RATES OF SEDIMENT ACCUMULATION IN A TIDAL FRESHWATER MARSH[1]

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ABSTRACT: Rates of sediment accumulation were determined for a Delaware River tidal freshwater marsh utilizing radiometric, palynological and sediment flux estimating techniques plus historical reviews. All techniques showed good agreement, indicating that tidal freshwater marshes are capable of preserving evidence of processes and events that have shaped the estuary through time. Prior to 1940, the marsh was a slowly accreting swamp accumulating material at the rate of 0.04 cm yr^{-1} prior to colonization of the region in the late 1600s and a somewhat more accelerated rate of 0.12 cm yr^{-1} prior to the introduction of regular tides in 1940. Between 1940 and 1988 average rates of accumulation ranged between 1.04 and 1.38 cm yr^{-1}, being highest near the tidal channel. During the period 1954–65, rates averaged 1.67 cm yr^{-1} due to increased storm activity. Since 1966, storm activity has decreased and sediment accumulation rates have averaged 0.97 cm yr^{-1}, reflecting these changes. The current average rate of accumulation is four times the rate of sea-level rise for this region of the estuary. It is hypothesized that sediment accumulation will continue to exceed sea level rise until the marsh surface approximates mean high water.

INTRODUCTION

Our present understanding of rates and processes of sediment accumulation in tidal marsh systems comes largely from studies conducted in tidal salt marshes (Armentano and Woodwell 1975; Harrison and Bloom 1977; DeLaune et al., 1978; McCaffrey and Thomson 1980; Brush et al. 1982; Stumpf 1983; Clark and Patterson 1984; Sharma et al. 1987; Oertel et al. 1989). Sediment accumulation rates have been determined through a variety of techniques including radioisotope analysis (Armentano and Woodwell 1975; McCaffrey and Thomson 1980; DeLaune et al. 1978; Clark and Patterson 1984; Sharma et al. 1987), palynological investigations (Brush et al. 1982; Clark and Patterson 1984), the application and/or identification of time line horizon markers (McCaffrey and Thomson 1980; Harrison and Bloom 1977; Clark and Patterson 1984; Cahoon and Turner 1989; Knaus and Van Gent 1989) or some combination of techniques. These techniques have rarely been employed in brackish marsh systems (Hatton et al. 1983; Stevenson et al. 1985; Kearney and Ward 1986) and are even less common for tidal freshwater marshes (Kearney et al. 1985). No studies have utilized the combination of radiometric analysis, palynology and sediment flux measurements to reconstruct the depositional history of tidal freshwater marshes. This study integrates these techniques to establish the developmental history of an upper Delaware River estuary tidal freshwater marsh.

STUDY SITE

The upper Delaware River estuary around Philadelphia, PA is tidal freshwater with a tidal range of 1.8 m and an average rate of submergence of 0.267 cm yr^{-1} (Lyles et al. 1988) during the last 50 years. River sediments are comprised of Pleistocene sands and clays and Holocene clay-dominated muds (Spangler and Peterson 1950). Biggs and Beasley (1988) estimated that 68% of the Delaware River sediment budget comes from the reworking of sediments within the tributaries, 20% from storm events, and the remainder from continual shoreline erosion. Suspended sediment load in the river ranges from a low of 5 mg l^{-1} towards the lower estuary to a high of 230 mg l^{-1} in a turbidity maxima located just south of Philadelphia (Biggs and Beasley 1988).

The study site was the Princeton-Jefferson branch of the Woodbury Creek-Hessian Run Marsh, a tidal freshwater marsh located approximately 7 km south of Philadelphia at National Park, New Jersey (Fig. 1). The site, inundated twice daily, has a tidal amplitude of 1.57 m. Tidal waters reach the marsh surface through numerous small channels and depressions as well as sheet flow during high neap and all spring tides. Water drains from the surface at a reduced rate through small channels and downward percolation. Discharge from storm drains is an additional source of water and heavy metal pollution to the site (Simpson et al. 1983b). The marsh is surrounded on three sides by residential and light commercial

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development. Lawns and thick brush characterize the upper border immediately adjacent to the marsh. The contribution of sediments from upland sources is thus limited except in the two areas where fill has been placed at the marsh fringe.

The vegetation of the Princeton-Jefferson Marsh is dominated by mixtures of *Zizania aquatica* var. *aquatica, Peltandra virginica, Bidens laevis, Sagittaria latifolia, Amaranthus cannabinus, Impatiens capensis, Ambrosia trifida* and three species of *Polygonum* (*P. arifolium, P. sagittatum* and *P. punctatum*), typical of tidal freshwater marshes of the Delaware River (Leck et al. 1988). Seasonal changes in macrophyte dominance follow patterns described by Simpson et al. (1983a). *Peltandra* is the spring–early summer dominant. *Zizania* and *Impatiens* become co-dominants in mid-summer before giving way to *Polygonum, Bidens* and *Amaranthus* in September. The upper borders are dominated by mixtures of *Prunus, Betula, Alnus, Quercus* and *Acer* spp. in association with *Salix* and *Rosa* spp.

METHODS

Field Sampling

Cores for pollen, gross morphology and sediment grain size analyses were collected in 1986 and 1987, and radioisotope samples were collected in 1987 and 1988. Cores were removed using a stainless steel side-chambered sectional Russian peat sampler, a device that theoretically eliminates vertical compaction. Materials for bulk density measurements were collected with a modified 6.0 cm diameter piston corer. Compaction in these cores ranged from 2.5% to 8.5% and has been compensated for in the calculations. No measurable vertical compaction was found in any cores taken with the Russian peat sampler. Cores ranged in length from 0.5 m to 2.0 m. Beginning at the tidal creek bank and extending to the upland border, complete sets of cores were removed at 15 m intervals along the length of two transects (Fig. 1) and dominant color changes were immediately recorded. Core sections for pollen and sediment analysis were placed, undisturbed, in plastic sheets for transport to the laboratory. Cores for ^{210}Pb and ^{137}Cs were sectioned at 2.0 cm intervals and transferred directly to plastic bags in the field. Basal samples for radiocarbon dating were collected at the contact between unconsolidated wetland and consolidated upland sediments, wrapped in aluminum foil and placed in plastic bags in the field. All radiometric samples were stored at 4°C until analysis could be completed.

