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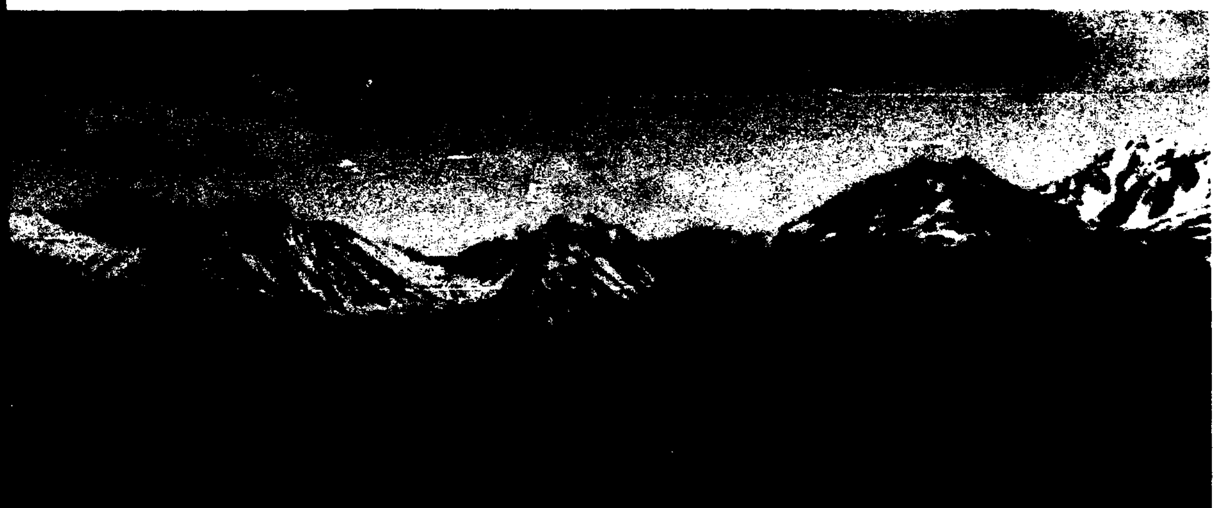
Preliminary Assessment of Sedimentation and Erosion in Eagle River Flats, South-Central Alaska

Daniel E. Lawson and Bruce E. Brockett

December 1993



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Abstract
The physical processes of sedimentation and erosion within the tidal mudflats and salt marshes of Eagle River Flats (ERF), an area used as an artillery impact range by the U.S. Army since 1945, must be understood to evaluate potential treatments of a high duck mortality resulting from ingestion of white phosphorus (WP) particles. The WP originates from smoke-producing devices detonated here. A preliminary assessment of erosion and sedimentation during May to September 1992 indicates that the physical system is complex and the intensity of these processes spatially variable. Deposition from suspension sedimentation generally varied with morphology and elevation, increasing inland from levees on the Eagle River (1 to 2 mm) across vegetated (3 to 6 mm) and unvegetated (5 to 12 mm) mudflats, and into ponds (10 to 19 mm) and salt marshes (10 mm). Resedimentation rates in ponds ranged from 8 to 16 mm. Recession rates of eroding gully headwalls were highly variable, ranging from negligible to over 3.9 m. White phosphorus particles may be in suspended transport through gullies during ebb. Further studies are necessary to better define annual sedimentation and erosion rates, with improved sampling techniques used at an expanded number of sites. Basic data on tidal inundation, sediment influx and efflux, and WP particle transport are required to develop appropriate treatment methods.

Cover: Headward erosion of gullies in Eagle River Flats results from currents and mass failure mechanisms. Erosion rates measured in 1992 suggest that gullies may soon drain ponds in which waterfowl feed.

For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380-89a, *Standard Practice for Use of the International System of Units*, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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Prepared for
U.S. ARMY 6TH INFANTRY DIVISION (LIGHT)

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PREFACE

This report was prepared by Dr. Daniel E. Lawson, Research Physical Scientist, and Bruce E. Brockett, Physical Science Technician, both of the Geological Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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The authors gratefully acknowledge the support and assistance of the 6th Infantry Division. They particularly thank William Gossweiler, Supervisory Wildlife Biologist, and Douglas Johnson, Chief, Environmental Division, Public Works, 6th Infantry Division, for valuable logistical assistance and discussions. The authors are indebted to the personnel of the 176th Ordnance Detachment (EOD) for escorting them into the field area, as well as Bill Smith and Laurie Angel of DPW for their assistance in organizing and conducting the field studies.

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This publication reflects the views of the authors and does not suggest or reflect policy, practices, programs or doctrine of the U.S. Army or of the Government of the United States. The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

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Preliminary Assessment of Sedimentation and Erosion in Eagle River Flats, South-Central Alaska

DANIEL E. LAWSON AND BRUCE E. BROCKETT

INTRODUCTION

Previous work by CRREL has shown that an unusually high mortality of ducks within Eagle River Flats (ERF), a 1000-ha high tidal estuarine salt marsh at the mouth of Eagle River on Cook Inlet (Fig. 1), is attributable to ingestion of elemental white phosphorus (P_4) particles (Racine et al. 1992a,b). This subarctic tidal flat has been used since about 1945 by the U.S. Army as an artillery impact range, where howitzer shells and mortar rounds containing high explosives or smoke-producing compounds have been fired. White phosphorus originates from the smoke-producing devices, detonated either on the ground or above it (Racine et al. 1992a).

White phosphorus (WP) particles are now present in the near-surface sediments at numerous locations within ERF, including the pond and marsh bottoms where dabbling ducks ingest it during feeding. WP is also found in the sediment at depths greater than 30 cm or more (Racine et al., in press).

To evaluate potential treatments for reducing or eliminating duck mortality from WP ingestion, the physical processes of sedimentation and erosion within the tidal mudflats and salt marshes of ERF must be understood. These processes are particularly important in determining the availability of WP to feeding organisms. Sedimentation processes, for example, could bury the WP in ponds and marshes, thereby removing it from feeding areas naturally. In contrast, erosion could entrain and transport WP particles from the mudflats, ponds and marshes to other locations within ERF or into the Eagle River. Resedimentation of WP particles could also relocate WP to other areas of ERF that are accessible to feeding ducks and other organisms. In addition, transport of WP particles into the Eagle River via gullies draining the tidal flats could potentially make these particles available for ingestion by fish, invertebrates and mammals elsewhere in Cook Inlet.

Both the short- and long-term viability and stability of mitigation treatments will be affected by the type and intensity of erosion and deposition. How those treatments affect the parameters controlling these processes and the physical system will likewise determine their success.

In this report, we present the first results of an analysis of the complex physical processes of sedimentation and erosion within ERF and of the rates of deposition, erosion and transport of sediment by these processes. In addition, we describe a preliminary assessment of WP transport using sedimentological principles. These results are preliminary, representing only one summer's observations and measurements within a limited part of ERF; these data should therefore only be considered characteristic of the area of study during 1992.

ENVIRONMENTAL CONDITIONS

Eagle River Flats (ERF) is one of several estuarine salt marshes within the upper Cook Inlet region of south-central Alaska (Fig. 2). It lies at the mouth of Eagle River on the southeast side of Knik Arm and is about 2.75 km wide at the coast, narrowing inland. This region has a transitional maritime to continental climate, with generally moderate annual temperatures (daily mean 1.9°C; minimum –2.2°C) and precipitation (330 to 508 mm) (Evans et al. 1972).

The Eagle River flows generally through the middle of ERF, with the primary drainage occurring laterally from ponds and marshes through vegetated channels and gullies into the river channel (Fig. 3). About 20% of ERF along the coast, however, drains by gullies directly into Knik Arm. Its north and south boundaries are defined by uplands of glacial deposits covered by spruce and birch forests.

In ERF, as with other salt marshes in Cook Inlet (e.g., Hanson 1951, Vince and Snow 1984, Rosenberg 1986), vegetation zones are commonly determined by elevation. This relationship is believed to be a function of flooding frequency, salinity, drainage and sedimentation rates. Levees, outer

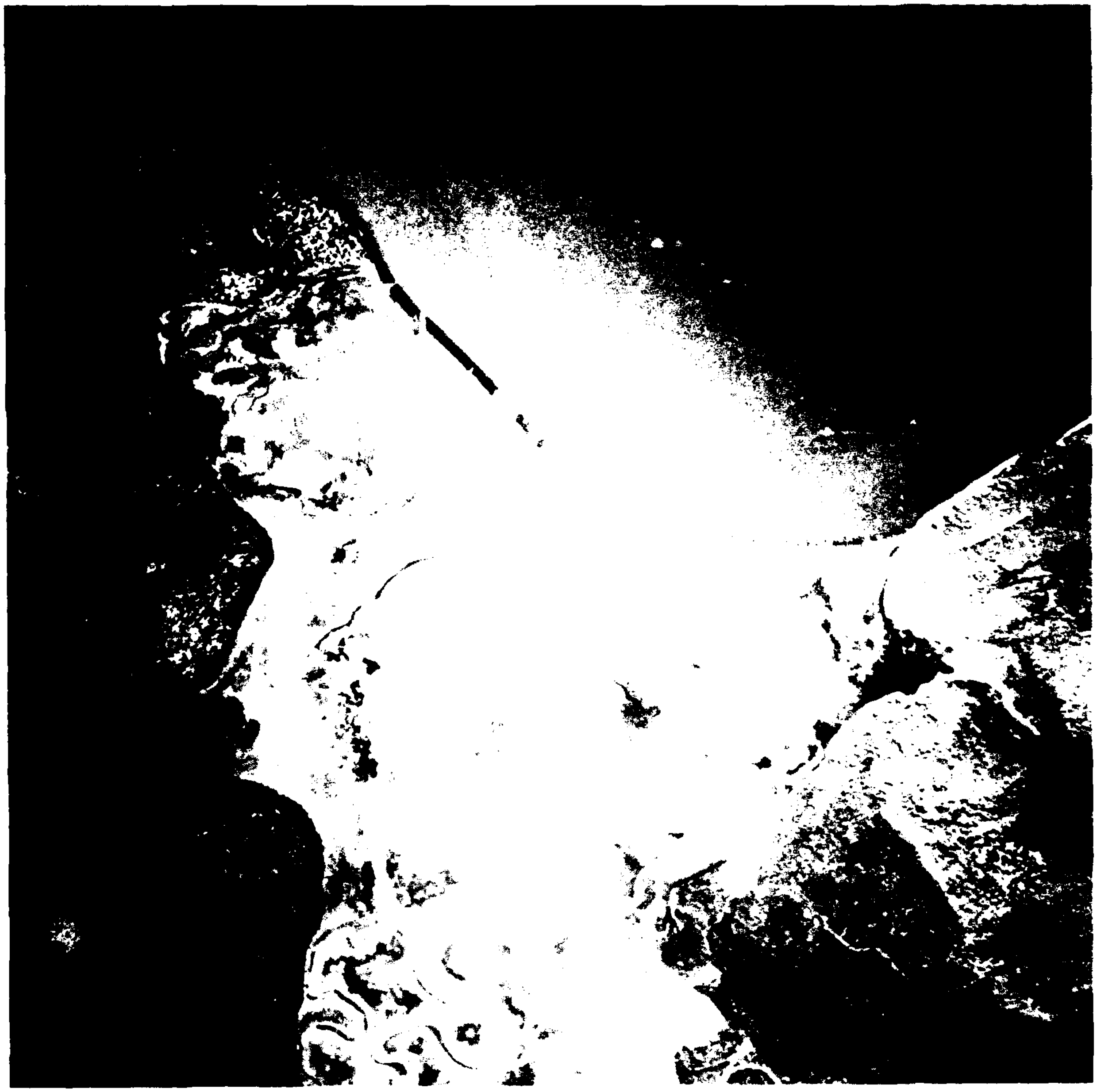


Figure 1. Aerial photograph from 8 July 1993 of Eagle River Flats (ERF), Fort Richardson, near Anchorage, Alaska.

and inner mudflats, outer and inner marshes, and shallow ponds (to 50 cm depth) are arranged in a pattern that approximately parallels the Eagle River and coastline (Racine et al. 1992a). Freshwater ponds or shrub bogs also lie along the upland bordering ERF.

