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Interagency Expanded Site Investigation

Evaluation of White Phosphorus Contamination and Potential Treatability at Eagle River Flats, Alaska

FY 95 Final Report

Prepared for

U.S. ARMY, ALASKA
DIRECTORATE OF PUBLIC WORKS
William A. Gossweiler, Project Manager

Prepared by

U.S. ARMY COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
David W. Cate and Charles H. Racine, Report Editors

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Table of Contents

OUC 0023935

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CONTRIBUTORS

C. Racine, M.E. Walsh, C. Collins, D. Lawson, S. Bigl, L. Hunter, E. Chacho, R. Haugen, M.R. Walsh, P. Robinson, R. Bailey, J. Mullen
U.S. Army Cold Regions Research and Engineering Laboratory

J. Cummings, J. Davis, P. Pochop, C. Yoder, R. Johnson, K. Gruver, K. Tope
U.S. Department of Agriculture, Denver Wildlife Research Center, Denver, CO

C. Rossi
U.S. Department of Agriculture, Animal Damage Control Center, Palmer, AK

W. Eldridge
U.S. Fish and Wildlife Service, Division of Migratory Bird Management, Anchorage, AK

L. Reitsma, B. Steele
New England Institute for Landscape Ecology, Canaan, NH

B. Roebuck
Dartmouth Medical School, Hanover, NH

Points of Contact:

W.A. Gossweiler
Director of Public Works
600 Richardson Drive #6500
ATTN: APVR-PW-ENV
Fort Richardson, Alaska 99505
(907) 384-3017
(907) 384-3047 Fax

Charles M. Collins
CRREL
72 Lyme Road
Hanover, NH 03755
(907) 353-5180
(907) 353- 5142 Fax

I. EXECUTIVE SUMMARY

INTRODUCTION

This is the sixth annual report (1990-1995) describing the results of white phosphorus contamination studies in Eagle River Flats (ERF), a 865-ha estuarine salt marsh artillery impact range on Ft. Richardson, Alaska. Waterfowl mortality occurs here as a result of ingestion of white phosphorus (WP) particles from artillery smoke rounds. ERF is the first documented case of WP poisoning on a US Army training area, although since then other artillery range training areas have been found to be contaminated with WP. In 1991 and 1992 efforts were focused on determining the nature and extent of WP contamination in ERF and on the monitoring of waterfowl mortality. In 1993 more detailed studies of the problem were initiated:

- WP toxicology studies;
- Invertebrate and fish studies (with no detection of WP effects); and
- Radiotelemetry of ducks, shorebirds and eagles to monitor movement and mortality.

Pilot field treatability studies began in 1993 and were expanded in 1994 and 1995 to include dredging, barriers, chemical repellents, natural attenuation and pond drainage. In 1992 it was determined that although WP has a reputation for being easily oxidized (natural attenuation), it is very stable as a solid particle underwater and in saturated sediments where waterfowl feed. Investigations of physical system dynamics began in 1992 and continued to the present. Waterfowl censusing by aerial survey began in 1989 and have continued to the present.

II. SITE CONDITIONS

II-1. Physical System Dynamics, WP Fate and Transport, and Remediation

Daniel E. Lawson, Lewis E. Hunter and Susan R. Bigl

The focus of these investigations was on the role of the physical system in the burial or transport of white phosphorus in this tidal flat area. Specifically, these investigations evaluated whether the processes of gully erosion, headward recession, and drainage of contaminated ponds, and of burial of contaminated pond sediments, could produce a natural attenuation of WP contamination. The erosion and potential for off-site transport of WP was examined.

Several important conclusions result from this and previous year's work:

- Physical system processes result in the burial and transport of WP.
- Gully erosion and headwall recession will drain areas of contaminated ponds in about 1–10 years, potentially resulting in in-situ WP degradation and attenuation due to drying. This is a cost-effective alternative to artificial pond draining. Historical analyses, field data and process analyses indicate that Bread Truck Pond will probably begin draining in 1 year, while C/D, Lawson's Pond and a large area of C Pond will begin to drain in 10–15 years or less.
- Pond sedimentation rates are high and could, over time, bury WP-contaminated pond sediments to a depth sufficient to prevent feeding waterfowl exposure.
- Natural sedimentation and burial, perhaps artificially enhanced in some locations by introducing additives to increase flocculation, is a cost-effective alternative to the installation of a barrier, particularly in certain pond areas. Gully erosion and extension may subsequently drain and dry these same areas, furthering the permanency of remediation.
- Ice rafting can move WP by plucking it from the bottoms of contaminated ponds and moving it to other areas.

- WP in sediments is eroded from ponds and drainages by ice and water and subsequently transported by currents into the Eagle River and possibly off-site (Knik Arm), where its fate is unknown. Contaminated sediment is also transported to other locations within ERF.
- Racine Island Pond has neither high gully erosion and headward recession rates, nor high sedimentation rates. This pond also floods at relatively low tidal heights and contains organic-rich sediments. It appears, therefore, that it can only be effectively remediated and readily restored through artificial drainage and temporary berm containment to permit long-term drying and in-situ WP degradation.

Based on the investigations to date, the following recommendations are made:

- Cost-effective remediation can be accomplished to a significant degree by allowing the physical system to remove or isolate WP contamination over time.
- WP contamination of Bread Truck Pond and 50% or more of C Pond, including potentially Lawson's Pond in the long term, should be treated by natural or enhanced drainage and subsequent in-situ WP degradation by drying.
- Sedimentation and burial of WP may be effective in removing it from feeding waterfowl in the short term; in the long term, burial will reduce waterfowl mortality during natural pond drainage in the C, Lawson's and C/D pond areas.
- Racine Island Pond may be effectively remediated by gully extension, artificial pond drainage and pumping, and long-term containment with a temporary berm to permit in-situ WP degradation by extended drying of pond bottom sediments. By simply removing the berm after WP has attenuated naturally, the pond environment will be restored.
- Erosion and recession rates, pond sedimentation, groundwater, pond drainage and drying, and WP degradation and attenuation should be monitored to ensure that remediation is taking place as predicted by physical system analy-

ses and to assess ecosystem impacts of artificial remediation techniques during feasibility studies and remediation.

- WP migration and contamination in Knik Arm should be evaluated, focusing on areas of near-shore zones and mid-Arm bars where there is a potential for WP exposure to receptors.
- The potential for natural attenuation of white phosphorus as the result of mechanical abrasion during transport by gully and tidal currents should be evaluated.

II-2. Climate and Tides

Richard K. Haugen

Weather and tidal activity provide the driving forces for physical and biological processes in the Eagle River Flats area. A meteorological site was installed at the edge of the EOD pad in May 1994. This station has provided a basis for climatic comparisons with Anchorage and other study locations at ERF. Data obtained at the EOD meteorological site included air, ground and surface temperatures, incident and reflected solar radiation, relative humidity, wind speed and direction, and precipitation. A comparison with the 1994 season (May–September) shows that the seasonal average temperature during 1995 was about the same but that precipitation during the 1995 season (250 mm) was over twice that of the 1994 season.

A comparison of 1995 air temperature data for 30 May to 29 October between the EOD site, ERF coastal site and Anchorage showed Anchorage to be warmer than EOD by 2.3°C, and EOD to be warmer than the ERF Coastal Site by the same amount. The 1994 ERF report showed the coastal site to be warmer than the EOD site but it is now apparent that daily *maximum* temperatures were used to represent the coastal site in the 1994 analysis, rather than the daily average temperatures. The –2.3°C difference found with the 1995 data between the EOD pad site and the coastal site should be considered representative.

Data analysis includes discussion of relative humidity, wind speed and air and ground temperature at the EOD site, together with solar radiation. Comparisons between net solar radiation, soil surface temperature and soil moisture measurement are shown graphically. Evapotranspiration rates for the ERF area and for historical time series were calculated. An existing computer program was used to calculate evapotranspiration with different methods, depending on the amount of available input data. Anchorage Summary of the Day records were obtained back to 1952 to calculate historical means and extremes for the summer season for a large number of parameters. Time series of tidal flooding gaps using three flooding heights, precipitation, and estimated evapotranspiration were developed for the growing seasons of 1995–2000. These data should be useful for planning research and remediation activities.

III. RISK ASSESSMENT AND FOOD CHAIN EFFECTS

III-1. Waterbird Utilization of Eagle River Flats and Upper Cook Inlet: April–October 1995

William D. Eldridge and Donna G. Robertson

Aerial surveys were flown over Eagle River Flats from April to November 1995. Thirty-seven surveys were flown with a single-engine, fixed-wing aircraft using standard USDI methodology. 1995 was a wet year in upper Cook Inlet, so ponds were full most of the season. Fall temperatures were mild, which delayed migration through upper Cook Inlet. Numbers and species of waterbirds counted on ERF were similar to other years, dominated by dabbling ducks and Canada geese, particularly in fall. Utilization of standard study areas within ERF by waterbirds was recorded and presented by season.

Other marshes in upper Cook Inlet were surveyed in 1995 to compare to ERF. These included Palmer Hay Flats, Goose Bay, Susitna Flats, Trading and Redoubt Bays and Chikaloon Flats. Twenty-five surveys were conducted from April to May. More than 90% of the waterbirds counted were found on marshes other than ERF during the season. Waterbirds concentrated on broad intertidal mudflats in marshes other than ERF, Goose Bay and Palmer Hay Flats, where this habitat type is poorly represented. Species composition of waterbirds was similar on all areas. Numbers by species and area are presented by season.

III-2. Waterfowl Use and Mortality at Eagle River Flats

Benjamin B. Steele and Leonard R. Reitsma

The objectives for 1995 were to monitor waterfowl mortality at ERF, measure mortality in an uncontaminated reference area, measure mortality in noncontaminated areas of ERF, and evaluate mortality in swans. Mortality at ERF was compared to previous years to monitor decreasing exposure of ducks to white phosphorus from either remediation efforts or natural processes. We measured mortality in uncontaminated reference areas to develop a background level of mortality so that mortality rate at ERF can be used as a measurement endpoint. Mortality was measured by the same methods used since 1992. Counts of carcasses on permanent transects were compared to the number of ducks exposed, calculated from censuses made each morning. Mortality on reference areas was measured by the same method.

The mortality rate at ERF during fall 1995 was lower than in fall 1994. This decline continues a trend that has been seen since 1992, when the mortality rate was approximately ten times higher than in 1995. The fact that the mortality rate decreased in 1995 despite an increase in exposure rate shows that this decline does not result from hazing or other activity on the Flats. Rather, ducks are less exposed to white phosphorus because of natural attenuation, sedimentation on top of contaminated pond bottoms, or high water causing ducks to feed in noncontaminated areas.

The mortality rate in spring was very low but could not be compared statistically to previous years because of a low exposure rate and because no carcasses were found on transects. Only one carcass was found on transects in reference areas in Goose Bay and Susitna Flats. Thus, background mortality may be as much as one tenth that currently occurring at ERF, but more data are needed to accurately measure background mortality. We found only one carcass on transects in uncontaminated areas of ERF (areas B and D). These areas still do not represent a hazard to ducks. Five swan carcasses were found, mostly before swans had been observed in contaminated areas. These deaths raise the possibility that swans ingest white phosphorus in areas thought to be safe for ducks: area D, area B or the pond in area C/D. Swans feed in deeper water than ducks and may be exposed in different areas than ducks are.

The fact that the mortality rate continues to decline before full-scale remediation has begun suggests that the no-action alternative may be sufficient to remediate at least some areas of ERF.

III-3. Analysis of White Phosphorus in Biota at Eagle River Flats, 1995 Field Season

Bill D. Roebuck

Tissues from animals found dead on Eagle River Flats during 1995 were analyzed for white phosphorus to help confirm the cause of death. A total of 31 animals were examined: 30 birds and 1 coyote. The coyote did not contain WP. Of the birds, approximately 20% did not have WP in their tissues. These birds (six in total) are either individuals that died of other causes (some of which may be natural causes, or individuals in whom the WP dissipated prior to their ultimate death.

III-4. Movement, Distribution and Relative Risk of Waterfowl and Bald Eagles Using Eagle River Flats

John L. Cummings, Christi A. Yoder, Richard E. Johnson, Patricia A. Pochop, Kenneth S. Gruver, James E. Davis and Kenneth L. Tope

This project determined the spatial distribution, movements, turnover rate and mortality of waterfowl and bald eagles using Eagle River Flats during fall migration, August 1 to October 17, 1995. Eighty-two ducks and 14 bald eagles were captured on ERF using various techniques. Of the waterfowl, 17 mallards, 16 northern pintails and 21 green-winged teal were fitted with radio transmitters. Of the 14 eagles, 8 were fitted with satellite transmitters, the others with standard transmitters. Waterfowl transmitters were programmed to be on from August to November 1995, and again from April to June 1996. Eagle transmitters are expected to last 24 months. Tracking data indicated that transmitters did not appear to inhibit the movements or activities of either ducks or bald eagles. Daily waterfowl movements indicate that all species moved among areas quite readily. Mallards spent about 60% of their time in areas B and A; pintails spent about 87% of their time in areas A, C/D and D; and teal spent about 63% of their time in areas A and D. After the hazing program was started, waterfowl use patterns changed on ERF. The average number of days spent on ERF by mallards, pintails and teal was 40, 46 and 27 days, respectively. The average daily turnover rate for waterfowl was about 3.8%. The greatest turnover of waterfowl occurred prior to September 5 where 47% mallards, 37% pintails and 43% teal departed ERF. The mortality of instrumented ducks using ERF from August 1 to October 17 was five ducks, or about 9%. Most of the telemetry contacts with eagles, excluding the two nesting birds, indicated that eagles spent an average of 1.4 days on the Flats. Instrumented eagles were only observed in areas A, C and C/D during the spring and A and C/D during the fall. The nesting success of eagles on ERF did not differ significantly from eagles nesting on Susitna or Chickaloon Flats. Eagles on ERF produced an average of 1.3 eggs and fledged an average of 0.33 eaglets. No adult eagle mortality has been documented from instrumented birds, even though eagles scavenge dead ducks (which has included instrumented ducks).

IV. TREATABILITY STUDIES

IV-1. Hazing at Eagle River Flats

Corey Rossi

Hazing of waterfowl from ponds contaminated with white phosphorus was conducted during both the spring and fall migrations. The hazing operations was successful, as ADC observations, DWRC telemetry work and waterfowl surveys by NBS and NEILE all indicated a dramatic decrease in waterfowl numbers in hazed areas compared with those of unhazed areas on ERF.

