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Topography and Flooding of Coastal Ecosystems on the Yukon-Kuskokwim Delta, Alaska: Implications for Sea-Level Rise

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ABSTRACT

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We measured surface elevations, stage of annual peak flooding, and sedimentation along 10 toposequences across coastal ecosystems on the Yukon-Kuskokwim (Y-K) Delta in western Alaska during 1994–1998 to assess some of the physical processes affecting ecosystem distribution. An ecotype was assigned to each of 566 points, and differences in elevations among 24 ecotypes were analyzed within individual toposequences and across the 40 × 40-km study area. Elevations of vegetated ecotypes along the longest toposequence rose only ~1 m over a distance of 7.5 km, and mean elevations of most ecotypes across the study area were within 0.5 m of mean higher-high water (1.47 m). During 1994 to 1998, monitoring of annual peak stage using crest gauges revealed flooding from the highest fall storm surge reached 2.58 m (1.11 m above mean higher-high tide). In each year, only the highest surface was unaffected by flooding. Mean annual sedimentation rates for the various ecotypes were 8.0 mm/y on tidal flats, 1.4 to 3.8 mm/y on the active floodplain, 0.1–0.2 mm/y on the inactive floodplain, and 0 mm/y on the abandoned floodplain. If sea levels in the Bering Sea rise ~0.5 m by 2100, as predicted by some on a global basis, large portions of the coastal margin of the delta could be regularly inundated by water during high tides, and even the highest ecotypes could be affected by storm surges. Predicting the extent of future inundation is difficult, however, because of the changes in the ground-surface elevation through sedimentation, organic matter accumulation, and permafrost development.

ADDITIONAL INDEX WORDS: Arctic, delta, surface elevations, GPS, sedimentation, flooding, sea-level change.

INTRODUCTION

The threat to coastal ecosystems and local economies in low-lying areas throughout the world from sea-level rise is of increasing concern (IGBP, 1992; HOUGHTON *et al.,* 1996). Globally, sea level is estimated to have risen at a rate of ~1.8 mm/yr over the last 100 yrs, and many researchers believe that sea levels probably will rise ~0.5 m (range 0.2–0.9 m) by 2100 due to thermal expansion of water and melting of glaciers and ice caps (WARRICK *et al.,* 1996).

Assessing the potential risks of sea-level rise on coastal ecosystems in Alaska is hampered by insufficient resolution of existing topographic data. The vertical resolution (7.6 m) of existing 1:63,360-scale topographic maps produced by the U.S. Geological Survey in the 1950s is inadequate to identify the extent of potential inundation. In addition, standard photogrammetric techniques do not have sufficient precision to resolve 10-cm level differences across broad areas, and recent development of interferometric techniques using synthetic aperture radar (SAR) imagery for mapping topography (ZEBKER *et al.,* 1994) appear to have only ~1–2 m resolution on heterogeneous tundra (JORGENSON *et al.,* 1997). In another approach, flood distribution obtained with SAR imagery, along with point measurements of water depths during flooding, were used to calculate surface topography within an estimated accuracy (±1 SD) of 19 cm (RAMSEY III *et al.,* 1997). This approach, however, relies on the unlikely probability of obtaining simultaneous measurements. To address this poor topographic resolution on the Yukon-Kuskokwim (Y-K) Delta, we conducted topographic field surveys along representative toposequences and analyzed the relationship between elevation and ecosystems. We then used these relationships to evaluate which coastal ecosystems are most susceptible to tidal inundation from sea-level rise.

Sea-level rise and related effects of storm surges are of great concern because most of Alaska's population, as throughout most of the world, lives near the coast. The Y-K Delta supports the highest concentration of indigenous people living a predominantly subsistence life-style in the North American Arctic (SEDINGER and NEWBURY, 1998). Numerous villages in low-lying areas are subjected to damage from fall storm surges; these villages will be at increased risk from sea-level rise. Storm surges in the Bering Sea have been rel-

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atively common over the last century (MASON *et al.*, 1996), and climate models predict that the frequency and intensity of cyclonic storms will increase in the future (WALSH *et al.*, 1996; SERREZE *et al.*, 1997). Storm surges have caused relocation of several villages in the central delta, and have had negative effects on subsistence economies (FIENUP-RIORDAN, 1999). In addition, the Y-K Delta is one of the most productive avian habitats in North American (SPENCER *et al.*, 1951), and habitat changes likely will affect population dynamics (SEDINGER and NEWBURY, 1998). Thus, the close interaction between terrestrial and marine ecosystems (THORSTEINSON *et al.*, 1989), global linkages of the migratory avian herbivores (SEDINGER *et al.*, 1994), and the importance of the subsistence economy (WENTWORTH, 1994) make the Y-K Delta one of the most sensitive high-latitude ecosystems to global change.

Previous investigations found that topographic gradients, along with salinity, sedimentation, moisture, and thaw depths, are important factors affecting ecosystem distribution along arctic coastlines (VINCE and SNOW, 1984; BLISS and GOLD, 1994; EARLE and KERSHAW 1989; KINCHLOE and STEHN 1991). KINCHLOE and STEHN (1991) investigated differences in relative elevations among coastal plant communities in our study area around Hazen Bay, but were unable to reference those relative elevations to a common datum or an estimate of mean sea level and did not relate vegetation to geomorphic processes. TANDE and JENNINGS (1986) mapped vegetation at a scale of 1:63,000 through the entire study area, and BABCOCK and ELY (1994) helped define the floristics of inland plant communities—information that we have incorporated into our ecological land classification.

This study augments these earlier works by further developing the relationships of ecosystem characteristics to elevational gradients. First, we utilized an ecological land classification (ELC) approach (WILKEN, 1981; ECOMAP, 1993; KLUN and UDO DE HAES, 1994) that relates vegetation and environmental factors to geomorphic settings with characteristic soils and depositional environments. Deltaic ecosystems are highly interspersed because of the numerous complex environmental gradients, and the ELC approach provides a framework for aggregating ecosystems across various spatial scales. In this study, we used the most detailed level of classification, "ecotypes" (local ecosystems—1:1,000-scale units that have homogenous topography, soils, hydrology, and vegetation), as the basis for analysis. Second, we analyzed the distribution of ecotypes relative to surface elevations using a geodetic control network based on a common datum throughout the study area. The use of both an ecological land classification approach and a common datum for the topographic surveys, improved our ability to assess potential effects of sea-level rise. Third, we monitored peak flooding and sediment accumulation annually to assess the extent of current flooding and how flooding may affect surface elevations through sediment accumulation. This topographic analysis is part of a larger, ongoing effort to develop dynamic spatial models for predicting the effects of climate change and sea-level rise on coastal ecosystems on the Y-K Delta (RUESS *et al.* 1997; SEDINGER and NEWBURY 1998; JORGENSON, 2000).

STUDY AREA

The study area is near Hazen Bay in the central portion of the YK Delta (61°15′N, 165°30′W). Sampling was conducted adjacent to the Manokinak, Tutakoke, and Kashunuk Rivers (Figure 1). The area is within the Yukon Delta National Wildlife Refuge and near the village of Chevak, Alaska.

The climate is moderated by the Bering Sea and a strong gradient in coastal temperature. Mean monthly air temperatures range from 10°C in July to −14°C in mid-winter. The mean annual temperature at Bethel (1923–1984) is −1.6°C and mean annual precipitation is 43 cm, with 27 cm of rain and 160 cm of snow (TANDE and JENNINGS, 1986). Prevailing winds are from the southwest during summer and from the northeast during winter (THORSTEINSON *et al.*, 1989). Storms are more common in the fall and may occur as frequently as 3–5 times per month.