Levees are better drained and covered by *Elymus arenarius,* while the mostly bare outer mudflat zone along the coast is sparsely vegetated by arrow grass (*Triglochin maritima*). Mudflats parallel to the levees have a higher percentage of cover, predominantly arrow grass (*Triglochin maritima*), *Plantago maritima* and *Potentilla egedii.* Inner sedge marshes are dominated by tall Lyngbyae's sedge (*Carex Lyngbyaei*) or bulrush (*Scirpus validus),* while outer marshes are mixed *Carex ramenskii, Triglochin maritima* and *Potentilla egedii.* Ponds and smaller pools of water up to 50 cm deep lie within the inner marsh zone and support aquatic vegetation that includes *Potamogeton pectinatus, Zannichellia palustris* and *Ruppia spiralus.* Islands of emergent species *Hippurus tetraphylla* and bulrush occur within and adjacent to the ponds. Racine et al. (1992a, in press) describe the vege-

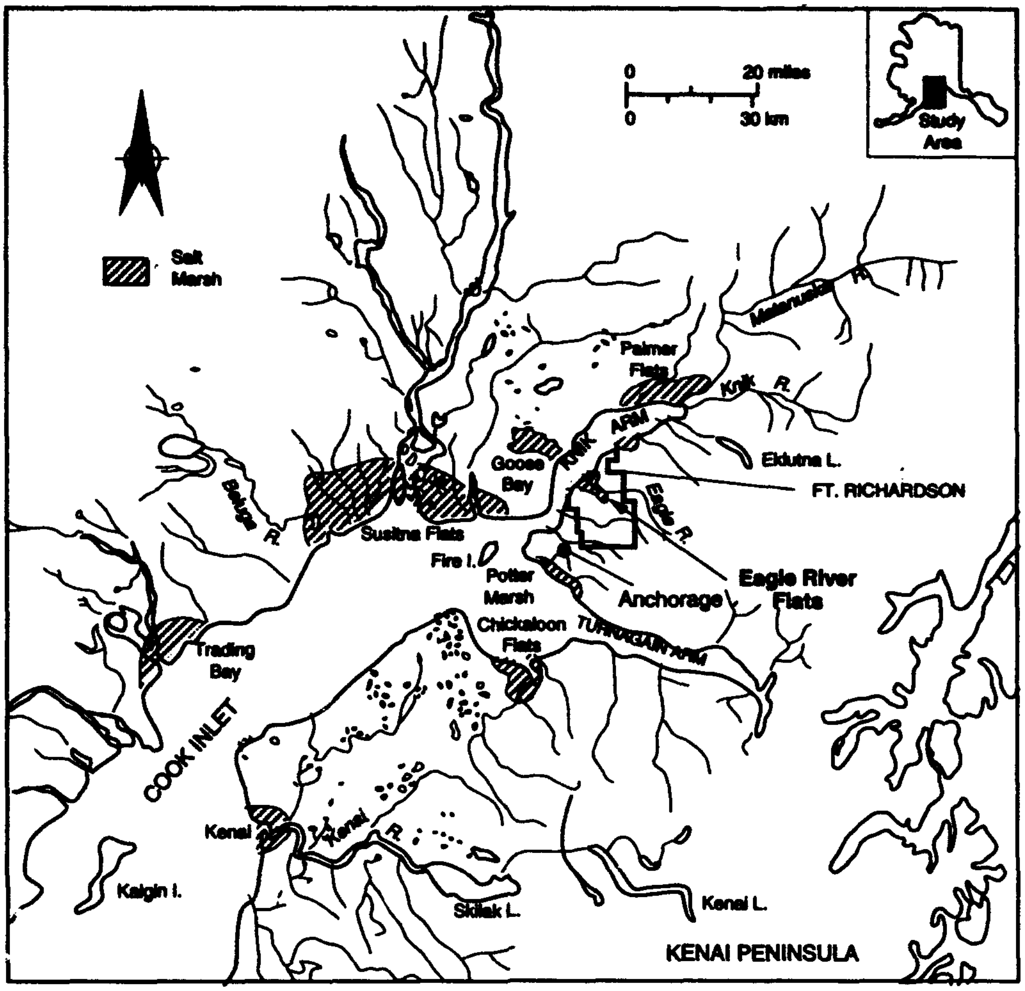


Figure 2. Upper Cook Inlet region showing ERF and several other estuarine salt marshes (shaded areas).

tation in more detail.

In ERF, a high tidal range with semi-diurnal fluctuations of 9.1 to 11 m and sediment-laden glacial discharges are critical factors affecting sedimentation and erosion. Tidal inundation results from both the rise in tide in Knik Arm and the resultant overflow from the Eagle River as it meets the rising tide. Floods dominated by both freshwater and saline water have been reported (Racine et al. 1992a).

The Eagle River drains a 497-km^2 basin that is covered by glaciers over 13% of its extent. Average discharge is about 14.7 m^3/s. Maximum and peak discharges take place during the primary glacial melt season in July and August. Then, average daily discharge exceeds 42.5 m^3/s, while peak discharges can range from 65.1 to 76.4 m^3/s. Rainfall-induced floods during peak melt periods can exceed 105 m^3/s.

Sediments within both the glacial discharges and the tidal flood waters from Knik Arm and Cook Inlet are derived mainly from glaciers. Massive quantities of silt- and clay-size particles are suspended within the numerous large rivers draining into the Inlet. These materials can remain suspended for extended periods and are transported into intertidal wetlands by tidal inundation. The Eagle River also transports suspended sediment of glacial origin throughout the melt season. The quantities of suspended sediment in transport by river and tidal waters are, however, unmeasured.

BACKGROUND

The fundamental sedimentary processes of high tidal flats and salt marshes are not well under-

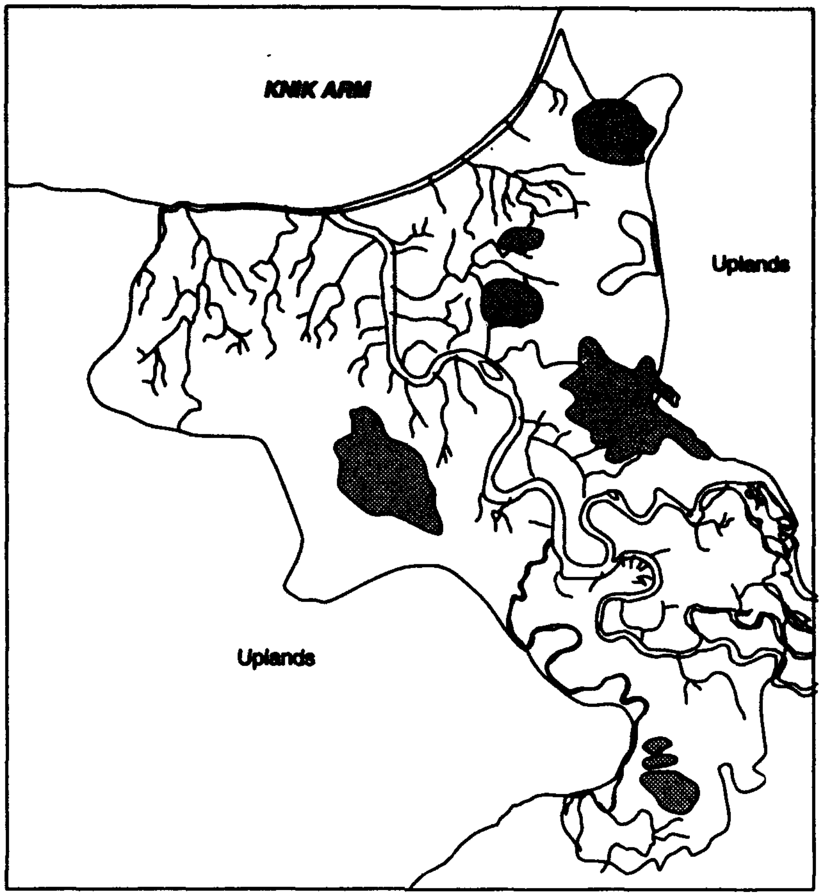


Figure 3. General distribution of ponds (shaded area) and the primary drainage system of gullies and vegetated channels within ERF.

stood; those within subarctic and arctic regions less so. The nature and behavior of these processes can vary in response to factors that include sediment supply, tidal regime, wind–wave climate and sea-level movement, but these relationships have not been quantified (e.g., Collins et al. 1987, Stoddart et al. 1989, Reed 1990). Fewer studies have examined the processes and rates of sedimentation in tidal flats and marshes where glaciers are the primary sediment source (e.g., Ovenshine et al. 1976a,b).

Field studies and simulations of short- and long-term sediment accumulation have suggested that process and morphology are related to elevation, and thus the frequency and depth of inundation, sediment supply and regional flooding are controlled by eustatic sea level rise (e.g., French 1991, 1993; Krone 1987; Allen 1990a,b). The resultant spatial variations in the texture and composition of sediment deposited within tidal flats and salt marshes are also expected to relate to the hydrologic processes, including sediment transport and deposition that are associated with tidal channels and gullies (Allen 1992).

Sediment balances for accretion and erosion in tidal flats and marshes have been estimated from short-term vertical sedimentation rates in systems dominated by mineral matter with only a small percentage of organic matter (e.g., Richard 1978, Harrison and Bloom 1977, Letzch and Frey 1980, Stoddart et al. 1989). Longer-term estimates have been made by dating subsurface horizons (e.g., Hubbard and Stebbings 1968, Allen and Rae 1988) and creating radionuclide profiles (e.g., Bloom 1984, Keene 1971, Kearney and Ward 1986). Both estimates, however, may be misleading owing to post-depositional compaction in the former case and time-dependent accretion rates in the latter (French 1993).

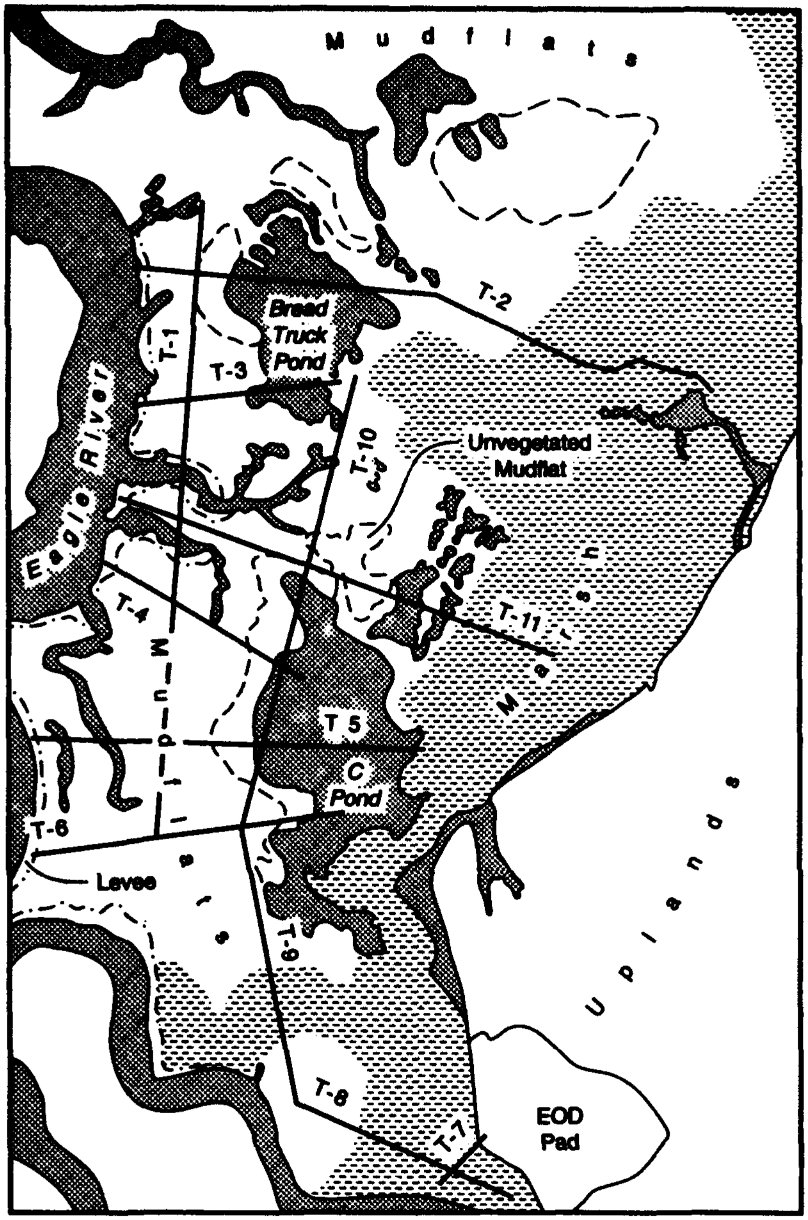


Figure 4. Location of surveyed transects within the areas around the C and Bread Truck ponds.