IV-2. Evaluation of AquaBlok™ on Contaminated Sediment to Reduce Mortality of Foraging Waterfowl

Patricia A. Pochop, John L. Cummings and Christi A. Yoder

The results of a study conducted in 1994 by covering the bottom of a pond indicated that AquaBlok™, a physical barrier to foraging waterfowl, could reduce mortality of waterfowl when applied to a WP-contaminated pond up to 0.5 ha in size. The objective in 1995 was to continue to evaluate the effectiveness of this barrier. Emergent vegetation growing through or on the AquaBlok™ recovered from 45% in 1994 to 76% in 1995. In 1991 (before application), vegetation cover in the pond was only 52%, indicating that there was no adverse impact of the AquaBlok™ on the vegetation. Analysis of AquaBlok™ indicated that WP concentration varied from below the detection limit to 0.02 mg/kg (mean = 0.01 mg/kg) of WP and was probably contamination from the sediment below the barrier. No mortality of waterfowl was observed during a second year of AquaBlok™ exposure to weather and tide events. AquaBlok™ thickness was reduced by 0–5 cm from values in 1994. However, this was largely influenced by heavy traffic (animal and human) and limitations in the sampling method. Tide plots indicated that erosion and movement of AquaBlok™ were lowest on Racine Island, where vegetation was important in stabilizing the barrier.

IV-3. Intrinsic Remediation of WP Particles in Intermittent Ponded Areas of ERF

Marianne E. Walsh, Charles M. Collins and Ronald N. Bailey

Natural attenuation of WP particles appears to be occurring at a highly contaminated site (Site 883) in the intermittent pond of Area C. When 41 samples were taken at this site in the fall of 1995 at the same locations as 41 samples in the fall of 1992, the number of samples with WP concentrations greater than 10 µg/g declined from four to zero, and the number of samples below 0.001 µg/g has increased from 15 to 28. In addition the number of WP particles at this site has decreased; in 1992, when 270 mL of sediment from this site were sieved, over 100 WP particles were isolated. In 1995, 1000 mL of sediment were sieved using the same procedure, and only one WP particle was found. Sediments at this site were desaturated during the summers of 1993 and 1994 when weather conditions and the length of time between flooding tides were favorable for pond shrinkage. During 1995, flooding tides occurred monthly, and sediments at this site were continually under water.

Samples were also obtained from the crater produced from the detonation of a WP UXO in 1992. The crater is also in the intermittent pond of Area C. The rim of the crater, which had a WP concentration of nearly 1000 µg/g when sampled in 1992, had concentrations of 0.0051 and 0.0006 µg/g when sampled in June and September 1995. The bottom of the crater, which is 32 cm below the rim, still has high concentrations of WP. The bottom of the crater was exposed in 1993 and 1994, but for much shorter lengths of time then the rim. WP particles were isolated by sieving 1000 mL of sediment from the crater bottom, and over 100 particles were found, most of which were less than 1 mm in length. WP particles were also isolated from a permanently saturated site on Racine Island. While most of the WP particles isolated were also less than 1 mm in length, several large particles (greater than 2 mm) were also found, with the largest particle measuring 6.6 mm in length. Such large particles were absent from sites in the intermittent ponded areas. We hypothesize that when sediments are exposed and desaturate, the smallest WP particles are the least persistent and disappear relatively quickly since small particles have large surface-to-volume ratios and sublimation occurs from the particle surface. Larger particles are much more persistent but shrink during periods of desaturation.

IV-4. Enhancement of Intrinsic Remediation of WP Particles by Sediment Warming in Intermittent Ponded Areas of Eagle River Flats

Marianne E. Walsh, Charles M. Collins and Ronald N. Bailey

This task was to study the enhancement of reduction of WP particles in intermittent ponded areas by sediment warming. The most important condition for loss of WP particles from ERF sediments is desaturation of the sediments, which occurs in summers with long periods between flooding tides. A secondary factor is sediment temperature. Since the vapor pressure of WP increases exponentially with temperature and oxidation is more likely at higher temperatures, loss of WP particles can be significantly accelerated by warming unsaturated sediments.

A field study was performed to test the effectiveness of passive solar warming techniques on increasing sediment temperature and promoting the loss of planted WP particles. One technique tested was the application of black sand to change the surface albedo. Also tested were two types of synthetic row covers (a spun-bonded polyester and a porous polypropylene) commonly used in agriculture. The row covers transmit short-wave (300–2500 nm) solar radiation and trap long-wave radiation (4000 nm) from the sediment surface, producing a greenhouse effect. Sediment temperatures were monitored at a depth of 5 cm, and all three treatments slightly increased the sediment temperatures relative to the controls. Because of monthly flooding tides during the summer of 1995 and frequent rainfall during July, August and September, sediments were saturated except for a few days prior to the June flooding tides. None of the treatments appeared to significantly inhibit evaporation during this brief period of favorable drying conditions. The amount of time when sediments were unsaturated was so short that most WP particles remained essentially unchanged, except for a few particles under one of the row covers and one particle in the control plot. These results show that row covers are a tool that may be used to raise sediment temperatures, but attention must be focused first on enhancing desaturation of the sediments using methods such as temporary pond drainage.

A laboratory experiment was also performed using a more aggressive method to heat sediments with planted WP particles. The purpose of the experiment was to test the hypothesis that heating the sediments would increase the vapor pressure of the WP sufficiently to initiate oxidation, which in turn would generate heat to sustain continued sublimation and oxidation after the outside heat source was removed. To test this hypothesis, unsaturated sediments were equilibrated at 13°C (typical average temperature for ERF sediments during the first part of June), and then a hot air gun was used to heat the sediments briefly to 40°C. Then the sediments were cooled to 13°C and WP particles were recovered. This treatment failed to rapidly remove WP from the sediments. The average WP mass remaining in the heated sediments was not significantly different from the control, indicating that a longer period of heating would be necessary to accelerate WP loss. However, the energy requirements for prolonged heating in situ would be prohibitive.

Given that intrinsic remediation is occurring in some parts of ERF in areas that naturally desaturate, ways to enhance natural drying should be employed where possible before active methods of raising sediment temperatures.

A third task was to study the reduction in size of WP particles following pond drainage. This was conducted in conjunction with the pond drainage treatability study by C.M. Collins. Along a transect through the intermittently and permanently flooded areas of the Bread Truck Pond, WP particles were planted in May at a depth of 5 cm, and the sediment moisture and temperature were monitored at 5- and 10-cm depths at sites. Because of procurement delays, the pond was not drained and sediments remained saturated throughout the summer.

A fourth task was to study the reduction in size of WP particles in dredge spoils. This was conducted in conjunction with the dredging treatability study by M.R. Walsh. To determine if the moisture levels and temperatures of the spoils reach those conducive for decontamination, monitoring sites were set up at four locations within the basin, and when dredging was completed for the season in September, WP particles of known mass were placed at known locations. The residue from these particles will be recovered next spring.

IV-5. Pond Draining Treatability

Charles M. Collins, Edward F. Chacho, Jr., Michael R. Walsh and Marianne E. Walsh

The overall objective of this treatability study was to assess if pond draining is a viable option for remediating the WP-contaminated Bread Truck Pond in Eagle River Flats. To achieve that objective several tasks were undertaken to determine if pond draining was technically feasible and what environmental conditions occur in the pond-bottom sediments following draining. Task 1 was to determine the environmental conditions in the BT Pond before and after temporarily lowering the pond level by using a pump system. We installed instrumentation at eight sites along a transect through the intermittently and permanently flooded areas of the Bread Truck Pond to measure the sediment moisture and temperature monitored at 5- and 10-cm depths in the pond bottom sediment. We also continuously measured the water surface elevation of the pond. WP particles were planted in May at a depth of 5 cm at each site to monitor any reduction in size. Because of procurement delays for the pumping system, the pond was not drained and sediments remained saturated throughout the summer.

Task 2 was to design, procure, deliver and install in the BT pond a large dewatering pump system to be used to temporarily drain the BT pond. Design specifications of the integrated pump and generator system were initiated in January 1995. We specified an integrated system consisting of a 2000-gal/min electric-powered pump mounted on a float platform. A diesel-powered electrical generator to power the pump was mounted on a separate float platform. Integrated controls allowed automatic control of the generator and automatic startup and stopping of the pump system, controlled by float switches that would cycle the pump as the pond emptied or started to refill. Once funds became available, the requisition process was initiated in March 1995. Procurement problems delayed the award of the sole-source contract for the purchase of the system until July. During the first week of September the contractor completed the pump system and conducted a performance test at the contractor's facility in Montana. After the final tests, the pump system was shipped by truck to Anchorage, arriving on 12 September. Because the delivery of the pump system occurred so late in the season, the pump was not deployed to the Bread Truck pond. Instead we deployed the system in Clunie Inlet to completely test the system and to run the generator for the initial 40-hour break-in period. This allowed us to check fuel procedures and fuel consumption rates and to ensure that all sensors and controls were operational. Initially we had some problems getting the controls to start the pump. It turned out that a control wire connection had come loose during transport and a fuse in the control panel blew after the loose wire shorted out. After we repaired the wire and replaced the fuse, the system was started normally. Water was pumped for approximately seven hours a day for five days until the generator had the required forty hours of running time on it. Following the completion of the test, the system was pulled out, the discharge line disassembled and the components shipped back to Ft. Richardson DPW for winter storage.

Task 3 was to determine the rate of surface water inflow into the C/D area from the adjacent uplands and how that rate of inflow might influence the BT pond. Two instrumented sites were installed in the C/D area in early June to monitor water conditions. One site was located at the eastern edge of the C/D area next to the upland border along the shore of a deep narrow pond running parallel to the upland border. The second site was located at the far western end of the pond system that extends through the C/D area toward the BT pond, perpendicular to the first pond and the upland border. These two sites were instrumented to monitor pond water levels as well as water temperature, salinity and specific conductance. Seven additional sampling sites were located along two transects, one parallel to the upland boundary and one perpendicular to the boundary. At these sampling sites, periodic water salinity and temperature measurement profiles of the water column were made and water quality samples taken. The measurements showed that a prism of fresh water discharged from a series of small springs and seeps along the upland border slowly displaced the brackish water that filled the ponds in this area after a flooding high tide. The formation and extension of the prism of fresh water as it rides over and displaces the brackish water could be seen in the weekly measurements of the water temperature and salinity of the water column at seven measurement sites. From the measurements, rates of inflow of fresh water were estimated. A model of freshwater flow was used to estimate a maximum volume of the freshwater inflow in the two connected ponds after 20 days of approximately 10,615 m^3. This equates to 530 m^3/day of fresh water produced by runoff, seeps and springs along the 445-m total length of upland boundary bordering the pond system. This is equivalent to 0.0061 m^3/s, or only about 1/20 the pumping capacity of the pumping system to be installed in the BT Pond, indicating the system would be more than capable of keeping up with freshwater inflow from the C/D area. Because of the unusually wet summer this year, with above-average rain from July through September, this discharge rate is probably higher than during an average summer.

IV-6. Dredging as a Remediation Strategy for White-Phosphorus-Contaminated Sediments at Eagle River Flats

Michael R. Walsh

This project covers the second deployment of the dredging system and the various factors involved in dredging and remediation of the spoils. This season's work can be divided into three categories: continued investigation of the hydrological properties of the Retention Basin, dredge operations, and initiation of the attenuation study in the Basin.

The hydrological studies of the Basin liner were conducted in mid-June. They consisted of constant-head percolation tests, in-situ density tests and moisture content tests. The percolation tests were run over a period of up to nine days.

While most tests indicated a percolation rate below the acceptable level of 10^{-6} cm/s, one test exceeded that level (<5 × 10^{-6} cm/s). However, the overall performance of the liner was sufficient for us to judge it acceptable for use again this year. In addition, moisture content and densities were tested near the percolation tests to complete the characterization of the Retention Basin liner. Moisture contents ranged from around 30% to around 70%. Densities generally ran around 0.9 g/cm^3 (55 lb/ft^3).

Some erosion had occurred around the concrete splash pad at the spoils line outlet, so a wooden weir was constructed along one side and flow channels around the remaining sides were blocked with stones. Finally, the geotextile silt fence at the drop inlet structure was subjectively checked with a knife to assure integrity. It was left it in place and covered with a tarp to reduce exposure to UV rays. Later problems with low supernatant salinity levels forced us to forego the use of the silt fence due to clogging problems.

Continued problems with the dredge equipment and the unique environment at the Flats precluded full operation of the dredge until September. At that time, the slurry pump had been reconfigured, the dredge sensors reprogrammed, the electrical work finished, spoils line repaired, the boom box removed, a new grate system installed on the dredgehead, and the lateral winch deadmen anchored. During dredge operations, 160 spoils-line soil samples and 23 supernatant (water) samples were obtained and analyzed, with a total of 26 soil sample WP hits and one water hit. The average concentrations were 6.16 and 4 µg/kg for the soil and water sample hits, respectively. Approximately 1650 m^3 of material was dredged from Clunie Inlet and Area C between and adjacent to Clunie and Canoe Points. Using the results of the analysis of the spoils, about 1420 lethal doses of WP were removed during dredging (based on a 37% mallard, 37% pintail, 26% teal mix). The fine particle size of the suspended solids in the supernatant diminishes the lethality of any WP returned to the Flats.

The attenuation study was initiated and some data obtained from the instrumentation installed in the Retention Basin. Six particles were planted in partially dewatered spoils in four locations, two adjacent to instrumentation stations, on 28 September. The dataloggers were allowed to operate until 7 December. At that time, the temperature was well below zero and the spoils had frozen solid. Only partial drying of the sediments occurred before freeze-up, so definitive data will not be collected and analyzed until next spring.

Due to equipment problems, It was not possible to dredge the entire 0.85-ha area that had been planned. However, by the end of the season, the dredge system was operating reliably and effectively. The ability of the dredge to remove contaminated material from the Flats has been demonstrated, although the cost will be high. The performance of the Basin as a remediation structure should be determinable by next July.

IV-7. Development of a Remotely Controlled Drilling and Sampling System for the Remediation Program at Eagle River Flats

Michael R. Walsh

The goal of this project was to develop, build, test and deploy a remotely operated drilling/coring platform for use in the Flats to assist in the study of remediation efficiencies for these projects. A market survey, including visits to manufacturers, was conducted and the capabilities of various equipment configurations discussed. Additional discussions were held with drilling experts at CRREL in NH and Alaska. From these discussions, a set of specifications was developed and bid requests sent out through the Ft. Richardson contracting office for a small, light-weight mobile drill.