Sediment Characteristics

In the laboratory a set of cores taken with the Russian peat sampler from each locale was examined for dominant texture and macrofossil identification to determine major stratigraphic units. After establishing stratigraphic units, subsamples for grain size analysis were removed from each major unit and weighed on a Sartorius analytical balance (±0.1 mg). The sample was then ashed at 475°C for 4 hr and separated using a nested sieve arrangement (425, 300, 212, 106, 75, 45 μm) on an ATM Sonic Sifter. The sediment fraction smaller than 45 μm was collected and soaked in 35% hydrogen peroxide, dispersed with sodium silicate in doubled distilled water and scanned with a Sedigraph 500 particle counter. While frozen, sediments were extracted from the piston cores and sliced into 2-cm-thick sections. Each 2 cm slice was weighed, dried at 100°C for 24 hr, reweighed, ashed at 475°C for 4 hr and reweighed again to determine bulk density of the substrate. Twelve randomly selected surface samples were collected by inserting an inverted 1 cm × 6 cm petri dish into the sediments. These samples were weighed, dried and ashed to determine bulk density of the surface sediments.

Radiometric Analysis

Radiometric analysis is useful for determining rates of accretion and sediment accumulation in tidal marshes. ^{14}C analysis has been used in tidal systems to determine long-term rates of accretion and historic patterns of sea level rise (Redfield and Rubin 1962; Bloom and Stuiver 1963; Stuiver and Daddario 1963; Redfield 1967). For deposits less than 100 years in age, ^{210}Pb analysis has been employed (Armentano and Woodwell 1975; McCaffrey and Thomson 1980; Clark and Patterson 1984). ^{137}Cs, a product of aboveground thermonuclear testing, has been used to establish horizon markers within the last 30 years (DeLaune et al. 1978; Sharma et al. 1987).

All ^{210}Pb and ^{137}Cs samples were analyzed by Teledyne Isotopes, Westwood, New Jersey. ^{137}Cs was analyzed using a high resolution gamma ray spectroscope (Ge(Li) detector) coupled to a nuclear data acquisition and reduction system, and the results were recorded in picocuries per gram of sediment. ^{210}Pb activity was determined radiochemically by assaying the beta activity of its bismuth-210 daughter series. To determine supported levels of activity, deep samples were averaged for each core. Age was determined using the following equation (Faure 1986):

$$t = \frac{1}{\lambda} \ln \frac{^{210}Pb^0}{^{210}Pb_A}$$

$^{210}Pb^0$ = unsupported activity at surface

$^{210}Pb_A$ = unsupported activity per unit weight at depth h

λ = decay constant of $3.11 \times 10^{-2}\ yr^{-1}$

t = age of sample

This equation yields a slope of

$$m = -\frac{\lambda}{a}$$

a = annual rate of accumulation

Radiocarbon samples were analyzed by Teledyne Isotopes, Westwood, NJ and Beta Analytic, Miami, FL. Samples were dispersed in hot acid, rinsed to neutrality and treated with a standard benzene synthesis. Counts were made based on the Libby half-life of 5,568 years.