STUDY AREA AND METHODS

General approach

Our study focused on the central area of ERF, east of the Eagle River in the vicinity of Bread Truck Pond and Pond C (Fig. 4). The basic morphological terrain units here include levees, gullies, upper vegetated mudflats, lower unvegetated mudflats, ponds and marshes. These morphological units were defined by combining ground observations with an analysis of aerial photographs taken in 1991 (see Fig. 1).

Transects were established across representative morphologic units. Each was surveyed in May 1992 to establish ground surface elevations relative to local benchmarks and the UTM grid. At each survey point, grab samples of the surface sediment to 5 cm depth were taken and subsequently analyzed for grain size distribution using standard sieving and hydrometer techniques. We

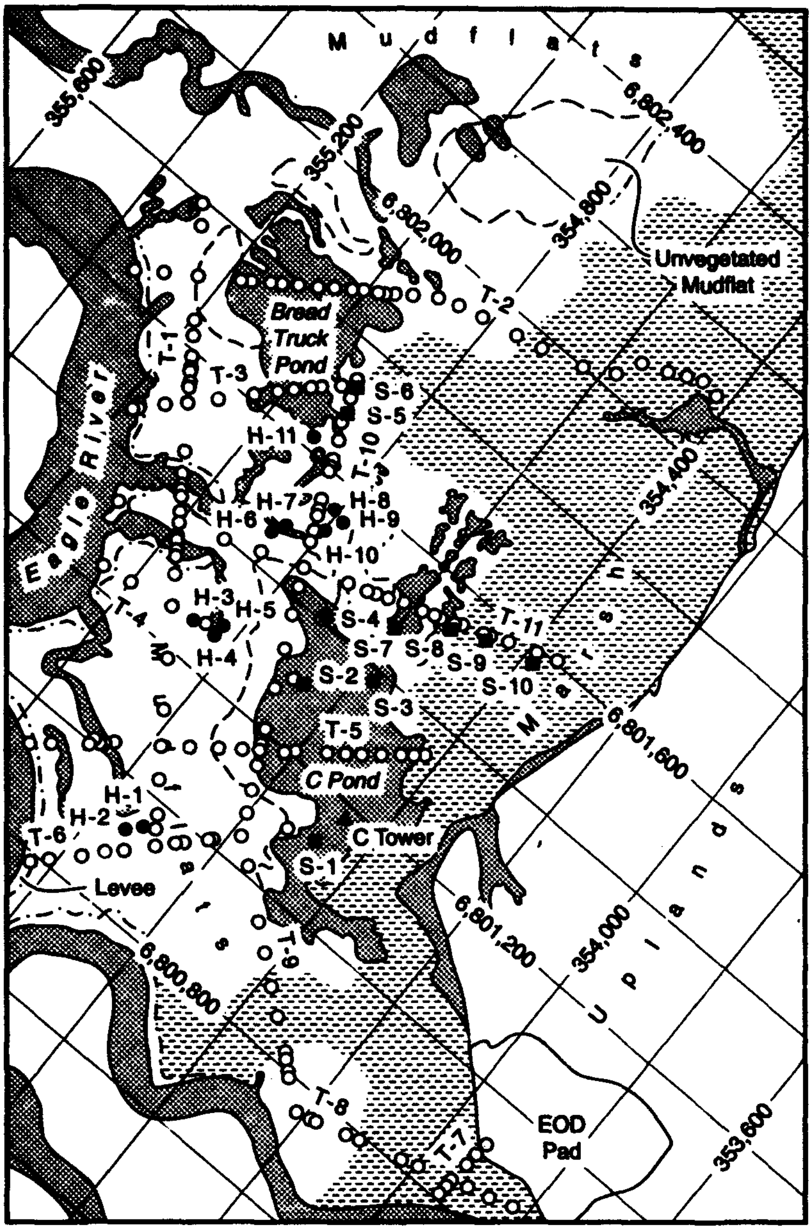


Figure 5. Surveyed locations of 156 surface grab samples on 11 transects east of Eagle River (open circles) relative to UTM grid. Open circles also mark locations of sedimentation stakes. Also located are 10 sediment (S-no., filled squares) and 11 gully headwall erosion measurement sites (H-no., filled circles).

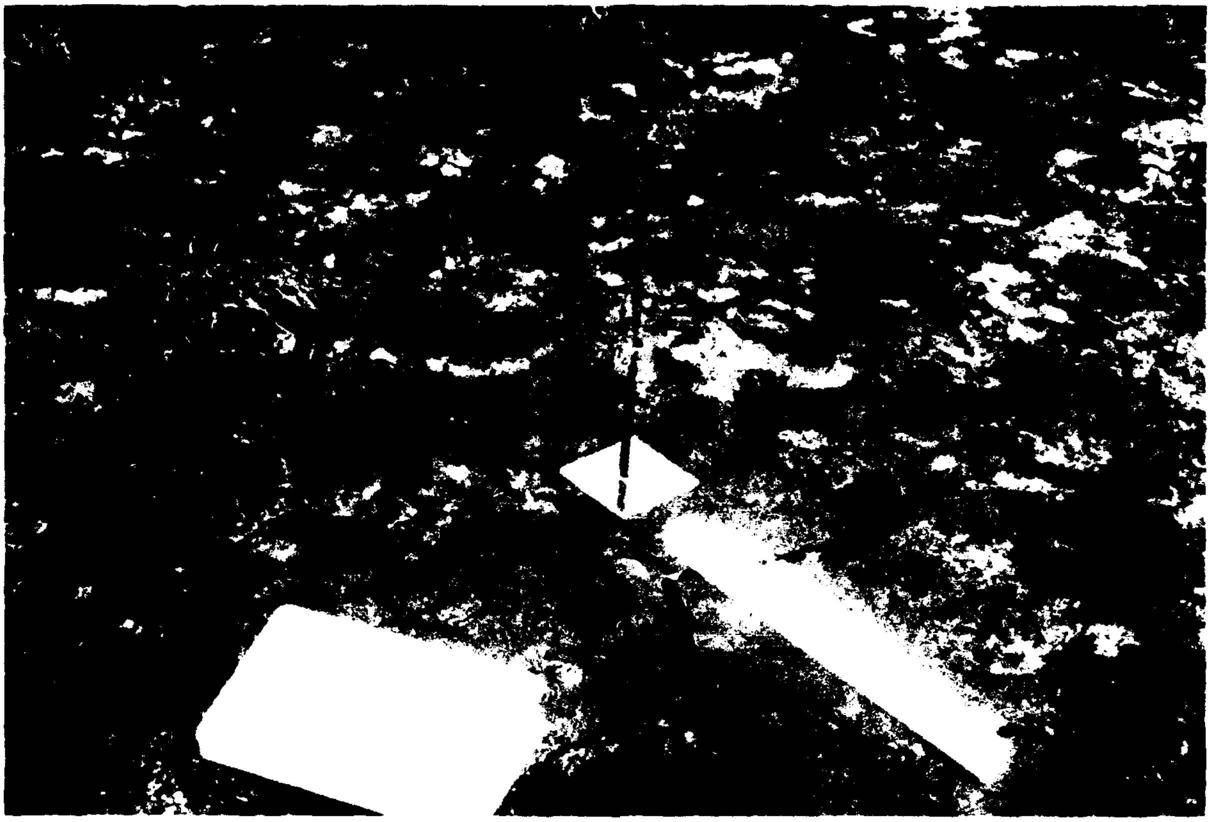


Figure 6. Sedimentation stakes. Plate slides freely on rod.

surveyed and sampled 156 locations along 11 transects (Fig. 5).

Deposition and erosion

Sedimentation rates within the tidal flats of Cook Inlet are generally considered to be low (several millimeters annually) (Vince and Snow 1984). Combined with the fine grain size and potential flocculation of sediment, rates are difficult to measure accurately. Within ponds and marshes, for example, only a slight disturbance is needed to resuspend bottom sediments into the water column. If these sediments are caught in sediment traps, erroneously high depositional rates would be measured. We therefore used several methods in an attempt to measure accurately the primary rates of sedimentation (or erosion) and the secondary rates of resedimentation from naturally resuspended sediment within ponds. We also measured deposition and erosion rates in the mudflats, levees and gullies. The various samplers described subsequently were installed during 24–28 May 1992, and measurements made several times between then and 22 September 1992.

Along each of the surveyed transects, at the locations from which sediments were grab sampled, "sedimentation stakes" were used to measure erosion and sedimentation (Fig. 6). These stakes consist of a rod and a square, rigid plate (about 7 cm^2) that slides freely on the rod. Erosion depth is defined by the increase in distance between the top of the rod and top of the plate, as measured periodically to the nearest 0.5 mm. The amount of accretion is the thickness of sediment deposited on the plate surface. The difference between these two readings defines the net sedimentation (or erosion) rate. We measured these rates in July, August and September following each monthly period of tidal flooding. A similar stake system was used previously in Turnagain Arm (Ovenshine et al. 1976a,b).

Sedimentation rates were also measured at 10 sites located within several of the ponds (Fig. 5). We expected these rates to be extremely low and possibly affected by resuspension of bottom sediments during the process of obtaining data. It was therefore unclear to us what relatively simple method would produce reasonably accurate results within the ponds; therefore, we used three methods at each site.