Concurrent with this contracting effort, the U.S. Army Tank Automotive Research Development and Engineering Command in Warren, MI, was tasked to develop, build and test a remote-control system for a vehicle similar to the carriers used with the drilling systems reviewed. A 6 × 6 vehicle was available for this purpose and sent to TARDEC as a test bed. Specifications for a remote camera system were also developed and a system ordered.

Contracting delays resulted in the awarding of the contract on 22 July, with an early September delivery date. This precluded any meaningful work at the Flats for the 1995 season, but through a superb effort by TARDEC, a working, tested system was delivered to the Flats on the 28 September. The drill unit is now in storage at Ft. Richardson, ready for a spring deployment for the 1996 field season.

The drilling of the EOD Pad wells also faced daunting contracting delays, but were drilled and installed the last week in September. Seven wells, each 6 m deep by 10 cm in diameter, were placed at the corners and down the middle of the EOD Pad. As work had ceased before completion of the wells, no attempt was made to instrument the wells with depth sensors. A groundwater sampling plan will need to be developed prior to sampling for chemical analysis.

The final task was to develop a remote-controlled coring machine for use in the Flats. This was to be a follow-on to the drill machine. Due to the delays in the drill project, development of the coring unit is delayed until FY 96. Work has been initiated in conjunction with TARDEC on retrofitting an M501 Hawk missile loader for this task using carry-over funds.

In summary, it was a frustrating field season two of the three tasks came very close to completion but were foiled due to contract delays. The only positive aspect to this situation is that a wet field season and contract delays in other programs resulted in the equipment not being needed as much this season as it will be next season. With the wells in place, a full season's data can be collected during next year's dredge deployment.

V. THE EAGLE RIVER FLATS SPATIAL DATABASE

V-1. The Eagle River Flats Spatial Database

Charles H. Racine, Peggy Robinson and John Mullen

This report describes the construction, use and contents of the Eagle River Flats (ERF) GIS (geographic information system) database. The purpose of the database is to help make and document decisions concerning the designation of WP "hotspots" to be treated, the selection of treatment methods to be used, and the success of the clean-up effort. At present, the database is designed primarily to identify hotspots to be treated, using a waterfowl risk assessment-exposure framework. The database includes both GIS coverages in ARC/INFO and/or ARCVIEW and tabular spreadsheet data residing on computers in the CRREL ERF GIS lab. Sharing of this database with other groups was initiated in an attempt to conduct analyses and make crucial decisions concerning hotspot location and waterfowl risk assessment. The database was originally started in 1993 to show the features of ERF (waterbodies, tidal gullies, vegetation-habitat, boundaries and craters) in relation to sediment and water samples, collected and analyzed for white phosphorus.

Much of the ERF GIS database effort during 1995 centered on the entry of waterfowl census, telemetry and mortality data, collected over the past three to four years, to locate areas where waterfowl use and therefore exposure to WP (if present) is high. In addition, the database for WP samples was updated and rebuilt to make analyses easier. The primary coverages include ERF natural features, white phosphorus sampling data (for 2549 point samples), waterfowl mortality sampling (1254 carcass point locations monitored in 1992, 1993, 1994 and 1995), waterfowl population aerial and ground censuses (1994 and 1995) and radiotelemetry locational data for 127 radio-collared ducks, 14 eagles and 20 shorebirds (1993, 1994 and 1995). About 39 primary coverages compose the master ERF GIS database.

Secondary coverages are also listed and may be important for future decisions at ERF. These include sedimentation-erosion studies, remediation tests, water quality and weather monitoring sites and GPS ground-truth data. To help accomplish the selection of appropriate clean-up method technologies, researchers will need to supply criteria for determining where their technologies would and would not work. The third decision concerning evaluation of clean-up success involves the design of endpoint criteria to be entered into the database.

II-1. PHYSICAL SYSTEM DYNAMICS, WP FATE AND TRANSPORT, AND REMEDIATION

Daniel E. Lawson, Lewis E. Hunter and Susan R. Bigl

U.S. Army Cold Regions Research and Engineering Laboratory

INTRODUCTION

Eagle River Flats (ERF) is a 865-ha tidal flat and salt marsh at the mouth of Eagle River on the Knik Arm, northeast of Anchorage, Alaska (Fig. II-1-1). The tidal flat has been used as an artillery impact range since the early 1940s. Previous work by CRREL has shown that an unusually high mortality of migratory waterfowl, particularly ducks, is attributable to the ingestion of elemental white phosphorus (WP) particles (Racine et al. 1992a,b). White phosphorus particles were introduced by smoke-producing compounds in devices detonated during military training (Racine et al. 1992a, 1993). WP is now present as particles and adsorbed to near-surface sediments at numerous locations in ERF, most notably in pond and marsh bottom sediments where dabbling ducks ingest it during feeding. In addition, WP-bearing sediment can be remobilized and transported to other locations within or external to ERF where it is redeposited (Lawson et al. 1995a) and may pose a threat to unidentified receptors.

ACKNOWLEDGMENTS
Funding and support for this research was provided by the U.S. Army Alaska, Environmental Resources Department, Directorate of Public Works, Fort Richardson, Alaska, through the Alaska Engineers District, Anchorage, Alaska. We thank William Gossweiler, Douglas Johnson, William Smith and Laurie Angell for helpful discussions, logistical support and assistance in the field, and their continuing support of our work, as well as Dr. Charles Racine, Charles Collins and Marianne Walsh for numerous scientific discussions and assistance in the field and laboratory on the Eagle River Flats project. We also thank Troy Arnold, Ron Bailey, Dennis Lambert, Beth Nadeau and Pat Weyrick for their assistance, Jodie Strasser and Audrey Krat for data analysis and plotting and Cora Farnsworth for her contribution in preparing this report.

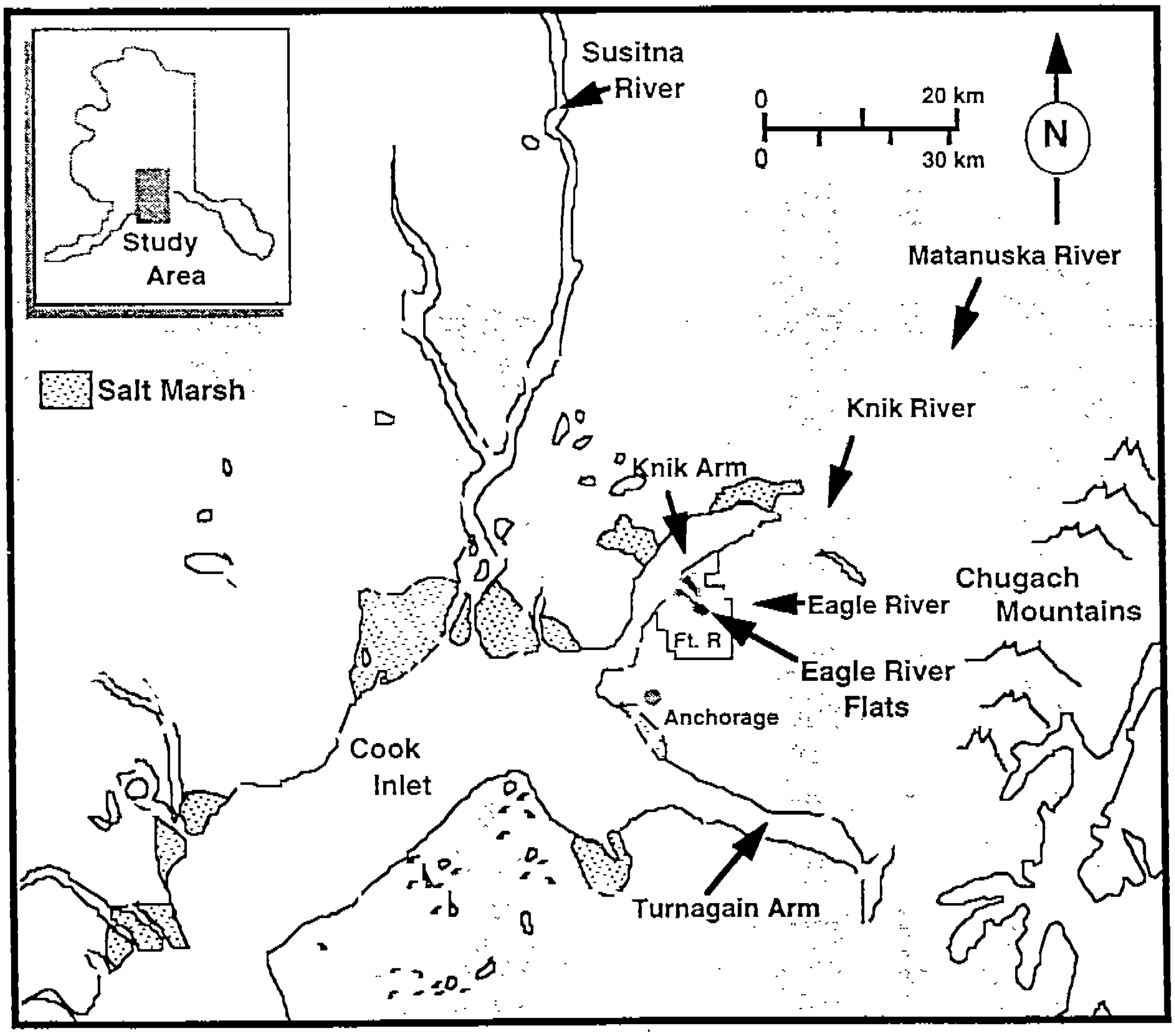


Figure II-1-1. Location of ERF and other salt marshes in upper Cook Inlet.

This report describes the results of 1995 investigations of the physical ecosystem of the Eagle River Flats and its role in the natural attenuation or intrinsic remediation of white phosphorus contamination. These studies included analyses of the tidal and river hydrology and associated factors critical to evaluating proposed remedial technologies for WP contamination. Our studies in 1993 and 1994 (Lawson et al. 1995a, b) suggested that the physical system, and specifically the processes of erosion and recession of gullies draining the contaminated ponds and mudflats, and the sedimentation within ponds, could both result in a natural attenuation and remediation of WP contamination over a significant portion of ERF. Therefore in 1995, we focused our efforts on understanding the rates at which these processes would alter the pond environments and result in removal or blockage of the WP pathway to migrating waterfowl. We also examined WP erosion and transport to further evaluate the potential for off-site migration of WP.

ENVIRONMENTAL CONDITIONS

Eagle River Flats is one of several estuarine tidal flats and salt marshes in the upper Cook Inlet region of south-central Alaska (Fig. II-1-1). Located at the mouth of the Eagle River, ERF is about 2.8 km wide at the coast and narrows inland. This subarctic region has a transitional maritime to continental climate, with moderate annual temperatures (daily mean 1.9°C; minimum mean –2.2°C) and precipitation (330–508 mm; Evans et al. 1972). Inundation results from both the semi-diurnal macrotidal fluctuations of 9–11 m in Knik Arm and the resultant overflow from the Eagle River as it meets the rising tide.

The Eagle River drains a 497-km^2 basin in the Chugach Mountains, 13% of which is covered by glaciers that significantly modify the runoff and sediment yield of the drainage basin (e.g. Lawson 1993). Glaciers modify peak discharges, the timing and volume of hourly, daily and seasonal discharges, the lag between precipitation and the resultant increase in runoff, and long-term trends in annual discharge of the basin (e.g. Gurnell and Clark 1987, Lawson 1993). Because of this glacial influence, maximum and peak discharges usually occur during the primary melt season of July and August. Sediment transport and sediment flux have diurnal, seasonal and annual variations caused primarily by glacial meltwater influx into the river basin (Lawson 1993). Massive quantities of silt- and clay-size particles are transported in suspension by the large rivers draining into Cook Inlet from glacierized basins in the Alaska Range, Chugach Mountains and Kenai Peninsula (e.g. Susitna, Knik and Matanuska River basins, Fig. II-1-1).

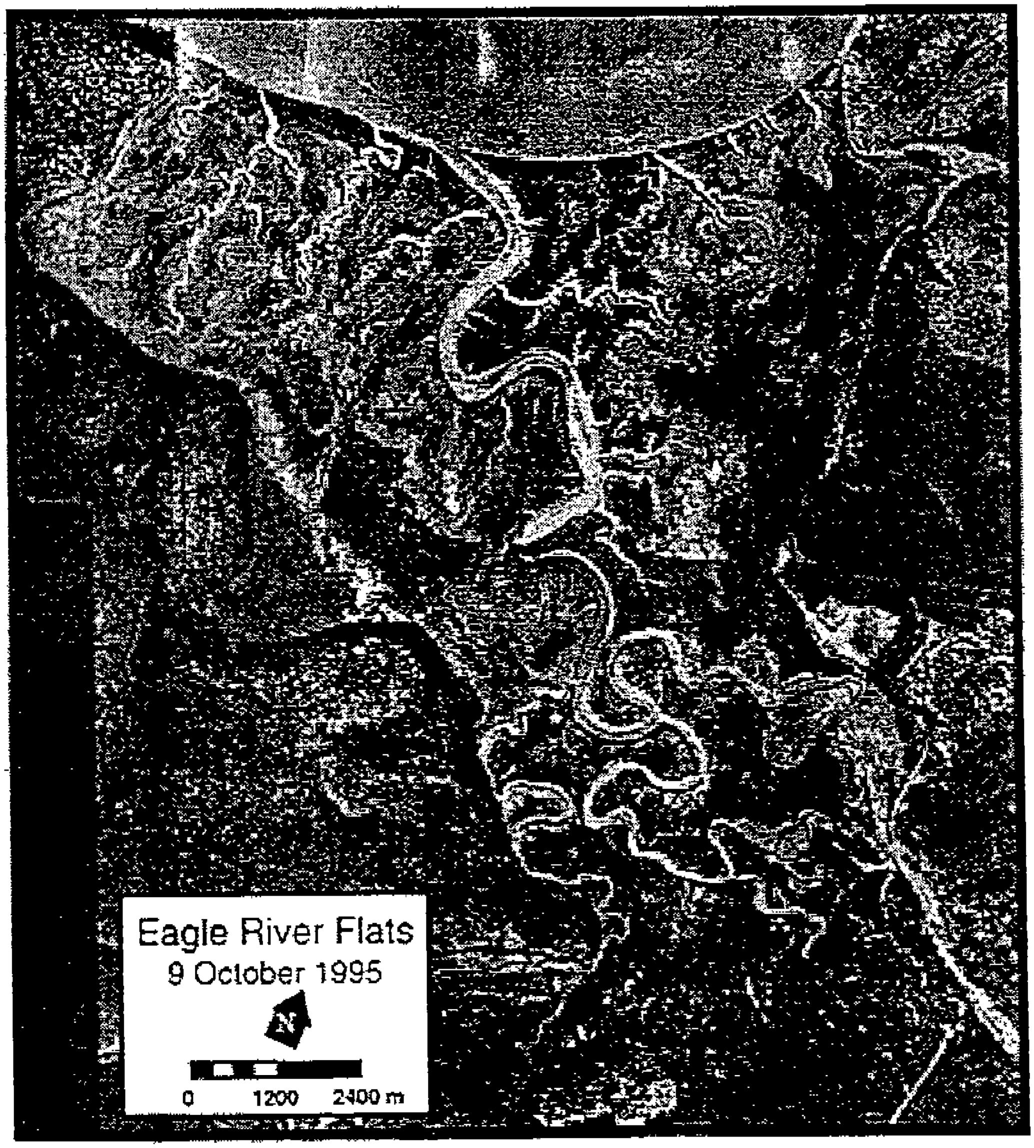


Figure II-1-2. 1995 aerial photograph of ERF showing the dendritic drainage network.