Due to the complex topography of the delta, the amplitude and phase of tides show a high degree of spatial variability, and no long-term record of tidal data exists for the area. A short-term record (seasonally 1982–1984) for Kokechik Bay (50 km north) indicates a mean diurnal range of 2.0 m and a normal maximum range of 3.1 m (NOAA 1987), whereas the diurnal amplitude in the northern delta is 0.1–0.4 m (MCDOWELL *et al.*, 1987). Tidal amplitudes rapidly decrease with distance upriver from the coast. Tidal rivers generally freeze in October–November, and spring breakup is in late May–early June. Flooding is usually associated with fall storms, although flooding also can be associated with spring breakup along inactive distributaries of the Yukon River. The most severe storms (generally average winds >30 mph and gusts >60 mph, or high flooding if wind data was not available) reportedly occurred in the fall period in 1900, 1910, 1913, 1945, 1946, 1950, 1960, 1964, 1974, 1977, and 1992 (MASON *et al.*, 1996).

Geomorphic units on both the emergent and submerged portions of the delta are depositional, and include prodelta, delta front, sub-ice platform, tidal flats, undifferentiated delta plain, chenier plain, and non-deltaic sediments (DUPRÉ, 1980, 1982). KLEIN and DUPRÉ (1980) characterized the peat-accumulating environments as lower delta plain, upper delta plain, and "dry tundra". Deposits in our study area include tidal flats and delta plain deposits, most of which are <2,500 years old (DUPRÉ, 1980). Discontinuous permafrost is found in many areas in the delta (DUPRÉ, 1980). HOARE and CONDON (1968), and later TANDE and JENNINGS (1986), subdivided the surficial deposits in our study area into recent estuarine deposits, old beach deposits, and old floodplain-delta deposits.

METHODS

Sampling was done along 10 gradient-directed transects distributed within 4 physiographic regions associated with a sequence of 4 deltaic surfaces with closely related depositional environments evident on aerial photography. Two long transects (7–8 km) were selected to cross the entire sequence of deltaic surfaces and provide a baseline survey for tying in shorter transects. Eight shorter transects (0.2–0.5 km) were placed within the physiographic regions, and were oriented

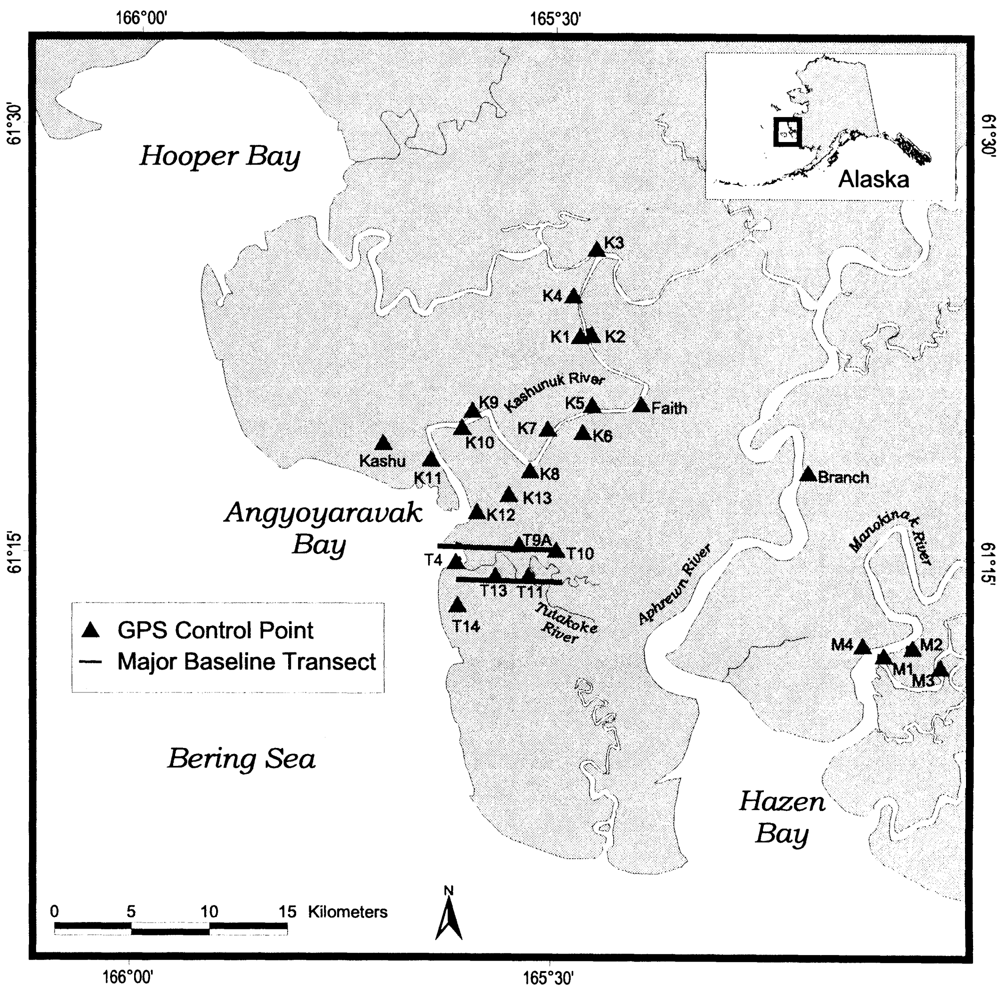

Figure 1. Map of study area, locations of toposequences, and geodetic control points, Yukon-Kuskokwim Delta, Alaska, 1998. Minor toposequences (0.2–0.5 km) were associated with most control points.

along the elevational gradient that ran perpendicular to tidal river channels. This orientation maximized the diversity of ecotypes along the transect. Elevations were surveyed along the toposequences with an autolevel and tied into a control network established using global positioning system (GPS) receivers.

A GPS survey was conducted 24–25 July 1997 by Crazy Mountain Joint Ventures, Anchorage, AK, to establish a horizontal and vertical control network for our topographic surveys (MITCHELL, 1997). The survey used three existing U.S. Coast and Geodetic Survey monuments (Faith, Kashu, and Branch) and established 23 new benchmarks (Figure 1). These control points were surveyed relative to each other and tied into the Continuously Operating Reference Stations (CORS) at Cold Bay, Kodiak, Kenai, and Fairbanks. Given the absence of a local datum based on a long-term tide gauge record, we referenced our local control network to the North American Vertical Datum 1988 (NAVD88). Initially, data were adjusted to the International Terrestrial Reference Framework positions of the CORS stations. The ellipsoid heights then were reduced to orthometric heights by applying the GEOID96 Geoid Height Model to obtain NAVD88 elevations (MILBERT and SMITH, 1997). We estimate the accuracy of the elevations of the control point network relative to each other to be <5 cm based on an observed precision of <2 cm for most points. The relationship between NGVD88 elevations and mean sea level has not been determined adequately, although sporadic measurements of high and low tides at Bench Mark (BM)-T4 indicated that mean sea level at that location was 13 cm higher than the NGVD88 value.

Vegetation data also were collected along the toposequences in order to classify ecotypes (local ecosystems). A hierarchical ecological land classification approach that integrated geomorphology, surface forms, and vegetation into ecotypes (local ecosystems) with associated characteristics was used and is reported more fully in JORGENSON (2000). Names of ecotypes were based on combinations of physiography, surface form, and vegetation physiognomy, and are described briefly below. Once the classification was established, a three-level approach was used to assign ecotypes to each elevation measurement. The most reliable classification was done for 79 points, based on quantitative vegetation sampling (50–150 points along a single transect), cluster analysis, and ordination. At 271 points, a list of dominant plant species was recorded and the list was used to assign ecotypes based on the differentiating species identified by the quantitative classification. Plant taxonomic nomenclature follows that of the U.S. Department of Agriculture's National Plants Database (*http://plants.usda.gov/plants/*). At 200 points, an ecotype was assigned in the field during surveying without compiling a plant list, providing lower quality data. Mean elevation values from the high-quality and low-quality data sets varied less than 10 cm from each other, thus they were combined for calculation of descriptive statistics in this paper.