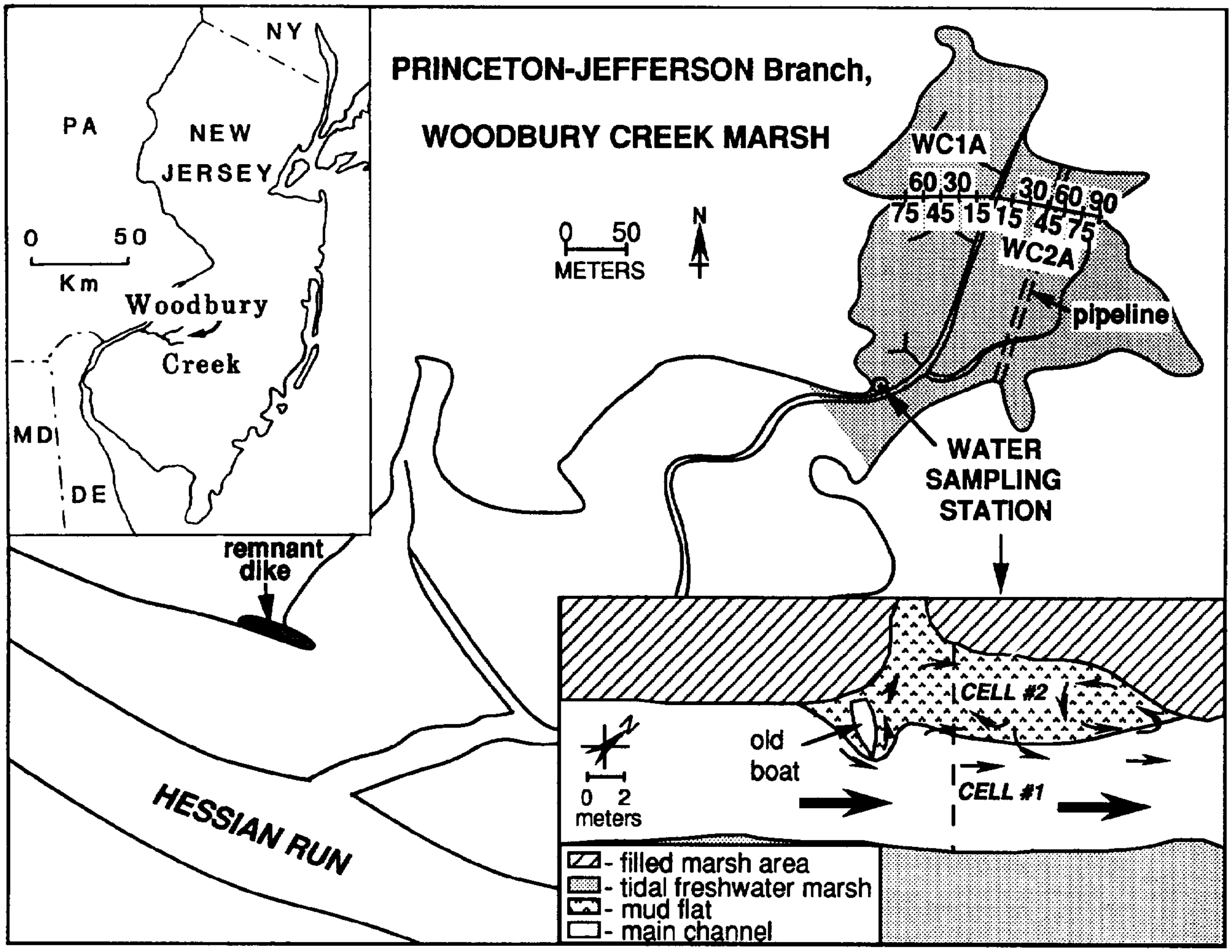

FIG. 1.—Map showing location of study site. Insert in lower right-hand corner shows sediment flux sampling station. Arrows indicate direction and intensity of flow on the flood tide. Dashed line represents sampling transect.

Palynology

The distribution of pollen through time is useful in determining historic rates of accretion and sediment accumulation in tidal systems. The appearance or disappearance of representative taxa at various depths in the marsh substrate can establish horizon markers, although this may at times be obscured by an over representation of local taxa (Clark and Patterson 1984). *Ambrosia* and *Plantago* have been suggested as markers of the colonial period (Heusser 1963; Russell 1980) and the decline of *Castanea* due to a blight marks the early 1900s (Anderson 1974). These pollen horizon markers can provide independent confirmation of dates established by radioisotope analysis.

Samples for pollen analysis were taken at 5 cm intervals through the entire length of one core at each transect location. Pollen preparations were completed according to modified procedures described by Faegri and Iversen (1975). A 1 cc sample of sediment was placed in a 15 ml centrifuge tube. A known concentration of *Lycopodium* spores (3,300 ± 110) was added to the sample as a concentration marker (Davis 1966). The sediment was then treated with warm 10% potassium hydroxide to deflocculate the suspension. To remove large particulates, the suspension was filtered through a 150 μm mesh screen and washed in distilled water. The sediment was then treated sequentially with mixtures of 95% ethanol and 10% hydrochloric acid to remove carbonates and hot hydrofluoric acid to disperse and dissolve siliceous material. The sediment was then placed in an acetylation solution (9 parts acetic anhydride : 1 part sulfuric acid) and rinsed in glacial acetic acid. The resulting slurry was rinsed twice in 95% ethanol, once in 100% ethanol and finally in tertiary butanol. When necessary, samples were centrifuged for 10 min at 2,500 rpm (1,150 gravities), except for the hydrofluoric acid step which was centrifuged for 25 min. Finally the prepared sediment was stirred for 10 minutes on a magnetic stirring plate before a drop was removed and placed on a slide containing silicone oil (10,000 centistokes). Two slides were prepared from each sample.

For each sample approximately 400 grains were count-

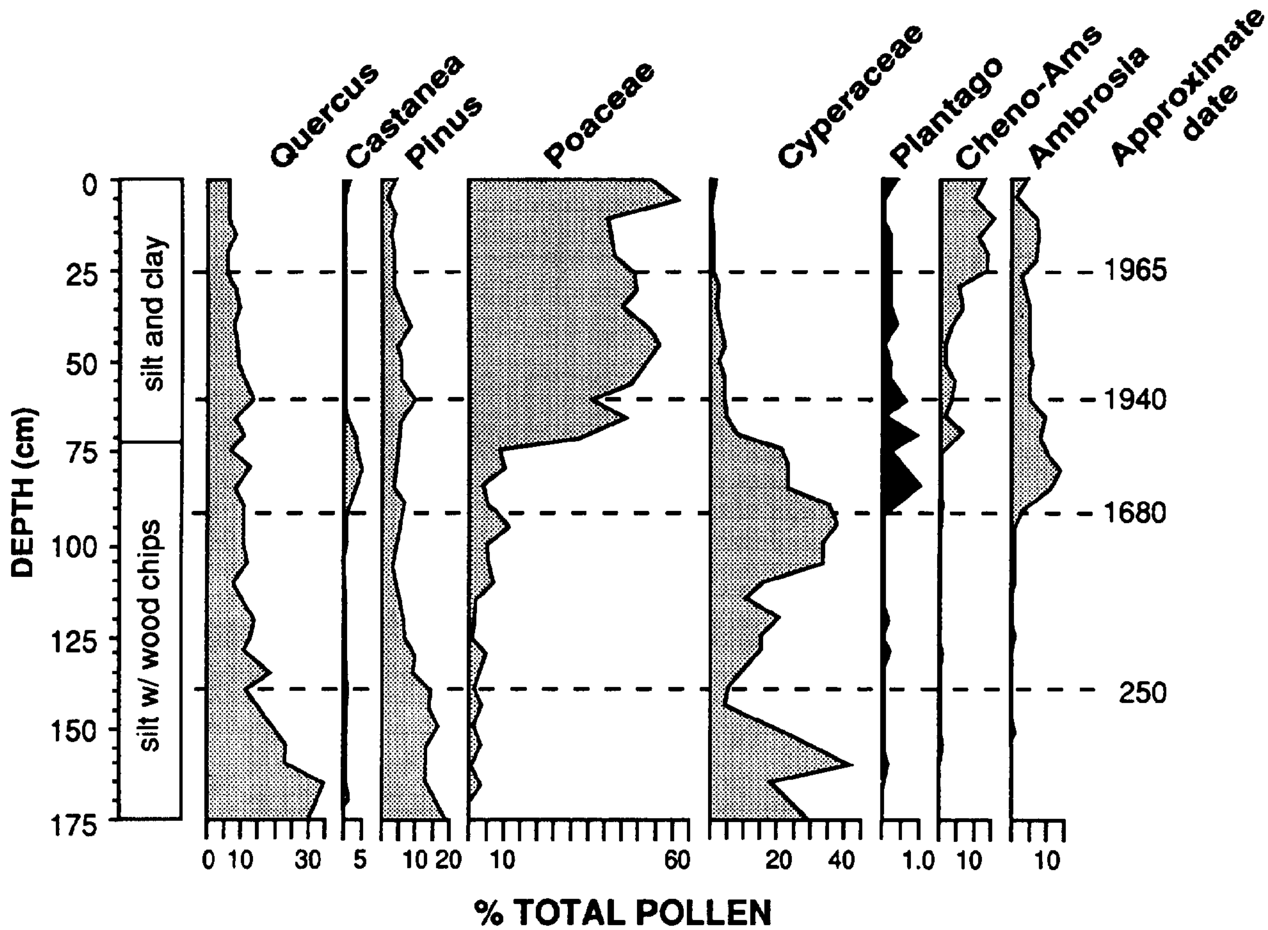

FIG. 2.—Pollen abundance of representative taxa for core WC1A-30. Dominant sediment types are listed at left. Black shading denotes change in scale. Dates extrapolated from radiometric and palynological results and listed based on the Gregorian Calendar.