These materials remain suspended for an extended time and are transported into intertidal wetlands during tidal inundation (Lawson et al., in review).

The Eagle River cuts approximately through the middle of ERF, with the primary drainage from ponds and marshes occurring through vegetated channels or drainageways and unvegetated tidal gullies that form a dendritic network (Fig. II-1-2). Where gullies and drainageways do not follow a dendritic course, their location appears to be controlled by relict drainage networks abandoned during evolution of ERF (Fig. II-1-3). The northern and coastal 20% of ERF is

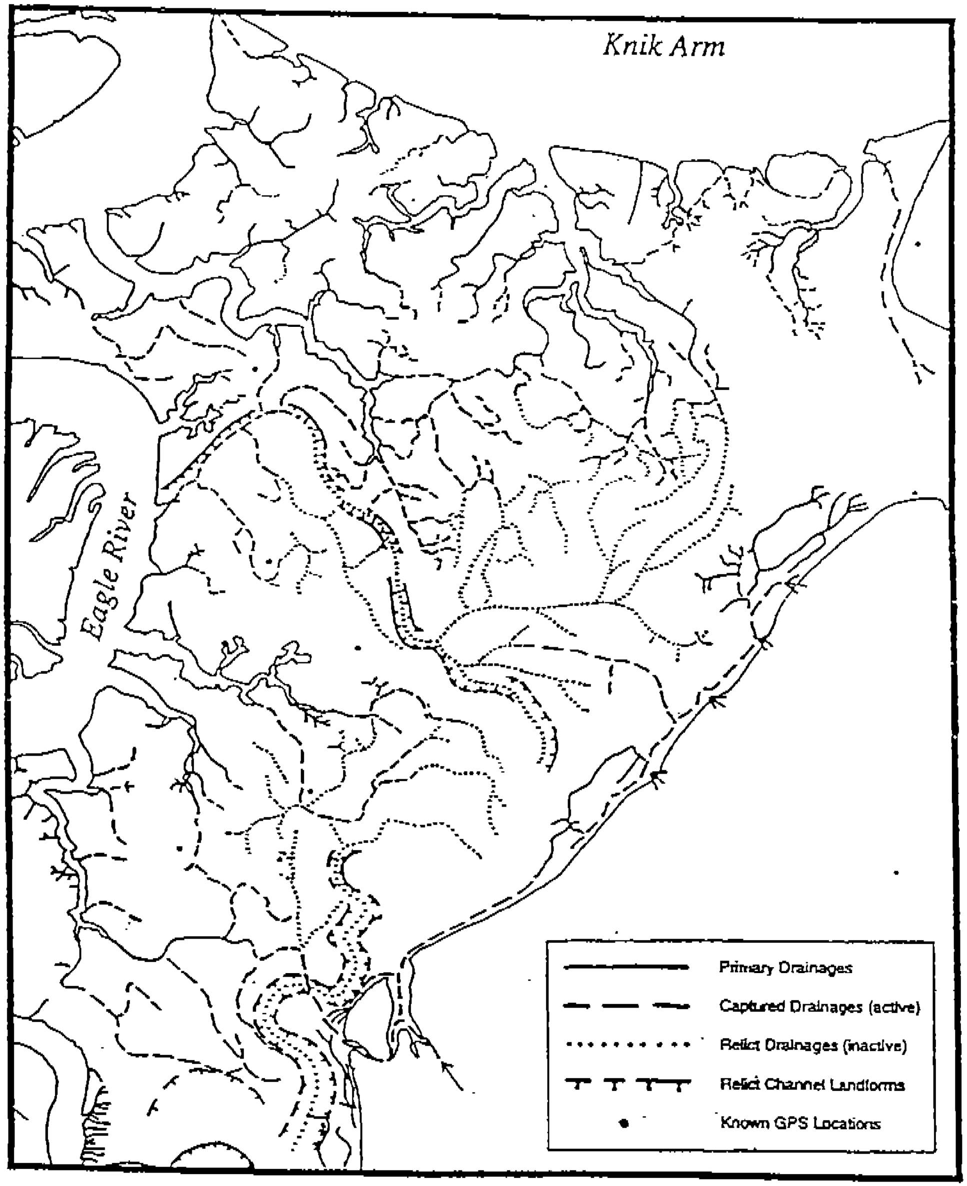


Figure II-1-3. Drainage network in the C and D areas of ERF.

drained through gullies that discharge directly into Knik Arm. The east, west and southern boundaries of ERF are defined by uplands composed of glacial deposits covered by spruce and birch forests.

As with other estuarine salt marshes in Cook Inlet (e.g. Hanson 1951, Vince and Snow 1984, Rosenberg 1986), vegetation occurs in zones that are commonly determined by elevation and related to the landforms of ERF (Fig. II-1-4). This relationship is believed to be a function of flooding frequency, drainage capacity and sedimentation rates. Levees, mudflats, marshes and shallow ponds (to 50 cm depth) are aligned approximately parallel to the Eagle River and coastline (Racine et al. 1992a). Freshwater ponds or shrub bogs lie along the northeast and southwest portions of the upland bordering ERF.

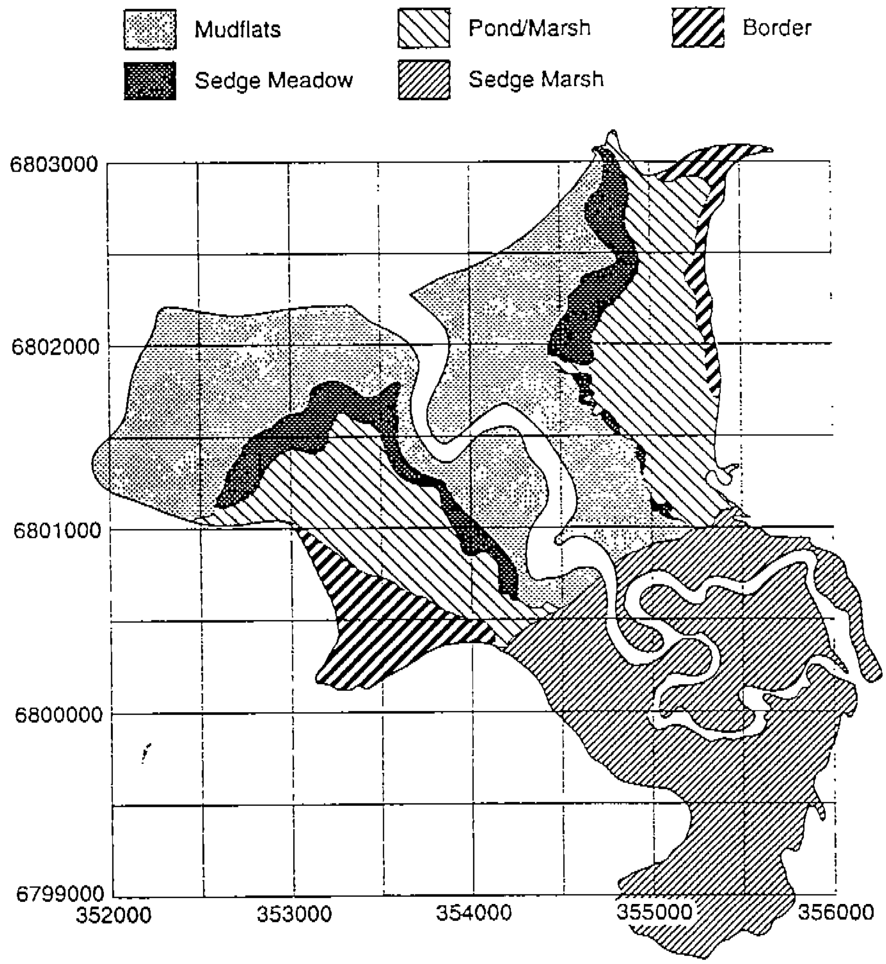


Figure II-1-4. Distribution of primary landform-vegetation units (from Racine et al. 1993).

RESULTS OF PREVIOUS PHYSICAL SYSTEM INVESTIGATIONS

Previous investigations have focused on characterizing the processes and factors affecting the physical environment of ERF (Tables II-1-1– II-1-4) and evaluating the fate and transport of WP, both critical to developing a conceptual model and the remedial technologies required for clean-up. Results of these investigations are summarized here.

Table II-1-1. Factors/controls on physical processes.

Factor
Internal
River
Tides
Glacial sediment/water sources
Substrate material properties
Vegetation
Sediment influx/efflux
Weather/climate
Human activity
Ground water conditions
External
Earthquakes
Tectonic activity
Eustatic sea level rise
Isostatic rebound
Subarctic climate
Glaciers
Surface and ground water systems

Table II-1-2a. Summer erosional processes.

Morphological unit	*Processes*	
Marshes	Currents (rare)	Wind waves (rare)
Ponds	Wind waves Wind currents Ducks and other bottom feeding organisms	Tidal currents Debris impacts (e.g., logs) Bioturbation
Gullies	Currents -tidal -runoff Overland flow -sheet -rill Wind waves	Ground water -piping -sapping Gravitational slope processes -slump -block collapse -sediment gravity flow
Mudflats	Currents -wind -tidal Overland flow -sheet -rill	Debris impacts (e.g., logs) Rain drop impact Bioturbation
Levees	Currents -tidal -river	Debris impacts Wind waves
Coast	Current scour Wind waves	Debris impacts Overland flow

Table II-1-2b. Winter erosional processes.

Morphological unit	*Processes*
Marshes	Ice plucking
Ponds	Freeze-on and ice plucking Ice shove Ice scour
Gullies	Plunge pool undercutting Freeze-thaw cycling Ice segregation and thaw Ice directed current scour
Mudflats	Ice plucking Ice shove (floating/expansion) Ice scour Ice cover confined scour Freeze-thaw cycling
Levees	Ice scour Freeze-thaw cycling Ice shove Ice-directed current scour
Coast	Ice plucking Ice shove (floating/expansion) Ice scour Ice block confined scour Freeze-thaw cycling Current scour Wind waves

Table II-1-3. Transport processes.

Summer processes	*Winter processes*
Currents (river)	Ice floes
Suspended load	Freeze-on
Bed load	Freeze-in
Saltation	Ice shove
Wind Currents (pond/mudflats)	Frazil Ice
Suspended load	Anchor ice
Bed load	Freeze-on
Gravitational slope processes	Freeze-in
Currents (tidal/gully)	
Flood	
Ebb	
Groundwater	
Piping	

Table II-1-4. Depositional processes.

Morphological unit	*Summer processes*	*Winter processes*
Ponds	Suspension sedimentation -settling-out -vegetation trapping	Ice entrapment and in situ melting
Gullies	Suspension sedimentation -settling-out Bedload deposition Sediment gravity flows Slumping	Ice growth entrapment and in situ melting Ice cover confined settling out
Mudflats	Suspension sedimentation -settling-out -vegetation trapping	Ice freeze-on and in situ melting Snow filtering and in situ melting Ice growth entrapment and in situ melting Ice cover confined suspension settling
Marshes	Suspension sedimentation -vegetation trapping	
Levees	Suspension sedimentation -settling-out -vegetation trapping	Ice freeze-on and in situ melting (sediment/organics) Snow filtering and in situ melting Ice growth entrapment and in situ melting Ice cover confined suspension settling out

The processes of erosion, transport and deposition vary seasonally, annually and over decades in response to a number of internal and external factors (Table II-1-1). Their relative importance and magnitude may also vary spatially across ERF in response to these same factors. The role these factors play in determining physical process relationships remains under investigation; previous work on process relationships are described in more detail in Lawson et al. (1995b).

External controls (Table II-1-1) on the physical system are difficult to define because their effects may last several decades or more and exert considerable control on internal factors that influence process relationships. In particular, tectonic and earthquake activity are virtually impossible to predict; however, their impact on the ERF physical system may be enormous. Eagle River Flats was affected by the 1964 Alaskan earthquake (magnitude 8.9 on the Richter Scale), with both sedimentary and tectonic subsidence modifying the site's elevation over time and thus the processes operating therein (e.g. Ovenshine et al. 1976a, Combellick 1990, 1991, 1994, Brown et al. 1977, Savage and Plafker 1991). A tectonic drop of about 0.6–0.7 m was recorded in the Anchorage region (Brown et al. 1977). Sedimentary subsidence caused by sediment liquefaction and solidification during the earthquake probably reduced the pond bottom elevations as it did in the Portage area of Turnagain Arm (Ovenshine et al. 1976a). Following the 1964 earthquake, about 20 cm of post-seismic uplift occurred by 1975 (Brown et al. 1977); Savage and Plafker (1991) have estimated that uplift is continuing at 1.0 mm/yr. Long-term responses of the physical system to these elevational changes are unknown; however, the increase in pond water depth and extent may have increased pond sedimentation rates (e.g. Ovenshine et al. 1976a), while tidal flat hydrology may be responding to the disequilibrium caused by tectonic uplift of this area, or the increase in flooding related to a larger influx of tidal waters because of the overall subsidence of the Flats (Atwater, 1996, personal communication).

Internally, tidal and river water dynamics control the amount of material available for deposition in ERF and affect the locations and rates of erosion. The amount of sediment transported in flood waters is a primary factor in determining the erosion and transport of sediments during ebb (Tables II-1-2 and II-1-3). The transport capacity changes seasonally with variations in glacial input and ambient air temperature. During winter months, sediment and water discharge in the Knik, Matanuska, Susitna and Eagle River catchments decreases. Flooding tides become less diluted and their temperature is depressed, resulting in a net increase in water density and transport capacity. The result is an increased ability for flood waters to erode and transport sediment during the late fall and early winter, although the total volume of material available for transport may be reduced.

