-1939
1940-1949
1950-1959
1960-1969
1970-1979
AGE GROUP

FIG 6

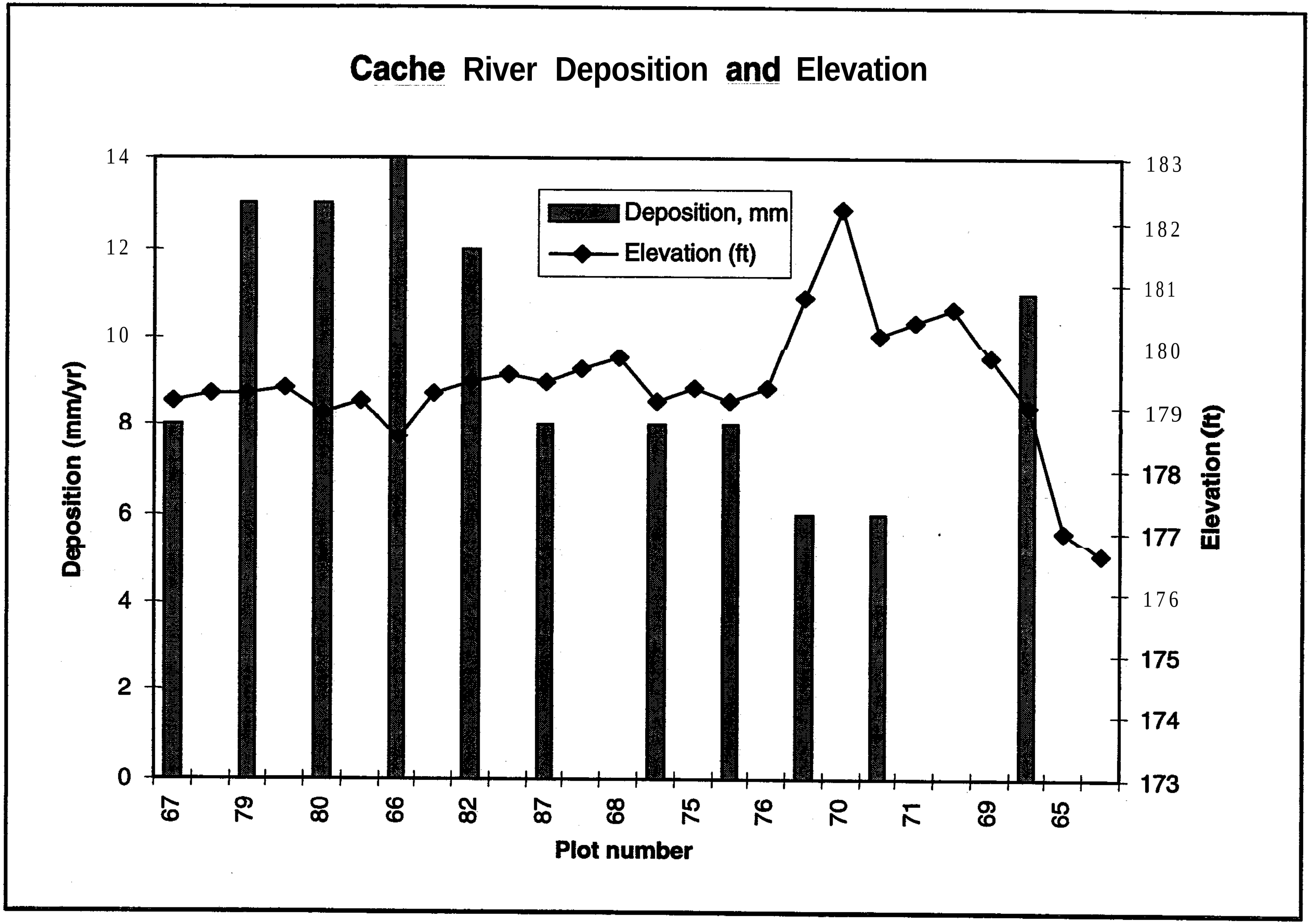
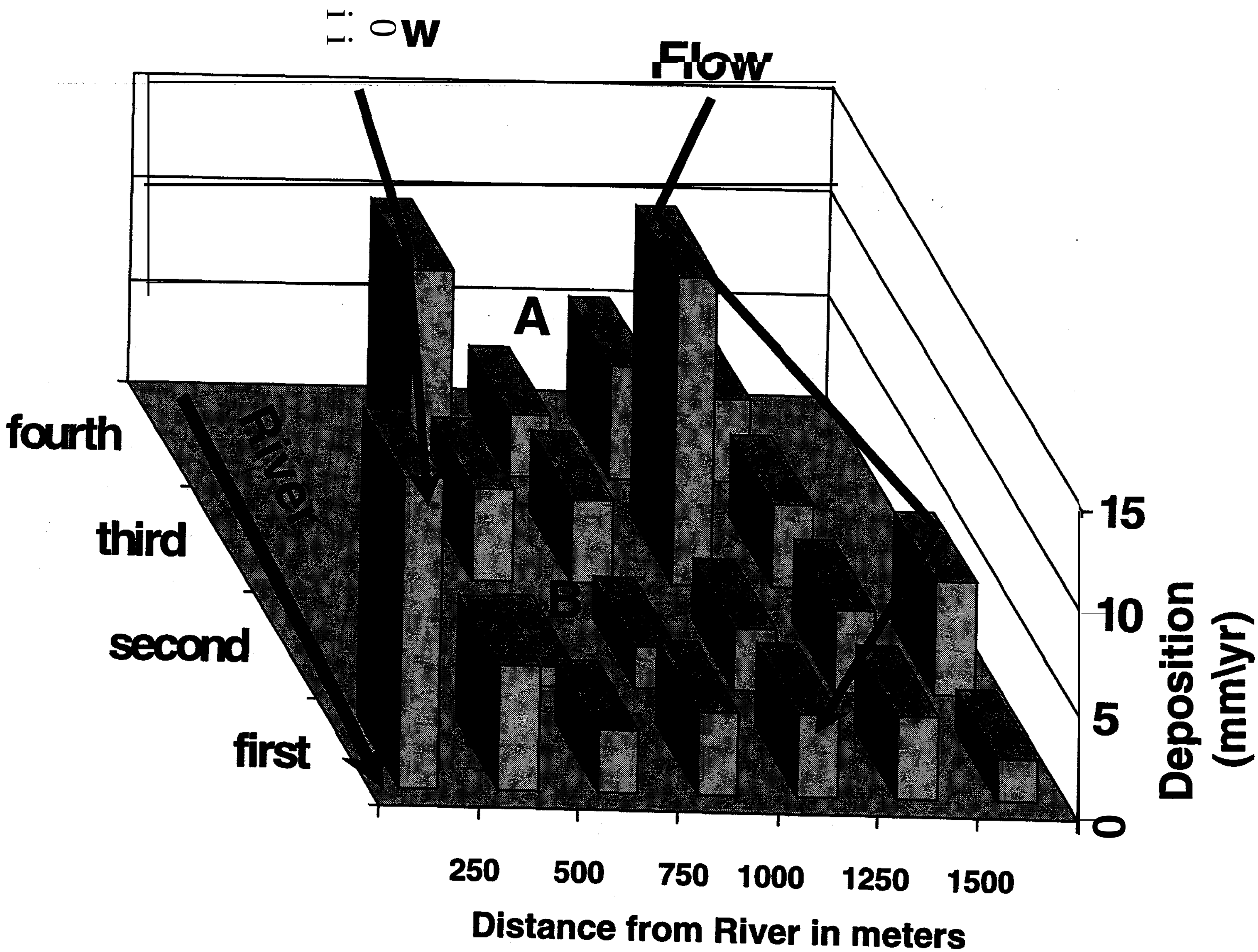