ed at 400× on an Olympus Vanox microscope. The counts were split between the two slides (200 grains each) and comparisons were made using Chi square analysis. Control grains (*Lycopodium* markers) were counted to estimate the number of total grains per cc of sediment. Identification of grains was based on reference collections and published keys (Kapp 1969; McAndrews et al. 1973; Faegri and Iversen 1975).

Sediment Flux

Sediment flux studies are the primary method of estimating sediment budgets for estuarine ecosystems and hence vertical marsh accretion. Estimates of material exchange can vary widely from study to study (Settlemyre and Gardner 1975; Hackney 1977; Ward 1981; Stevenson et al. 1985). The variation between studies may be due to a combination of factors including system characteristics, sampling scheme and seasonal weather patterns (Boon 1978; Kjerfve and Proehl 1979; Ward 1981; Roman 1984; Stevenson et al. 1985; Stern et al. 1986; Gardner et al. 1989). Sediment flux was measured for tidal cycles in June, August, October, November and December of 1987 and March and April of 1988. The tidal creek was divided into two cells and each was sampled as an individual unit to reduce sampling error (Fig. 1). Tidal velocity was measured at half-hour intervals during flood and peak ebb tides and hourly at low ebb tides when the tidal creek was less than 3 m wide and less than 20 cm deep. Velocity was measured with a Marsh-McBirney portable flow meter at the 0.2, 0.4 and 0.8 depth of the water column. For each velocity measurement, tide height and channel width were recorded and a 2.0 l water sample was taken at mid-depth using a modified alpha bottle sampler. The water sample was split between four 500 ml bottles and stored on ice until returned to the laboratory.

Three of the 4 subsamples were randomly chosen for filtering within 24 hr of collection. Each subsample was shaken vigorously and filtered through a 1.2 μm glass fiber filter using a Millipore filter apparatus. The filtrate was then passed through a 0.3 μm glass fiber filter to trap fine sediments. Each filter was dried at 100°C for 24 hr and weighed. The filters were then ashed at 475°C for 4 hr and reweighed. The particulate organic matter, particulate inorganic matter and the total particulate matter were determined for each subsample. The results from the 3 subsamples were averaged. The averaged weights were multiplied by the flow rate and area for each instantaneous measurement and then combined to calculate total suspended load for ebb and flood tides. Based on maximum tide height for the sampling date, an annual rate was determined by weighting the results based on the total number of tidal cycles represented by the individual sampling dates for the year and combining the weighted averages.

RESULTS

Sediment Characteristics

Sediments of the Princeton-Jefferson Marsh form two distinct layers: a lower layer of silty peat, high in macro-organic matter and friable in structure, that extends from 250 cm to ~70 cm and an upper layer dominated by silt and clay that extends from 70 cm to the surface (Fig. 2, Table 1) (note: this shift occurs between 45 and 55 cm at WC1A-45). At the interface between the two layers, bulk density doubles (Fig. 3) while organic matter and pore water decline by as much as 50% and 25%, respectively. The average dry weight of surface samples was 7.5 ± 1.1 g with a bulk density of .21 g cm^{-3}.

Radiometric Analysis

The radiocarbon analysis is shown in Figure 4. The oldest wetland sediments were dated at 2,580 ± 80 YBP. There is a strong correlation between depth of sample and ^{14}C age ($r^2 = 0.89$).

Lead-210 analysis shows an expected radioactive decay function over depth between 60 and 0 cm (Fig. 5). An average supported level of 0.49 pCi g^{-1} was subtracted from each sample and a regression equation was computed for excess activity as a function of depth. Based on these age determinations, average sediment accumulation rates ranged from 1.04 to 1.38 cm yr^{-1}.

Cesium-137 for core WC1A-30 (Fig. 6) exhibits a pattern of accumulation similar to that reported for Gulf coast tidal systems (DeLaune et al. 1978; Sharma et al. 1987; Lynch et al. 1989). The high concentration of ^{137}Cs at 30 cm, therefore, represents the 1963 peak in aboveground nuclear testing and the bottom of the curve represents 1954. ^{137}Cs results yield an average sediment accumulation rate of 1.20 cm yr^{-1} at 1963 and 1.32 cm yr^{-1} at 1954, consistent with the rate of 1.27 cm yr^{-1} based on ^{210}Pb at this location (Fig. 5).

Palynology

Representative taxa (*Quercus, Pinus, Castanea,* Cyperaceae, Poaceae and Cheno-Ams [Chenopodiaceae-Amamranthaceae]) and agricultural indicators (*Ambrosia* and *Plantago*) for core WC1A-30 are shown on Figure 2. At the Princeton-Jefferson Marsh, *Ambrosia* and *Plantago* increase from absent to 15% and 1% respectively at depths between 90 and 80 cm. This period marks the beginning of colonial activity in this region of New Jersey during the late 1600s (Horan 1964). *Castanea* also increases from < 1% to over 6% between 90 and 80 cm but declines to 0% by 60 cm, reflecting its prevalence during the late colonial period and subsequent decimation by a blight during the early 1900s (Anderson 1974; Russell 1980). Between 70 cm and 65 cm, Cyperaceae pollen declines from 25% to < 5%, while Poaceae pollen increases from 8% to >45%, representing the onset of tidal influences at the site.