To assess the current extent of flooding, the elevation of the water surface at peak stage during fall flooding was monitored with three mechanical crest gauges installed at each toposequence. The simple gauges consisted of a 5-cm diameter PVC pipe and a cork equipped with bristles. Holes were drilled in the PVC pipe every 2 cm. The design is intended to allow water to lift the cork, and the bristles on the bottom of the cork are designed to prevent the cork from sliding downward by becoming engaged in the holes in the pipe. Each year the corks were reset at ground level during late July and revisited one year later. Estimated precision of this technique is ~5 cm based on repeated testing. Data reported here are from crest gauges near Baseline Transect T1 (Figure 1). The trendline of the water-surface elevations versus distance from the coast for the data near the Tutakoke River ($n = 6$) was determined using linear regression analysis. Values at the zero-intercept are used to report water-surface elevations at the "coast".

Sedimentation was measured using small (10-cm diameter) sediment traps on the ground surface to evaluate effects of sedimentation on surface elevations. The sediment traps were located in representative patches within each ecotype encountered along each transect. Initially, 29 traps were established in 1994. Subsequently 94 were used in 1995, 95 in 1996, and 132 in 1997. Sediment traps were created by removing vegetation and litter down to the soil surface and spray painting the surface with a different color each year. Each year, the amount of annual sediment for each patch was determined by: (1) cutting a 2×2 cm plug from the patch, (2) measuring the thickness of sediment above the paint on the four sides of the plug with a ruler, and (3) averaging the four measurements. We estimate the accuracy of this technique to be ~0.5 mm. Trace amounts of sediment that were too thin to measure were assigned a depth of 0.1 mm to denote that flooding and minimal sedimentation had occurred. Attempts to measure sediment mass in small collection dishes were unsuccessful because of the excessive accumulation of organic detritus, especially insect remains. For analysis, mean annual accumulation was first calculated for each location (pooling data from 1–4 years), and these means then were averaged to determining means for each ecotype. For cumulative totals over the four-year period, annual accumulations at each location were used in calculating means by ecotype for each year, and these annual means were summed for each ecotype. This approach was necessary because sample sizes varied among years as new transects and sediment traps were added each year.

RESULTS

Ecosystem Distribution

The ecological land classification differentiated 19 terrestrial and 8 aquatic ecotypes (local ecosystems) that were grouped hierarchically by geomorphic unit, surface form, and plant association (Tables 1 and 2). The ecotypes were highly interspersed within the drainage network and strongly associated with four deltaic surfaces (Figure 2). Distribution of ecotypes along topographic gradients within each of the four deltaic surfaces is presented in Figure 3. Brief descriptions of the relative abundance of ecotypes on the four surfaces are provided below, based on more detailed analyses of the vegetative and edaphic characteristics of the ecotypes by JORGENSON (2000). The deltaic surfaces were used to organize the discussion of ecotype distribution because there were large differences among them. Surface 1 had mostly tidal flats, whereas Surface 2 had a mix of brackish and slightly brackish ecotypes. Surface 3 had mostly slightly brackish ecotypes, and Surface 4 had mostly nonsaline ecotypes.

Surface 1 has tidal flat, delta active-floodplain, and tidal and brackish pond geomorphic units (Figures 2 and 3). Tidal flats, which occur on higher, flat areas that usually are inundated only by higher tides, supports both tidal channel barrens and tidal flat barrens ecotypes. Active-floodplain deposits, which are subject to frequent inundation and sedimentation as indicated by the lack of organic-matter accumulation. They occur in slough margins, basins (flats), and levees. The slough margins, which have saturated, silt loam soils, support brackish fringe wet graminoid meadow and brackish fringe wet sedge meadow ecotypes. The basins behind the low slough levees, which have saturated, silt loam soils, support brackish wet sedge meadow and slightly brackish shallow open water ecotypes. The levees, which have moderately well drained, loamy soils, support brackish levee moist herb meadow and brackish levee moist dwarf scrub ecotypes.

Surface 2 is transitional between Surfaces 1 and 3, and is dominated by delta inactive-floodplain deposits and slightly brackish ponds, with a limited extent of tidal channels and active-floodplain cover deposits adjacent to the tidal channels (Figures 2 and 3). The inactive floodplain has infrequent inundation (usually by fall storms) and sedimentation, as indicated by the interbedded sequences of organic and silt loam materials near the surface and typically are oligosaline (800–8,000 μS/cm). Surface forms on the inactive floodplain include basins, pond margins, and ponds. Basins are dominated by brackish wet sedge meadow but also support slightly brackish wet sedge-shrub meadow in distal areas away from the channel network. Pond margins support the slightly brackish depression wet graminoid meadow ecotype. Ponds have both slightly brackish shallow open water and slightly brackish forb marshes. A dense network of active levees supports both brackish levee moist herb meadow and brackish levee moist dwarf scrub ecotypes.

Surface 3 is dominated by inactive floodplain deposits and

Table 1. *Classification and description of terrestrial ecotypes (local ecosystems) found in Hazen Bay area of the Yukon-Kuskokwim Delta, 1998.*

Ecotype	Description
Tidal Channel Barrens	Barren, saturated muddy sediments along the sloping margins of sloughs and tidal rivers.
Tidal Flat Barrens	Barren, saturated to imperfectly drained, muddy sediments on flats affected by frequent inundation.
Brackish Drained Pond Barrens	Barren, muddy pond sediments created by breaching and draining of ponds.
Brackish Fringe Wet Graminoid Meadow	Margins of tidal flats with soils that are frequently flooded, saturated, and mesosaline (8,000–30,000 μS/cm). Vegetation is dominated by *Carex subspathaceae* and *Puccinellia phryganodes.*
Brackish Fringe Wet Sedge Meadow	Margins of tidal flats and sloughs similar to above. Vegetation is dominated by tall, nearly monospecific stands of *Carex ramenskii.*
Slightly Brackish Fringe Wet Sedge Meadow	Margins of inland, brackish sloughs and tidal channels, with soils that are frequently flooded, saturated, oligosaline (800–8,000 μS/cm), and lacking organics. Vegetation is dominated by the large sedge *Carex lyngbyaei,* but often intergrades with *Hippurus tetraphylla* and *Arctophila fulva.*
Sl. Brackish Fringe Wet Grass Meadow	Similar to above, but vegetation is dominated by the grass *Arctophila fulva,* although vegetation intergrades with *Hippurus tetraphylla* and *Carex lyngbyaei.*
Brackish Wet Sedge Meadow	Areas on active-floodplains along the outer coast with soils that have interbedded fine sediments indicative of frequent sedimentation and that are saturated, mesosaline, and lacking in organics and permafrost. Vegetation is dominated by *Carex ramenskii* and *Potentilla egedii.*
Brackish Levee Moist Herb Meadow	Lower levees along tidal channels with frequent inundation and sedimentation. Soils are loamy, moist, well-drained, mesosaline, and lacking organics and permafrost. Vegetation is dominated by *Potentilla egedii, Elymus arenarius, Ligusticum scoticum, Triglochin palustris,* and *P. eminens.*
Brackish Levee Moist Dwarf Scrub	Higher levees along tidal sloughs with frequent inundation and sedimentation. Soils are silty to sandy loams, well-drained, mesosaline, and lacking organics and permafrost. Vegetation has *Salix ovalifolia, Deschampsia caespitosa, Carex glareosa,* and *Calamagrostis deschampsioides.*
Slightly Brackish Depression Wet Sedge Meadow	Pond margins and depressions on inactive-floodplains where inundation and sedimentation are infrequent. Soils have interbedded organics and silts, and are saturated, oligosaline, and lacking permafrost. The vegetation is dominated by *Carex mackenziei, Stellaria humifusa* and *C. ramenskii.*
Slightly Brackish Depression Wet Graminoid Meadow	Similar to above, except the vegetation is dominated by *Carex ramenskii, Dupontia fisherii,* and *Calamagrostis deschampsioides.*
Slightly Brackish Wet Sedge-Shrub Meadow	Basins (flats) on inactive-floodplains with soils that have interbedded organics and silt loam layers, and are saturated, oligosaline, and lacking permafrost. Vegetation is dominated by *Carex rariflora, Salix fuscescens, Chrysanthemum arcticum, Calamagrostis deschampsioides,* and *Empetrum nigrum.*
Slightly Brackish Bog Meadow	Basins (flats) and old levees on inactive-floodplains with soils that have interbdded organics and silt loam layers near the surface, are saturated, oligosaline, and lacking permafrost. Vegetation is dominated by *Carex rariflora, C. deschampsioides, S. fuscescens, E. nigrum,* and *Sphagnum.*
Slightly Brackish Moist Graminoid Meadow	Old levees on inactive-floodplains with soils that have interbedded organics and silt loam layers, are moderately well-drained, oligosaline, and lacking permafrost. Vegetation is dominated by *Calamagrostis canadensis, Carex rariflora, S. fuscescens, E. nigrum,* and *Elymus arenarius.*
Slightly Brackish Moist Dwarf Scrub	Old levees and incipient palsas on inactive-floodplains with soils that are well-drained, oligosaline, and usually underlain by a thin (~0.5–1 m) permafrost. The vegetation is dominated by *Empetrum nigrum, S. fuscescens, Carex rariflora* and the mosses, *Drepanocladus* sp. and *Sphagnum* spp.
Lowland Wet Sedge Meadow	Abandoned floodplains with soils that have thick organic accumulations and are nonsaline, saturated, strongly acidic, and lack permafrost. The vegetation is dominated by *Carex aquatilis* and usually includes *C. rariflora, Eriophorum russeolum,* and *Salix fuscescens.*
Lowland Sedge-Bog Meadow	Depressions or basins in abandoned floodplain dominated by *Carex aquatilis* and *Sphagnum* spp., and usually includes *Potentialla palustris, C. rariflora, C. lyngbyei, Salix fuscescens,* and *Empetrum nigrum.*
Lowland Moist Low Scrub	Abandoned floodplains with soils that have thick organic accumulations and are fresh, moderately well-drained, strongly acidic, and underlain by thick permafrost. Vegetation is dominated by *Betula nana, Empetrum nigrum, Ledum palustre, Rubus chamaemorus, Sphagnum* spp. and *Dicranum* spp.

