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ANTHROPOGENIC AND CLIMATE-CHANGE IMPACTS ON SALT MARSHES OF JAMAICA BAY, NEW YORK CITY

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Abstract: Field studies and aerial photograph interpretation suggest that large sections of Jamaica Bay salt marshes in New York City near John F. Kennedy International Airport are deteriorating rapidly. The relatively recent salt marsh losses may be caused by a variety of factors, potentially interacting synergistically. Possible factors include reduced sediment input, dredging for navigation channels, boat traffic, and regional sea-level rise. Field work included aboveground biomass measurements of *Spartina alterniflora*, mapping plant community distribution, and documenting biogeomorphological indicators of marsh loss. Current productivity (standing crop biomass), which ranged from approximately 700 to 1500 g m^{-2}, was typical of healthy marshes in this region, in spite of other indicators of marsh degradation. Historical aerial photographs of several islands showed that sampled marshes have diminished in size by ~12% since 1959. Overall island low marsh vegetation losses since 1974 averaged 38%, with smaller islands losing up to 78% of their vegetation cover. Ground observations indicate that major mechanisms of marsh loss include increased ponding within marsh interiors, slumping along marsh edges, and widening of tidal inlets. Projections of future sea-level rise, using outputs from several global climate models and data from local tide gauges, in conjunction with a range of plausible accretion rates, suggest that under current stresses, Jamaica Bay salt marshes are unlikely to keep pace with accelerated rates of sea-level rise in the future.

Key Words: salt marsh, *Spartina alterniflora*, climate change, global warming, sea-level rise, global climate models, erosion

INTRODUCTION

Coastal salt marshes of the Northeastern United States (Maine to New Jersey) formed within the last 4000 to 7000 years as the post-glacial rise in sea level slowed (Teal and Teal 1969, Redfield 1972, Thomas and Varekamp 1991). A string of highly productive coastal wetland marshes developed, which extended from the easternmost tip of Long Island to what is now New York City and north along the Hudson River (Tiner 1987). Within the last 100 years, however, the marsh-building process has reversed in a number of locations, in part due to the recent acceleration of sea-level rise with respect to the general trend of the last 1–2 thousand years (e.g., Gornitz 1995, IPCC 2001).

Recent tidal wetland loss through erosion, submergence, and related processes is well-documented in Louisiana, Chesapeake Bay, Southern New Jersey, and Cape Cod, as well as in the United Kingdom (Dean et al. 1987, Titus 1988, Allen and Pye 1992, Wray et al. 1995). However, the phenomenon has not yet been reported in the metropolitan New York region where, because of extensive development, losses cannot easily be compensated by inland expansion of the salt marsh onto adjacent upland or freshwater zones. Intertidal marshes in Jamaica Bay, New York City offer an opportunity to study an accessible and well-mapped coastal area with an available historic record from aerial photographs in a highly urbanized region (Figure 1).

The objectives of this paper are to analyze recent tidal wetland loss in Jamaica Bay and to investigate the impacts of future sea-level trends. This work builds on an earlier regional report to the U.S. National Assessment on Climate Variability and Change (U.S. Global Change Research Program). In this study, we compare the areal extent of marsh in Jamaica Bay before and after the promulgation of protective regulatory mechanisms in the 1970s. Since past changes occurred rapidly within the last 100-year time period, including major dredge and fill operations for navigation and upland construction, this analysis relies extensively on historic charts, maps, and aerial photography. In addition, extrapolations of historic trends and Global Climate Model (GCM) simulations of continued increases of anthropogenic CO_2 and other greenhouse gases in the atmosphere are used to project future sea-level rise and inundation of local marshes. While historic losses have been caused primarily by development activity, including filling and dredging of wetlands, future losses will most likely be due to inundation from sea-level rise (Hartig et al. 2001).

Sea-Level Rise and Accretion Rates

The rate of local sea-level rise in Jamaica Bay is around 2.7mm yr^{-1} as determined by tide-gauge data (1856–1996) from Battery Park in Manhattan. This can be compared to the mean global sea-level rise of 1.5 mm yr^{-1}, related to the global warming trend of the last century (Gornitz 1995, IPCC 2001). The difference between the global (eustatic) and the local New York (relative) sea-level trend is due to local subsidence resulting from crustal readjustments to the removal of ice following the last glaciation. The New York City region lies at the southern edge of the last ice sheet. The area to the south was upwarped during the Wisconsinan glaciation 20,000 years ago (the ‘‘peripheral bulge’’), while land to the north was depressed beneath the weight of the ice. As land formerly under the ice sheet rebounded, most of the Atlantic Coast has subsided.

Rising sea level is likely to increase inundation, erosion, and saltwater intrusion. This could result in the enlargement of tidal pools and channels, which would affect coastal wetlands and the wildlife they support. While marshes can withstand wave action to a certain degree, erosion may escalate with more frequent storm surges (from nor’easters, tropical storms, and hurricanes) superimposed on a higher sea level (Gornitz 2001, Gornitz et al. 2001). As sea level rises, salt marsh vegetation may become inundated for more hours in the tidal cycle than can be tolerated for sustained growth. It should be noted that a salt marsh requires some sea-level rise to maintain itself; the process is somewhat self-regulating, and salt marsh accretion rates, at a minimum, approximate sea-level rise (Allen and Pye 1992). The correlation between accretion rates and sea-level rise has been used as a tool to determine historical sea-level rise (Varekamp et al. 1992, Nydick et al. 1995, Nuttle 1997).

Most previous research of sea-level rise in salt marshes is based on long-term age-depth profiles in accreted layers of peat. Studies have shown that long-term surface deposition rates are correlated with historical changes in sea level (Redfield 1972, Bricker-Urso et al. 1989, Orson et al. 1998). Radioisotope analyses can establish vertical accretion in the marsh for periods in the range of years to a century (e.g., ^{137}Cs, ^{210}Pb; Orson et al. 1998). A technique for measuring marsh accretion with a resolution of several years uses Sediment Erosion Tables (SETs, Boumans and Day 1993, www.nwrc.nbs.gov/set/elev.html). SETs would be very useful, if installed, to document continued marsh loss in Jamaica Bay. In the United States, present rates of marsh accretion have been reported as exceeding or keeping pace with sea-level rise, except in Louisiana, parts of Chesapeake Bay (e.g., Blackwater Marsh and Bloodsworth Island, Maryland), and Barn Island, Connecticut (Dean et al. 1987, Boesch et al. 1994, Downs et al. 1994, Wray et al. 1995, Kearney 1996).

Role of Climate Change

Global climate change may alter hydrologic parameters upon which wetlands and the species that inhabit them depend. Climatic events, such as freezes and storms, can affect habitat diversity and temporal distribution of organisms. Future projections, extrapolated from both current trends and climate-change scenarios, indicate that tidal wetlands in the New York metropolitan region are at risk from sea-level rise and increased storm surges.

Ice formation is a distinguishing feature between northern salt marshes, such as those found in the New York Metropolitan region, and more southern salt marshes. Ice acts as both an erosive and depositional force on the salt marsh. Richard (1978) found that freezes in Flax Pond, a Long Island salt marsh, pull chunks of marsh off the land to create little islets of marsh, called tussocks. The tussocks hold growing *Spartina alterniflora* Loisel. plants and can be impor-