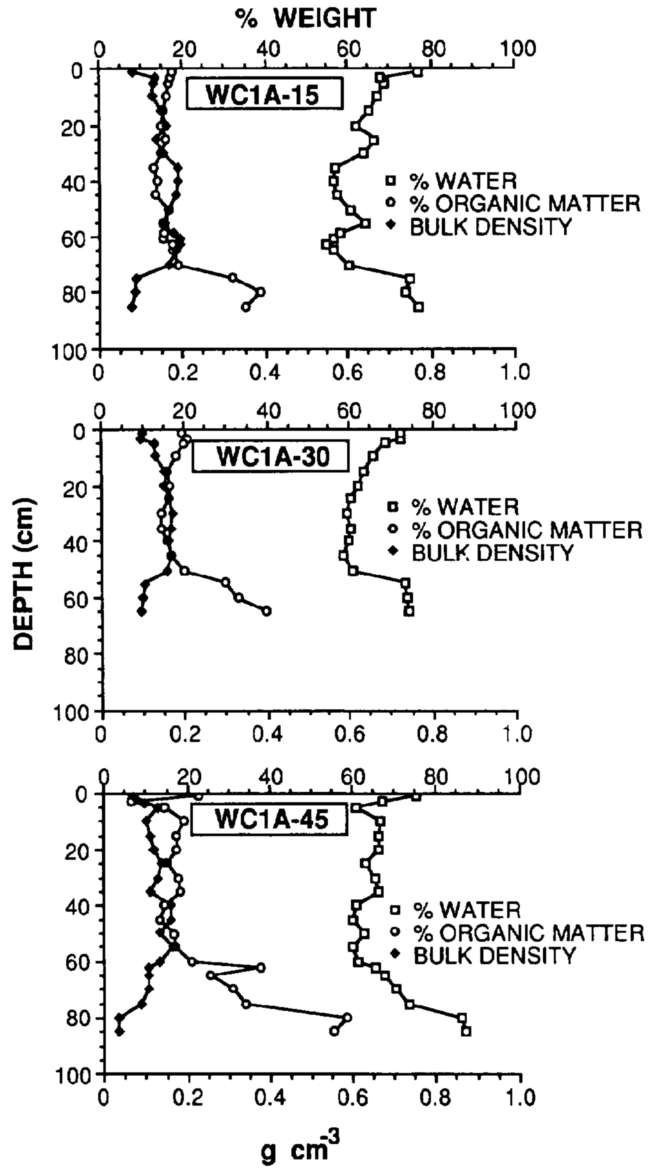

FIG. 3.—Percent water, percent organic matter and bulk density for cores along transect WC1A.

Sediment Flux Measurements

The Princeton-Jefferson Marsh is ebb tide dominated with a combined time and velocity asymmetry in tidal currents (Simpson et al. 1983b). Flow velocities ranged from < 3.0 cm s^{-1} at low ebb flows to a high of > 30.0 cm s^{-1} one hour past high slack water on the ebb tide.

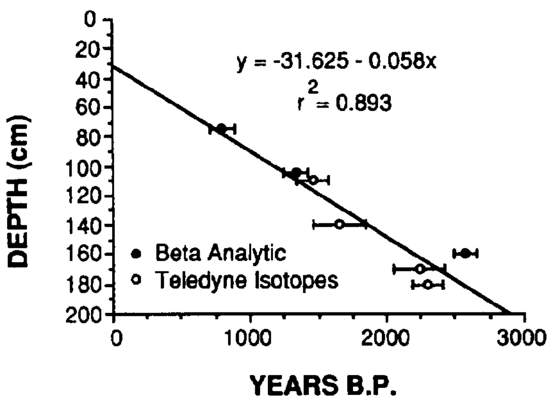

FIG. 4.—Radiocarbon dates from basal sediments taken along the transects WC1A and WC2A.

The generalized pattern of flow is one-third of the cycle in flood tide, one-third in high ebb tide and one-third in low ebb flows.

Suspended sediment load ranged from 0.5 mg l^{-1} at low ebb flows to over 1,000 mg l^{-1} on the flood tide fifteen minutes after low slack water. Sediment fluxes varied widely (Table 2). The greatest movement of suspended sediment occurred in November which had the highest exchange of organics on both ebb and flood tides and inorganics on the ebb tide. Inorganic particulates on the flood tide were greatest in March. Assuming that the instantaneous measurements represent the entire interval between samples (½ hour), net particulate flux estimates can be calculated. Total net annual flux to the marsh was approximately one-third particulate organic matter (20,552 kg) and two-thirds particulate inorganic matter (47,954 kg). Utilizing a weighted average, the annual average amount of sediment remaining in the system was 68,506 kg.

TABLE 1.—*Distribution of sediment size classes (Wentworth 1922) for cores along transect WC1A. Results based on percentage of weight of sample*

Core Location	Depth (cm)	% Grain Size Clay	Silt	Sand
WC1A-15	10	34	57	9
	30	33	59	10
	50	32	59	9
	80	14	80	7
	120	17	77	6
WC1A-30	10	34	57	9
	30	31	59	10
	50	32	58	10
	70	14	79	7
	120	15	79	6
WC1A-45	10	33	59	8
	25	32	60	8
	45	28	62	10
	55	14	80	6
	90	15	78	6

DISCUSSION

To understand rates of sediment accumulation at the Princeton-Jefferson Marsh, the major depositional environments must be identified. Throughout much of its history the marsh was a *Quercus*-dominated non-tidal swamp. During the 1800s a dike was constructed across the mouth of the site, and sometime before 1900 a sluice gate was installed. The dike functioned until the early 1930s when a series of dike/gate failures allowed tidal waters (range of > 1.0 m) to periodically enter the site. The dike failed for the last time between late 1939 and early 1940. Since then the site has been subjected to regular tidal flushing, and tidal freshwataer marsh has dominated the site.

Rates of Sediment Accumulation in the Non-Tidal Environment

The strong correlation between radiocarbon dates and depth suggests that non-tidal accretion rates have been consistent through time. We can, therefore, utilize this information in applying long-term rates of accretion to depths not specifically sampled.