slightly brackish ponds. The inactive floodplain deposits differ from those on Surface 2 in that the organic accumulations are much thicker, and silt layers are thinner and more infrequent (Figures 2 and 3). Surface forms include basins, levees, pond margins, and ponds. The basins support slightly brackish wet sedge-shrub meadow, and slightly brackish bog meadows, in which mosses have become better established. Most levees are inactive, as indicated by substantial organic matter accumulation near the surface, and support slightly brackish moist graminoid meadow and slightly brackish moist dwarf scrub ecotypes. Pond margins support slightly brackish depression wet sedge meadow on thick organic soils along recently drained ponds. The ponds support slightly brackish shallow open water (without emergents), slightly brackish forb marsh, and slightly brackish sedge marsh ecotypes. Some of the ponds form in inactive tidal channels that have permanent standing water.

Surface 4 is dominated by abandoned-floodplain deposits and lacustrine shallow isolated ponds (Figures 2 and 3). The abandoned floodplain is rarely, if ever, flooded by fall storms as indicated by thick accumulations near the surface of organic matter that lack interbedded thin mineral horizons. Soils typically are strongly acidic. Surface forms on the abandoned floodplain include low-lying freshwater basins, higher permafrost plateaus (commonly called "uplands"), and ponds. Freshwater basins, which lack permafrost, support lowland wet sedge meadow and lowland sedge bog meadow ecotypes. Permafrost plateaus, which are underlain by thick (>2 m)

Table 2. *Classification and description of aquatic ecotypes (local ecosystems) found in Hazen Bay area of the Yukon-Kuskokwim Delta, 1998.*

Ecosite	Description
Nearshore Water and Slough	Mesosaline (8,000–30,000 μS/cm) to polysaline (30,000–45,000 μS/cm) water in coastal nearshore water, tidal rivers and sloughs.
Tidal Shallow Open Water	Mesosaline to polysaline water in ponds subject to frequent tidal inundation.
Brackish Shallow Open Water	Mesosaline to polysaline, shallow ponds subject to inundation during storms.
Slightly Brackish Shallow Open Water	Oligosaline (800–8,000 μS/cm), shallow ponds on inactive floodplains subject to inundation during storms.
Slightly Brackish Forb Marsh	Oligosaline shallow ponds with emergent vegetation dominated by *Hippurus tetraphylla* and submerged plants including *Potomogeton filiformis* and *Myriophyllum spicatum.*
Slightly Brackish Sedge Marsh	Oligosaline shallow ponds dominated by the emergent sedge, *Carex lyngbyaei.* Other common plants include *Carex rostrata, P. filiformis* and *H. tetraphylla.*
Fresh Shallow Open Water	Fresh (<800 μS/cm), shallow ponds on abandoned floodplains. No emergent vegetation.
Fresh Forb Marsh	Fresh (<800 μS/cm), shallow ponds on abandoned floodplains. Emergent vegetation is dominated by *Hippurus tetraphylla,* while submergent plants include *Sparganium hyperboreum.*

permafrost, support the lowland moist low scrub ecotype. The ponds include both fresh shallow open water and fresh marsh ecotypes.

Topography

Coastal ecotypes of the Y-K Delta near Hazen Bay have extremely low elevational gradients. Vegetated ecotypes along Baseline Transect 1 rise little more than 1 m over a distance of 7.5 km, and elevations within brackish and slightly brackish meadow ecotypes varied less than 0.5 m over 7 km (Figure 4). An abrupt, rise of ~1 m onto the permafrost plateau occurred at the inland ends of the transects. More intensive sampling along shorter transects (Figure 3) also revealed small elevational differences (<0.3 m) among brackish ecotypes along toposequences within active and inactive floodplains (Surfaces 1–3) and slightly larger differences (up to 1.2 m) among terrestrial ecotypes on the abandoned floodplain (Surface 4).

When comparing mean elevations among all ecotypes across the study area (40 km across), we found differences were remarkably small (Figure 5). As expected, tidal channel barrens (0.69 m) and tidal flat barrens (1.53 m) were the lowest ecotypes. Within the active floodplain, mean elevations gradually increased ~0.5 m from brackish fringe wet graminoid meadow to brackish levee moist dwarf scrub. In contrast, on the inactive floodplain mean elevations varied little (1.96–2.05 m) among meadow ecotypes, except for slightly brackish depression wet sedge meadows (1.58 m), which occurred in depressions and along pond margins, and slightly brackish moist dwarf scrub (2.27 m), which has been raised by incipient permafrost development. The mean elevation of the highest ecotype, lowland moist low scrub, was distinctly higher (2.84 m, maximum of 3.55 m) than the other ecotypes.

There also was little variation in elevations of the sediment surface among aquatic ecotypes. Mean elevations of the bottom of ponds ranged from 1.34 m in tidal shallow open water to 1.67 m in brackish sedge marsh. Within more narrow ecological limits, mean elevations differed little between slightly brackish forb marsh (1.43 m), which was associated with the inactive floodplain, and fresh forb marsh (1.63 m), which was associated with abandoned floodplain.

We also evaluated whether an inland elevational gradient was associated with attenuation of tidal amplitude up the rivers and sloughs by examining the elevations of the brackish fringe wet graminoid meadows that occur across all deltaic surfaces (Figure 6). Regression analysis revealed only a weak ($R^2 = 0.17$, $P = 0.06$, $n = 33$) relationship of decreasing elevation of the fringe meadows with increasing distance from the coast. This decreasing trend undoubtedly contributes to the variability observed in elevations among ecotypes when compared across the entire study area.