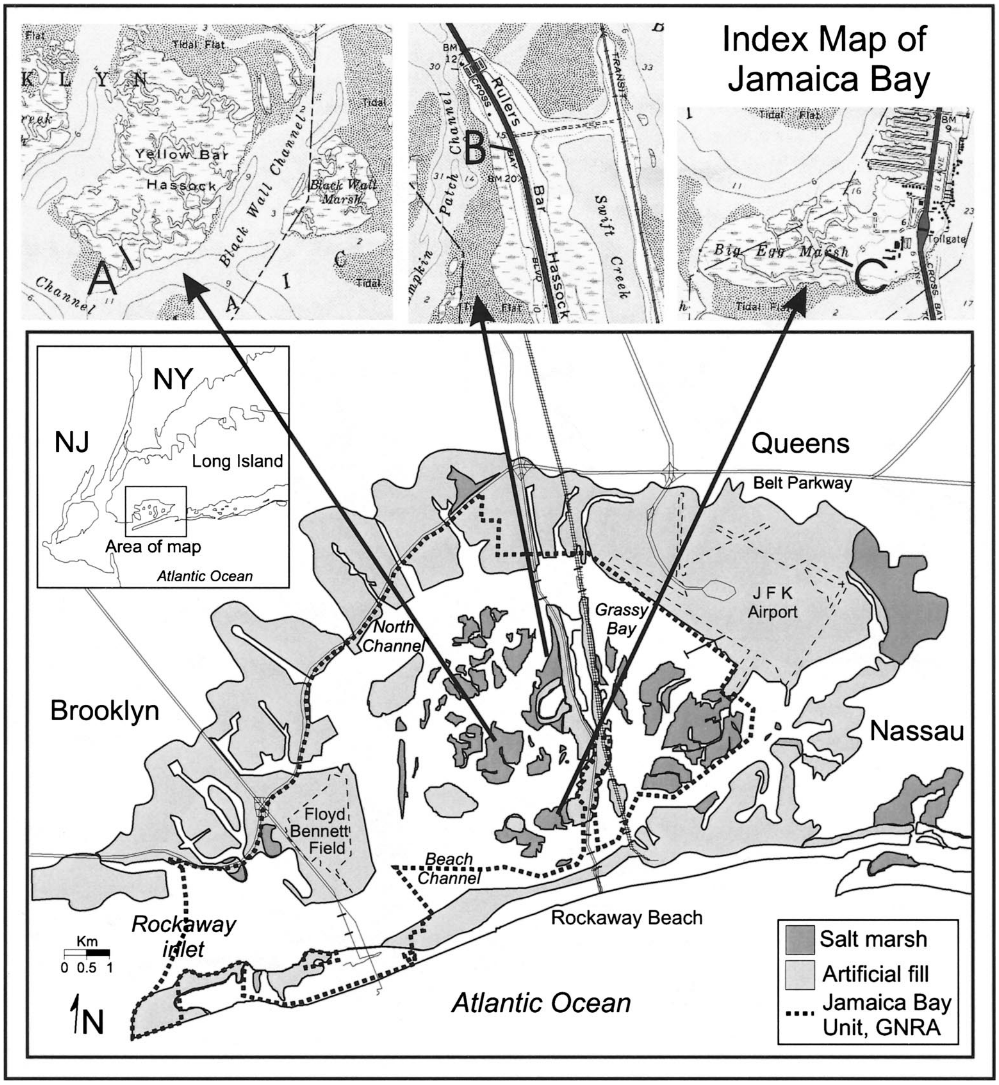

Figure 1. Index map of the Jamaica Bay. Insets show field sampling sites within (A) Yellow Bar Hassock, (B) Rulers Bar Hassock, and (C) Big Egg Marsh. Light grey indicates placement of artificial fill material since 1907. Boundary line indicates extent of Jamaica Bay Unit, Gateway National Recreation Area (GNRA). Sources: Englebright (1975) and USGS 7.5' series (Jamaica and Far Rockaway).

tant for extending the range of marshes seaward. However, ice can also scour and remove plant material and sediments from salt marshes. A single severe freeze in Flax Pond, Long Island destroyed 16 months worth of accretion (Richard 1978). While ice-scoured regions may create habitats for microinvertebrates in crevices and muddy strata in the marsh, repeated extensive scouring can diminish marsh landmass over the long-term.

Global climate model (GCM) projections indicate less severe winters during the 21st century, leading to less frequent icing events (Rosenzweig and Solecki 2001). The marshes may, therefore, be less affected by ice scouring in the future. However, as temperatures rise, evaporation increases and the hydrologic cycle intensifies, leading to an increased frequency in storm events. In addition, as sea level rises, the amount of flooding with each storm may increase, along with increased wave heights, leading to greater erosion. The marshes will become increasingly vulnerable to erosional impacts from storminess.

METHODS

Study Site

This report concentrates on salt marshes of Jamaica Bay, one of the largest coastal ecosystems in New York State (Hart and Milliken 1992). Jamaica Bay encompasses the Jamaica Bay Wildlife Refuge (JBWR), protected since 1972 as part of the Jamaica Bay Unit of Gateway National Recreation Area (GNRA) administered by the National Park Service (Tanacredi and Badger 1995). Located near John F. Kennedy International Airport, the geographical coordinates of Jamaica Bay are 41° N, 74° W (Figure 1). While other units of GNRA are found in Staten Island and New Jersey, the Jamaica Bay Unit includes the uplands, wetlands, and waters south of the Belt Parkway in Brooklyn and Queens. Although most of the island marshes lie within the Jamaica Bay Wildlife Refuge in GNRA, some fringing marshes are located outside the wildlife refuge and lie outside the GNRA boundaries. Jamaica Bay is an estuary with diverse habitats, including open water (littoral zone), coastal shoals, bars, mudflats, intertidal zones (low and high marshes), and upland areas.

Jamaica Bay provides prime habitat for migratory birds. The intertidal mudflats are principal feeding grounds for migratory shorebirds such as Black Skimmers, plovers, and knots. The Bay provides prime wintering grounds for Brant (2000 in a peak year), Mallards, American Black Duck, Canvasback Duck (more than 2500 in a peak year), and other waterfowl (Wells 1998). Other wildlife, such as reptiles, amphibians, and small mammals, can be found at Jamaica Bay (Tanacredi and Badger 1995).

Much of the original tidal wetlands of Jamaica Bay have disappeared due to human activities for infrastructure development. In 1907, Jamaica Bay encompassed 9979 ha of waters and marsh islands, as well as an extensive network of shoreline marshes extending beyond today's Belt Parkway (Figure 1) (Englebright 1975). Marshes covered an estimated 6549 ha. Waters of the Bay covered 3430 ha, much of it shallow channels averaging 1 m in depth. By 1970, total area with remaining shoreline marshes was 5265 ha, of which 1620 ha were marshland. Waters covered approximately 3645 ha, much of the increase due to dredging (e.g., Grassy Bay) or for navigation maintained to depths greater than 10 meters. Losses of wetlands up to 75% through the early 1970s (Black 1981) were due primarily to human activity. However, changes after 1972, once the wetlands of the Jamaica Bay Unit were under the jurisdiction of the National Park Service, have not been documented previously.

Mean tide range for seven sites around the Bay varies between 1.5 m and 1.6 m. Natural and human processes probably have altered the hydrodynamic regime of Jamaica Bay, although specific impacts have not been well-established. The prevailing westerly littoral drift along the south shore of Long Island (Kana 1995) has almost doubled the length of the Rockaway spit since the early 19th century (Englebright 1975). However, the Rockaway inlet has been stabilized by jetties since the 1930s. Urbanization of the Rockaway Beach barrier island during the 20th century has effectively halted the delivery of sand to Jamaica Bay via overwash during periodic intense storms. Although there are no long-term tide-gauge records from Jamaica Bay, an increase in water depth (such as that caused by dredging of navigation channels) generally leads to an increase in tidal range. This may, in turn, enhance tidal currents and erosion.

Aerial Photograph Analysis and Mapping

In a preliminary assessment, changes in Jamaica Bay island salt marshes were determined by standard photointerpretation techniques using black and white aerial photographs covering a center section of Jamaica Bay in 1959, 1976, and 1998. Stereopairs with greater than 60% overlap were acquired from two companies. The 23 cm x 23 cm photographs are at scales of 1:15,000 in 1959 and 1998, and 1:12,000 in 1976. All were flown during early spring, March to April, at different times within the tidal cycle. Flight records show that the April 7, 1959 (9:15am) aerial photographs were acquired slightly after high tide (7:45am). The 1976 aerial photographs (March 29, 1976, 12:40pm) were taken at low tide (1:28pm). Although the exact flight time for the 1998 photography was unavailable, it was estimated from shadow lengths and depth of water along embankments on the photographs. From that, the tidal stage was inferred to be around mid-tide. Only changes in the land-water boundary were delineated; no further differentiation between intertidal vegetated and unvegetated terrain was made. Thus, this classification is more inclusive than that employed in the NYSDEC analysis (see below).

Areas of three selected salt marsh sites (Yellow Bar Hassock, Black Wall Marsh, and Big Egg Marsh) were calculated directly from the aerial photographs using a transparent grid overlay (3mm^2 grid cells). Although the salt marsh/water boundary can be estimated to within 0.5mm, which corresponds to 6–7.5 m on the ground, the island area was estimated by counting the number of grid cells with greater than 50% land cover. Tidal creeks and large tidal pools were classified as ''water.'' Cells were counted three times for each photograph, and the average of the counts for each marsh was recorded. The gridding process resulted in an error range of 4%.

A quantitative trend analysis of wetland change over a longer time period covering all Jamaica Bay salt marsh islands was conducted using digitized aerial photographs for the years 1924, 1974, 1994, and 1999 in a Geographic Information System (GIS) software (ArcView).

The New York State Official Tidal Wetlands Inventory is maintained by the Geographic Information System Unit, Bureau of Marine Resources, New York State Department of Environmental Conservation (NYSDEC) in East Setauket, NY. The Tidal Wetland Boundaries (TWB) were initially mapped in 1974 for the New York State tidal wetland mapping inventory, as required by the Tidal Wetlands Land Use Regulations 6 NYCRR Part 661, Article 25 of the ECL (Environmental Conservation Law). To determine the effectiveness of tidal wetland regulations and to conduct a tidal wetland trend analysis, aerial photography was obtained in 1999. The 1974 and 1999 series of photographs were flown to ECL specifications for inventory mapping; digital orthoquads (1:12,000) were produced from aerial color infrared photography flown at an altitude of approximately 1850 m close to low tide between mid-August to mid-October and thus are directly comparable. The 1994 digital orthoquads (1:12,000) were produced from aerial color infrared photography obtained April 8, 1994 during a rising tide.