Utilizing the regression of sediment age as determined by radiocarbon versus depth of sample, an average unadjusted long-term sediment accumulation rate of 0.078 cm yr^{-1} was calculated. However, the top 60 cm of substrate reflecting the tidal freshwater marsh phase of development has accumulated at rates in excess of 1.0 cm yr^{-1}. Removal of the tidal portion of the substrate yields an average adjusted long-term accretion rate of 0.042 cm yr^{-1} for the non-tidal sediments. Applying this rate to a basal radiocarbon date of 1,660 ± 190 YBP at 1.40 m at WC1A-30 suggests that it would take approximately 1,200 years to accumulate the 50 cm of substrate below the *Ambrosia* horizon. This places the beginning of the colonial period at 450 ± 190 YBP, an estimate within the range of the actual colonization date (300 YBP).

Ambrosia and *Plantago* pollen exhibit patterns of accumulation similar to those found by Heusser (1963), Soloman and Kroener (1971), and Russell (1980) for other wetland sites in New Jersey. Assuming the distribution of these taxa are regional, these assemblages can be utilized as markers of the colonial period. Based on the appearance of *Ambrosia* and *Plantago* in the pollen profile, the average rate of sediment accumulation between the onset of the colonial period (ca. 1680) and the introduction of tides to the site (ca. 1940) was 0.12 cm yr^{-1}, a three-fold increase in long-term adjusted non-tidal rates of accretion. This supports the contention that colonial land-clearing practices may have accelerated rates of sediment accumulation in wetland ecosystems (Wolman 1967; McCaffrey and Thomson 1980; Russell 1980). An additional horizon marker is the decline of *Castanea* pollen, which has been noted for other sites in New Jersey (Heusser 1963; Soloman and Kroener 1971; Meyerson 1972; Russell 1980) and which can be used to establish the early 1900s (Anderson 1974). At the Princeton-Jefferson Marsh the *Castanea* decline correlates well with the period just prior to the establishment of tidal influences.

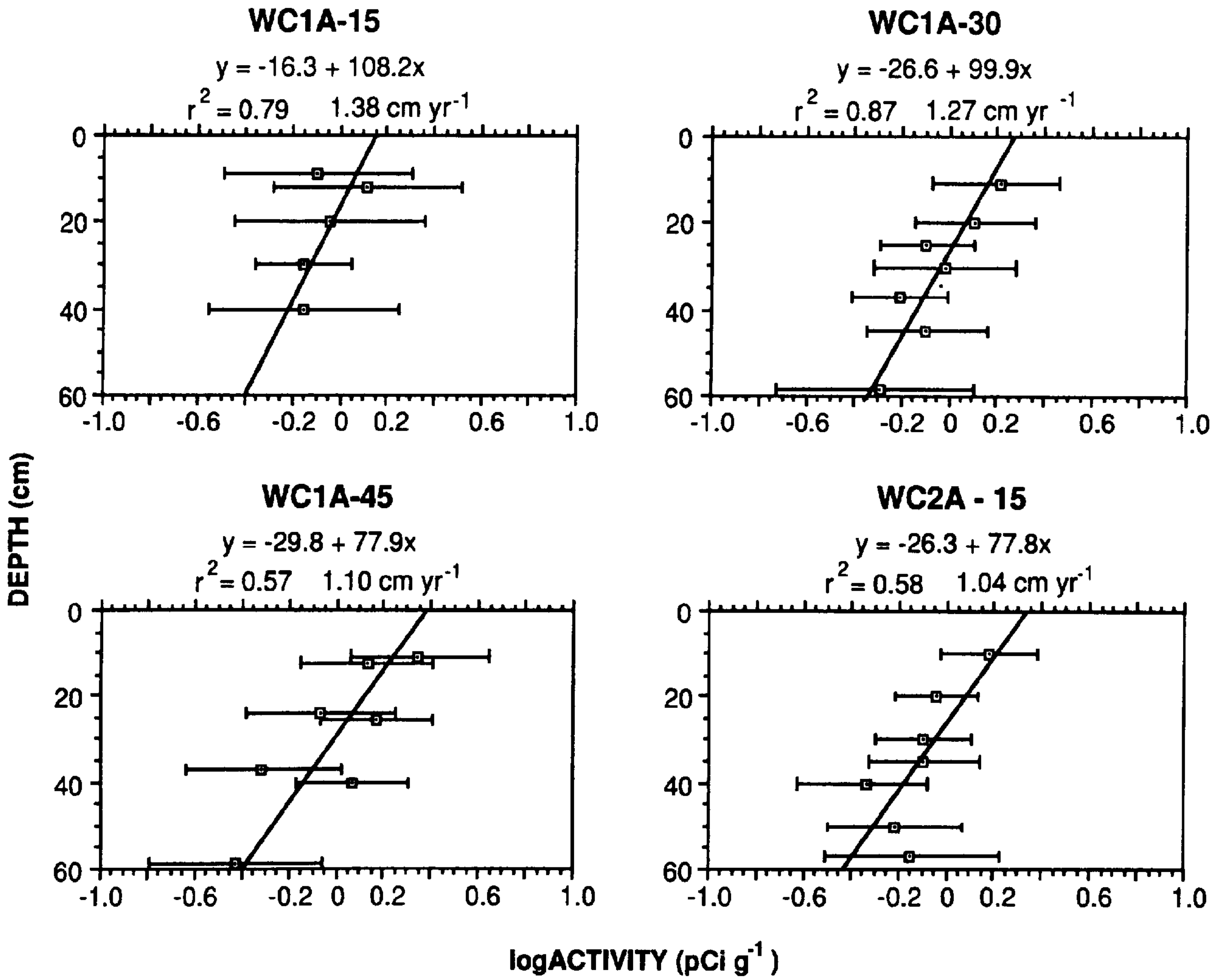

FIG. 5.—Excess lead-210 activity from cores along transcts WC1A and WC2A. Location and average rates of accumulation are listed. WC1A-45 is based on two cores taken from the site.