Flooding and Sedimentation

Flooding at annual peak stage, usually associated with fall storm surges, covered nearly all of the Surfaces 1–3 every year (Figure 4). The water-surface elevations of the annual peak stages at the coast (zero-intercept distance), as determined from regression analyses using data from the crest gauges, were 2.33 m, 2.58 m, 2.14 m, and 2.48 m in 1994–1997, respectively, representing the peak stages that occurred the previous fall. Thus, the stages of peak flooding at the coast were 0.67 to 1.11 m above the estimated mean higher high water level of 1.47 m. Water-surface elevations decreased inland due to tidal attenuation. The slope of the water surface ranged from 0.06–0.09 m/km, except in 1994 when the slope anomalously increased 0.04 m/km with distance. The exact dates of flooding are unknown.

Large differences in sedimentation were found among ecotypes (Figure 7). Mean annual sedimentation rates were highest for tidal flat barrens (8.0 mm/y) and brackish fringe wet graminoid meadow (6.5 mm/y), which occurred on or along the margins of the tidal flats. Accumulation was intermediate for brackish fringe wet sedge meadow (3.4 mm/y), brackish wet graminoid meadow (2.7 mm/y), and brackish levee moist herb meadow (3.8 mm/y), and brackish moist dwarf scrub (1.4 mm/y), which occur on the active floodplain. On the inactive floodplain, sedimentation was recorded in only two ecotypes, slightly brackish wet sedge-shrub meadows (0.1 mm/y), which occur in basins, and slightly brackish moist

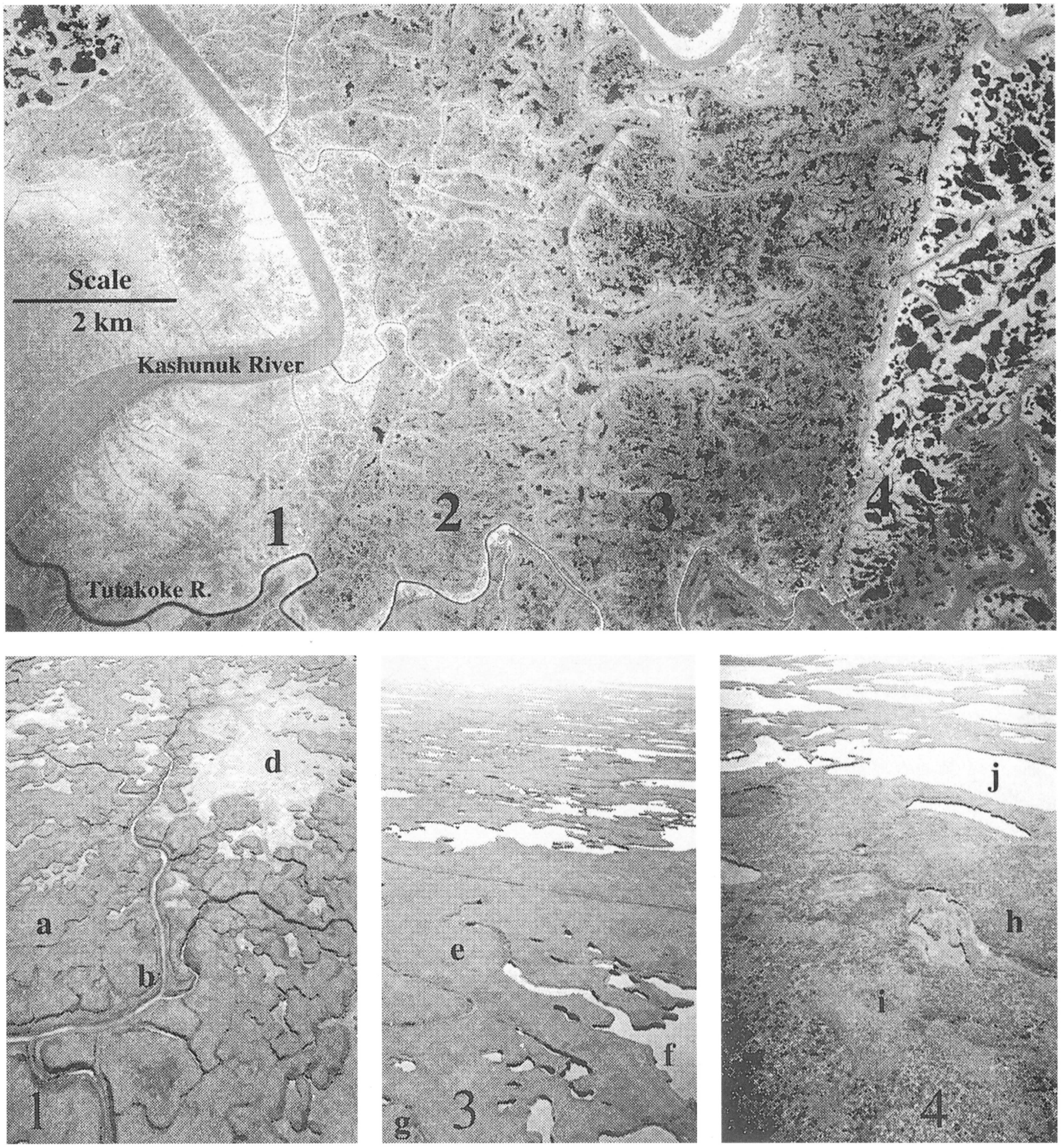

Figure 2. Aerial photographs of the landscape on the Yukon-Kuskokwim Delta showing the distribution of ecosystems on 4 depositional environments (1—delta active-floodplain deposit; 2—inactive floodplain; 3—inactive floodplain with thick organics; 4—abandoned floodplain). The active floodplain (1) is dominated by brackish wet sedge meadows (a), brackish levee moist herb meadows (b), brackish fringe wet sedge meadow (c), interspersed with barren tidal flats (d). The inactive floodplain (3) mostly has slightly brackish wet sedge-shrub meadows (e) and slightly brackish shallow open water (f), with minor amounts of slightly brackish depression wet sedge meadows (g). The abandoned floodplain (4) is dominated by lowland moist low scrub (h), lowland sedge-bog meadows (i), and freshwater ponds (j).

graminoid meadows (0.2 mm/y), which occur on inactive levees. No sedimentation was observed on the abandoned floodplain. Large standard deviations within ecotypes indicate large spatial and temporal variability (Figure 7). When comparing differences among years, sedimentation was greatest in 1996 (after fall storms in 1995), whereas amounts in the other years were similar.

When combined, results from the crest gauges and sediment traps indicate that most ecotypes are flooded every year. All ecotypes on the tidal flats and active floodplain