TWB inventory wetlands are classified by a combination of tidal influence and vegetation. They are divided into two salt marsh vegetation categories, intertidal marsh (IM) and high marsh (HM); one freshwater tidal category, fresh marsh (FM); and two aquatic non-vegetated categories, littoral zone (LZ), and coastal shoals, bars, and flats (SM). The updated inventory for New York State tidal wetlands is not yet completed. In this paper, only salt marsh and more aquatic non-vegetated wetlands are compared. All digital data were referenced to the 1974 TWB using the 1994 photography as a base.

Field Investigations

Of more than 15 named marshes in Jamaica Bay, three were selected for measurement of vegetative species composition and *Spartina alterniflora* aboveground biomass (i.e., Yellow Bar Hassock, Big Egg Marsh, and Rulers Bar Hassock; Figure 1). The latter two marshes are both on Broad Channel Island. Big Egg Marsh is adjacent to the Broad Channel Island residential community. Rulers Bar Hassock is located on the northern tip. Adjacent to each are uplands dominated by shrubs and thickets, including stands of Northern Bayberry (*Myrica pennsylvanica* Loisel.). Yellow Bar Hassock lies to the west of Broad Channel Island (Figure 1). Yellow Bar Hassock and Big Egg are peat-rich marshes with extensive meandering tidal channels, whereas Rulers Bar Hassock is a sandy shore tidal marsh with limited channel inlets. All three marshes are dominated by *Spartina alterniflora*. Field investigations consisted of detailed observations of biogeomorphological indicators of marsh deterioration and vegetation sampling.

Geomorphological Investigations. Field work during the summer of 1999 focused on documenting ground evidence of erosion and degradation processes in selected portions of our three study sites. The geomorphological processes were categorized into a framework outlining the mechanisms of marsh loss, and examples of the various types are given.

Plant Community Composition. Species composition at Big Egg Marsh, Rulers Bar Hassock, and Yellow Bar Hassock was recorded from 1.0 m^2 quadrats, placed 15 m apart along linear transects (Figure 1, insets A, B, and C). Logistical constraints limited field observations in Big Egg Marsh to the more landward marshes, as the large channels were not passable by foot during low tide. In Yellow Bar Hassock, sampling was limited to the southern portion of the island. Observed species were listed on field data sheets. Because surveyed elevation data were unavailable for marsh locations, we used the vegetation assemblages to infer tidal zonation and approximate elevation for the cross-sectional drawings (e.g., Bertness and Ellison 1987, Kana et al. 1988, and Bertness 1991).

Biomass Measurements. Measurements of *Spartina alterniflora* aboveground biomass were taken from the middle to close to the end of the growing season, July through October, 1999 and August to October, 2000. Data were collected to provide a baseline for long-term studies of response to climate variability and change and to evaluate effects of marsh erosion or inundation on salt marsh productivity. At the three marsh sites in Jamaica Bay (Big Egg Marsh, Rulers Bar Hassock, and Yellow Bar Hassock), 1.0 m^2 plots were spaced 15 m apart along linear transects for sampling (Figure 1, insets A, B, and C). Within preselected swaths largely determined by accessibility, transect starting locations were selected randomly. For each transect, *Spartina alterniflora* was clip-harvested from within a 0.25 m^2 corner of each 1.0 m^2 quadrat. Collected material was dried to constant weight at 105°C (Nixon and Oviatt 1973).

Sensitivity Study–Salt Marsh Response to Sea-Level Rise

Sea-level rise could increasingly affect shoreline change and wetlands loss (Orson et al. 1985, Wray et al. 1995). A rise in global mean temperature of 1–5°C, mainly due to increased CO_2 and other greenhouse gases, would cause thermal expansion of ocean waters and melting of mountain and high latitude glaciers. This could result in a rise of more than 1 m above

Table 1. Surface accretion rates measured in the salt marshes of the New York region compared with the mean rate of sea-level rise (SLR).

Method	State	Marsh Zone	Accretion Rate (mm/yr)	Time (years)	SLR (mm/yr)	Source
^{210}Pb	Guilford CT	low	2.5	134	2.5	Anisfeld et al. (1999)
	CT	high	1.8–2.0	58	2.5	Orson, Warren and Niering (1998)
		low	3.3			
	Stony Brook (LI, NY)	high to low	2.4–2.8	134	2.2	Cademartori (2000)
	Alley Pond (Queens, NY)	high	3.5	134	2.4	Cochran et al. (1998)
	Goose Creek (Bronx, NY)	high	2.4	134	2.4	
	Hunter Island (Bronx, NY)	high	1.1	134	2.4	
	Caumsett Park (LI, NY)	high	4.1	134	2.3	
	Flax Pond, (LI, NY)	high	2.1	134	2.2	
	Shelter Island (LI, NY)	high	3.0	134	2.5	
	Jamaica bay (Queens, NY)	high	5.0	100	2.7	Zeppie (1977)
		low	8.0			
Particle layer	CT	high	2.0–6.6	10	2.6	Harrison and Bloom (in Richard 1978)
	CT	low	8.0–10.0	10	2.6	Bloom (in Richard 1978)
	NY	low	2.0–4.2	1	2.9	Richard (1978)

present mean sea level at certain localities within the New York City metropolitan region by the end of the century (Gornitz et al. 2001). The tide gauge at Battery Park, New York City was used to determine recorded historic changes in sea level at Jamaica Bay. As yet, there are no permanent tide gauges within the Jamaica Bay itself. An advantage of the gauge at Battery Park is that measurements for the location have been recorded since 1856, one of the longest records available in the United States.

The historic rate of sea-level rise of 2.7 mm yr^{-1} was compared with published regional accretion rates (Table 1). Accretion rates, using the particle-layer method (e.g., feldspar), ranged from 2.0 to 10.0 mm yr^{-1} in low marsh intertidal zones, while rates measured by the ^{210}Pb method ranged between 2.5 and 8 mm yr^{-1}. The ^{210}Pb method measures accretion rates over periods up to 100 years or more, whereas the particle-layer method generally covers much shorter-term rates. Considerable natural variability exists, and the ranges obtained by the two principal methods overlap to a large extent. As these marshes are 1–3 m thick, overlying hard substrates such as sand on Long Island, compaction even over the centennial period is not expected to be significant. This contrasts with Louisiana salt marshes, which overlie several kilometers of less dense organic material (S. Goodbred, SUNY Stony Brook, pers. comm). Only one analysis of accretion rates for Jamaica Bay salt marshes using the ^{210}Pb method has been published (Zeppie 1977). Low marsh was found to accrete at 8mm yr^{-1}, while high marsh accreted at 5mm yr^{-1}. These rates may have been anomalously high because they spanned a period of major anthropogenic transformations within the Bay (see Study Site).

To study impacts of sea-level rise on tidal marshes in New York City through the 2090s, we used a suite of sea-level rise projections based on historic data from local tide gauges and two Global Climate Models (GCMs). The GCM outputs are based on scenarios of CO_2 and other greenhouse gas increases over time (Rosenzweig and Solecki 2001). We present five sea-level rise projections: 1) extrapolation of current trends, 2) the Canadian Climate Centre model using greenhouse gas increases only (CCGG), 3) the Canadian Climate Centre model using greenhouse gases plus sulfate aerosols (which partially offset the global warming effect) (CCGS), 4) the United Kingdom Hadley Centre model with greenhouse gases only (HCGG), and 5) the United Kingdom Hadley Centre model with greenhouse gases plus sulfate aerosols (HCGS; Gornitz 2001, Gornitz et al. 2001). Projected sea-level trends have been adjusted for local land subsidence.

In a sensitivity study, we assume that if a salt marsh is near a state of equilibrium, accretion rates will closely match local rates of sea-level rise (Redfield 1972, Bricker-Urso et al. 1989). Although in the short-term, the accretion rate may differ significantly from the rate of local sea-level rise, a marsh must accrete at a rate approximately equal to or exceeding the rate of local sea-level rise in order to survive (Nuttle 1997). We applied this assumption to estimate marsh losses in Jamaica Bay due to sea-level rise for the decades of the 2020s, 2050s, 2080s, and 2090s given by the above-mentioned suite of sea-level rise projections and three assumed accretion rates, which span the range of