Rates of Sediment Accumulation in the Tidal Environment

Church et al. (1981) noted that variations in sediment grain size, salinity and organic content in tidal salt marshes can affect the interpretation of ^{210}Pb results. The tidal portion of the substrate of the Princeton-Jefferson Marsh is low in salt (< 1 ppt) and is consistent in grain size and organic content thereby minimizing potential variability associated with radioisotope analysis. Combining the results of all ^{210}Pb activity from the Princeton-Jefferson Marsh yields an average sediment accumulation rate of 1.20 cm yr^{-1}. ^{137}Cs results (1.20 to 1.32 cm yr^{-1}) correlate well with the average ^{210}Pb rate, suggesting that the rate of 1.20 cm yr^{-1} is a general rate of sediment accumulation for the tidal freshwater marsh portion of the substrate.

Early dike failure is represented in the pollen record by a sharp decline in Cyperaceae and a sudden increase in Poaceae and Cheno-Ams at 70 cm. Between 65 and 60 cm Poaceae decline, reflecting a period between 1937 and

TABLE 2.—*Total suspended particulates for each tidal cycle sampled. Values presented in kilograms and adjusted for flow over the tidal cycle*

	Sampling Date						
	6/87	8/87	10/87	11/87	12/87	3/88	4/88
Total Flood Particulates	2,718	2,583	2,528	2,616	1,354	2,537	2,459
Total Flood Organic Particulates	941	840	563	1,227	383	473	979
Total Ebb Particulates	1,770	1,226	1,248	2,366	934	1,323	1,759
Total Ebb Organic Particulates	712	760	319	904	281	209	704
Total Net Particulate Influx	948	1,357	1,280	250	420	1,214	700

1939 of reduced tidal influence when dike failure was minimal. At 60 cm the resurgence of Poaceae represents continuous tidal freshwater marsh development after collapse of the dike in 1940. Pollen profiles combined with historic records indicate an average sediment accumulation rate of 1.25 cm yr^{-1} for the tidal portion of the substrate, a rate consistent with radiometric results.

Rates of sediment accumulation, however, do not appear to be constant through time. ^{137}Cs results suggest that the 1954 horizon in aboveground nuclear testing occurred at approximately 45 cm in depth. Between 1954 and 1963 rates of accretion averaged 1.67 cm yr^{-1}. A pipeline was installed across the marsh in 1965 and 1966 between 45 and 60 m on transect WC2A. During installation, basal sandy sediments were excavated and redeposited as a 2 mm thick sand band which now is preserved between 20 and 25 cm in cores along transect 2A. Based on this sand band, the average rate of accumulation for the marsh was 0.97 cm yr^{-1} over the last 23 years.

Storm events are important factors controlling rates and processes of sediment accumulation in tidal marsh systems (Harrison and Bloom 1977; Stumpf 1983; Rejmanek et al. 1988; Reed 1989; Brush 1989). During the last fifty years large-scale regional storm events such as hurricanes and northeasters have averaged 2 to 3 events annually. Between 1952 and 1965 storm frequency in the mid-Atlantic states increased from 2 to 3 major storm events to an average of 5 or more major storms per year (Maurer and Wang 1973). Further, at least 7 major storm events occurred annually between 1958 and 1962, with 12 storms occurring in 1958 and again in 1962, including the largest storm ever recorded for the area (March 1962). While a major regional storm event could not be included in the flux study, a small localized event (6.9 cm in 24 hr based on rain gauge measurements taken at Pemberton, New Jersey, NOAA 1987) resulted in the highest single concentration of suspended sediment (~120 kg) of all instantaneous measurements taken on the flood tide. Thus as for other tidal marsh studies, storms appear to play a major role in controlling the rates of sediment accumulation in tidal freshwater wetlands.

Sediment Flux Estimates

Stern et al. (1986) found that material transport in a Louisiana tidal freshwater marsh was high during winter, spring and early summer and decreased during late summer and early fall. They also noted that increases in concentrations in November were followed by a decrease in January. Suspended loads monitored at the Princeton-Jefferson Marsh show increases in early spring, late summer and early fall and decreases in late fall, winter and early summer (Table 2). Although the concentration of total particulates is higher in November when compared to the December sampling date, total net particulate influx increases between November and December.

Sediment flux estimates permit calculation of current accretion rates for the marsh surface. Based on the average dry weight for surface samples, it takes 7.5 ± 1.1 g of material to accumulate 28 cm^3 of substrate. Flux estimates show that 68,506 kg of dry suspended load remains in the system on an annual basis. The marsh surface area covers an area of 38,333 m^2, yielding a total weight of 111,608 kg based on a 1-cm-thick slice across the surface. Assuming the sediments are evenly distributed across a smooth surface, an accretion rate of 0.61 cm yr^{-1} is estimated based on tidal inputs alone. Studying Delaware River tidal freshwater marshes, Whigham et al. (1989) showed that approximately 20% refractory organic material from *in situ* plant sources (*Zizania, Peltandra* and *Bidens*) remained on the marsh after one year. This refractory material is equivalent to about 0.20 cm yr^{-1} of the sediment accumulation rate as determined by ^{210}Pb and ^{137}Cs analysis. The estimates of tidal inputs (0.61 cm yr^{-1}) combined with *in situ* organic accumulations (0.20 cm yr^{-1}) yields an estimated total accretion rate of 0.81 cm yr^{-1}. This estimated total rate of acretion accounts for about 68% of the rate established through radiometric analyses for this site. If the sand band on WC2A is utilized to estimate accretion rates during the last 23 years, then about 84% of the annual accretion rate may be accounted for.

Flux estimates have shown that sufficient suspended material moves into the site on an annual basis to account for much of the estimated sediment accumulation rate. We do not know what portion of the suspended load was contributed directly by the Delaware River. Biggs and Beasley (1988) noted that much of the material available for transport in the Delaware River is a function of the reworking of sediments from within the tributary, and Pestrong (1972) and Letzsch and Frey (1980) suggest that erosion of the tidal channels within salt marshes provides much of the sediment for deposition and building of the marsh surface. These studies suggest that much of the material available for accumulation in the Princeton-Jefferson Marsh is probably derived from within the Woodbury Creek Marsh system. However, during and following major storm events, the Delaware River may be the dominant contributor as appears to be the case in the period from 1952 to 1963.