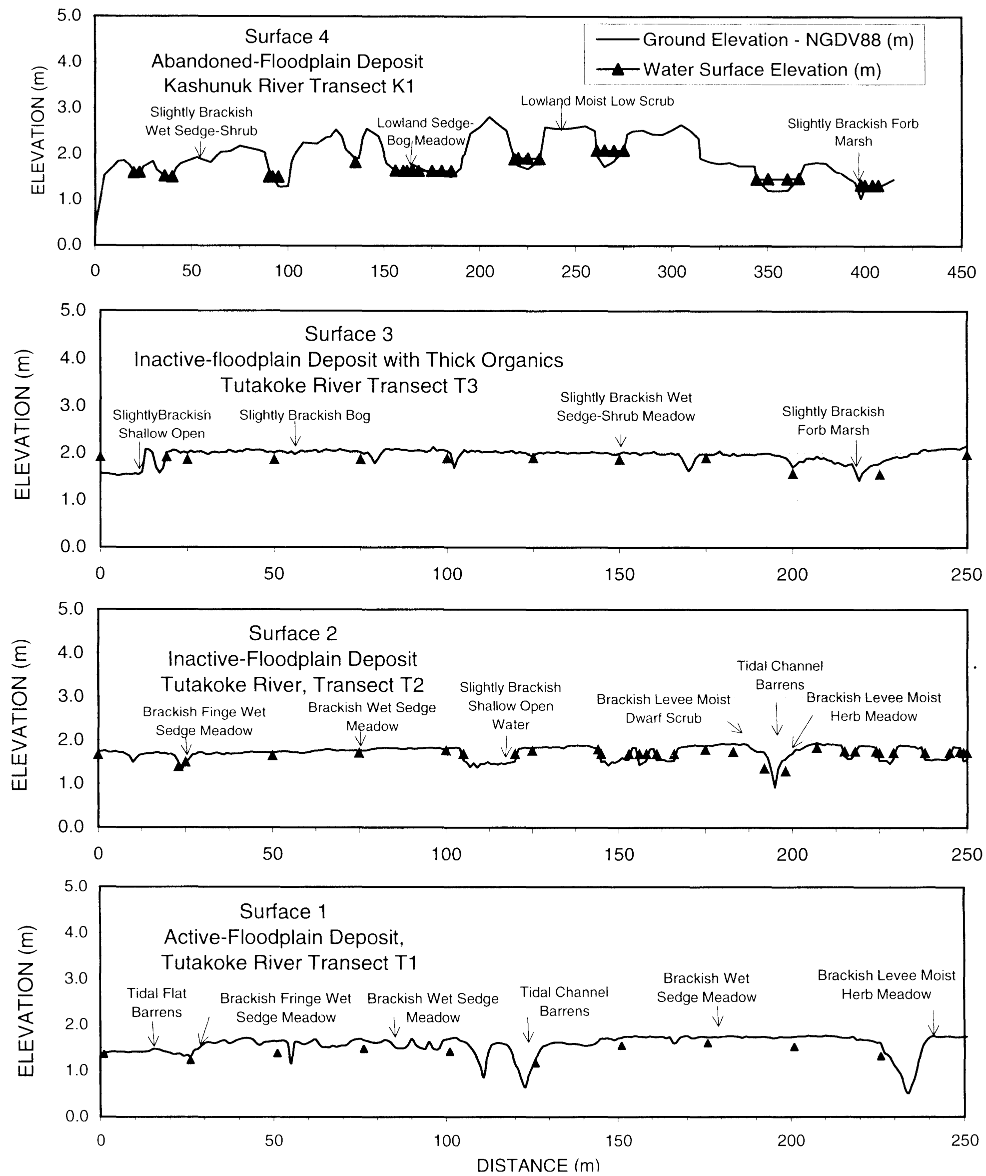

Figure 3. Representative toposequences showing topography and distribution of common ecotypes on four deltaic surfaces, near the Tutakoke River, Yukon-Kuskokwim Delta, Alaska, 1998.

were inundated and had some sediment accumulation every year. On inactive floodplains, the crest gauges indicate that all ecotypes were flooded 3 out of the 4 years. Sediment was found every year on slightly brackish wet sedge-shrub meadows, but never observed on slightly brackish depression wet sedge meadows and slightly brackish bog meadows, which are common on Surface 3. On abandoned floodplains, neither flooding nor sedimentation was observed during the 4-year period.

DISCUSSION

The results indicate that the area is remarkably flat and that coastal ecotypes occur along a predictable gradient. Our measurements were similar to those obtained by KINCHLOE and STEHN (1991), who found that mean relative elevation (based on position of upper border of Carex subspathacea mats) for lowland moist low scrub (their type 10c) was 0.81 m higher than for slightly brackish wet sedge-shrub meadow (their 6d) and 0.99 m higher than for brackish fringe wet sedge meadow (their 6a). Our comparable differences were 0.88 m and 1.34 m, respectively. For their "down-river" transects, they found that slightly brackish wet sedge-shrub meadows were 0.37 m higher than brackish fringe wet sedge meadow, similar to our difference of 0.46 m. Differences among some ecotypes were not much larger than the measurements errors associated with geodetic control (~5 cm),

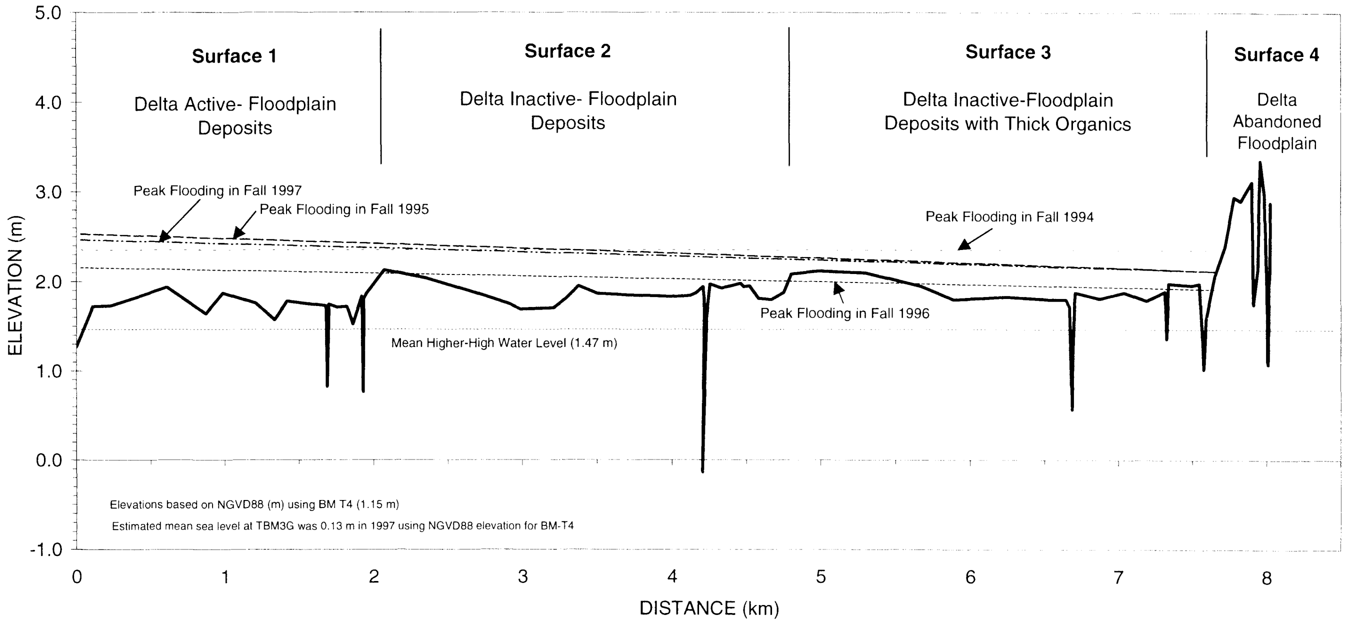

Figure 4. Toposequence crossing four deltaic surfaces with differing distributions of geomorphic units and coastal ecosystems, near the Tutakoke River, Yukon-Kuskokwim Delta, Alaska, 1998. Water-surface elevations at peak flooding during fall storms are included as dashed lines.