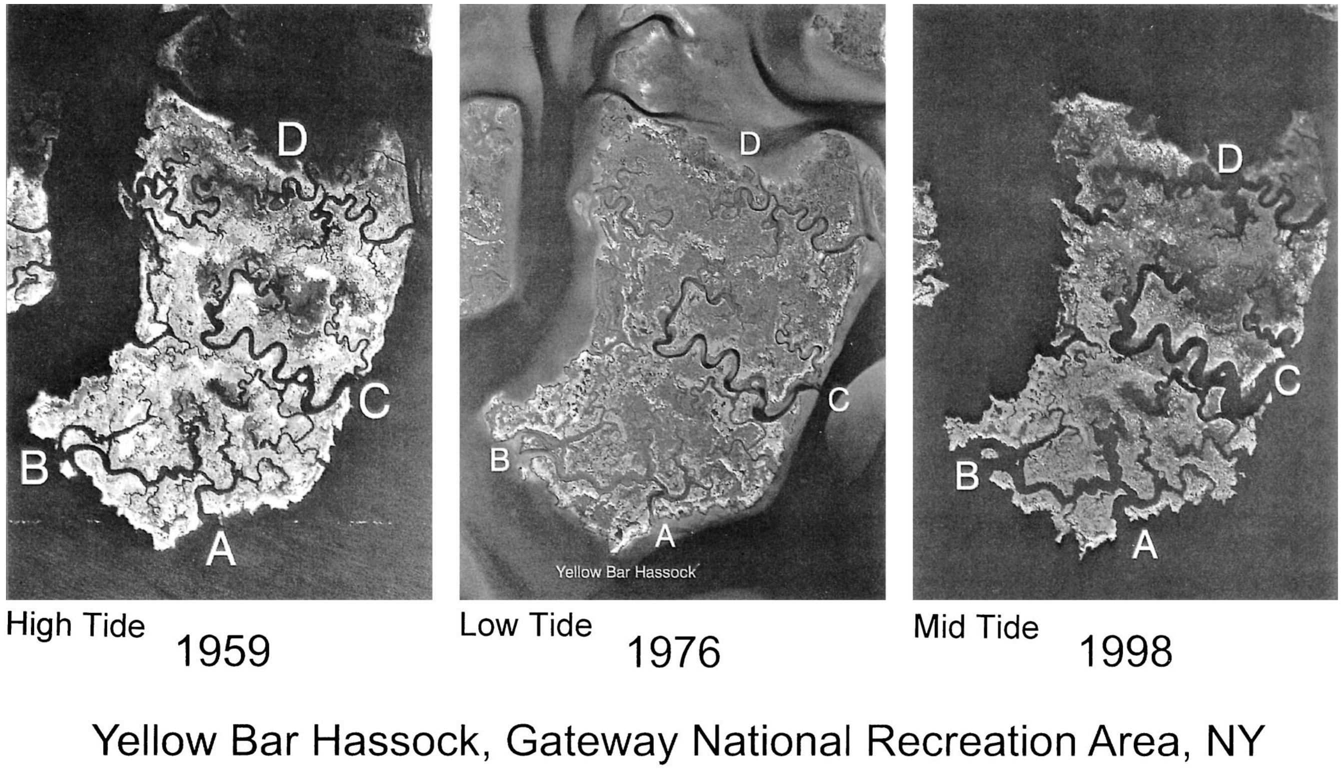

Figure 2. Aerial photographs of Yellow Bar Hassock showing marsh loss over a 39-year period. April 7, 1959 at 9:15am (high tide 7: 45am); March 29, 1976 at 12:40pm (low tide 1:28pm); and March 13, 1998 (mid-tide). Sources: Robinson Aerial Surveys, Inc., Newton, NJ (1959) and AeroGraphics Corp., Bohemia, NY (1976 and 1998).

published values: Low (L) = 0.2 cm/yr, Medium (M) = 0.5 cm/yr, and High (H) = 0.8 cm/yr. The medium accretion rate, the CCGG sea-level rise scenario, and the methodology of Kana et al. (1988) and Titus (1988) are used to illustrate projected changes in vegetation in Big Egg Marsh.

RESULTS

Salt Marsh Trends–Aerial Photograph Interpretation and Mapping

Land loss was immediately apparent upon examination of aerial photographs in the preliminary assessment. Two processes were clearly identified: 1) loss of shoreline on island edges and 2) loss of internal marshland along large meandering tidal inlets and their tributaries. For example, a comparison of points A-D in Figure 2 reveals a number of changes at Yellow Bar Hassock over a 39-year period. At Point A, the section of marsh seaward of the tidal channel had narrowed significantly in 1998 relative to 1976 and 1959. The tidal channel had also widened over this period. Similarly, at Point B, a small island clearly visible in 1959 had disappeared by 1998, the tidal inlets had expanded, and the shore between A and B had become scalloped by 1998 relative to 1959. The width of the tidal channel at Point C had also increased. By 1998, the promontory at the eastern end of the channel mouth at point C was reduced to a thin sliver. Tidal channels to its north (as at D) had also expanded by 1998.

Table 2 lists estimated areas and percent land loss since 1959, including both outer peripheries and tidal creeks, for the three island salt marshes studied: Yellow Bar Hassock, Black Wall Marsh, and Big Egg Marsh. These marshes show ~12% (av.) reduction in landmass between 1959 and 1998. This estimate of wetland loss is based on photographs taken at different times within the tidal cycle. However, since the 1959 photograph was taken at high tide when more of the marsh was inundated, the percent reduction in later photographs taken during mid- to low tide is regarded as a conservative figure. If one assumes that the marsh has remained stable over this period, the 1959 photograph at high tide should show the least land area. Instead, the two later photographs from 1976 and 1998, taken at low and mid-tide, respectively, show much less remaining marshland.

The more extensive remapping of wetland boundaries of Jamaica Bay salt marsh islands for New York State regulatory purposes, digitizing the Tidal Wetlands Boundary (TWB) from historic photographs and maps using GIS software, shows major changes in

Table 2. Changes in area between 1959 and 1998 at three salt marsh islands in Jamaica Bay, New York City.

		1976		1998		
Marsh Name	1959 Ha	Ha	% Loss Since 1959	Ha	% Loss Since 1976	% Loss Since 1959
Black Wall Marsh	17.8	17.4	2	16.6	5	7
Big Egg Marsh	30.4	30.8	−1	25.9	16	15
Yellow Bar Hassock	76.5	70.0	8	66.8	5	13
Total area	125	118	5%	109	8%	12%

wetland boundaries over a 75-year period (Figure 3). Table 3 summarizes marsh losses over this period for Black Wall Marsh, Big Egg Marsh, East High Meadow Marsh, Elders Point Marsh, Jo Co Marsh, and Yellow Bar Hassock, as well as for the entire Jamaica Bay island complex. Between 1924 and 1974, a total of more than 205 ha were lost, or approximately 4 ha yr^{-1} on average (Table 3). From 1974 to 1999, approximately 304 ha were lost, or 12 ha yr^{-1}. Most of the losses in the earlier period can probably be attributed to filling, dredging, or draining activities. However, by 1974, these activities were stopped through federal and state wetland regulations and creation of the Gateway National Recreation Area. Therefore, the more recent 12 ha yr^{-1} loss is completely unexpected and needs to be explained. Both aerial photography and field studies suggest that most of the lost *Spartina alterniflora* marshes have been converted to coastal shoals, bars, and flats based on comparison of 1974 tidal wetlands boundaries with 1999 digital orthoquads. While not to identical mapping specifications, 1994 color infrared photography from the same season offers further insights. Between 1994 and 1999, 89 ha were lost at an average annual rate of 18 ha yr^{-1}. Fig-