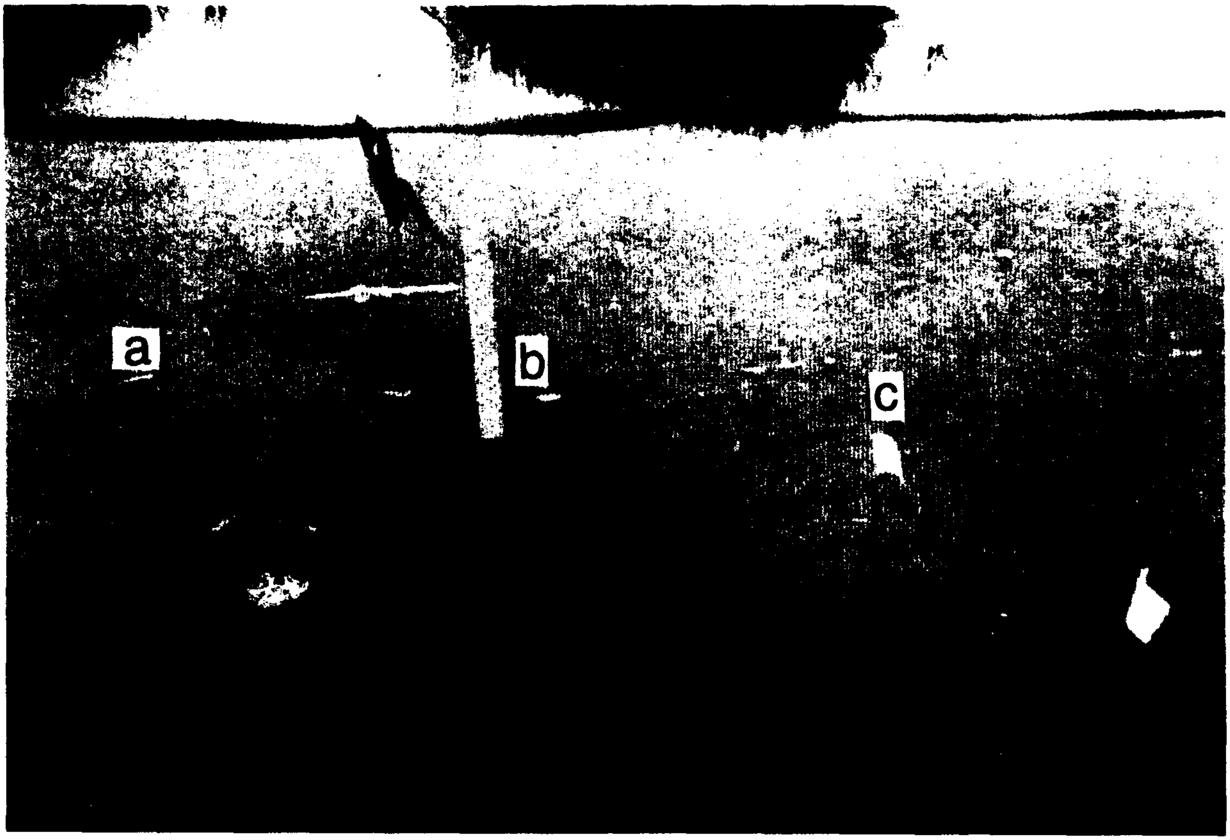


Figure 7. Sedimentation station in pond site. Meter stake (a), cup sampler (b) and plate sampler (c) are shown in position. Plate sampler is between two survey flags.

First, gross deposition, which includes new sediment brought into the ponds by tidal inundation and river currents, and previously deposited sediment that has been resuspended by wind waves, dabbling ducks or other mechanisms, was measured with a 4-in.-diameter (10.2-cm-diameter) PVC "cup" glued to one end of a short length of 2-in.-diameter (5-cm-diameter) PVC pipe. The pipe was inserted into the pond bottom sediments until the bottom of the cup was in contact with the bed (b on Fig. 7).

Second, to measure net sedimentation rates, a thin, flat plate, about 30 cm square, was cut from a rigid sheet of clear plastic and placed gently on the pond bottom where it was secured in each corner by aluminum tent pegs (c on Fig. 7). In contrast to the cup, which traps and holds all sediment deposited by settling from suspension and resuspension in the water column, the plate not only can become covered by sediment from suspension sedimentation, but allows this sediment to be reworked and resuspended as well. In addition, its dimension of about 30 cm^2 may indicate any local spatial variability in the rate of sedimentation or erosion. Each plate was covered by sediment and aquatic vegetation within several weeks of placement; this negated the possible effects of their smooth surfaces on their sediment trapping efficiency.

Third, a stake with a millimeter graduated scale on its face was inserted into the pond bottom, and the height of the pond bottom and the water column were measured, basically as a check on the plate measurement (a on Fig. 7). While simpler than the plate, any wind waves or water surface glare on sunny days commonly made this a difficult measurement to obtain. In addition, aquatic vegetation on the bed commonly covered the critical bottom height indicator.

For each method, readings could be made to the nearest 0.5 mm. In some areas, algae and aquatic vegetation commonly grows on the bottoms of ponds during summer; this vegetation obscured and in some cases completely covered the samplers by the middle of July. In attempting to move this vegetation, we disturbed and resuspended some sediments; measurements at these locations therefore indicated rates that were less than the actual amount deposited, perhaps by as much as 2 mm. Sedimentation rates at pond sites were also measured in August and September, following the monthly inundations of the tidal flats during high tides.

Gully erosion and recession

Field observations in May confirmed earlier interpretations of aerial photography that suggested that the headwalls and possibly lateral walls or scarps of gullies draining the tidal flats into the Eagle River were actively receding. Erosion by currents during tidal influx and efflux appear to undermine slopes and cause failure by collapse, slumping and other mechanisms, including piping during groundwater outflow.

To see if the erosion of gully headwalls was actively extending them into the ponds and to determine the rate of headwall recession, we picked 11 sites to evaluate retreat rates (Fig. 5). At each site, stakes were driven into the ground along a straight line at known distances from one another and from the crest of the gully (Fig. 8). A "hub" stake was set at a known distance from this stake line, and the distance from the hub across the top of each stake to the crest of the gully scarp was measured in succession with a tape measure. The distance to the edge of the scarp was identified with a plumb line suspended from the tape measure. We then inserted flagged wire stakes at the initial point of measurement along the crest of each headwall. We repeated these measurements in June and September following the monthly period of tidal inundation.

On the basis of repeated measurements at singular points without any retreat (as indicated by the continuing presence of wire flags), we consider these measurements reproducible at ±2 to 5 cm. Accuracy is, however, limited by how well we could define the crest of the gully scarp, whose shape is highly irregular. Accuracy is probably limited to ±10 cm.

White phosphorus particle transport

Because of limited funding for this initial study, sophisticated equipment for obtaining samples of sediment and any WP particles suspended in the

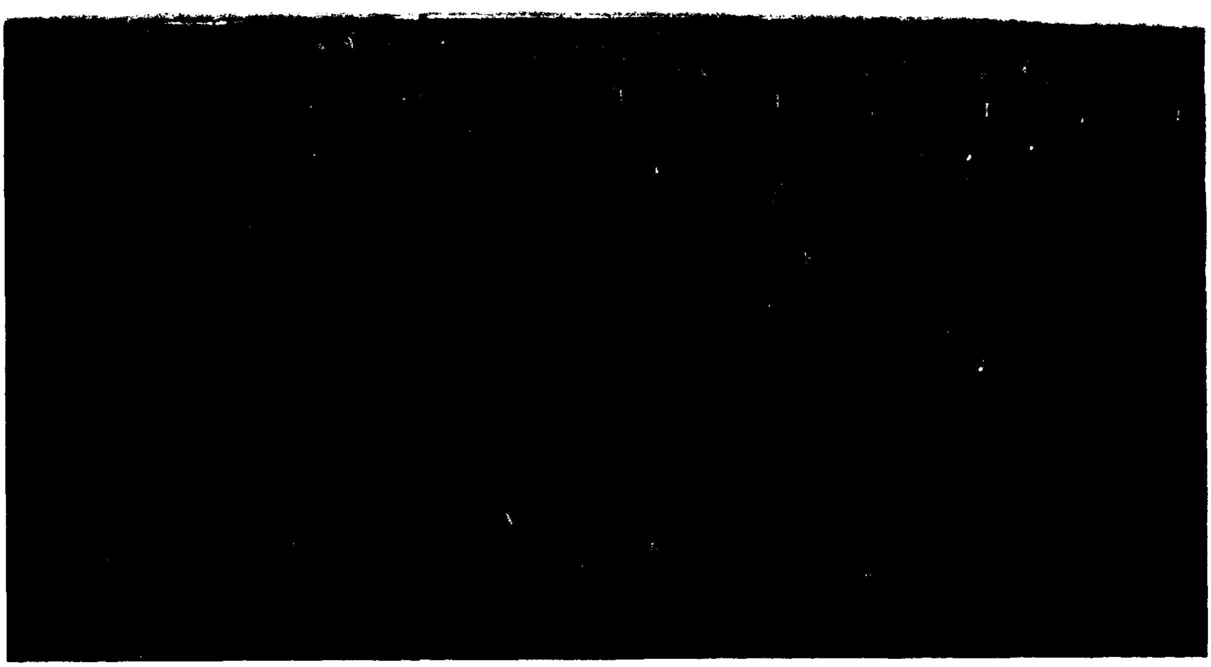


Figure 8. Headwall erosion site. Line of stakes approximately parallels gully crest. Hub stake right of center behind stake line.

water discharging through gullies during tidal events could not be purchased. These samples are necessary to evaluate quantitatively whether WP particles are being transported in suspension, and thus whether WP is being transferred to different locations within or outside of ERF.

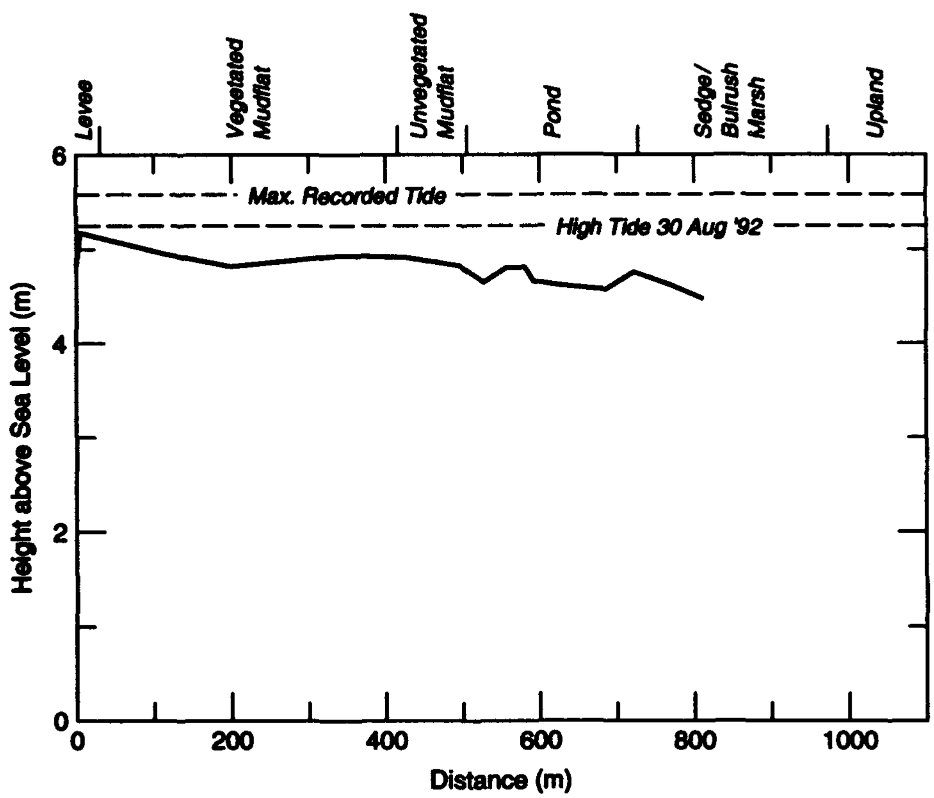
In an attempt to determine if WP particles are in transport during tidal inundation, we sampled recent deposits on the beds of gullies after the tide had ebbed. These samples were analyzed for WP content under the assumption that the sampled sediments were deposited by the most recent discharge through the gully; therefore, they were surrogates for material suspended in the gully discharge. The source of the WP (e.g., whether eroded from gully walls or pond bottoms) is not defined. This approach is limited in its validity because the suspended sediment and WP particles are fine-grained and would be deposited only during a relatively quiescent state of flow, such as in the final stages of ebb when water pools within the channel thalweg. Thus, it is probable that if WP particles are in transport, this approach would only sample a small fraction of them.

MORPHOLOGY

General relationships

Morphological terrain units in the study area are generally distributed relative to the Eagle River and the adjacent uplands (see Fig. 4). As with vegetation, a zonal pattern exists, with the following general sequence: levees, mudflats, unvegetated mudflats, intertidal ponds and marshes. Freshwater dominated ponds abut the uplands in several areas where stream and groundwater-fed springs discharge. There are significant levee deposits along the Eagle River and adjacent to gullies near their juncture with the river. Gullies extend generally eastward toward the uplands, joining vegetated drainage channels on the upper mudflats that extend into the ponds and marshes.