Cache River Deposition and Elevation
Deposition, mm
Elevation (ft)
Deposition (mm/yr)
Elevation (ft)
Plot number
14
12
10
8
6
4
2
0
183
182
181
180
179
178
177
176
175
174
173
67
79
80
66
82
87
68
75
76
70
71
69
65

FIG 7



Flow
A
B
River
fourth
third
second
first
15
10
5
0
Deposition (mm\yr)
250
500
750
1000
1250
1500
Distance from River in meters

FIG 8

A

B

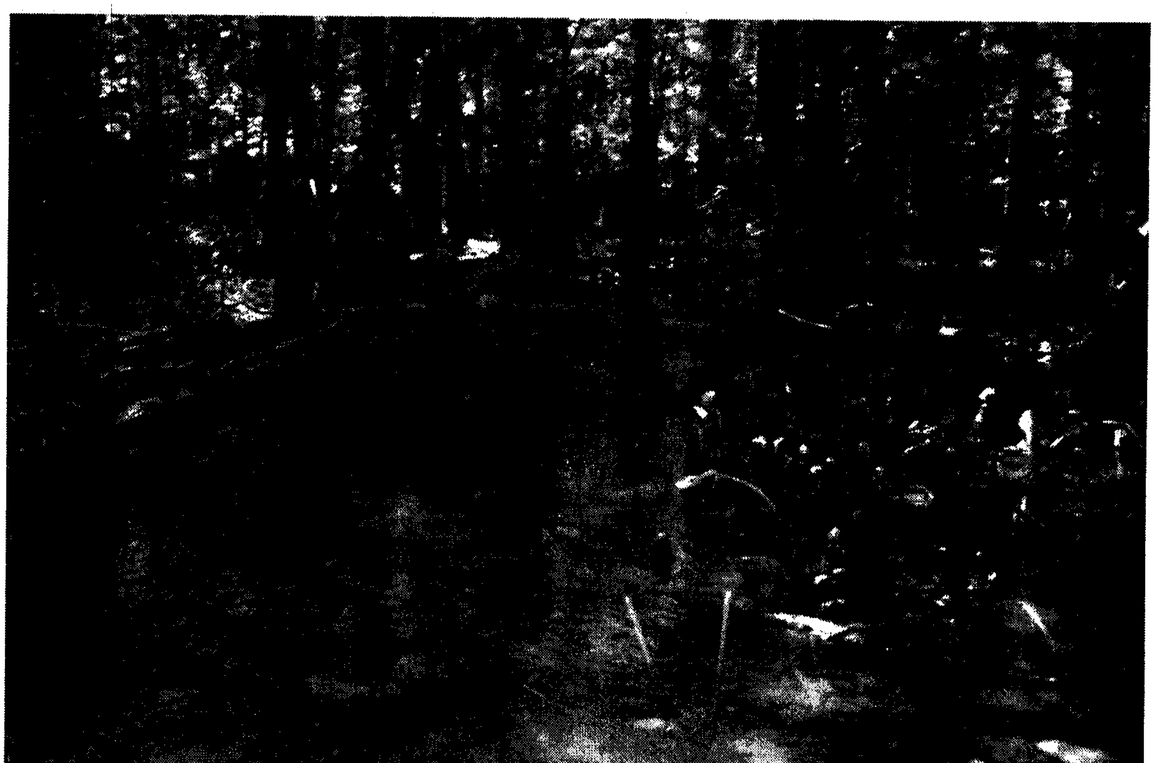
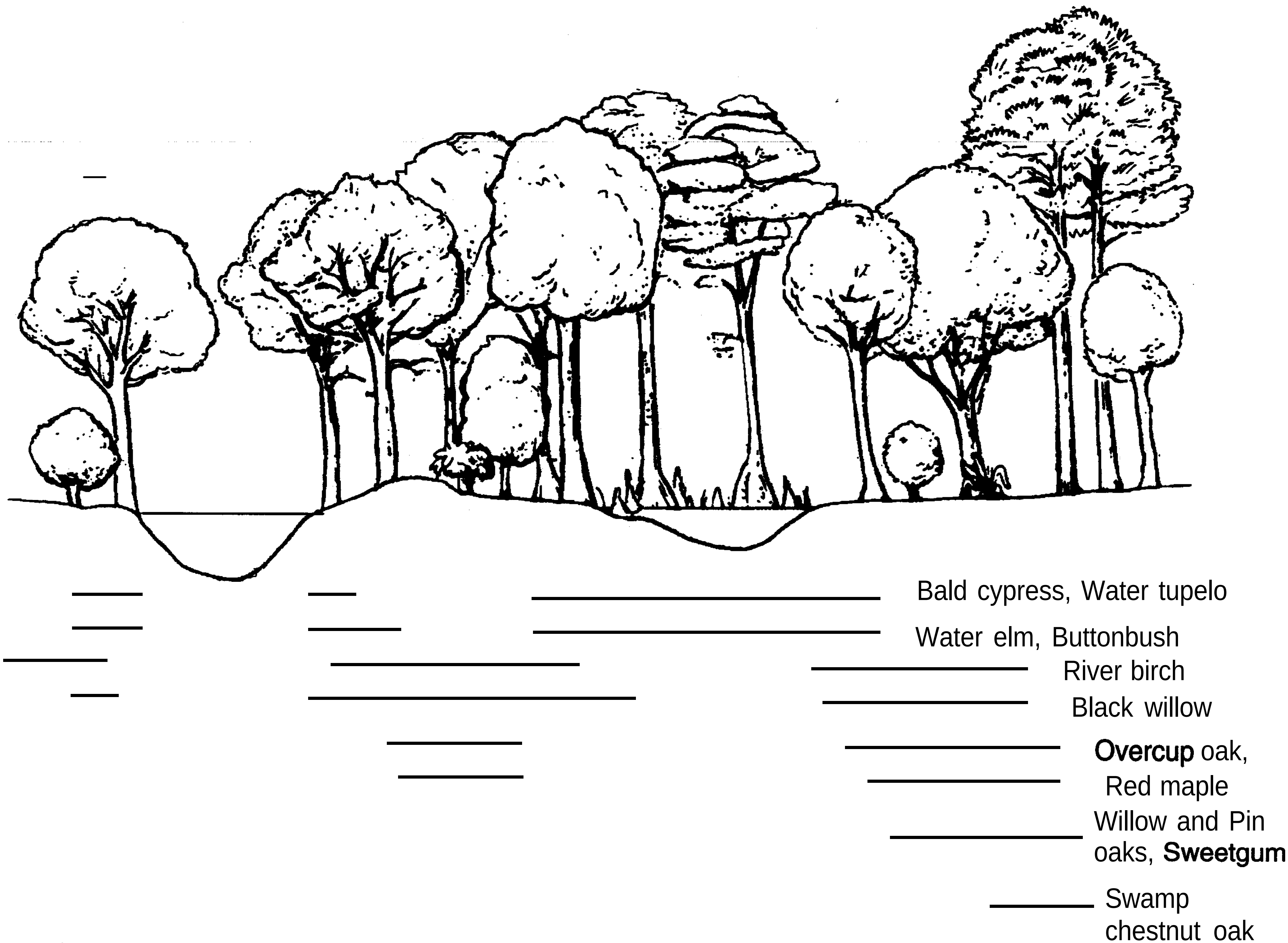


FIG 9

	I	II	III	IV	V	VI
Zone	Aquatic ecosystem	Bottomland hardwood ecosystem				Bottomland upland transition
		Floodplain				
Name	Open water	Swamp	Lower hard-wood wetland	Medium hard-wood wetland	Higher hard-wood wetland	Transition to upland
Water modifier	Continuously flooded	Intermittently exposed	Semipermanently flooded	Seasonally flooded	Temporarily flooded	Intermittently flooded
Flooding frequency, % of years	loo	-100	51-100	51-100	11-50	1-10
Flooding duration, % of growing season	100	-100	>25	12.5-25	2-l 2.5	<2

FIG 10



Bald cypress, Water tupelo
Water elm, Buttonbush
River birch
Black willow
Overcup oak,
Red maple
Willow and Pin
oaks, Sweetgum
Swamp
chestnut oak

FIG 11