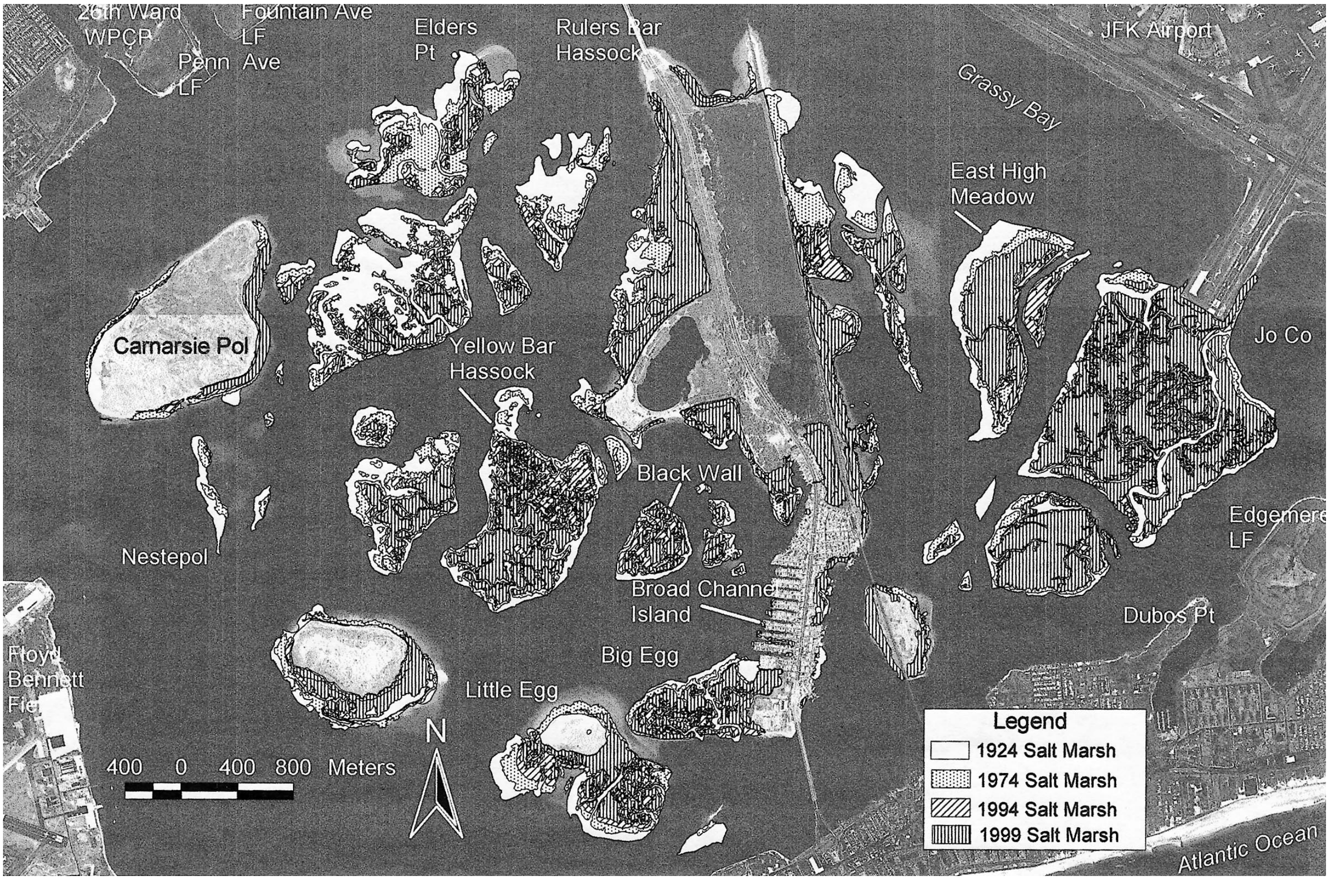

Figure 3. Changes in extent of Jamaica Bay island salt marshes, 1924–1999. Aerial photographs digitized by F. Mushacke and D. Fallon (NYSDEC). Sources: 1924 Fairchild Aerial Surveys Inc.; 1974 Earth Satellite Corp. Mark Hurd Aerials, Inc.; 1994 NYS Department of State, Division of Coastal Resources, GIS Unit, Albany, NY; 1999 TVGA, Elma, NY.

Table 3. Reductions in extent of vegetated salt marsh, 1924–1999, for individual island marshes and for more than 15 named island marshes of Jamaica Bay.

Marsh Examples/ Total Island Marshes	1924 Ha	1974 Ha	1974 % Loss Yr^{-1} Since 1924	1994 Ha	1994 % Loss Yr^{-1} Since 1974	1999 Ha	1999 % Loss Yr^{-1} Since 1994
Black Wall Marsh	21.1	16.7	0.4	13.8	0.9	8.3	8.0
Big Egg Marsh	39.1	34.1	0.3	29.9	0.6	21.0	5.9
East High Meadow	73.9	56.4	0.5	41.0	1.4	33.2	3.8
Elders Point Marsh	53.4	39.8	0.5	15.3	3.1	8.8	8.5
Yellow Bar Hassock	95.0	69.7	0.5	58.7	0.8	38.8	6.8
Jo Co Marsh	197.5	168.4	0.3	153.2	0.5	155.5	−0.3
Total Island Marshes (>15 Named Islands)	1004.2	798.9	0.4	583.7	1.4	495.2	3.0

ure 3 shows that greater losses of island marshes during the 1924–1974 period appear to have occurred along outer marsh edges, particularly on the north, northwestern, and southwestern portions of the islands. In more recent decades (i.e., 1974–1999), interior losses have become relatively more important. At present, interior pooling and vegetation decline appear to be the dominant processes (see Geomorphology below).

Similarities and differences in salt marsh island areas for selected islands (Tables 2, 3) are instructive, even though the data were acquired under non-identical conditions and time intervals. In general, the islands in Table 2 show fewer losses for the most recent period as compared to Table 3 because, in the former case, total marsh extent, including both vegetated and unvegetated landmass (i.e., mudflats), is counted, whereas in the latter, only remaining vegetated areas are shown. Thus, marsh loss appears to be underestimated in the former case, with respect to the latter. While the total wetland area is reduced to a lesser degree, the extent of loss in the low marsh intertidal zone is much greater. This comparison indicates how slight differences in mapping classification could mask significant transformations of vegetated low marsh to unvegetated mudflats.

Geomorphology

Geomorphological indicators of marsh loss at Jamaica Bay include island perimeter erosion, tidal channel widening, and expansion of tidal pools. Erosion occurs by slumping and undercutting of peat along both island edges and interior tidal channel banks (Figure 4). No signs of marsh expansion have been observed. On Yellow Bar Hassock, for example, vegetated marsh has been cut back by erosion along a tidal channel, exposing underlying peat and mud layers (Figure 5). This illustrates a transitional stage in the widening of tidal channels, which is one important process of marsh loss.

Many pools are surrounded by a low-density to zero vegetation zone (Figure 6). A helicopter overflight of Jamaica Bay on July 18, 2001 at an altitude of 100m to 150m during low tide revealed extreme dissection and fragmentation of the low marsh on many islands (Figure 7). For example, at Big Egg Marsh, in areas of degraded *Spartina alterniflora*, *Ulva lactuca* L. (sea lettuce) now carpets the surface, and the peat substrate is decomposing to a ‘‘soupy’’ consistency (Figure 6). In many portions of Jamaica Bay low marsh, unusually dense concentrations of ribbed mussels (*Geukensia demissus* Dillwyn) are found attached to the bases of *Spartina alterniflora* stems. The unusually high mussel populations may be an early indicator of marsh subsidence or of excess nutrient levels. These biogeomorphological features, taken together, suggest an increased level of waterlogging, which has contributed to the disintegration of the underlying peat root network and the undermining of marsh stability. Based on the long-term historic mapping, field work, and recent overflights (Figures 2, 3, 6, 7), the mechanism of marsh loss through interior ponding and expansion of interior mudflats seems to be more significant at present than that of slumping and widening of tidal channels. The geomorphological changes can be summarized as follows.

(A) Erosion.

  (1) Slumping, undercutting, and inward retreat of peat from bank ledges along island peripheries and tidal creeks (Figures 4, 5).
  (2) Widening of tidal channels (Figure 5).

(B) Inundation.

  (1) Expansion and coalescence of internal tidal pools and adjacent bare spots forming mudflats (Figure 6).
  (2) Widespread fragmentation and dissection of marsh vegetation (Figure 7).

Figure 4. Slumped peat block adjacent to intact marsh along tidal creek, Yellow Bar Hassock, at low tide.

(3) Excessive peat porosity with ''soupy'' consistency.
(4) Residual mounds from die-off of *Spartina alterniflora*, some with mussels (*Geukensia demissus*) still attached.
(5) Conversion of low marsh to mudflats (Figures 6, 7).

Species Composition

The dominant species in low marsh areas, between mean sea level (MSL) and Mean High Water (MHW), including all of Yellow Bar Hassock, was *Spartina alterniflora* (average 70% ± 13% cover, N = 39 0.25 m^2 quadrats). The main vegetation type in sampled areas of high marsh (between Mean High Water and Mean Higher High Water, MHHW) was *Spartina patens* (Aiton) Muhl. (10 ± 3% cover, N = 18 0.25 m^2 quadrats), found on Big Egg Marsh only. Traces of *Salicornia virginica* L. were observed on Big Egg Marsh and Yellow Bar Hassock. Species also seen in the high marsh zones of Big Egg Marsh and Rulers Bar Hassock included *Iva frutescens* L. and *Distichlis spicata* Greene. The transitional upland area located in the interface between MHHW and upland areas contained some *Myrica pennsylvanica* and *Phragmites australis* Trin. ex Steudel. The presence of extensive stands of high marsh on Yellow Bar Hassock, inferred from textural analysis of vegetation in the 1959 photographs, was not confirmed by the field studies.

Biomass Measurements

The mean aboveground biomass of *Spartina alterniflora* was averaged for each date and marsh sampled (Tables 4, 5). For all three selected marshes over the entire field season, mean biomass was 950 ± 512 gm m^2 by dry weight in 1999 and 1068 ± 493 gm m^2 in 2000. High marsh communities were restricted or missing in the communities sampled, particularly on Yellow Bar Hassock. These productivity values are typical of healthy marshes in the region (Table 6), in spite of the indicators of marsh deterioration outlined above. Heights of *Spartina alterniflora* were typically on the order of 1m, with mean heights ranging from 69 to 132 cm (Table 4). The quadrats included the nearest vegetated edge to barren features, such as pools and creeks that crossed the transect. While averaging low biomass patches near pools along with stands of healthy, relatively dense vegetation within a quadrat may reduce the average biomass determination somewhat, it gives a more representative value for growing marsh vegetation. This was most evident on Yellow Bar Hassock. Our transects intersected marsh areas

Figure 5. Erosion of low marsh along tidal channel, Yellow Bar Hassock, exposing underlying peat layers. This represents a stage in the widening of tidal channels, leading to marsh loss.

that are still fairly intact and may, therefore, underestimate the status of salt marsh in a more deteriorated condition. The relatively large variability in mean biomass is likely associated with the patchy distribution of *Spartina alterniflora* growth or, perhaps, small sample sizes.