Excluding gullies, the distribution of morphological units is related to elevation (Fig. 9). Elevation generally decreases as much as 1.0 m from the tops of levees along Eagle River to the bottoms of marshes next to the uplands. Levee surfaces lie about 5 m above the Eagle River bed. The active



a. Transect 11.

Figure 9. Transects with approximate boundaries of morphological units.

drainage system channels (gullies) interconnect with an older drainage system, whose channels are generally submerged within the ponds and marshes. The patterns of these older channels are not consistent with those on the mudflats. Their intersection is sometimes disjunctured, with channels joining one another at obtuse angles.

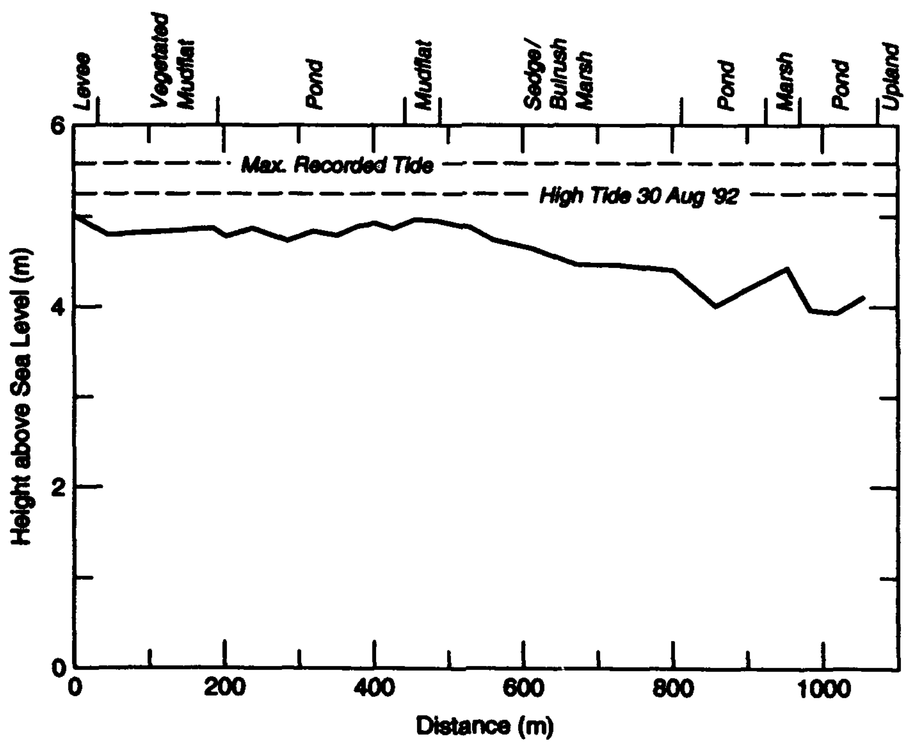
The presence of an older drainage system suggests that the active drainage system has developed in response to significant changes in tidal flat morphology, perhaps related to Eagle River migration, or to subsidence caused by the 1964 Alaskan earthquake (e.g., Ovenshine et al. 1976a, Small and Warton 1969). Both processes could have altered the tidal flats' hydrology and drainage within a geologically short time and caused the older system to be abandoned.

Most of the upper Cook Inlet shoreline, for example, subsided 0.3 to 1.2 m during the 1964 Alaskan earthquake, the shoreline of Knik Arm in the ERF area falling 0.6 m (Small and Warton 1969). Many near-shoreline areas that subsided were also inundated after the earthquake, but have been raised in elevation to near that prior to the earthquake by the deposition of sediment suspended within river discharges entering Cook Inlet (e.g., Ovenshine et al. 1976a,b). Remnants of the drainage system prior to 1964 may have survived in areas with less subsidence and low sedimentation rates.

Inundation

Two tide levels, the maximum recorded and the highest tide during the period of study (10.12 m, Anchorage tide datum, 30 August 1992), are shown on Figure 9. Levee elevations suggest that only tides in excess of 10.09 m completely inundate the study area. This height, however, neither accounts for water discharging in the Eagle River nor the effects of a southeasterly prevailing wind during tidal flooding. If discharge is high, such as during spring when snowmelt runoff is at a maximum, or during a river flood, the combined backup and overflow of the river by tidal flood waters can effectively increase the volume of flood waters and result in inundation of a greater area of ERF than tide levels alone suggest.

In addition, the height of water required to inundate the mudflats, ponds and marshes is controlled by the elevation of the drainage system. Water moving up the gullies need only reach an elevation estimated at 4.4 to 4.5 m to begin spreading across parts of the mudflats in the study area. Further, channels draining from the ponds appear



b. Transect 2.

Figure 9 (cont'd).

to have a minimum elevation of 4.6 m (approximately 9.48-m tide)—based, however, upon only three survey points—at the point of discharge from the pond. If this is indeed their lowest elevation, flood waters exceeding this height will flow into the ponds. This elevation is therefore the water height that the combined tidal flood and river discharge must exceed to enter the ponds, and is thus a critical control on sedimentation rates.

Grain size variability

The grain size distribution of surface materials also varies with morphology. Sediments generally are silt- and clay-size, with fine sand (less than 3%) present only in levee deposits. The primary modal fraction typically ranges from medium to fine silt (0.04 to 0.02 mm) but may be clay-size in some pond samples. Organic content is typically less than 5%. Figure 10 presents cumulative grain size distribution curves representative of the 156 samples analyzed from the 11 transects.

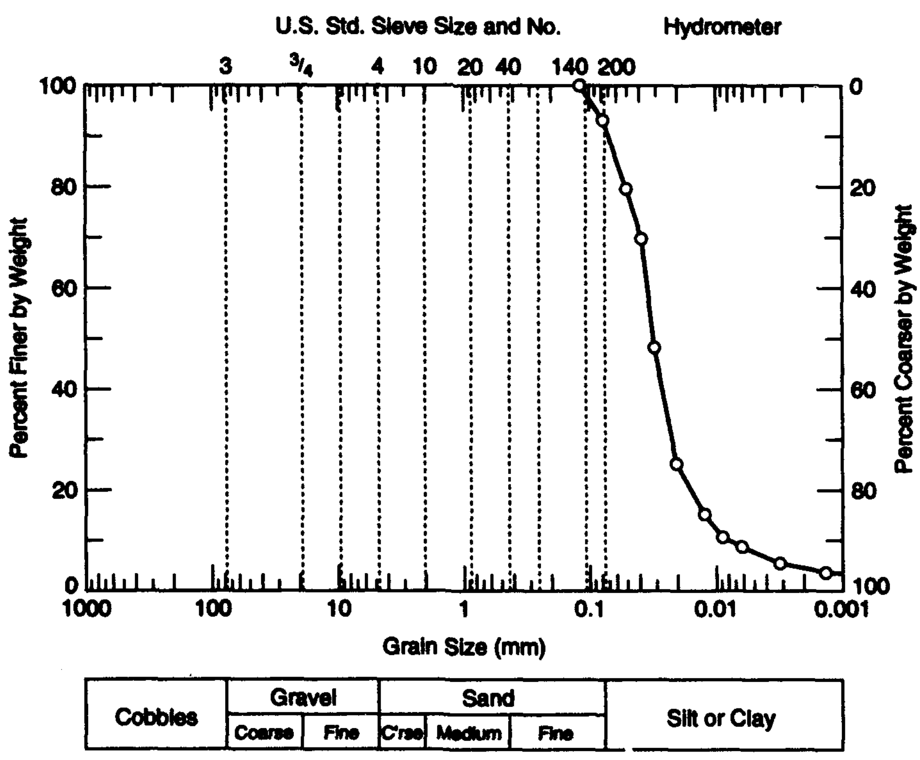
Surface sediments generally become finer eastward from the Eagle River to the uplands, with the clay-size fraction increasing in proportion to the silt-size fraction along a general transect from the levees to the marshes. Sediments from the centers of ponds and open pools within marshes were commonly the finest materials, with up to 95% finer than 0.02 mm.

PROCESSES

Types

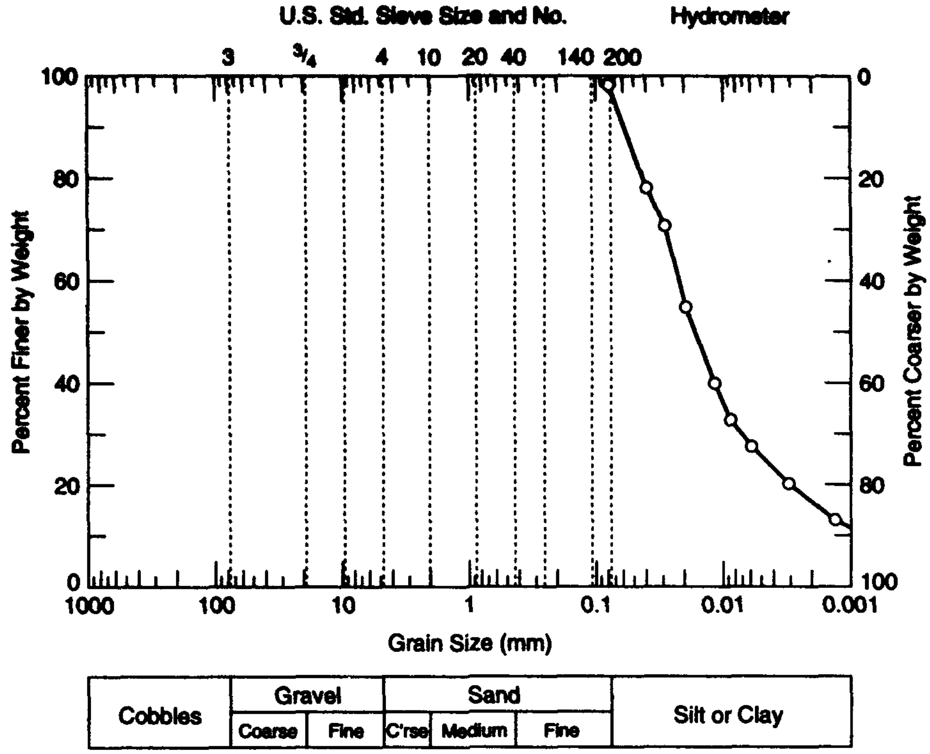
Within the different morphological areas, physical processes of sedimentation and erosion differ in importance in space and time. The principal processes of deposition and of erosion during the summer season are summarized in Tables 1 and 2 respectively. While sediment is mainly deposited by settling-out in the water column, including deposition of sediment trapped by vegetation, erosional processes are more numerous and commonly interact.