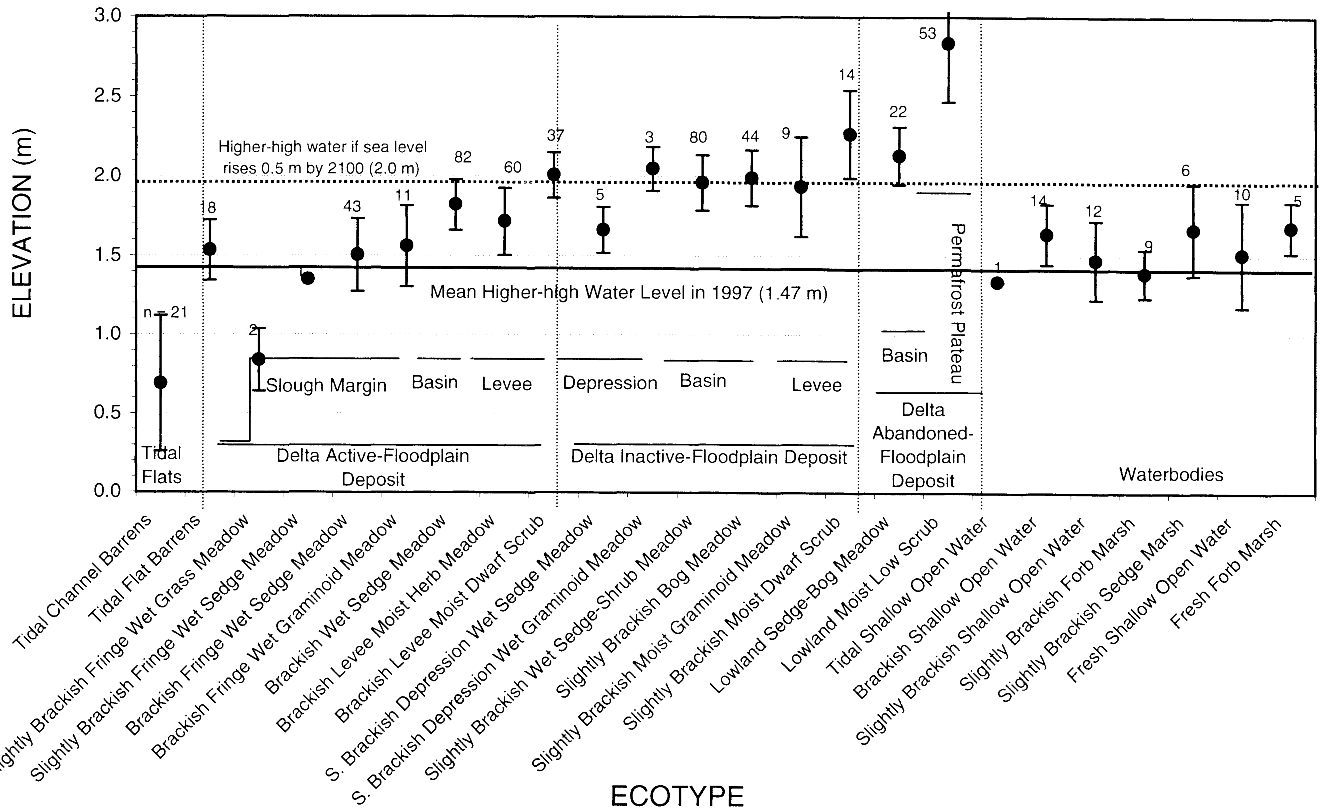

Figure 5. Mean (±SD) elevations (based on NGDV88) of ecotypes near Hazen Bay on the Yukon-Kuskokwim Delta, Alaska, 1998.

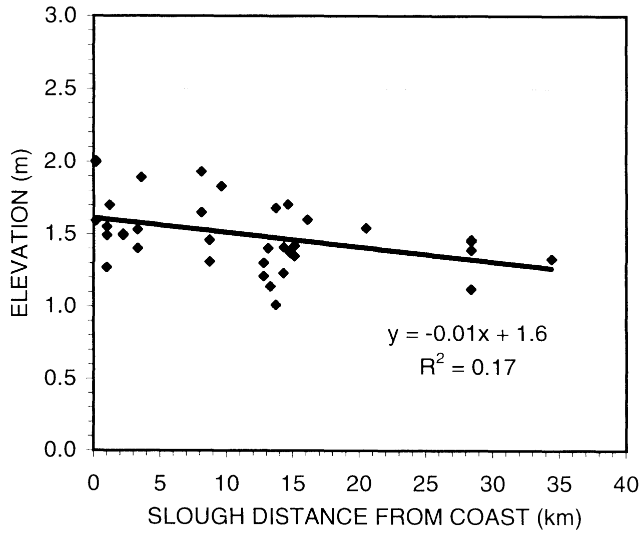

Figure 6. Elevations of Brackish Fringe Wet Sedge Meadows (*Carex ramenskii*) along rivers and sloughs relative to distance from coast, Yukon-Kuskokwim Delta, Alaska, 1998.

leveling (<10 cm depending on the length of the transect), and spongy tundra surface (~5 cm).

The elevations observed in our study only apply to the Hazen Bay area of the delta, because the tidal amplitudes vary from a normal maximum range of ~3 m in Kokechik Bay (NOAA 1987) to as little as 0.1–0.4 m in the northern delta (McDowell *et al.*, 1987). We would expect, however, that the elevations would retain proportional differences among landscape positions across the broader delta region.

The broad expanse of low-lying ecosystems with only small differences in elevations indicates that a large portion of the outer Y-K delta is likely to be affected by sea-level rise. The Intergovernmental Panel on Climate Change (IPCC 1996) developed a consensus best estimate of a sea-level rise of 49 cm by 2100, although their range varied from 20 to 86 cm. Although we have no basis for independently estimating sea level changes in the Bering Sea, for purposes of evaluation flooding effects, we assume sea level changes will be similar to those that are predicted to occur globally. With this assumption, an increase in sea level of 49 cm has the potential to cover most brackish terrestrial ecotypes in the area during high tide, because most ecotypes occur at surface elevations within 50 cm of mean higher-high water, based on our estimate of the water-surface elevation for mean higher-high water (1.47 m) at the mouth of the Tutakoke River. An increase of that magnitude would result in most non-saline lowland ecotypes being inundated by fall storm surges. Risks may be

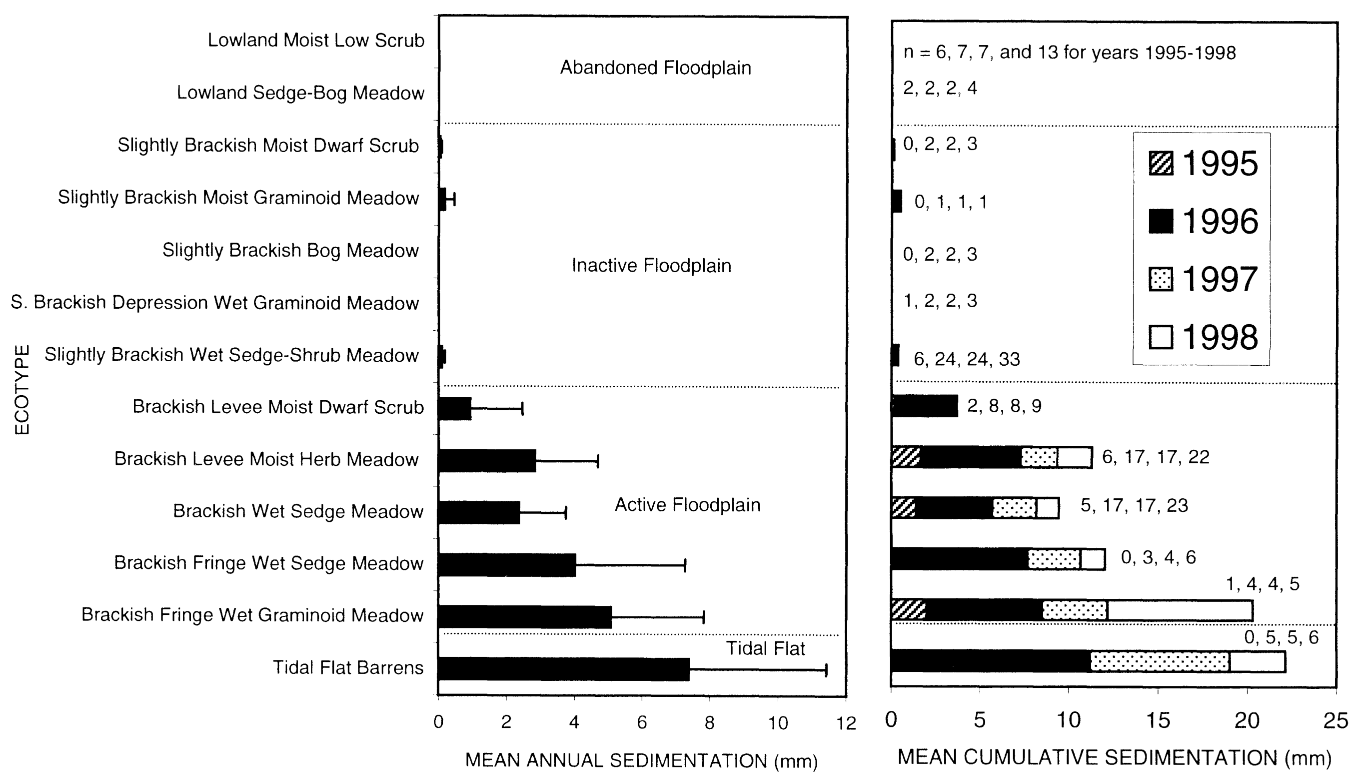

Figure 7. Mean (±SD) annual and cumulative sedimentation accumulation by ecotype on the Yukon-Kuskokwim Delta, Alaska, 1994–1998. Mean annual sedimentation was calculated using data from 1–4 years; samples sizes for each ecotype and year are included in the mean cumulative sedimentation.

even greater still, because under most global change scenarios storm surges will likely be more frequent and of greater amplitude (WALSH *et al.,* 1996; SERREZE *et al.,* 1997).