Sensitivity Analysis: Salt Marsh Response to Sea-Level Rise

Accretion rates for the intertidal zone in Connecticut and New York are summarized in Table 1. The accretion rate for Jamaica Bay has only been measured once. Low marsh accreted at 0.8 cm yr^{-1} and high marsh at 0.5 cm yr^{-1} (^{210}Pb method). These values lie toward the upper range of those in Table 1. However, the sampling covered a 100-year time span when accretion may have been especially great due to dredging and filling activity, such as construction of John F. Kennedy International Airport, landfills, and uncontrolled outfall from sewage-treatment plants and combined sewage overflow (CSO). New controls presently in effect, particularly at the 26th Ward Water Pollution Control Plant and installation of above-ground CSO tanks, likely reduced the accretion rate, as did landfill closure and completion of major construction activities around the Bay. The actual accretion rate at Jamaica Bay has not been measured since the 1977 study, and new determinations are urgently needed. Here, we illustrate the potential effects of sea-level rise, assuming that none of the other recently observed perturbating factors are operating.

In the sensitivity study, we compare projected sea-level rise (Table 7) for the five climate-change scenarios (see Methods) with a set of assumed rates of marsh accretion. If current levels of atmospheric greenhouse gases remain the same, local sea level will continue to rise at around 2.7mm yr^{-1} over the next 100 years. With increasing levels of greenhouse gases (even with partial mitigation by sulfate aerosols), the global climate models (GCMs) project a generally ever-increasing sea-level rise over time (Table 7). Assuming that accretion rates tend to approximate sea-level rise in a stable marsh, we then compare our climate model projections of sea-level rise with low (0.2cm), medium (0.5cm), and high (0.8cm) accretion rates, which span the range of published values for this region (Table 1).

Table 8 lists the difference between the elevation of the marsh due to accretion and the sea-level rise for the decades of the 2020s, 2050s, 2080s, and the 2090s (negative numbers indicate that sea-level rise exceeds

Figure 6. View of Big Egg Marsh at low tide looking southwest toward the Marine Parkway Bridge. Note extent of exposed tidal pools and sparse growth of *Spartina alterniflora*.

accretion). In the Canadian Center scenarios (CCGG and CCGS), sea-level rise almost always surpasses the accretion rate, except for the highest accretion rate during the first half of this century. In the Hadley Center projections (HCGG and HCGS), marsh accretion lags sea-level rise only for the low and medium accretion rates. This exercise shows that, given sufficiently high rates of accretion, marshes should be able to withstand even moderately high rates of sea-level rise. Since the aerial photo-analysis and field observations reveal major reductions in marsh extent that have already occurred (Tables 2, 3), this implies that accretion rates in Jamaica Bay may be insufficient, even at present rates of sea-level rise, to compensate for losses due to erosion and other factors (see Discussion). Thus, the ability of many of the Jamaica Bay island marshes to survive the higher projected rates of sea-level rise (Table 7) for more than a few decades is in question. Nevertheless, Table 8 illustrates the range of accretion rates needed to keep pace with anticipated rates of sea-level rise.

As a schematic illustration of potential impacts of sea-level rise alone on marshes, the Canadian Climate Centre CCGG scenario was applied to a cross-section of Big Egg Marsh (Figure 8). Wetland vegetation and upland land use, based on field observations, were combined with a 1900 navigation chart and a 1988 aerial photograph (at a scale of 1:4800) to draw transects representing three time periods: 1900, 2000, and 2100. To illustrate future conditions, the medium accretion rate (0.5 cm yr^{-1}) was used, together with the CCGG scenario, to project the changes in vegetation assemblages and the estimated loss of marsh to inundation. The net difference between the accretion rate and sea-level rise under these conditions is ~ -60 cm (Table 8).

DISCUSSION

Coastal wetlands are maintained by an intricate system of negative feedbacks among rates of sea-level rise, upward accretion, wave erosion, and sediment deposition (Nuttle et al. 1997). A change in any of these factors, if not balanced by compensating changes in the others, could alter the stability of the salt marsh. A salt marsh lies very close to mean sea level and experiences frequent inundation by the tides, which provide nutrients and suspended sediments for accretion. If the marsh grows too high, tidal inundation decreases, with a corresponding decrease in nutrient and sediment supply, thus slowing down the accretion and upward growth (Cahoon and Reed 1995). Wherever

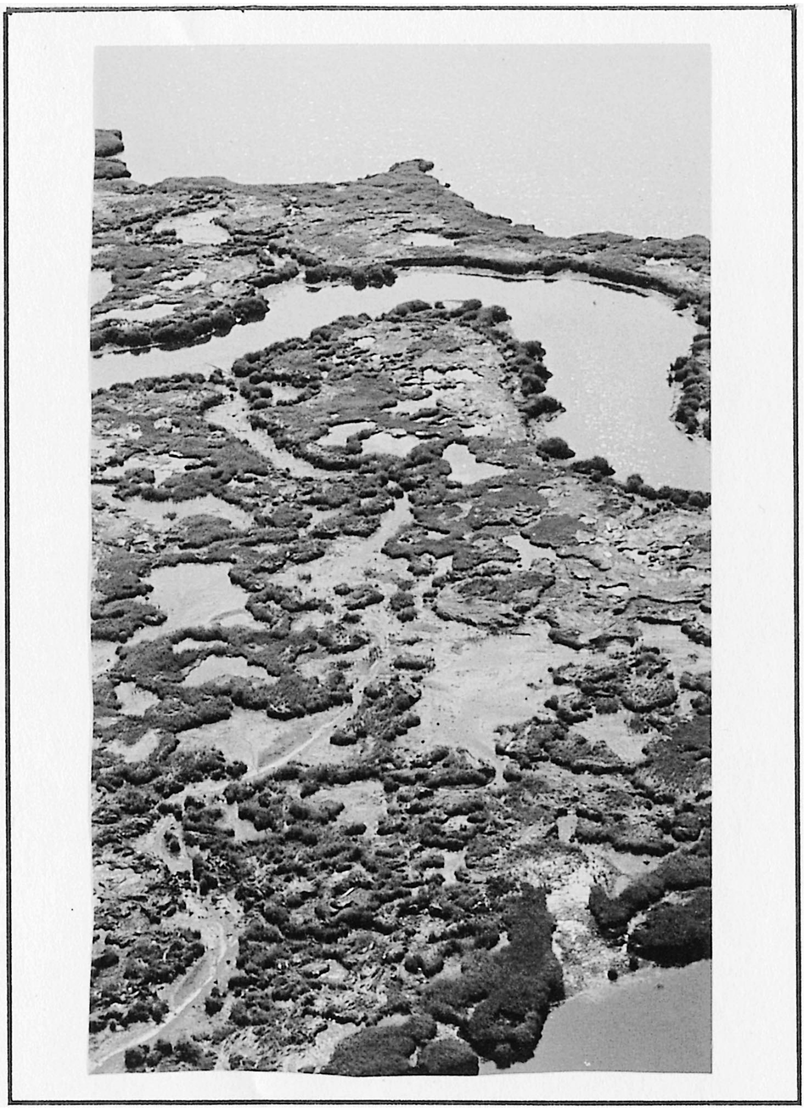

Figure 7. Helicopter view of Yellow Bar Hassock at low tide looking southeast (July 18, 2001). Note dissection and fragmentation of *Spartina alterniflora* vegetation cover and extent of barren mudflats.

the inorganic sediment and nutrient supply are sufficient, accretion rates match or exceed present-day local sea-level rise, as is the case for most marshes along the U.S. Gulf of Mexico and Atlantic coasts (Dean et al. 1987, Nuttle et al. 1997). However, where an imbalance exists (i.e., where relative rates of sea-level rise exceed rates of mineral sedimentation and/or organic accretion, as is happening in Louisiana and in the Chesapeake Bay (Boesch et al. 1994, DeLaune et al. 1994, Downs et al. 1994, Wray et al. 1995, Kearney 1996)), the marsh may begin to drown in place.

Shifts in marsh vegetation distributions are also sensitive indicators of changes in rates of sea-level rise vs. accretion. In Connecticut, Warren and Niering (1993) found high marsh converting to low marsh, an observation not inconsistent with the recent period of sea-level rise (see also Varekamp and Thomas 1998). Similarly, Fallon and Mushacke (1996) have recorded examples of high to low marsh conversion and the disappearance of several tidal wetland islands at various sites along the south shore of Long Island.