Water level changes from tidal inundation show a 20- to 40-minute delay in peak tidal flood height across ERF, in the Eagle River and at the coast relative to that predicted at Anchorage. The flooding height of the delayed tide is also generally 0.5 m or more greater than the Anchorage datum, reflecting at least in part the funneling of water out of Cook Inlet into the narrower Knik Arm. Tidal flooding of the Bread Truck, C, A and Racine Island areas may be enhanced seasonally by the discharge of the glacially fed Eagle River, particularly by snowmelt and precipitation in the river's watershed. In contrast, inundation along the coast is a function of tidal height, which may be influenced by the direction and velocity of the wind, ice cover, and storm-driven surges in Knik Arm, and discharge characteristics of the Knik and Matanuska rivers.

Tidal current measurements indicate that velocities are higher during ebb than during flood, and thus sediment transport and channel erosion are potentially greatest during ebb. Peak velocities in 1994 ranged from about 0.8 to 1.9 m/s and varied from site to site and with the elevation of tidal flooding. The velocity variations reflect differences in gully width, depth, roughness and network configuration.

The Eagle River provides access for tidal waters to inundate the innermost reaches of the Flats. Stage and discharge of the Eagle River are affected by high tides that increase river stage by tidal damming. Damming locally increases depositional rates as flood waters become slack. Sedimentation in the northern two-thirds of ERF is tidally dominated, whereas the southern one-third appears to be river-dominated. Tidally dominated sedimentation ranges from several mm per year on levees, 10–15 mm/yr on mudflats, and up to 20–40 mm/yr in ponds. Sedimentation at the head of ERF appears to be in the form of an alluvial fan (Fig. II-1-5), indicating that deposition here is mainly derived from overbank flooding of the river.

Suspended sediment concentrations measured in 1994 in the Eagle River, tidal gullies draining the ponds and mudflats, and Knik Arm indicate that most of the sediment is derived from Knik Arm tidal waters. The total suspended solids (TSS) in waters of ERF vary with tidal stage, location, source and season. The glacially-fed Eagle River varies seasonally from peak TSS values of 100–700 mg/L between break-up in May and freeze-up in October. Two seasonal highs apparently occur annually, the first during snowmelt runoff and the second during the peak glacial melt season. In contrast, TSS of Knik Arm water ranges from about 1000 to 2800 mg/L from May to October. During a tidal cycle, TSS measurements at gully sites increase steadily through the flooding tide and decrease at a slower rate during the ebb. Seasonally, TSS values in gully and Knik Arm waters increased from spring to fall; the cause of this increase is unknown.

Gullies are actively extending into the mudflats and ponds in the Bread Truck, C, A, D and C/D (Lawson's pond) areas. Headwalls and adjacent lateral walls receded at variable rates ranging from 0.1 to 4.9 m during summer 1992, 0.4 to 6.3 m during winter 1992-93, 0.0 to 9.8 m during summer 1993, 0.0 to 2.3 m in winter 1993-94, and 0.0 to 2.6 m in summer 1994. Large tidal flooding events in 1993 and 1994 caused the highest headwall recessional rates. Two gully headwalls, one on the west side of Bread Truck and the other near the pond complex between Bread Truck and C ponds, are advancing at a rate sufficient to cause increased drainage of those ponds within 15–20 years at mean rates during 1993-94.

Surveyed longitudinal profiles of tidal gully thalwegs revealed non-uniform gradients that reflect their progressive and episodic elongation into the mudflats and ponds, and a lack of equilibrium with present conditions and factors. Gully gradients are relatively steep near their mouths, but are reduced in the lower and mid-reaches of the gully. Channel gradients again steepen in the upper most reaches below a nearly vertical headwall that ranges in height from 1 to 2.5 m. Incipient drainageways from ponds and mudflats into tidal gullies exhibit very low gradients. Several sharp increases in gradient (knick points) occur in each gully, marking channel adjustment as the tidal gully progressively extends into the mudflats and ponds.

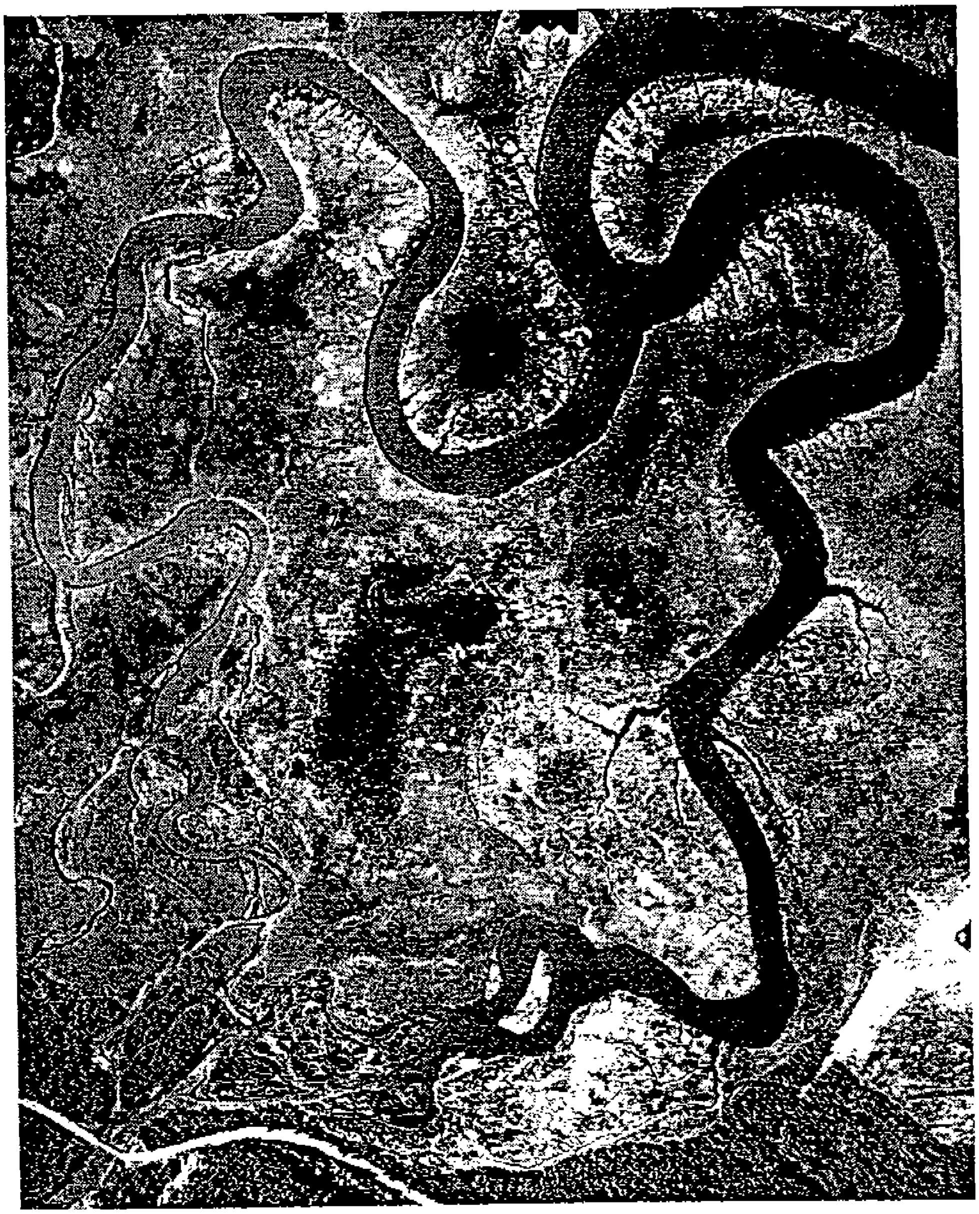


Figure II-1-5. Aerial photograph of Racine Island taken 16 August 1995 showing remnant channel surrounded by overbank deposits.

Aerial photographs from 1950, 1967 and 1993 reveal changes in the distributary channel pattern entering ERF (Fig. II-1-6). Three main channels entered the Flats in 1950, but by 1967 the western most channel was abandoned and the eastern and middle channels diverged just northeast of the Route Bravo bridge. The two primary channels entering the Flats were characterized in 1967 by partial braiding and a divergent pattern characteristic of an alluvial fan (Fig. II-1-6b). Deposits in the fan area are relatively featureless overbank materials deposited by

a. 1950.

Figure II-1-6. Aerial photographs of ERF.

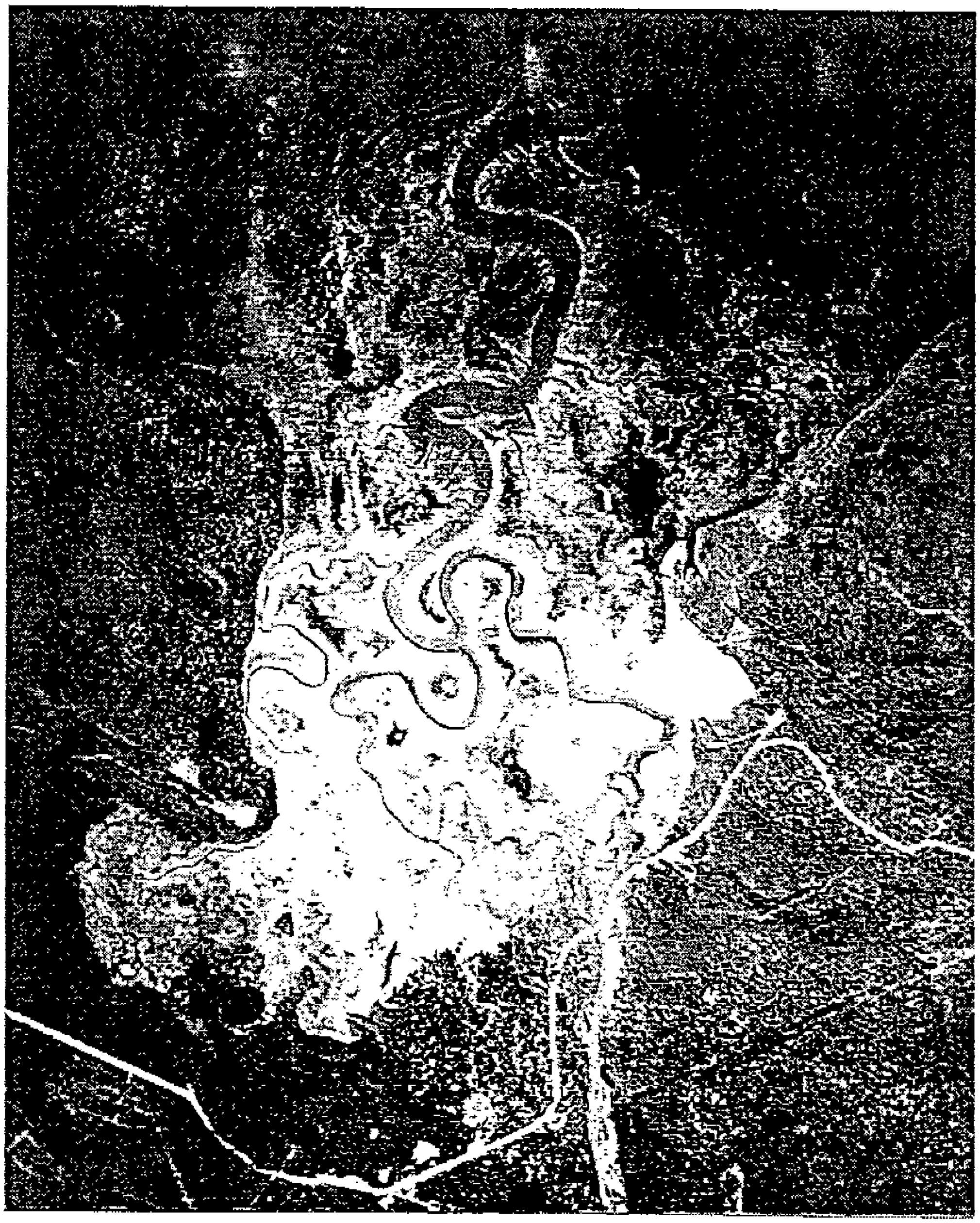
Eagle River flooding. Only the center of the Racine Island area (Fig. II-1-5) is characterized by intertidal ponds and an abandoned gully. The westerly channel was abandoned this September (1995) during flooding of the Eagle River when channel scour and migration shifted the easterly channel further to the north-east.

In contrast, the northern two thirds of ERF have landforms typical of tidal

b.1967.

Figure II-1-6 (cont.). Aerial photographs of ERF.

flats near river mouths (e.g. Ovenshine et al. 1976b) and consist mainly of levees, vegetated marshes and abandoned channels and point bars. Significant changes in the relatively tight meander loops in this lower section of the river have however also taken place over the last 40 years. Channel changes are a natural progression resulting from the erosion and recession of the outer banks of meander bends, deposition of sediments as point bars in the inner parts of each



c.1993.

Figure II-1-6 (cont.). Aerial photographs of ERF.

bend, and a general downstream migration of the channel (e.g. Allen 1982). Meander scars, abandoned meander loops, and point bar deposits are common along the length of the active channel and are evidence of changes further in the past.

Tributary channels with dendritic patterns, referred to as vegetated drainageways, drain water from the mudflats and ponds into the tidal gullies (Fig. II-1-3 and II-1-7). A second set of channels intercepted by the active tributary system

Figure II-1-7. 1992 aerial photograph of northeastern ERF.

unconformably crosses other landforms including ponds (such as C and Bread Truck). Their pattern is irregular and unrelated to the active gully drainage system. These secondary channels are parts of former drainageway and gully systems that are now inactive and therefore relict. Their fragmentary presence indicates significant changes to the drainage system in the past. The cause of such change is unknown, but events such as river avulsion, channel migration, or earthquake-induced subsidence may result in abandonment of drainageways.

Chemical analyses of a limited number of sediment trap and plankton net samples indicate that WP undergoes suspension, transport and redeposition in ERF, as well as transport through tidal gullies into the Eagle River and Knik Arm. Tidal and wind driven currents can scour pond bottoms, resuspending and transporting WP, whether as particles or sorbed to sediment, while plunge pool erosion and scour of vegetated drainageways and gullies can entrain and transport WP in suspension or as bed load. In addition, pond and mudflat sediments can freeze to the base of the ice cover during its growth, and subsequently be rafted during tidal inundation. Bathymetric profiling offshore of ERF shows no evidence of deposition of ERF sediments as a delta at the mouth of the Eagle River. White phosphorus entering Knik Arm is potentially diffused by tidal and river currents, but several potential sites of WP deposition exist and need to be evaluated (Lawson et al. 1995b). These sites include intertidal bars and nearshore deposits.