The response of ecosystems and their likelihood of being flooded and damaged is complicated, however, because of the accretion of the ground surface through sedimentation, organic matter accumulation, and permafrost development, and the differential sensitivity of coastal ecosystems to salt damage. Analyses of differences in salinity levels of coastal ecotypes indicates that all brackish and slightly brackish ecotypes are tolerant of occasional flooding (JORGENSON 2000). We observed virtually no salt damage to plants common to brackish and slightly brackish terrestrial ecotypes from inundation by fall storms in 1994–1997. We did observe, however, some mortality of *Sphagnum* mosses colonizing in small patches in slightly brackish bog meadows. Because we speculate that *Sphagnum* colonization affects both acidification and the soil thermal regime that facilitates permafrost formation, damage to *Sphagnum* from sea-level rise could provide a feedback that reduces surface accretion.

Although the rate of accretion of surface materials due to sedimentation has been quantified, at least over a short period, additional surface changes due to organic-matter accumulation and permafrost aggradation/degradation are uncertain. Sedimentation rates for ecotypes on active floodplains (1.4–6.5 mm/yr) appear capable of maintaining the surface against rising sea levels, even though we did not factor in compaction of the sediments as they become more deeply buried. In contrast, we observed no sediment accumulation at many sites within slightly brackish ecotypes at greater distances from the coast, indicating that these areas are at highest risk from sea-level rise. The building up of the ground surface along active levees probably will lead to increased impoundment of water within the basins behind the levees and lead to the expansion in the size of waterbodies at the expense of meadows. The persistence of seasonal frost into late July–early August contributes to this pond formation by impeding subsurface drainage through most of the summer. Given the low rates of sedimentation and the possibility that saltwater inundation will impede moss accumulation, we believe it highly probable that areas within Surfaces 2 and 3 will become increasingly dominated by slightly brackish ponds and slightly brackish forb marshes. We hypothesize that the increased size and smoothness of the margins of waterbodies within Surface 3 is a result of the impoundment process associated with sea-level rise during the last couple of hundred years.

The fate of nonsaline, lowland ecotypes on the abandoned floodplain associated with Surface 4 is more problematic. These acidic ecotypes dominated by *Sphagnum* and ericaceous shrubs are highly sensitive to salt damage. The plants are associated with low salinity levels and we have observed damage to *Betula nana* and *Sphagnum* on some of the lower margins of the permafrost plateaus. The rate of rise in surface elevations due to organic accumulation and permafrost development is unknown and needs further study. Due to expansion of water upon freezing (9%), frost penetration into underlying sediments should raise the surface by about 9 cm for every meter of frost penetration. We speculate that most of the 1-m rise in ground surface on the abandoned floodplain is due to ice expansion in the sediments and estimate that permafrost is about 10-m thick underneath the plateaus. In addition, segregated ice can accumulate at the top of the permafrost table during annual freezing of the active layer, and we have observed small amounts of thin, lenticular ice in permafrost cores. The widespread occurrence of these permafrost plateaus indicates that frost jacking has exceeded sea-level rise in the past. Whether this process is ongoing, or will continue in the future, is an important question, given expected climate warming and slower frost penetration as permafrost becomes deeper. A final uncertainty is the lack of information on compaction of sediments and land subsidence. Our establishment of a high-resolution network of vertical bench marks tied into the CORS network provides baseline data for addressing this question in the future.

CONCLUSIONS

A survey of surface elevations on coastal ecosystems in the Yukon-Kuskokwim Delta near Hazen Bay found topographic variation to be low. Elevations of vegetated ecotypes along the longest toposequence rose only ~1 m over a distance of 7.5 km, and brackish and slightly brackish meadow ecotypes varied <0.5 m over the first 7 km. Generally, we observed an abrupt, small rise of ~1 m onto the surface of permafrost plateaus that support nonsaline lowland ecotypes. Mean elevations varied little among all ecotypes across the entire study area. As expected, mean elevations were lowest for tidal channel barrens (0.69 m) and tidal flat barrens (1.53 m). On the active floodplain, where frequent sedimentation prevents organic layer development, mean elevations increased from 1.50 m for brackish fringe wet sedge meadow (dominated by *Carex ramenskii*) to 2.01 m for brackish levee moist dwarf scrub (*Salix ovalifolia-Deschampsia caespitosa*). In contrast, elevations varied little on the inactive floodplain; mean elevations in two of the most abundant ecotypes ranged from 1.96 m for slightly brackish wet sedge-shrub meadows (*C. rariflora-Salix fuscescens*) to 1.99 m for slightly brackish bog meadows (*C. rariflora-Sphagnum*). Two exceptions were slightly brackish depression wet sedge meadows (1.66 m, dominated by *Carex mackenziei*), which occurred in depressions and along pond margins, and slightly brackish moist dwarf scrub (2.27 m, dominated by *Empetrum nigrum*), where incipient permafrost development has started to raise the surface. The mean elevation of the highest ecotype, lowland moist low scrub (dominated by *Betula nana* and lichens) was distinctly higher (2.84 m) than other ecotypes.

During 1994 to 1998, monitoring of annual peak stage using crest gauges revealed flooding from the highest fall storm surge reached 2.58 m, 1.11 m above mean higher-high tide. In all years, all coastal ecotypes, except those on the highest surface, were flooded. Mean annual sedimentation for the various ecotypes ranged from 8.0 mm on the tidal flats, 1.4 to 3.8 mm on the active floodplain, 0.1–0.2 mm on the inactive floodplain, to absent on the abandoned floodplain.

Assuming a predicted rise in global sea levels of ~0.5 m by 2100 (HOUGHTON *et al.,* 1996) applies to the Bering Sea, large portions of the coastal margin of the delta could be inundated by water during high tides, and even the highest ecotypes could be affected by storm surges. Predicting the potential inundation of ecosystems is complicated because of the change in ground surface through sedimentation, organic matter accumulation, permafrost aggradation or degradation, and subsidence though compaction of sediments. We presume that brackish ecotypes on active floodplains probably are in equilibrium with sea-level rise and composition and productivity will not change much. In contrast, slightly brackish ecotypes on inactive floodplains receive little sediment because of their distance from the coastal fringe, thus slightly brackish ponds are likely to expand in the basins behind the low levees. Greater uncertainty exists about the effects of sea-level rise on nonsaline, lowland ecotypes on the 1-m-high permafrost plateaus. Although these ecotypes are sensitive to salt damage, jacking up of the surface through permafrost formation may exceed the rate of sea-level rise and prevent inundation. Whether permafrost aggradation will continue under a predicted warming climate is unknown. In summary, we conclude that ecosystems on the delta are at substantial risk of inundation and potential change, but numerous properties (e.g., storm frequency and magnitude, sedimentation, organic matter accumulation, permafrost aggradation, subsidence, and channel migration) need to be assessed before better predictions can be made of the future inundation and response of coastal ecosystems.

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