Not much has been published on the spatial evolution of Jamaica Bay salt marshes over the past several thousand years. A single ^{14}C date of 2065 ± 110 yrs BP was obtained on wood in sand at the base of a 2.85-m core in Jo Co Marsh (Liberman and Peteet 2001, Peteet and Liberman 2001). The lithology grades from basal sand to a thin clay layer to peat above 2m. The onset of peat formation therefore occurred less than 2000 years ago. A zone at 1.1–0.4m, high in *Ambrosia* (ragweed) pollen, marks the onset of land clearance and settlement. The upper 0.3 m is

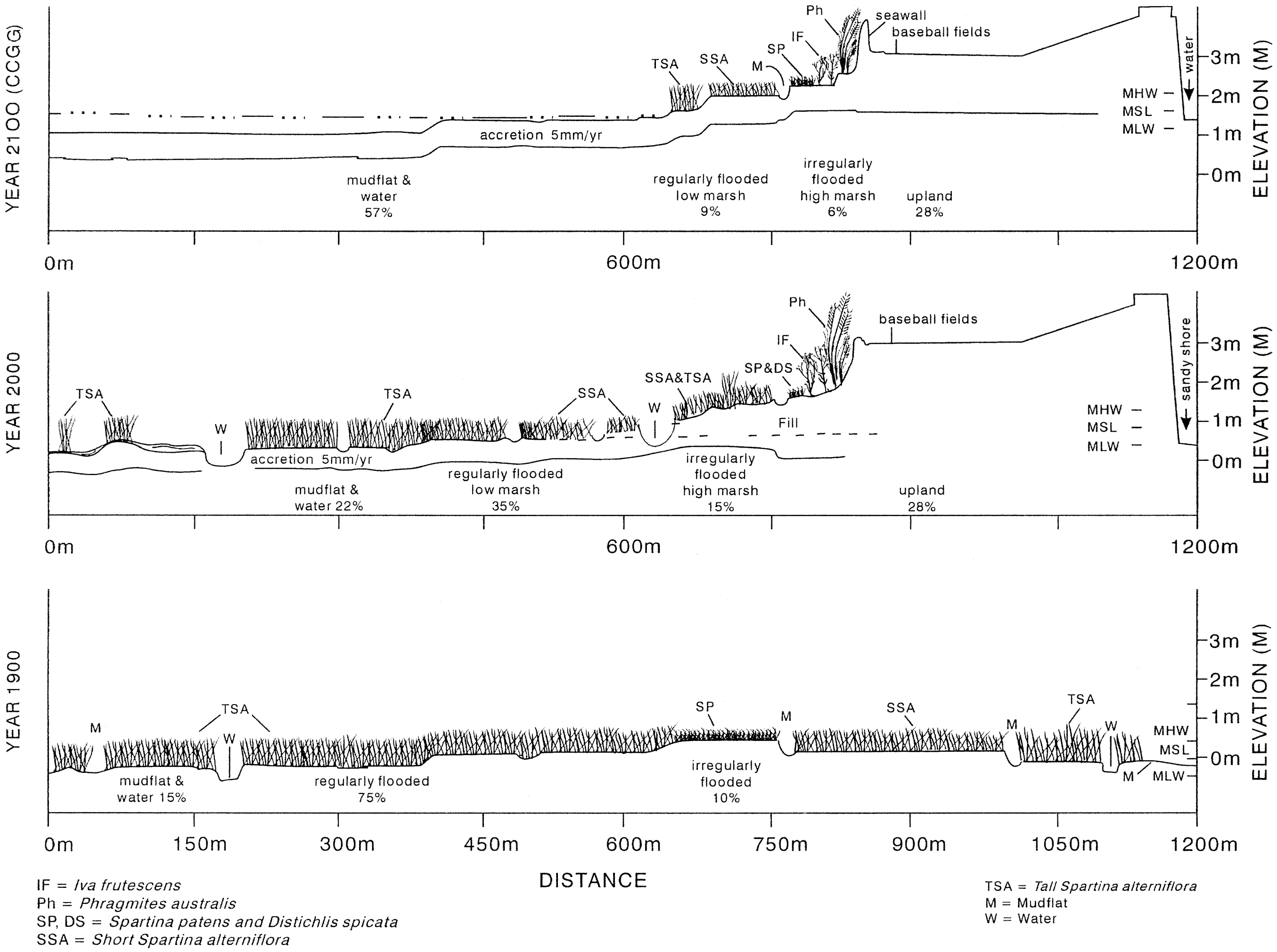

Figure 8. Transect of historic, current, and future conditions (years 1900, 2000, and 2100) in Big Egg Marsh. Sources: Adapted from Kana et al. (1988) and Titus (1988); 1988 aerial photography 1:4800; 1899 navigation chart digitized by S. McDevitt, Army Corps of Engineers, New York District.

Table 4. Mean biomass of *Spartina alterniflora* (gm m^{-2}, dry weight) 1999, Jamaica Bay.

Location	Period	N	% Cover	Mean Height (cm)[1,2]	Mean Biomass gm m^{-2}	Mean Biomass gm m^{-2}
Big Egg Marsh	Jul 22	6	60	98.0 (42.2)	1065 (616)	
	Sep 13	6	50	91.6 (28.4)	768 (460)	
	Oct 11	6	60	103.9 (37.0)	1053 (773)	962 (646)
Rulers Bar Hassock	Jul 15	2	80	101.5 (42.4)	1442 (717)	
	Sep 8	3	85	132.2 (32.5)	1156 (254)	
	Oct 10	3	85	130.0 (31.5)	1012 (382)	1173 (407)
Yellow Bar Hassock	Jul 27	5	60	68.8 (26.1)	699 (498)	
	Aug 20	4	70	102.7 (19.9)	988 (340)	
	Oct 6	4	75	84.5 (18.9)	744 (102)	805 (364)
Total		39	69 (13)	98.5 (16.4)		950 (512)

[1] Height based on 10 randomly selected stems per quadrat.

[2] Means and standard deviations (in parentheses) of all quadrats sampled in site(s) indicated.

Table 5. Mean biomass of *Spartina alterniflora* (gm m^{-2}, dry weight) 2000, Jamaica Bay, New York.

Location	Period	N	% Cover	Mean Height (cm)	Mean Biomass gm m^{-2}	Mean Biomass[2] gm m^{-2}
Big Egg Marsh	Aug 29	7	60	N.D.[1]	833 (465)	
	Oct 26	5	65	N.D.	1002 (481)	903 (457)
Rulers Bar Hassock	Aug 29	3	90	N.D.	1262 (451)	
	Oct 26	3	85	N.D.	1394 (909)	1328 (668)
Yellow Bar Hassock	Aug 2	7	95	N.D.	1021 (430)	
	Sept 14	4	90	N.D.	1125 (202)	1058 (199)
Total		29	78 (21)	N.D.		1068 (493)

[1] N.D. = Not determined.

[2] Means and standard deviations (in parentheses) of all quadrats sampled at site(s) indicated.

dominated by *Salicornia* seeds. To reconstruct the complete paleoenvironmental history of Jamaica Bay would require additional cores on several marshes.

The aboveground plant biomass of *Spartina alterniflora* at Jamaica Bay is comparable to regional values (compare Tables 4, 5 and 6) in spite of the biomorphological features indicative of recent erosion and inundation seen from both the ground and air and the measured marsh losses. Increased aboveground productivity can accompany increased marsh flooding or immersion (Reed 1995). Growth may be stimulated even as tidal heights increase. However, the observed fragmentation and decreases in vegetation density, enlargement and coalescence of tidal pools, and replacement of low marsh by barren mudflats, suggest that the island wetlands of Jamaica Bay are rapidly becoming waterlogged and are drowning in place. These features could represent an early warning sign of the effects of rising sea level. However, other localized effects probably predominate at present. Although a detailed investigation into the causes of marsh deterioration at Jamaica Bay is beyond the scope of this paper and will form the subject of a separate report, we examine here some likely hypotheses, which can be grouped into three main categories: climate change, anthropogenic-induced stresses, and biological factors.

Table 6. Mean biomass of *Spartina alterniflora* at regional salt marsh ecosystems.

Marsh Location	Biomass (gm m^{-2})	Source
Virginia	1290	Wass and Wright (1969)*
Maryland	1100	Johnson (1970)*
Delaware	560	Morgan (1961)*
Delaware Bay	1023–1623	Teal and Howes (1996)
Delaware Bay	1487	Roman and Daibler (1984)
New Jersey	1600	Good (1972)*
New Jersey	400–1160	Burger and Shisler (1983)
Long Island	827	Udell et al. (1969)*
Rhode Island	840	Nixon and Oviatt (1973)*

* Source: Nixon and Oviatt (1973).

Climate Change

The New York metropolitan region has experienced a temperature rise of about 1°C during the 20th century (Rosenzweig and Solecki 2001). During this period, local sea level has risen by nearly 30 cm in New York City and between 22–39 cm regionally. As previously mentioned, over half of this regional sea-level rise is linked to global warming, the balance to local land subsidence (Gornitz 2001, Gornitz et al. 2001). While this historic rise in sea level may have contributed to some island marsh loss, it does not completely explain the recently *accelerating* trends (Table 3), since the rate of sea-level rise has remained relatively constant throughout the 20th century (Gornitz 2001). Neither has storm activity shown an upward trend during this period, although numbers and strengths of storms have varied considerably from decade to decade (Zhang et al. 2000).

Anthropogenic Stresses

Most wetland losses in Jamaica Bay prior to 1974 were probably linked directly or indirectly to anthro-

Table 7. Mean sea-level rise (cm) for the decades of the 2020s, 2050s, 2080s, and 2090s for the Battery, New York City tide gauge. Changes in mean sea level are with respect to the 2000 decadal mean.