Previous investigations suggest that natural attenuation and remediation of WP contamination is possible, but further work is needed to assess the length of time over which this may occur and identify specific locations where natural attenuation is the remedial method of choice. The relative importance of erosional and depositional processes vary from area to area in response to tidal and river hydrology; however, changes in the system over seasonal, annual or decadal time periods are possible. Pond sedimentation rates appear to be sufficiently high in some areas to provide a natural method of WP burial, thereby reducing the exposure risk for waterfowl. The drainage system is also actively changing as tidal gullies expand across mudflats into ponds; certain ponds are likely to drain in 20 years or less. Drier conditions will permit in situ degradation and natural remediation of WP contamination. Erosion will however continue to release WP from mudflat and pond sediments over time, while ice and water transport mechanisms will move WP particles into tidal gullies, the Eagle River and Knik Arm. Whether these particles survive mechanical transport and persist in Knik Arm is unknown, but simple laboratory flume tests of WP particle resistance to abrasion could determine if transport destroys them. Again, this process would remediate the contamination naturally.

STUDY SITES AND METHODS

Sedimentation transects

Sedimentation rates are measured along transects across representative landforms of ERF, with eleven landform transects being set out in May 1992 (Lawson and Brockett 1993), one in June 1993, and eleven in 1994 (Fig. II-1-8). Their locations and elevations were surveyed using an electronic theodolite. Grab samples of surface sediment (to 5-cm depth) were taken at each survey point along the transects, and their grain size distribution was analyzed using standard sieving

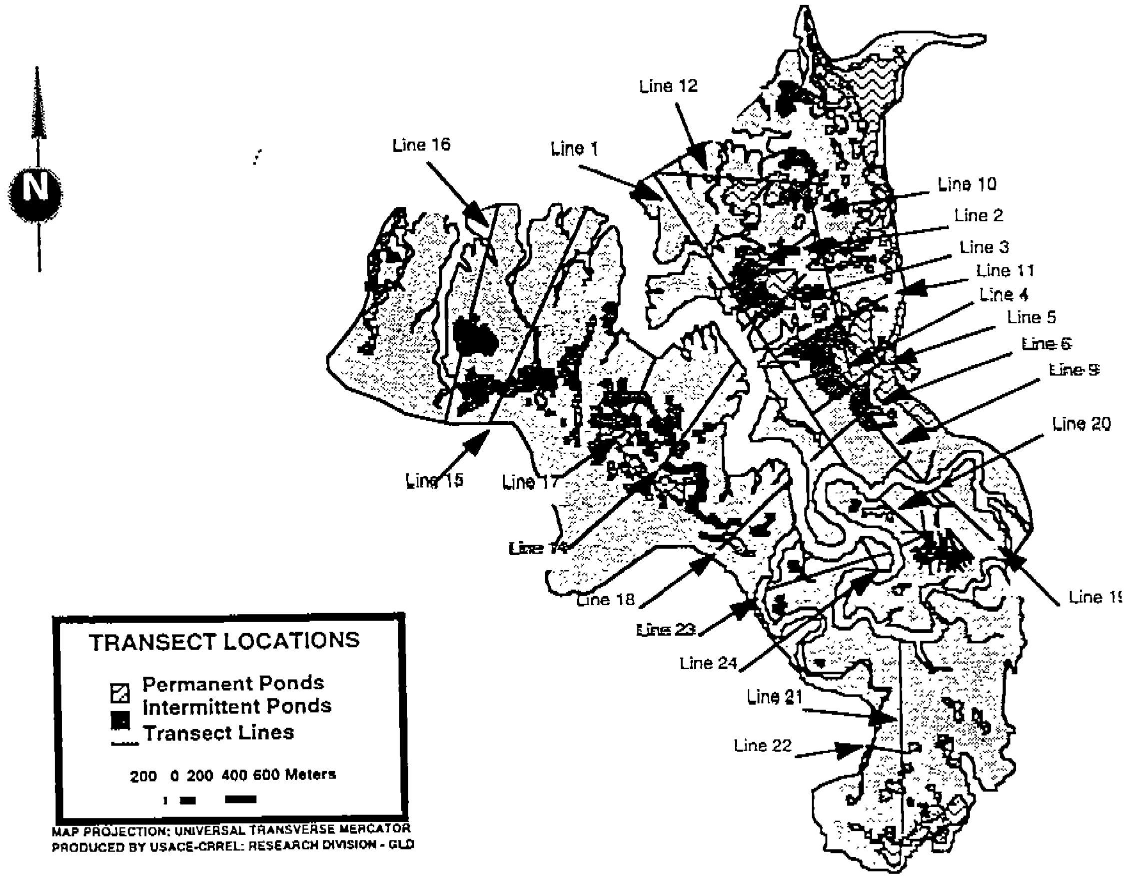


Figure II-1-8. Mudflat sedimentation transect locations.

and hydrometer techniques. These data delineated textural trends in surface materials and the relative importance of tidal or riverine sediment sources to sedimentation and landform development.

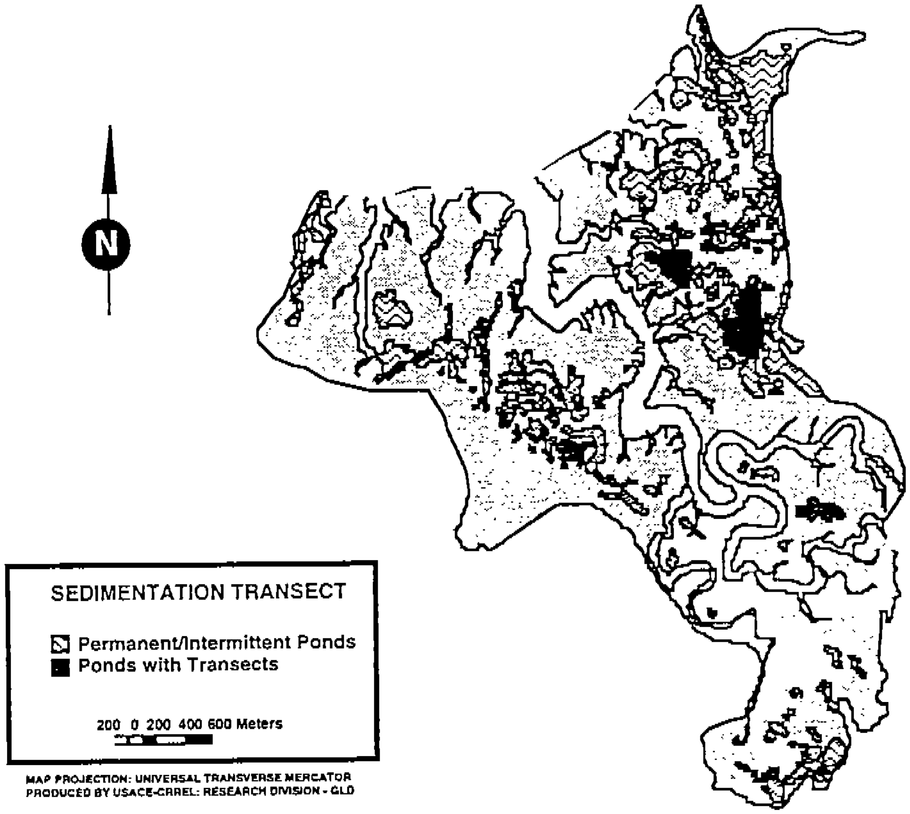
New transects were established in May 1995 for detailed measurements of sedimentation rates in six ponds (Fig. II-1-9). Two orthogonal transects were usually established in each pond, with traps located about every 20 m along them.

Sedimentation measurements

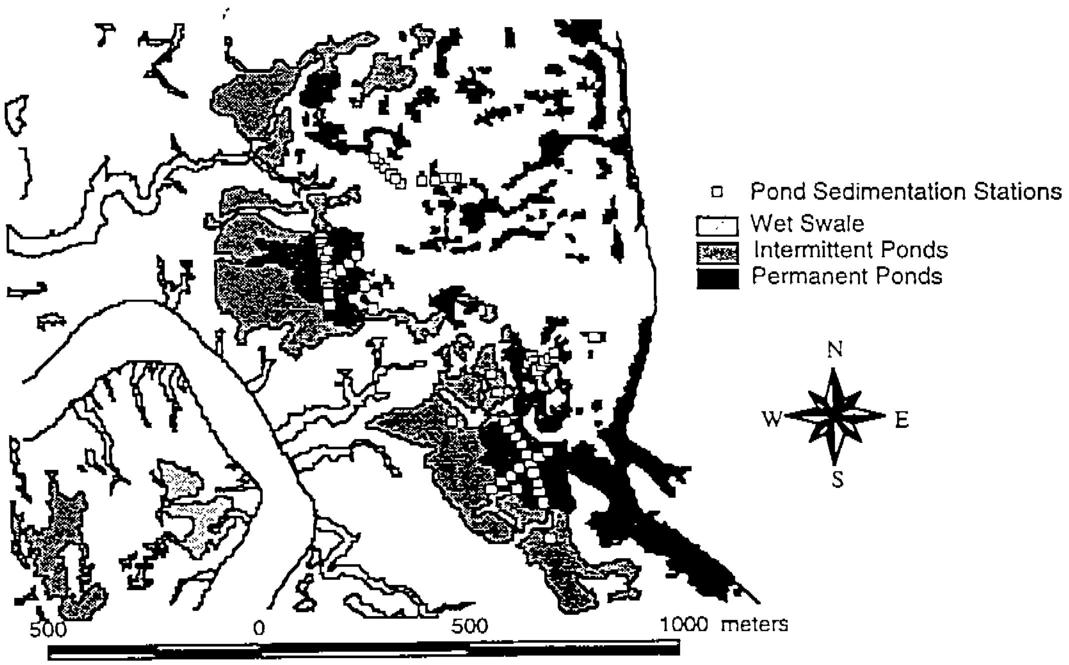
Sedimentation rates in permanent ponds and marshes are difficult to measure accurately because a slight disturbance of the water column can resuspend the fine-grained materials covering their bottoms. If they are caught in sediment traps, sedimentation rates will be measured as higher than the actual rate. We therefore used two methods in permanent ponds to measure sedimentation and to evaluate resedimentation resulting from natural resuspension of pond and marsh sediments by wind, waterfowl and other processes.

Sedimentation stakes were used to measure erosion and deposition at transect points where the surface was wet or standing water was temporarily present (Fig. II-1-10). These stakes consist of a rod and a square, rigid plate (about 7 cm^2) that slides freely on the rod as used by Ovenshine et al. (1976 a,b) in Turnagain Arm, Alaska. Erosion depth is defined by the increase in distance between the top of the rod and the 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. Monthly rates were measured in July, August and September 1992 following each monthly period of tidal flooding, while seasonal rates were measured in May and September 1993, 1994 and 1995.

Sedimentation on levee and mudflat surfaces was monitored by spraying an area (~30 × 30 cm) on the ground surface with pavement marking paint and locating the corners of this area with wire survey flags (Vince and Snow 1984). Paint was applied at certain sites in June and August 1992, August 1993 and

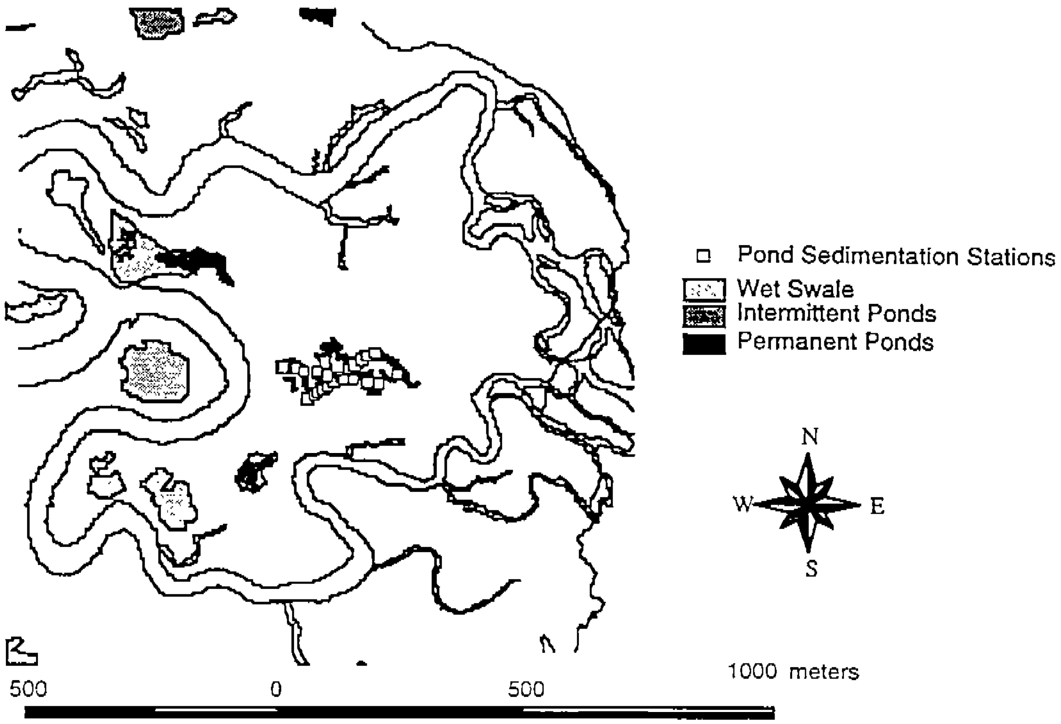


a. Individual 1992-1994 measurement sites and locations of pond transects.