Erosion is particularly active in the gullies and rills draining the ponds and mudflats, with water current, overland flow, groundwater piping and slope failure interacting to erode the thalwegs and walls of gullies. Mudflats are affected by these

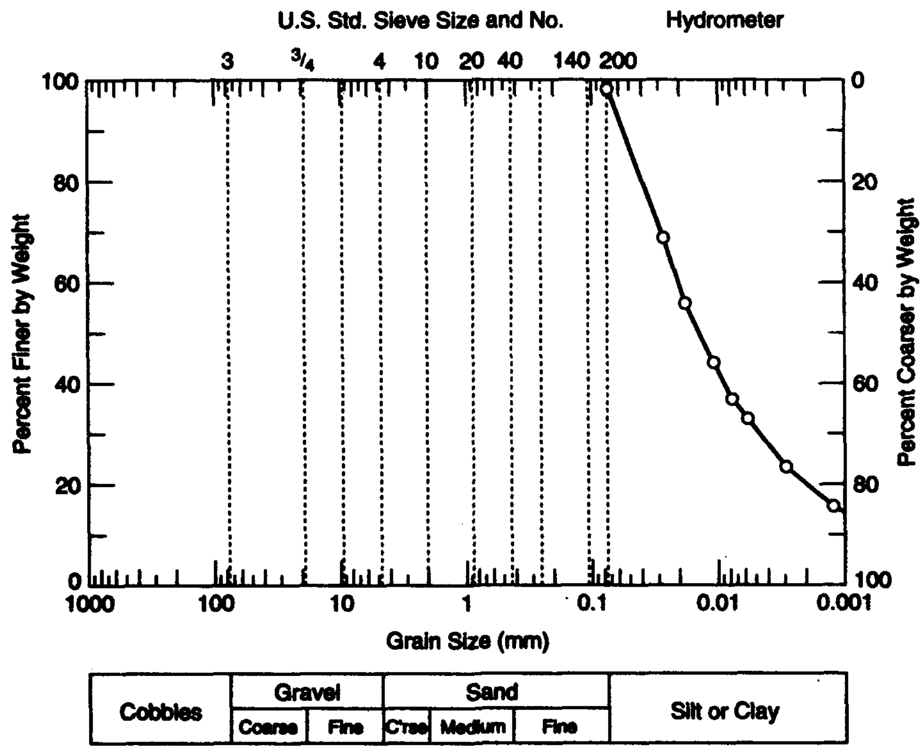


a. Levee.

Figure 10. Representative cumulative curves of grain size distribution for morphological units.

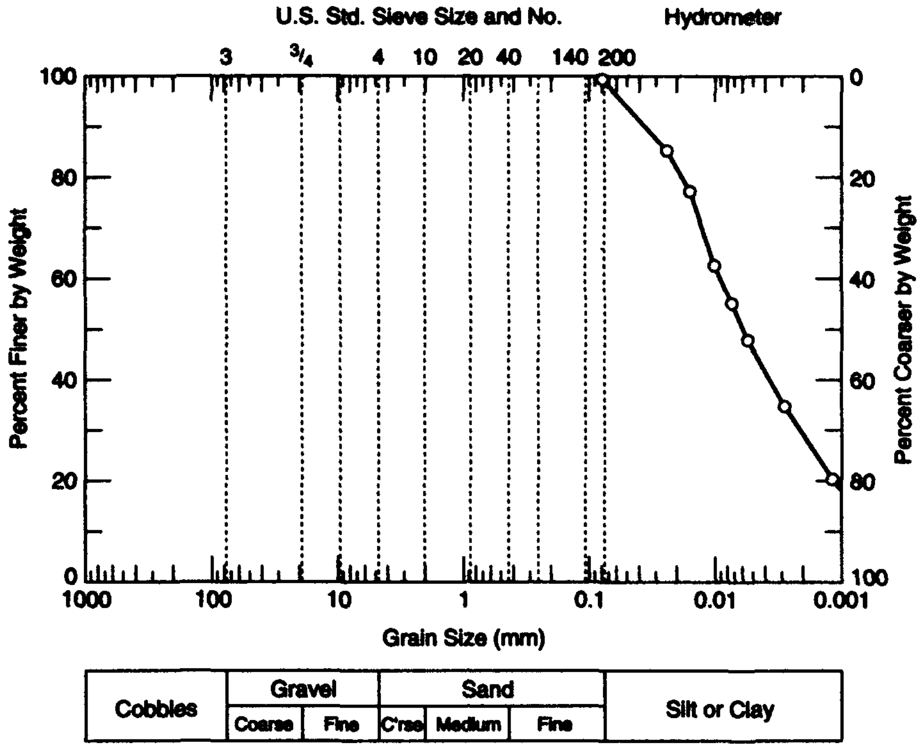


b. Upper vegetated mudflat.

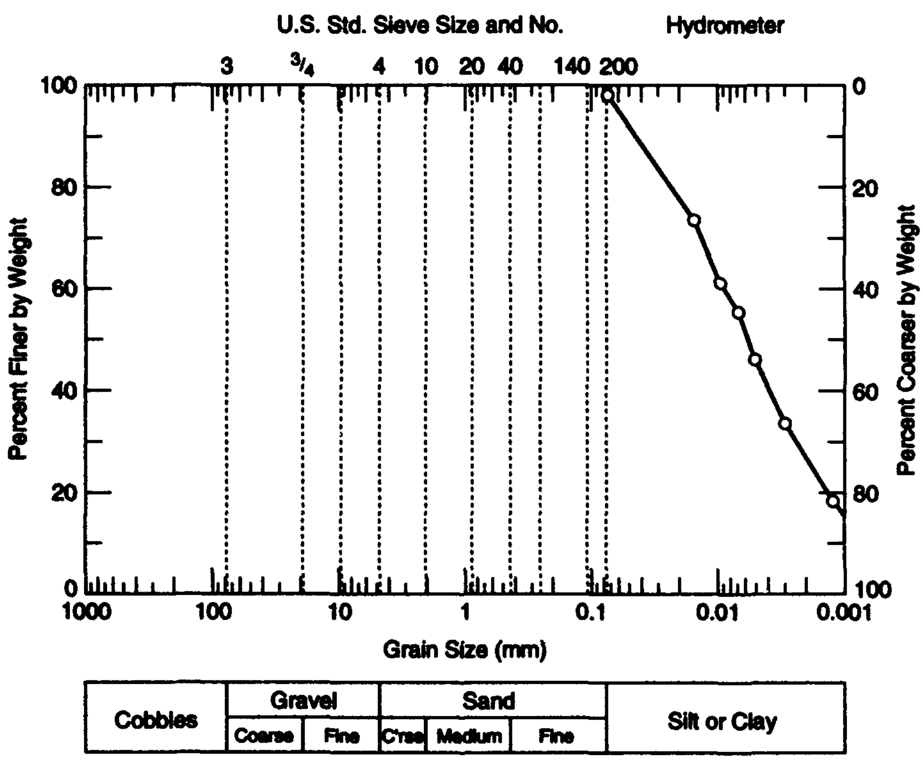


c. Unvegetated mudflat.

Figure 10 (cont'd).

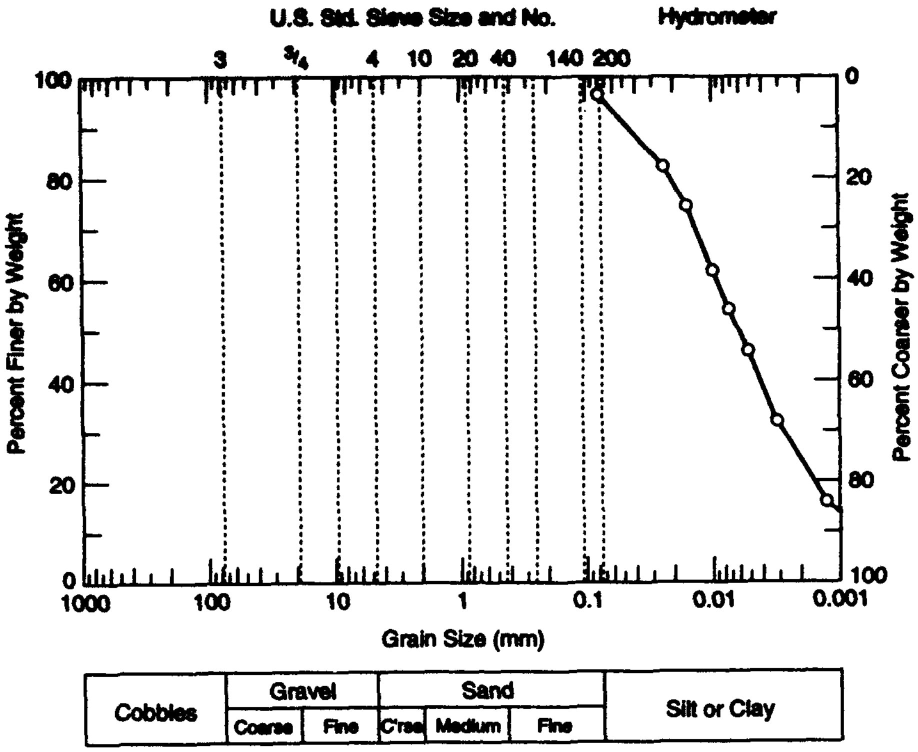


d. Shallow pond center.

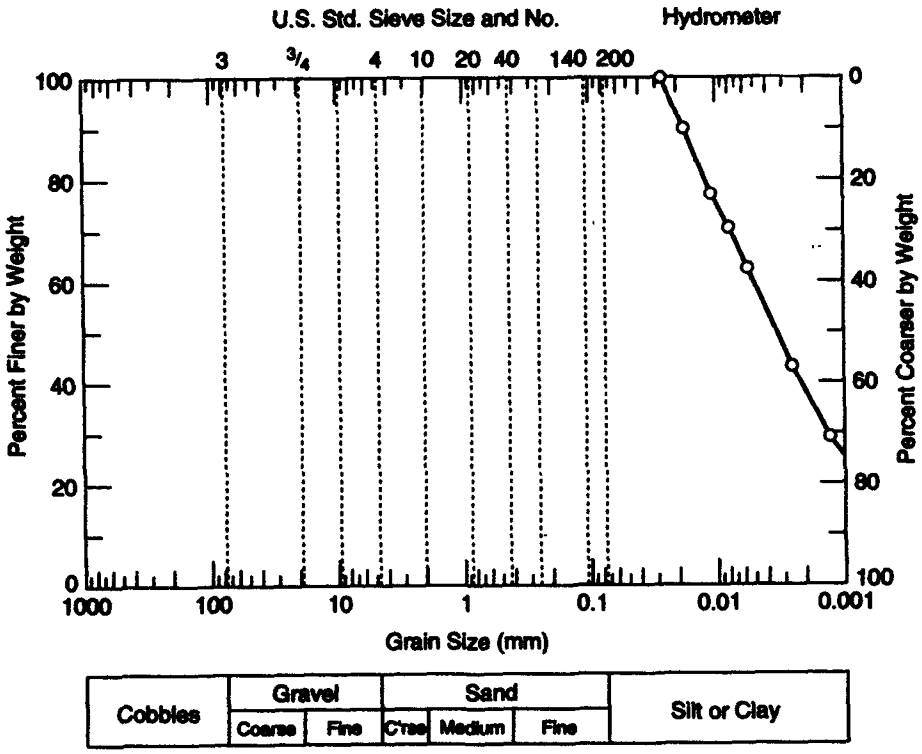


e. Small pond on transect 11.

Figure 10 (cont'd). Representative cumulative curves of grain size distribution for morphological units.



f. Small pond in marsh.



g. C pond.

Figure 10 (cont'd).

Table 1. Depositional processes (summer).

Morphological unit	*Processes*
Ponds	Suspension sedimentation —settling-out —vegetation trapping
Gullies	Suspension sedimentation —settling-out Bedload deposition Sediment flows Slumping
Mudflats	Suspension sedimentation —settling-out —vegetation trapping
Marshes	Suspension sedimentation —vegetation trapping
Levees	Suspension sedimentation —settling-out —vegetation trapping

processes as well, but wind waves and tidal currents during flooding can also erode and suspend mudflat materials. Wind waves and currents coupled with the effects of bottom feeding by ducks and shore birds appear to be the principal mechanisms of erosion and resuspension of bottom sediments in ponds. During ebb, runoff can produce currents that erode unvegetated areas of the mudflats while transporting material suspended in the water column. In contrast, the marshes are apparently rarely affected by erosion because of their dense vegetation cover during summer. We do no know whether winter processes (such as ice shove or freeze–thaw) cause significant erosion in the marshes, ponds and mudflats.

Tidal interactions

The interactions of erosional, transport and depositional processes are complex and their interplay sometimes depends on and is directly related to the tides. The flood cycle normally results in a progressive rise in the water level and gradual flooding of the tidal flats, apparently beginning along the coast first while progressively moving inland up the Eagle River channel and gullies before spilling across the inner mudflats and into ponds. Except during river floods, the levees are the last areas to be inundated. During the ebb, our observations suggest that the drop in water level begins within the coastal mudflats and progresses into the river channel, gullies, ponds and vegetated mudflats, reaching the southernmost parts of the tidal flats and marshes late in the cycle.