	Sea-Level Rise			
GCM	2020s	2050s	2080s	2090s
CCGG	14.6	41.6	86.0	105.0
CCGS	12.2	38.0	66.4	89.1
HCGG	7.5	23.9	45.8	51.4
HCGS	6.3	18.2	35.0	41.9
Cur. Tr.	5.5	13.6	21.8	24.6

Table 8. Difference between rates of accretion and sea-level rise (cm) at Big Egg Marsh for low, medium, and high accretion rates for the decades of the 2020s, 2050s, 2080s, and 2090s. Changes in sea level are with respect to the 2000 decadal mean.

	2020s			2050s			2080s			2090s		
GCM	L	M	H	L	M	H	L	M	H	L	M	H
CCGG	**−10.6**	**−4.6**	1.4	**−31.6**	**−16.6**	**−1.6**	**−70.0**	**−46.0**	**−22.0**	**−87.0**	**−60.0**	**−33.0**
CCGS	**−8.2**	**−2.2**	3.8	**−28.0**	**−13.0**	**−2.0**	**−50.4**	**−26.4**	**−2.4**	**−71.1**	**−44.1**	**−17.1**
HCGG	**−3.5**	2.5	8.5	**−13.9**	**−1.1**	16.1	**−29.8**	**−5.8**	18.2	**−33.4**	**−6.4**	20.6
HCGS	**−2.3**	3.7	9.7	**−8.2**	**−6.8**	21.8	**−19.0**	5.0	29.0	**−23.9**	3.1	30.1
Cur. Tr.	**−1.5**	4.4	10.5	**−3.6**	11.4	26.4	**−5.8**	18.2	42.2	**−6.6**	20.4	47.4

L = Low (0.2 cm/yr), M = Medium (0.5 cm/yr), and H = High (0.8 cm/yr) accretion rates.

pogenic activities (e.g., filling and dredging, urbanization, construction and expansion of John F. Kennedy International Airport, and surrounding highways (Englebright 1975)). Early to mid-20th century dredging of navigational channels has deepened the average water depth of Jamaica Bay from 1 to 3 m. Current depths within some of the channels ringing the Bay equal or exceed 10 m (USGS 7.5 min. Topo sheets: Coney Island, Jamaica, and Far Rockaway Quadrangles). Examples include Grass Hassock Channel in the southeast of the Bay, Island Channel to the west and northwest, and Grassy Bay, to the northeast, adjacent to the airport. These channels and deeps may have strengthened tidal currents and have initiated a cycle of erosion, which may have passed a critical threshold in recent decades. The deeper areas may trap suspended sediments that otherwise would have been deposited on the marshes. Furthermore, the historic westward growth of the Rockaway spit and its subsequent stabilization in the 1930s (Englebright 1975) may have reduced the movement of offshore sediments into the Bay. Urbanization of Brooklyn, Queens, and Nassau Counties also may have diminished upland sediment sources and blocked storm overwash deposition. The sediment deficit may have intensified in recent decades, as dredge and fill operations were curtailed following establishment of Gateway National Recreation Area. Armoring by seawalls and bulkheads along the Bay shoreline may have increased wave reflection and refraction, thus exacerbating erosive tendencies. Waves generated by recreational boat traffic also could generate some marsh erosion.

Biological Factors

Die-offs of *Spartina alterniflora* may be partially responsible for marsh loss. *Spartina alterniflora* helps maintain salt marsh stability through a tightly interwoven root network that increases soil strength (Redfield 1972, DeLaune et al. 1994). Furthermore, trapping of sediments in the *Spartina* stems contributes to the vertical accretion. As noted earlier, the large variability in our biomass data is indicative of a patchy pattern in plant growth, probably caused by *Spartina* die-offs. While future research should determine the cause of this die-off, it is quite likely that the loss of *Spartina alterniflora* plays an important role in the observed marsh deterioration. Anomalously high populations of ribbed mussels (*Geukensia demissus*, Franz 1997) have been implicated in the deterioration of Jamaica Bay (D. Franz, Brooklyn College, CUNY, priv. comm.). The unusually high mussel density within the *Spartina alterniflora* zone may act as a barrier, preventing efficient draining of water during the ebb tide and leading to waterlogging of the marsh. It also has been suggested that encroachment of sea lettuce (*Ulva lactuca)* onto the low marsh may be smothering *Spartina alterniflora*. It is also possible that the presence of *Ulva* indicates conversion to a more marine environment. *Ulva* proliferation under eutrophic conditions and reduced abundance of small invertebrates has been reported on the Navesink River estuary, New Jersey (MacKenzie 2000). Field observations on several fringing marshes have shown wave-driven dried *Ulva* mats, concentrated at the wrack-line (MHW), which cover *Spartina alterniflora* stalks and impede their growth. Thick *Ulva* stands also carpet the muddy shoals surrounding many of the island marshes, particularly in the northwestern part of Jamaica Bay. Whether such high *Ulva* population densities are normal or whether they reflect excess nutrient loading from the 26th Ward Water Pollution Control Plant is uncertain at this point, but studies by MacKenzie (2000) and others suggest a link to eutrophication. *Ulva* also seems to thrive in interior tidal pools. Another biological factor could be herbivory by grazing waterfowl. The Jamaica Bay salt marshes and shoals are prime nesting and feeding sites for many types of aquatic birds, including geese (particularly Brant (*Branta bernicla* L.)) and ducks (Hart and Milliken 1992, Tanacredi and Badger 1995). It is unclear whether Brant populations have increased dramatically within the last few decades or whether their normal activities are further stressing an already highly-stressed environment.

Further work is needed to determine whether the over-abundance of ribbed mussels and sea lettuce in the low marsh environment represents an early stage in the development of a more aquatic environment or high nutrient levels in Jamaica Bay waters. High nutrient loading is suggested by elevated chlorophyll *a* levels, which have shown an upward trend since the 1980s (NYCDEP 2000). However, chlorophyll levels have fluctuated sharply over the past five years, with maxima coinciding with prolonged algal blooms and presence of ‘‘nuisance algae’’ in some fringing tributaries and canals. Although dissolved oxygen levels have shown improvement over the last 30 years, oxygen levels show considerable interannual variability, and surface waters are often supersaturated due to algal blooms.

The results of the sensitivity study (Table 8) suggest that, under sufficiently high rates of accretion, marshes should be able to withstand even moderately high rates of sea-level rise. The significant marsh deterioration already underway, documented by remote sensing and field observations (Tables 2, 3), implies that accretion rates in Jamaica Bay may be insufficient, even at present rates of sea-level rise, to compensate for losses due to erosion and the other factors discussed here. Thus, the ability of many of the Jamaica Bay island marshes to survive the even higher projected sea levels resulting from climate change (Table 7) for more than a few decades is in question, unless remedial action is undertaken shortly.

The salt marshes of Jamaica Bay may be more vulnerable to the impacts of future sea-level rise than neighboring marshes on Long Island because of the apparent sediment deficit and other potential stressors outlined above. Jamaica Bay marshes are either on islands or constrained on their landward sides by existing urban development, which limits their potential to migrate inland with rising sea levels. The areal extent of low marsh *Spartina alterniflora* is already decreasing rapidly and probably could not survive accelerated rates of sea-level rise anticipated due to global warming. Further research is urgently needed to establish the causes of marsh loss. A key variable is measurement of the accretion rate, which will determine the ability of the marsh to keep pace with accelerated sea-level rise (e.g., SETs). Because of likely sediment starvation, remediation efforts should include placement of thin layers of sediment on the marsh surface to supplement any existing vertical accretion. In addition, containment cells can be constructed on segments of severely eroded marshes in which sediments would be placed. Such initial projects can be instituted on a trial basis.

CONCLUSIONS

The extent and rapid rate of marsh loss in Jamaica Bay were quite unexpected. The field observations corroborate the remote sensing measurements of significant marsh losses. Processes of erosion include slumping and inward retreat of peat along banks of creeks and island edges, as well as widening and extension of tidal channels. Expansion and coalescence of interior pools, fragmentation of *Spartina alterniflora* cover, and conversion to mudflats point to increased waterlogging and inundation. Our map (Figure 3), supported by observations during a recent aerial overflight (Figure 7), shows that at present, inundation processes seem to be much more significant than erosion. An underlying cause may be the relative sea-level rise; however, at present, other local processes are probably even more significant. For Jamaica Bay, several factors have been proposed, potentially interacting synergistically. Among these, the general sediment deficit may be the most critical. Also contributing to erosion are the deepening of the Bay through dredging, waves generated by boat traffic, and excessive waterfowl grazing. The mean marsh standing crop biomass is comparable to those of other healthy marshes in the region. The large variability at a given site may reflect the general patchiness and abrupt changes in plant density–signs of marsh deterioration, while the intersite variability may indicate variations in nutrient levels.

Regardless of the ultimate causes, marsh losses are occurring rapidly and may even be accelerating at Jamaica Bay. At current rates of attrition, most of the *Spartina alterniflora* could be lost within the next few decades, well before the full impacts of accelerated sea-level rise due to global climate warming are felt. The fate of the island marshes of Jamaica Bay serves as a wake-up call regarding the hazards facing other coastal wetlands due to the intertwined impacts of human-induced stresses and sea-level rise.

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