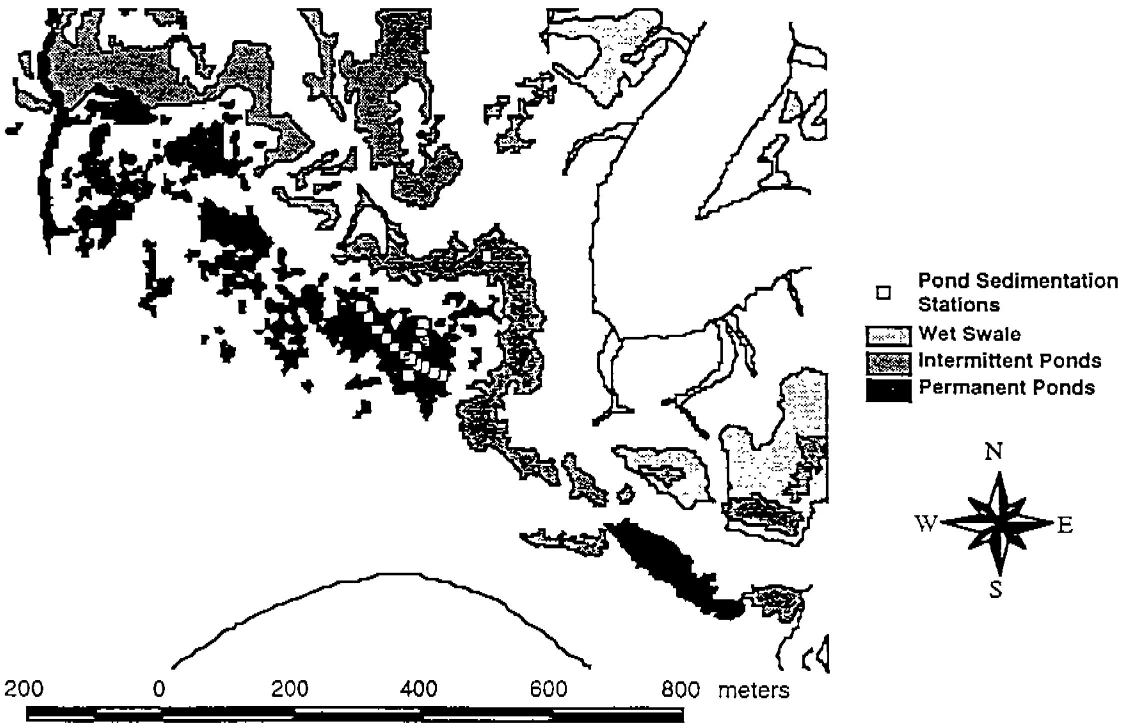


b. Transects in C- and Bread Truck ponds.

Figure II-1-9. Pond sedimentation measurement locations.

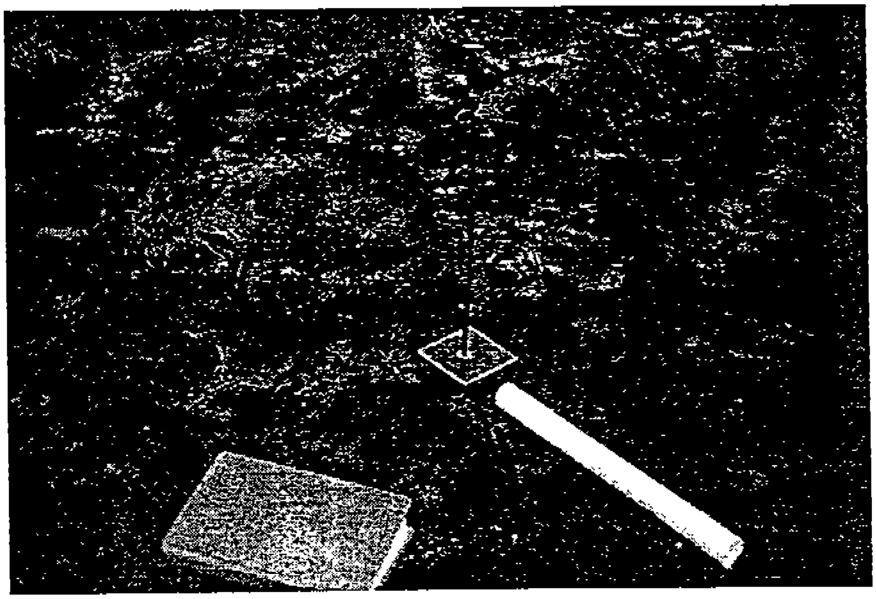


c. Racine Island Pond transects.

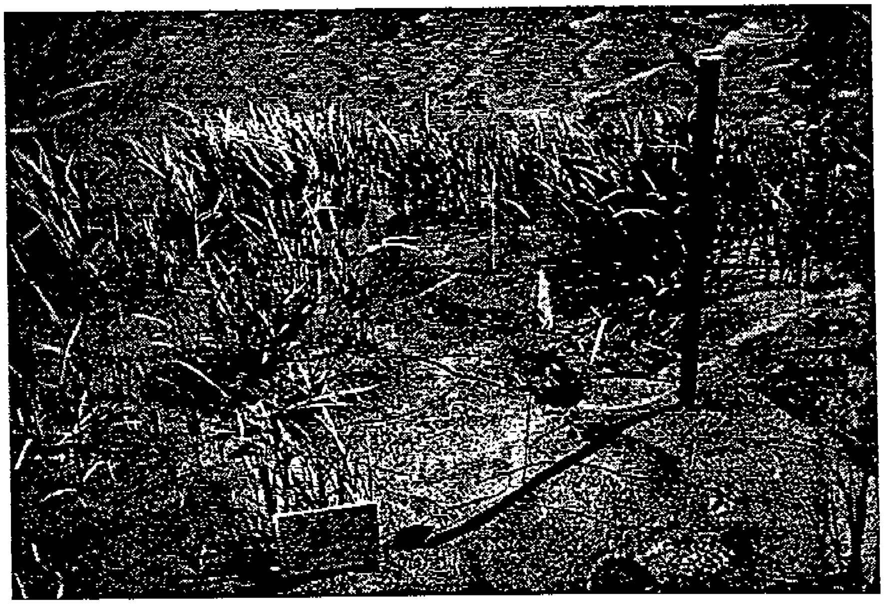


d. A Pond transects.

Figure II-1-9. Pond sedimentation measurement locations.



a. Sedimentation stake with plate.



b. Wire flags mark an area of painted ground.

Figure II-1-10. Sedimentation measurement techniques.

May/June 1994. Net accumulated sediment is measured by cutting and removing a block of sediment with a putty knife or spatula (Fig. II-1-11). The thickness of sediment above the paint layer is then measured to the nearest 0.5 mm. In contrast to sedimentation stakes that are commonly broken or removed by ice

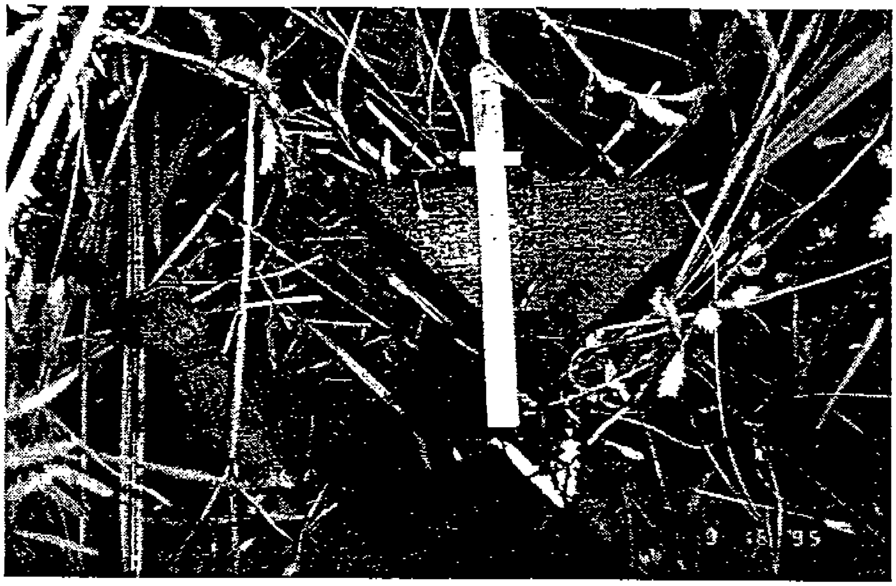


Figure II-1-11. Wedge-shaped sediment block used to measure vertical accretion. Note subhorizontal laminations.

in winter, the wire flags and buried paint horizons enable us to acquire a continuous record of net sedimentation rates. Over an extended period, post-depositional compaction is also accounted for by paint horizon measurements.

Gross sedimentation rate in ponds was measured at 18 sites following tidal inundations in June, August and September 1992, and in May and September 1993, 1994 and 1995 (Fig. II-1-12). Gross (total) deposition from tidal and river inundation as well as resuspended bottom sediments was measured in a sediment trap consisting of either a 4-in.-diameter (10.2-cm-diameter) schedule-40 PVC pipe end cap glued to a short length of 2-in.-diameter (5-cm-diameter) schedule-40 PVC pipe at pond stations, or a 16-cm-diameter end cap at the new pond transect stations established in May 1995. The pipe was inserted into pond sediments until the bottom of the cup was in contact with the bed (Fig. II-1-13). Sediment trapped in the cup includes new sediment brought into the ponds by tidal inundation and river currents, and materials resuspended by wind waves, dabbling ducks or other mechanisms. The quantity of accumulated sediment is measured to the nearest 0.5 mm by inserting a graduated scale into the sediments at three places. After measurement, the sediment in the cup is cleared or saved for analysis of white phosphorus concentration.

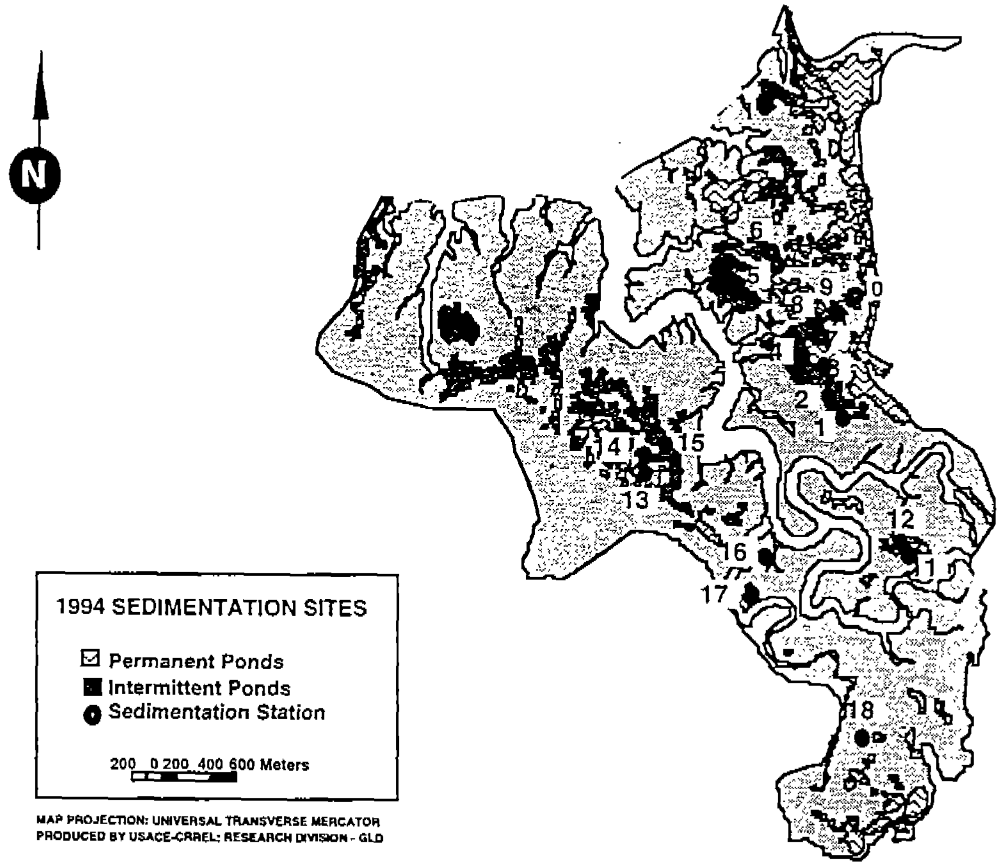


Figure II-1-12. Locations of 1992-1994 pond sedimentation stations.

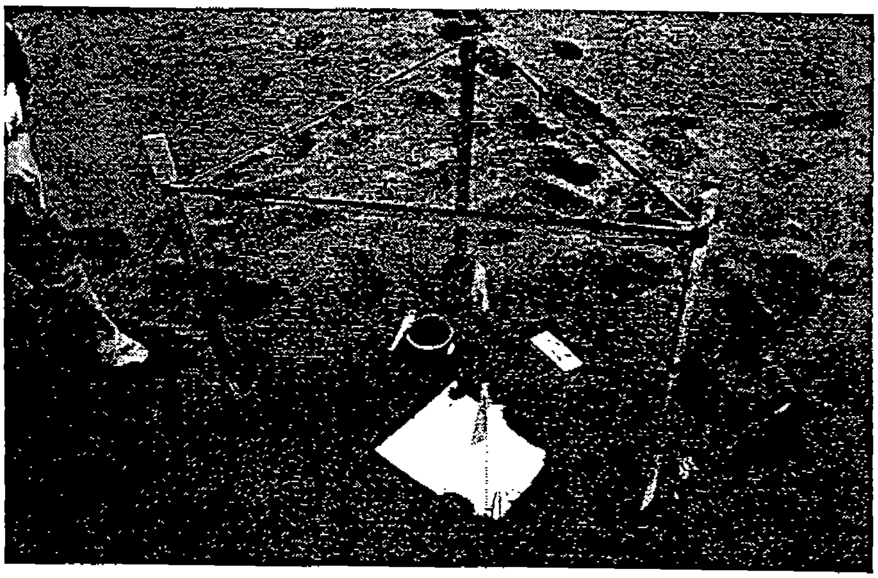


Figure II-1-13. Example of sedimentation station at an intermittent pond location showing layout of cup and plate sampler.

Net sedimentation rate in ponds on stations or transects is measured using a thin, but rigid plastic plate of about 30 cm square that is pushed gently into the pond bottom until the plate surface is flush with the bottom surface. The corners of the plate are secured by aluminum tent pegs (Fig. II-1-13). Sediment in suspension settles onto this plate, but this sediment can also be reworked and resuspended by wind or other mechanisms, thereby delineating a net rate. The thickness of sediment is measured to the nearest 0.5 mm using a graduated scale.

Gully erosion and headwall recession

Tidal gullies draining ponds and mudflats are actively extending inland by erosion at their heads. We established 86 sites between June 1992 and May 1995 to evaluate retreat rates, with periodic relocation of stakes at each site as recession takes place (Fig. II-1-14). At each site, stakes are driven into the ground along a straight line at known distances from one another and from the crest of a gully scarp (Fig. II-1-15). A "hub" stake is set at a known distance from this stake line.