While our observations suggest that tidal flooding does not normally cause significant erosion, drainage during ebb apparently causes most gully headwall and lateral wall erosion. Sediments probably become fully saturated during flood inundation, which reduces their mechanical strength and their resistance to shearing, and increases their erodibility. In addition, groundwater discharge from the face of gully walls causes piping and toe erosion as the gullies drain, also increasing slope instability and the potential for failure of these materials.

Because sedimentation results primarily from settling-out of particles in suspension, sediments are deposited in the mudflats during slack high tide and in the early stages of the ebb cycle. In the ponds and marshes, exchange and mixing of tidal waters with marsh waters during inundation increases the amount of sediment suspended in the

Table 2. Erosional processes (summer).

Morphological unit	*Processes*	
Ponds	Wind waves Wind currents Ducks and other bottom-feeding organisms	Tidal currents Debris impacts (e.g., logs)
Gullies	Currents —tidal —discharge (runoff) Overland flow —sheet —rill Wind waves	Groundwater —piping —sapping Slope failure mechanisms —slump —block collapse
Mudflats	Currents —wind —tidal Overland flow —sheet —rill	 Debris impacts (e.g., logs) Rain drops
Marshes	Currents (rare)	
Levees	Currents —tidal —discharge	

water column; it may then deposit sediment uninterrupted from the time of flooding through the ebb and into the next flooding event, some 12 hours later.

Sources

Sediments in both the Eagle River discharge and the tidal waters of Knik Arm originate primarily from glaciers, with major glacial rivers such as the Susitna, Knik and Matanuska transporting sediment in suspension into Cook Inlet. The latter sources of sediment may be important in ERF; Ovenshine et al. (1976a,b) found that the primary sediment source infilling the Portage area tidal flats in upper Turnagain Arm, after it subsided over 1 m during the 1964 Alaskan earthquake, was the Susitna drainage, not the glacial streams that enter the Arm. The accretion rate and any time dependency in it will be affected by the total amount of sediment in transport and its characteristics, particularly grain size, shape and mineralogy. These characteristics are unknown and their role in suspension sedimentation across ERF undefined.

SEDIMENTATION RATES

Gross sedimentation rates across the study area ranged from as low as 1 mm to over 35 mm during 28 May to 22 September 1992. There were four monthly cycles of tidal inundations during this period. On the basis of our estimated tidal elevation of 4.6 m for partial flooding of ponds (a 9.48-m tide), a minimum of 17 sediment-bearing tidal floodings would have entered ponds in the study area. Most of these took place during late July to early August and late August to early September. As stated previously, the number of floodings is based on tidal elevations alone and does not consider the effects of river discharge or wind, which could potentially increase this number. River discharge could not be monitored and its influence on inundation is unknown.

Sedimentation rates vary with respect to morphological unit, and in a general sense, to elevation. The overall trend in rates is an increase eastward from the Eagle River levees, across the mudflats, and into the ponds. Marshes, however, apparently had lower accretion rates than the ponds (Table 3), while within gullies, deposition rates could far exceed these values. Lower sedimentation rates in marshes may reflect problems in sampling within the thick sedges, including an unknown amount trapped in the vegetation, rather than the actual rate of accretion.

Table 3. Gross sedimentation rates, 28 May–22 September 1992.

Morphological unit	*Range (mm)*
Levee	1–2
Vegetated upper mudflat	3–6
Unvegetated lower mudflat	5–12
Pond	18–35*
Marsh	2–10 (est.)
Gully	100–300

*Of this total, an estimated 8 to 16 mm is from material resuspended from pond bottom sediments

Gross sedimentation rates recorded in the pond sites ranged from about 18 to 35 mm for the period, while on levees, rates ranged from only 1 to 2 mm. Sedimentation rates during the single inundation period of 26 August to 2 September—which had the highest tides of the summer, ranging from 9.17 to 10.0 m (Anchorage datum)—varied from a trace (less than 0.2 mm) to 12 mm, with pond sedimentation rates ranging from 7 to 12 mm. During this period, 10 tides exceeded 9.48 m (4.6 m elevation) and apparently entered the ponds. In contrast, levee elevation data suggest that only two tides were sufficiently high to inundate them completely.

Within ponds, the amount of material that originated by resuspension of bottom sediments was estimated using the difference between the cup and plate samplers at each sedimentation site. On this basis resuspension sedimentation ranged from 8 to 16 mm for May to September, or approximately equivalent to the thickness of new sediments deposited in the ponds during the same period. During the late August to early September flooding cycle, 3 to 6 mm of new material was deposited while 2 to 6 mm of material had been resuspended and redeposited.

Within the gullies, deposition involves several processes and occurs mainly along the lateral slopes away from the channel thalweg. Depending on the process, rates could be extremely high, ranging from 10 to 30 cm for the summer period, with several or more centimeters being deposited during a single flood and ebb cycle. These rates, however, primarily reflect adjustments in the gully cross section rather than deposition from tidal flood waters. Mass movements of slope material account for the majority of the sediment deposited on lateral slopes. Sedimentation rates are therefore highly variable from place to place.

Suspension sedimentation within a gully could not be separated easily from that originating by slope movement. Pools within the thalwegs of the gullies, however, derive most of their sediment from suspension and settling out; rates here were similar to or slightly greater than in the ponds.

EROSION AND RECESSION RATES

Erosion of gully headwalls is causing their progressive elongation into the mudflats and, presumably with continued growth, into the ponds. In the study area, headwalls are currently located about 100 to 200 m from the edges of the ponds, depending upon the drainageway selected for measurement.

We measured the composite rates of recession resulting from erosion of the gully headwall and adjacent lateral wall for 28 May to 22 September 1992. The amount of recession of the scarp crests was highly variable within a gully, as well as among the 11 headwall erosion sites (Fig. 11). Maximum rates at each site ranged from 0.2 to 3.9 m, while parts of each monitored headwall did not retreat (Table 4).

The variability in recession reflects the nature of the erosional processes. Recession is mainly caused by erosion by currents and the subsequent failure of the lower, unvegetated part of the near-vertical gully walls (Fig. 12). The uppermost 20 to 30 cm of material is consolidated and root-bound; this soil and root mat is undermined by current erosion and only fails after an approximately 0.5-m or deeper niche is cut below it. Block collapse follows and further action by currents eventually breaks

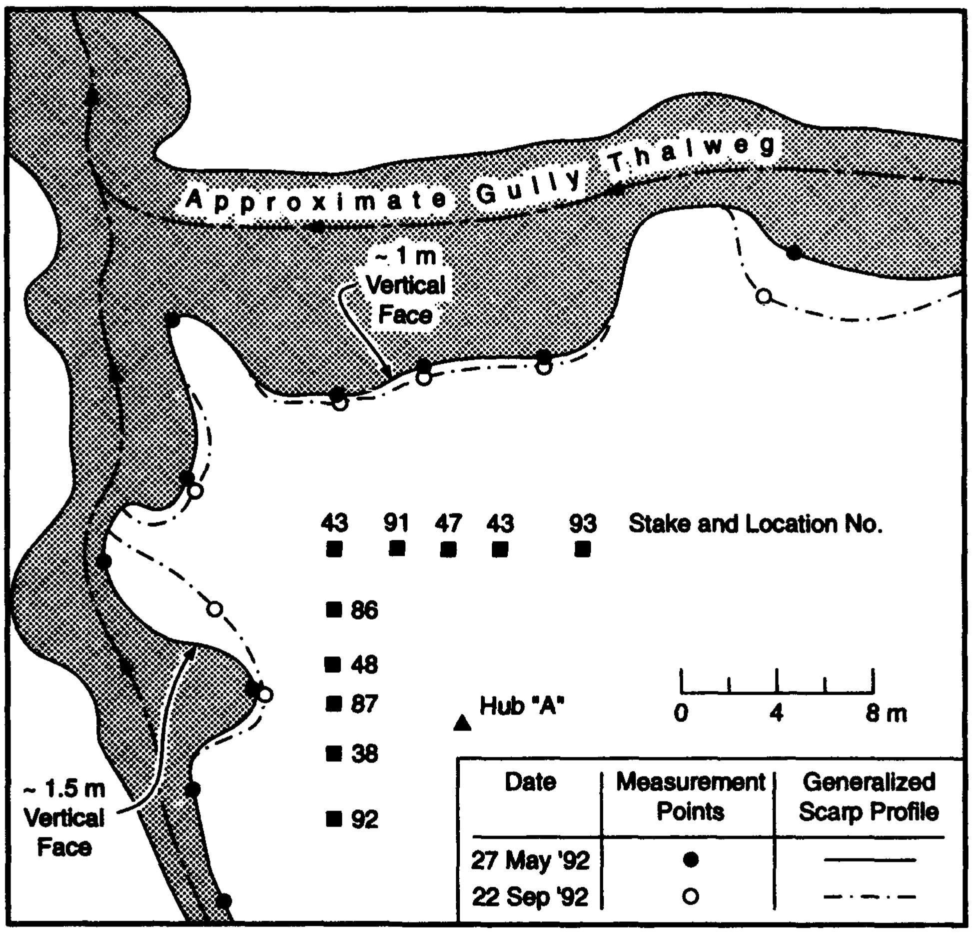


Figure 11. Schematic of gully headwall erosion site illustrating the variability in location and rate of recession common to each of the 11 sites analyzed in 1992 from 28 May to 22 September.

Table 4. Headwall recession rates for 28 May–22 September 1992 (site locations on Fig. 5).

Headwall site	*Recession range (m)*
1	0.05 to 2.1
2	0 to 3.9
3	0 to 0.8
4	0.1 to 3.0
5	0.1 to 1.3
6	0 to 1.8
7	0 to 1.0
8	0 to 0.2
9	0 to 0.5
10	0 to 0.2
11	0 to 0.2

down and removes these materials. In some cases, blocks of rootbound material remain intact as they are later transported downslope by slow moving mudflows that are active in the latter stages of the ebb cycle. Because this sequence of events happens at different times and rates, recession varies within as well as among the study sites. The lateral walls of gullies, which tend to develop lower angle slopes as adjacent headwalls recede, fail mainly by retrogressive slump-flow, the lower half or more of the slope commonly creeping slowly as a mudflow into the gully channel (Fig. 13).

WHITE PHOSPHOROUS PARTICLE TRANSPORT

We obtained 25 samples of sediment from the bottoms of gullies following monthly tidal floodings (Fig. 14). These samples were taken from the most recent deposits within the gully channels, mainly those in pools within the channel thalweg that we thought were deposited from suspension by settling out of the ebb discharge. In some cases, however, these materials may have originated in part from local materials composing adjacent lateral slopes and headwalls of the gullies, rather than the ponds and mudflats.

a. Eroding headwall with undermined, root-bound block above erosional niche and below vegetated channel.

Figure 12. Headwall erosion.

b. Collapsed blocks undermined by erosion.

Figure 12 (cont'd). Headwall erosion.

Of the 25 samples, 3 tested positive for WP at relatively high concentrations (Racine et al., in press). Each of the three positive samples were obtained from the bottoms of thalweg pools and it is therefore probable that they contain suspended material from a recent ebb. These results suggest that WP particles may be in suspended transport in waters draining ERF.