Sea Level Rise and Marsh Accretion

Since 1922 sea level has risen an average of 0.267 cm yr^{-1} in the upper Delaware River estuary (Lyles et al. 1988). Once tidal freshwater marsh was initiated in 1940, sediment accumulation has been 4 to 6 times the rate of sea level rise. Therefore a discrepancy exists between the rates of sea level rise and average marsh accretion rate. Several factors may be responsible for this difference, including autocompaction of the peat, oxidation and/or drying of the substrate, and adjustments to mean high water (MHW). Autocompaction of the peat may be compensating for upward adjustments of the surface as sediments accumulate. However, studies have shown that tidal salt marshes can track sea level rise even when overlying swamp peats that are greater in depth than those reported for this site (Redfield and Rubin 1962; Bloom 1964; Orson et al. 1987). Likewise, the sediments of the Princeton-Jefferson Marsh never dry completely and be-

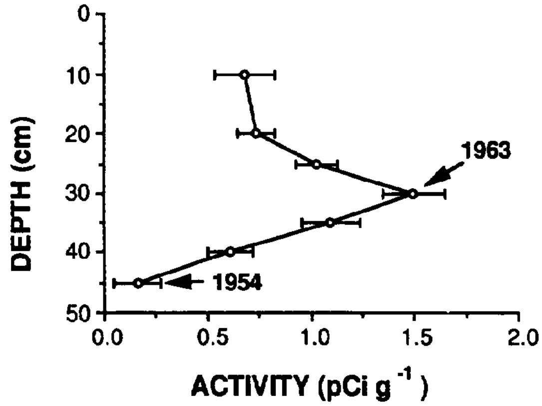

FIG. 6.—Cesium-137 activity with depth for core WC1A-30.

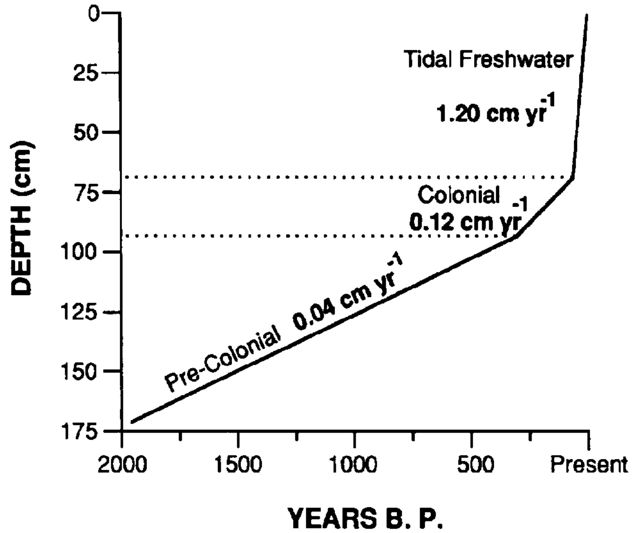

FIG. 7.—Change in rates of sediment accumulation through time.

low ~1 cm are generally anoxic. Knight (1934), Redfield (1972) and Chapman (1976) noted that low marsh areas can maintain high rates of accretion until MHW is reached. Pethick (1981) suggested that maximum high-water spring tides act as an upper vertical limit to tidal salt marsh surface elevations. Pethick noted that the relationship between depth and period of tidal inundations and marsh surface elevations were asymptotic, with the marsh surface never fully achieving high water. At the Princeton-Jefferson Marsh, MHW presently extends 15 to 20 cm above the marsh surface during most neap and spring tides. Therefore, as suggested by Pethick (1981), rates of accretion may not track sea level rise until the marsh surface approximates MHW.

It appears that rates of sediment accumulation increase from the lower to the upper estuary for systems located along the Atlantic coast. Brush et al. (1982) found rates of sediment accumulation varied from 0.17 cm yr^{-1} to 1.55 cm yr^{-1} moving up the Potomac River estuary. Kearney et al. (1985) reported an increase in sediment accumulation from the lower (0.18 cm yr^{-1}) to the upper (0.74 cm yr^{-1}) portion of a Chesapeake Bay tributary. R. A. Orson (unpubl. data) found that long-term rates of accretion were 2 to 4 times higher in tidal freshwater marshes of the Connecticut River estuary when compared to their saline counterparts. Likewise, for the Delaware River estuary, accretion in tidal salt marshes of the lower estuary is 0.5 cm yr^{-1} (Stumpf 1983) in contrast to the current rate of 0.97 cm yr^{-1} for the Princeton-Jefferson tidal freshwater marsh of the upper estuary. Clearly the processes controlling differential accretion in estuarine marshes require additional study.

CONCLUSIONS

Several techniques, including radioisotope analysis, palynological techniques, historical reviews and sediment flux estimates, were combined to determine rates of accretion for a tidal freshwater wetland of the upper Delaware River estuary. The results for ^{210}Pb (1.20 cm yr^{-1}), ^{137}Cs (1.20 to 1.32 cm yr^{-1}) and pollen/historic analysis (1.25 cm yr^{-1}) showed good correspondence between all techniques used to determine rates of sediment accumulation for the Princeton-Jefferson Marsh. Results show three distinct periods of wetland development, a pre-colonial period with sediment accumulation rates of 0.04 cm yr^{-1}, colonial period with accretion of 0.12 cm yr^{-1}, followed by a tidal period beginning in 1940 (Fig. 7). Current rates of sediment accumulation are 0.97 cm yr^{-1}, but during the period of 1954 to 1963 when storm frequency was quite high, rates averaged 1.67 cm yr^{-1}.

The tidal freshwater marshes appear to be well suited for investigating rates of accretion. The tidal portion of the substrate lacks salt and is uniform in both sediment grain size and organic content, factors that can reduce the variability in ^{210}Pb. Rates of accretion are also high enough to allow for well-defined ^{137}Cs profiles. Pollen cores are consistent throughout the marsh, suggesting disturbance to the substrate is minimal. The high ratio of annuals in the plant community at the Princeton-Jefferson Marsh limits the development of a dense belowground component and restricts the downward translocation of materials associated with root and rhizome mats. Collectively, these factors combine to limit the variability often associated with the dating of estuarine sediments. It is clear from this investigation that tidal freshwater marshes are capable of preserving evidence of processes and events (land clearing, local disturbances, introduction of tides, increased storm activity) that have shaped the upper estuary through time.

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