CONCLUSIONS

Our preliminary assessment of sedimentation and erosion in the C and Bread Truck pond areas of ERF during summer of 1992 indicates the following:

1. The physical processes of erosion and sedimentation are complexly interrelated and vary in importance in both time and space.
2. Deposition in ponds and across mudflats results mainly from settling-out of particles suspended in the water column. In gullies, tidal currents and slope processes are primarily responsible for sedimentation.
3. Erosion occurs mainly in the gullies draining the mudflats. The headwalls recede because of toe erosion, erosional niche formation by currents, block collapse of the upper part of the slope, and further erosion by currents. Adjacent lateral slopes retrogressively slump and flow as gully walls gradually reduce from a near vertical orientation to angles of 20° or less.
4. Net sedimentation rates generally increase inland from levees on the Eagle River to pond centers nearer the uplands. Net rates from 28 May to 22 September 1992 generally varied from about 1 to 2 mm on levees, 3 to 6 mm on vegetated mudflats, 5 to 12 mm on unvegetated mudflats and 10 to 19 mm in ponds. Marshes received an estimated 10 mm of net sedimentation, but sampling problems may have affected these measurements.
5. Accretion rates apparently reflect the periods of inundation, these being more frequent and

Figure 13. Laterial gully slope altered by retrogressive slump-flow.

longer in ponds and marshes than elsewhere. In all cases, sedimentation rates are primary; secondary processes of consolidation will significantly reduce this thickness (e.g., Bloom 1984).

6. Pond bottom materials are resuspended by wind currents, wind waves, bottom-feeding waterfowl and other disturbances. Resedimentation rates of resuspended material are estimated at 8 to 16 mm for 28 May to 22 September. It is interesting that this amount approximately equals that of new sedimentation during river and tidal inundation (10 to 19 mm).

7. Recession rates of gully headwalls and adjacent lateral scarps from 28 May to 22 September varied from imperceptible to over 3.9 m, but were highly variable within and among 11 sites.

8. White phosphorous particles may be in suspended transport in ebb waters draining from ponds and mudflats through gullies into the Eagle River. This conclusion is based upon surrogate samples of suspended materials deposited in thalweg pools of gullies that contained significant concentrations of WP.

RECOMMENDATIONS

From the results of this preliminary assessment of sedimentation and erosion, we recommend the following studies:

1. Sedimentation and erosion rates should be measured at an expanded number of locations, employing more accurate sampling techniques for both primary and resuspended sedimentation and should be done annually to include winter processes. Sediment transport rates in the Eagle River and tidal flood waters entering ERF from Knik Arm should be measured. In addition, the number of flooding events and height of tides and river stages causing inundation need to be determined accurately.

These data are required to define annual rates of sedimentation and erosion. Based upon the single summer's data, natural sedimentation rates in mudflats and ponds appear to be significant and could be important in defining treatability. Similarly, high rates of gully erosion and recession may

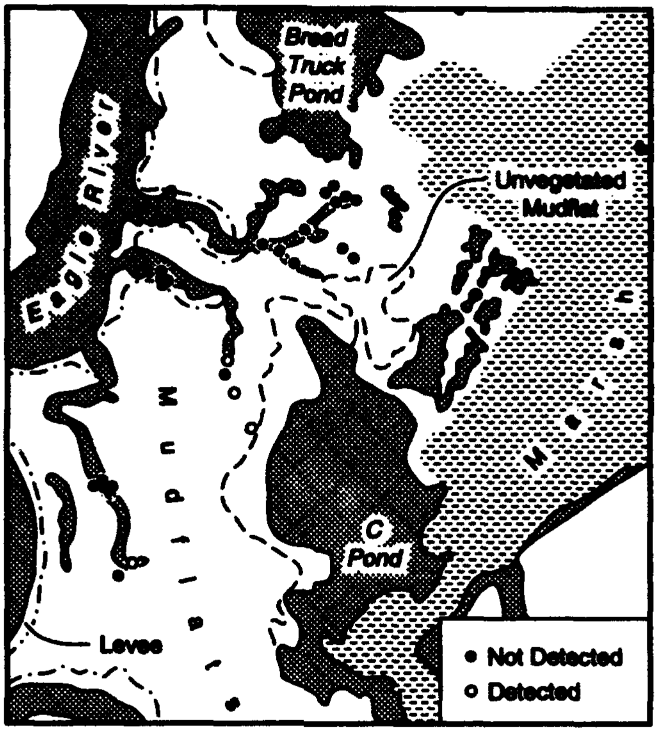


Figure 14. Location of gully samples analyzed for WP content. Three samples from pools within the thalweg tested positive for WP.

affect the viability of treatment methods. At best, the single summer's data presented in this report can only be considered representative of this period. Further analyses through the four seasons are needed.

2. Aerial photographs from the 1940s through the present should be analyzed to define large-scale morphological changes, such as induced by Eagle River migration or the 1964 Alaskan earthquake. The hydrology and drainage patterns as well as the stability of ponds within ERF are affected within a relatively short time by such events. Long-term rates of gully erosion likewise need to be defined. Such changes bear on the strategy used in future treatments.

3. In-situ suspended sediment samples of ebb tidal waters draining through gullies into the Eagle River need to be obtained and analyzed for WP content to determine if WP particles are being eroded and transported by tidal waters. Sediments composing intertidal bars within Knik Arm should also be analyzed to determine if WP particles are being redeposited outside ERF.

LITERATURE CITED

Allen, J.R.L. (1990a) Constraints on measurements of sea-level movements from salt marsh accretion rates. *Journal of the Geological Society London*, **147**: 5–7.

Allen, J.R.L. (1990b) Salt marsh growth and stratification: a numerical model with special reference to Severn Estuary, S.W. Britain. *Marine Geology*, **95**: 77–96.

Allen, J.R.L. (1992) Large-scale textural patterns and sedimentary processes on tidal salt marshes in Severn Estuary, Southwest Britain. *Sedimentary Geology*, **81**: 299–318.

Allen, J.R.L. and J.E. Rae (1988) Vertical salt marsh accretion since the Roman period in the Severn Estuary, southwest Britain. *Marine Geology*, **83**: 225–235.

Bloom, A.L. (1984) Peat accumulation and compaction in a Connecticut coastal marsh. *Journal of Sedimentary Petrology*, **34**: 599–603.

Collins, L.M., J.L. Collins and L.B. Leopold (1987) Geomorphic processes of an estuarine marsh: preliminary results and hypotheses. *International Geo-*

morphology, 1986, p. 1049–1072.

Evans, C.D., E. Buch, R. Buffler, G. Fish, R. Forbes and W. Parker (1972) The Cook Inlet environment: A background study of available knowledge. University of Alaska Sea Grant Program.

French, J.R. (1991) Eustatic and neotectonic controls on saltmarsh sedimentation. In *Coastal Sediments '91* (N.C. Kraus, K.J. Gingerich and D.L. Kriebel, Ed.). New York: American Society of Civil Engineers, p. 1223–1236.

French, J.R. (1993) Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, north Norfolk, U.K. *Earth Surface Processes and Landforms*, **18**: 68–81.

Hanson, H.C. (1951) Characteristics of some grassland, marsh and other plant communities in western Alaska. *Ecological Monographs*, **21**: 327–378.

Harrison, E.Z. and A.L. Bloom (1977) Sedimentation rates on tidal salt marshes. *Journal of Sedimentary Petrology*, **47**: 1484–1490.

Hubbard, J.C.E. and R.E. Stebbings (1968) Spartina marshes in southern England III. Stratigraphy of the Keyworth marsh, Poole Harbour. *Journal of Ecology*, **56**: 707–722.

Kearney, M.S. and L.G. Ward (1986) Vertical accretion rates in brackish marshes of a Chesapeake Bay tributary. *Geo-Marine Letters*, **6**: 41–49.

Keene, H.W. (1971) Postglacial submergence and salt marsh evolution in New Hampshire. *Maritime Sediments*, **7**: 64–68.

Krone, R.B. (1987) A method for simulating historic marsh elevations. In *Coastal Sediments '87* (N.D. Krause, Ed.). New York: American Society of Civil Engineers, p. 316–323.

Letzch, W.S. and R.W. Frey (1980) Deposition and erosion in a Holocene salt marsh. *Journal of Sedimentary Petrology*, **50**: 529–542.

Ovenshine, A.T., D.E. Lawson and S.R. Bartsch-Winkler (1976a). The Placer River Silt: An intertidal deposit caused by the 1964 Alaskan earthquake. *Journal of Research, U.S. Geological Survey*, **4**: 151–162.

Ovenshine, A.T., S.R. Bartsch-Winkler, N.R. O'Brien and D.E. Lawson (1976b) Sediment of the high tidal range environment of upper Turnagain Arm, Alaska. In *Recent and Ancient Sedimentary Environments in Alaska* (T.P. Miller, Ed.). Memoir, Alaskan Geological Society, p. M-1–M-26.

Racine, C.H., M.E. Walsh, C.M. Collins, D. Lawson, K. Henry, L. Reitsma, B. Steele, R. Harris and S.T. Bird (in press) White phosphorus contamination of salt marsh sediments at Eagle River Flats, Alaska. USA Cold Regions Research and Engineering Laboratory, CRREL Report.

Racine, C.H., M.E. Walsh, C.M. Collins, D.J. Calkins, B.D. Roebuck and L. Reitsma (1992a) Waterfowl mortality in Eagle River Flats, Alaska. USA Cold Regions Research and Engineering Laboratory, CRREL Report 92-5.

Racine, C.H., M.E. Walsh, B.D. Roebuck, C.M. Collins, D. Calkins, L. Reitsma, P. Buchli and G. Goldfarb (1992b) White phosphorus poisoning of waterfowl in an Alaskan salt marsh. *Journal of Wildlife Diseases*, **28**(4): 669–673.

Reed, D.J. (1990) The impact of sea-level rise on coastal salt marshes. *Progress in Physical Geography*, **14**: 465–481.

Richard, G.A. (1978) Seasonal and environmental variations in sediment accretion in a Long Island salt marsh. *Estuaries*, **1**: 29–35.

Rosenberg, D.H. (1986) Wetland types and bird use of Kenai Lowlands. Anchorage, Alaska: U.S. Fish and Wildlife Service, Special Studies.

Stoddart, D.R., D.J. Reed and J.R. French (1989) Understanding salt marshes. *Estuaries*, **12**: 228–236.

Small, J.B. and L.C. Wharton (1969) Vertical displacements determined by surveys after the Alaska earthquake of March 1964. The Prince William Sound, Alaska Earthquake of 1964 and Aftershocks. Volume III, Research Studies and Interpretive Results, Geodesy and Photogrammetry (L.E. Leipold and F.J. Wood, Ed.). Washington, D.C.: U.S. Coast and Geodetic Survey, p. 21–33.

Vince, S.W. and A.A. Snow (1984) Plant zonation of an Alaskan salt marsh. II. An experimental study of the role of edaphic conditions. *Journal of Ecology*, **72**: 669–684.

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13. ABSTRACT (*Maximum 200 words*)

The physical processes of sedimentation and erosion within the tidal mudflats and salt marshes of Eagle River Flats (ERF), an area used as an artillery impact range by the U.S. Army since 1945, must be understood to evaluate potential treatments of a high duck mortality resulting from ingestion of white phosphorus (WP) particles. The WP originates from smoke-producing devices detonated here. A preliminary assessment of erosion and sedimentation during May to September 1992 indicates that the physical system is complex and the intensity of these processes spatially variable. Deposition from suspension sedimentation generally varied with morphology and elevation, increasing inland from levees on the Eagle River (1 to 2 mm) across vegetated (3 to 6 mm) and unvegetated (5 to 12 mm) mudflats, and into ponds (10 to 19 mm) and salt marshes (10 mm). Resedimentation rates in ponds ranged from 8 to 16 mm. Recession rates of eroding gully headwalls were highly variable, ranging from negligible to over 3.9 m. White phosphorus particles may be in suspended transport through gullies during ebb. Further studies are necessary to better define annual sedimentation and erosion rates, with improved sampling techniques used at an expanded number of sites. Basic data on tidal inundation, sediment influx and efflux, and WP particle transport are required to develop appropriate treatment methods.

14. SUBJECT TERMS

Alaska	Estuary	Sedimentation
Cook Inlet	Fort Richardson	Subarctic
Erosion	Pollution	Tidal flat

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