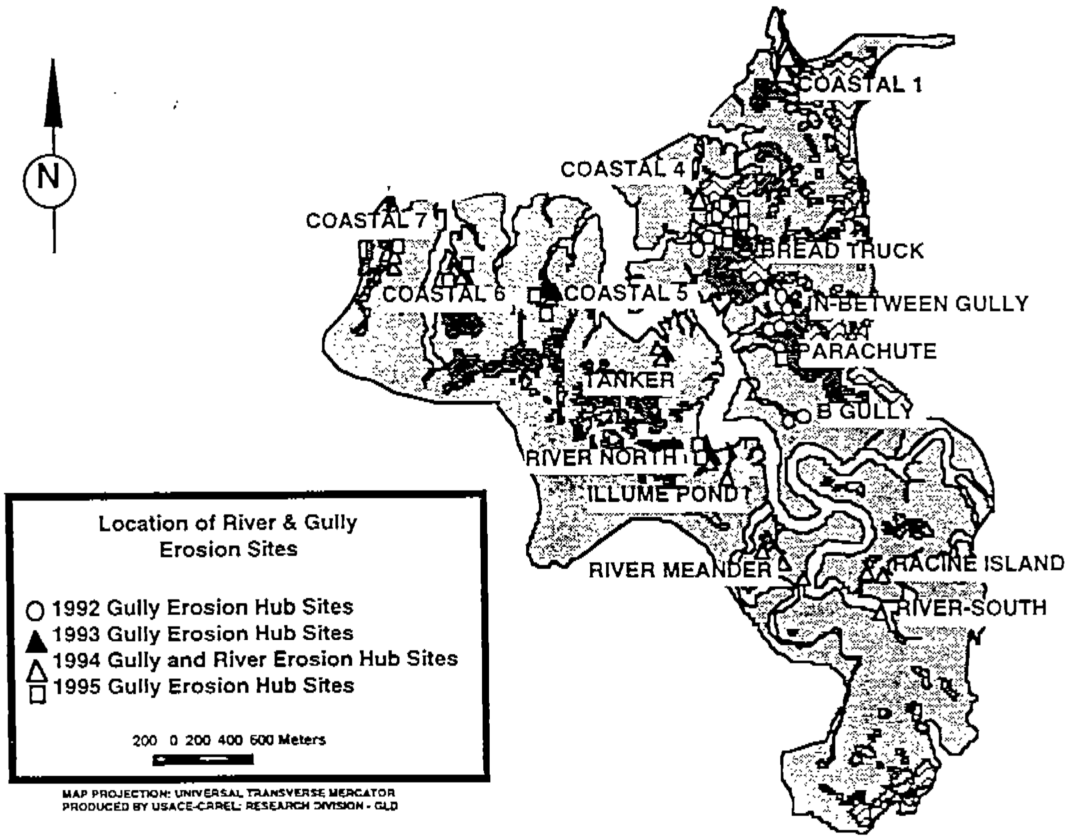


Figure II-1-14. Location of gully headwall and lateral wall erosion sites.

Figure II-1-15. Example of layout of hub and line stakes at River-North erosion site.

The distance between the hub and the crest of the gully scarp was measured across the top of each line stake with a tape measure. The position of the gully scarp crest was identified by lowering a plumb bob on a string from the tape measure, so that the horizontal distance could be read where the string and measuring tape met. Flagged wire stakes were then placed at each point of measurement along the headwall. Repetitive measurements using this technique enables us to monitor changes in scarp geometry with time, as well as the rate of gully recession.

Recession rates were measured in September 1992, 1993, 1994 and 1995, in May, 1993, 1994 and 1995, in November 1994 and late October 1995. The September measurements delineate summer rates, while those of May or June delineate winter rates. The October 1995 and November 1994 data provide constraints on the amount of erosion occurring since the end of summer measurements and the initial period of freeze-up. Repetitive measurements at points without any retreat (as indicated by the continuing presence of wire flags) indicate they are reproducible to ±2–5 cm. Their accuracy, however, is limited by how well the crest of the gully scarp can be defined, the shape of which is highly irregular and therefore accuracy is probably limited to ±10 cm in the worst case.

Recession data are presented as a range of maximum recession rates measured orthogonal to the gully or river at each site. This method differs from previous years where erosion measurements were reported as collected in the field and did not account for apparent distances created by the method (Lawson and Brockett 1993, Lawson et al. 1995a, b). These rates tended to be higher than actual wherever hub to line measurements were made at an acute angle to the scarp, thus recording an oblique distance. Measurements reported herein were taken from the scaled summary plots and are intended to summarize recession ranges, not absolute values for each hub to line stake measurement.

Historical aerial photographic analyses

During 1995, multiple aerial photography sets were acquired to increase our historical coverage of Eagle River Flats (Table II-1-5). Our current aerial photography archive provides a 45-year record of surficial changes at ERF for the interval of 8 August 1950 to 9 October 1995. The images are of variable quality and range from the highly blurred 1967 black and white images to the high resolution natural color photographs of 9 October 1995.

Historical changes were measured by studying aerial photographs taken at approximately a decadal time scale. Individual photography sets were chosen based on their clarity, which provided an ability to detect gully headwall scarps and their temporal setting. Five time frames (1950, 1960, 1972, 1984/86 and 1995) were chosen and the headwalls of B-Gully, Parachute, In-Between, Bread Truck, Mortar and Coastal 5 gullies were mapped to document their recessional histories.

Average rates of headward recession were calculated by transposing the position of the gully headwall scarps in 1950, 1960, 1972 and

Table II-1-5. Historic aerial photography of Eagle River Flats.

Year	*Date*	*Type*
1950	8 August	B/W
1953	27 June	B/W
1957	12 July	B/W
1960	30 August	B/W
1962	17 May	B/W
1967	Unknown	B/W
1972	July	False Color IR
1972	9 August	B/W
1974	7 May	B/W
1977	Unknown	False Color IR
1978	August	False Color IR
1984	12 August	False Color IR
1986	5 October	True Color
1986	12 September	LANDSAT TM (Digital)
1988	4 August	B/W
1991	21 June	Color IR
1992	22 May	Color IR
1992	2 August	Color IR)
1993	8 July	B/W Orthophotograph
1994	30 August	Color IR
1995	16 August	Color IR
1995	9 October	True Color

1984/86 onto gully basemaps produced from the 9 October 1995 aerial photographs. The distance of headward recession was measured as the centerline distance within each gully between the known points. The average rates were then determined by dividing the distance of center-line recession by the number of years between each measure.

Water quality parameters

Various water quality data have been collected at multiple sites to assess the surface hydrology and water quality of ERF. The majority of sampling sites were in small plunge pools at the heads of tidal gullies; three were newly located within ponds in 1995. Also in 1995, the sites were concentrated in the most heavily contaminated locations generally east of the Eagle River (Fig. II-1-16). The Mortar site receives tidal waters directly from Knik Arm, whereas Bread Truck, Parachute, B and In-Between are located in drainages which flow into the Eagle

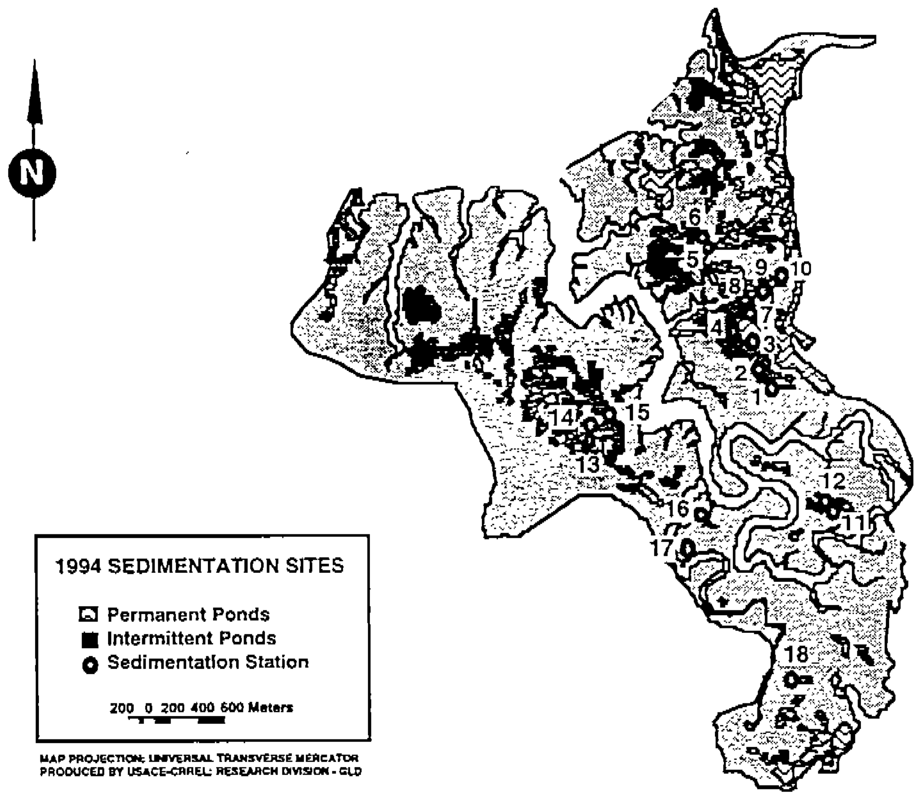


Figure II-1-16. 1995 locations of instrumentation recording water quality parameters and water depths. Locations of weather station and plankton net sampling sites are also shown.

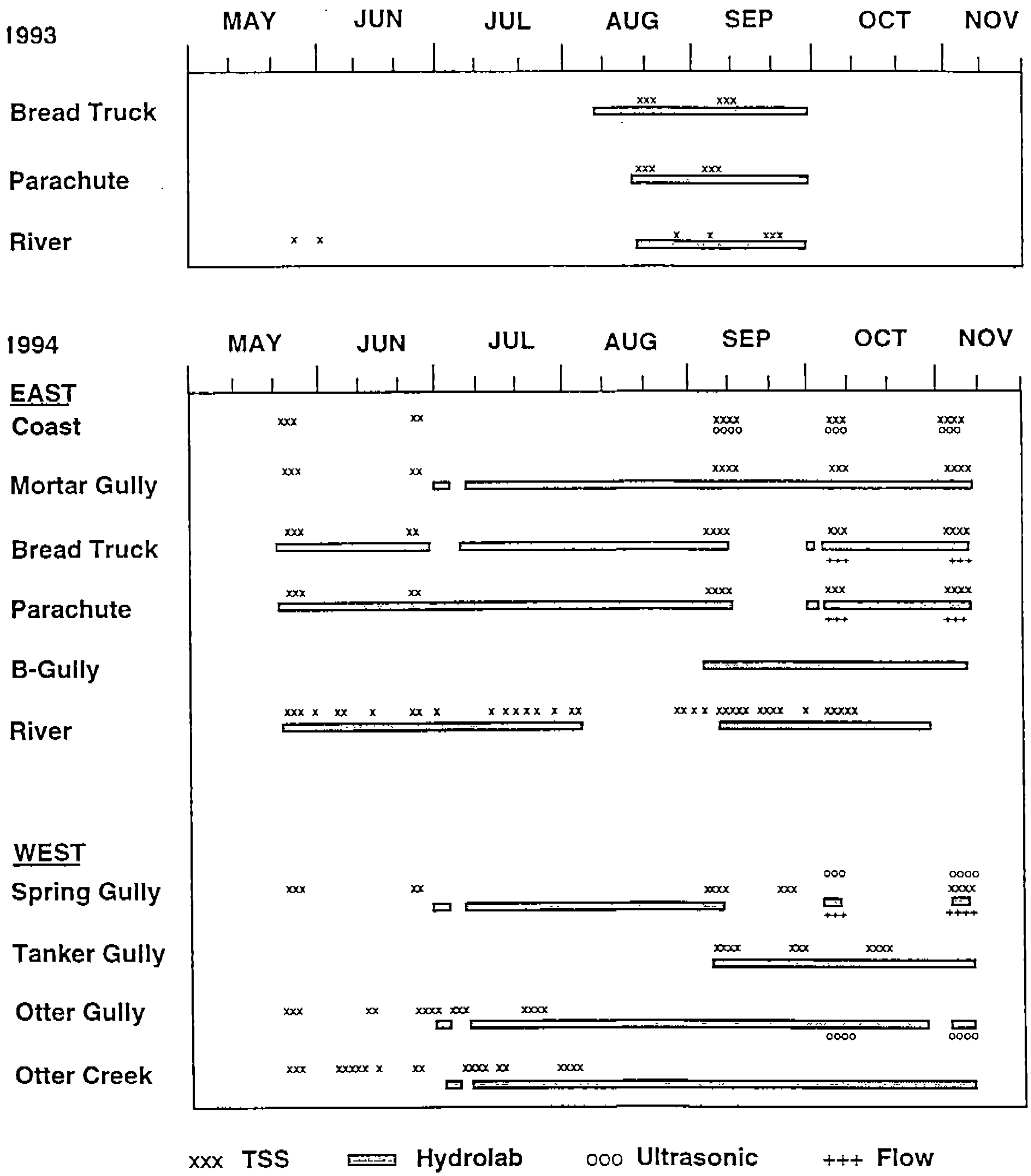
Table II-1-6. Specifications of sensors used in water quality measurements.

Instrument type	*Sensor*	*Accuracy*	*Resolution*
Hydrolab	Temperature	± 0.15°C	0.01°C
(H2O Multiprobe)	pH	± 0.2 units	0.01 units
	Specific oonductance		
	Fresh water	± 0.0015 to 0.1 mS/cm*	0.001 mS/cm
	Salt water	± 0.15 to 1.0 mS/cm*	0.01 mS/cm
	Salinity	± 0.2 ppt	0.1 ppt
	Dissolved oxygen	± 0.2 ppm	0.01 ppm
	Redox	± 20 mV	1 mV
	Depth	± 0.45 m water	0.1 m water
CRREL Thermistor	Temperature	± 0.02°C	0.01°C
Druck (PDCR 950)	Pressure (water depth)	± 0.008 m water	0.001 m water
OBS-3	Turbidity 5 V = 2000 FTU	± 100 mV	1 mV
Marsh-McBirney (model 512)	Water current (velocity)	± 6.10 cm/sec	2.13 cm/S
Cambell Ultrasonic (model UDG01)	Distance (water depth)	± 1 cm	.05 cm
Seagauge Wave/Tide	Pressure (water depth)	± 0.003 m water	0.0015 m water
(model SBE 26-03)	Temperature	± 0.02°C	0.01°C
Seacat CTD	Pressure (water depth)	± 0.75 m water	0.045 m water
(model SBE 16)	Temperature	±0.01°C	0.001°C
	Conductivity	± 0.001 S/m	0.0001 S/m
	Dissolved oxygen	± 0.1 mL/L	0.01 mL/L
	pH	± 0.1 units	
	OBS [5V=2000 FTU]	± 100 mV	3 mV

* Depends on which of three auto-adjusting ranges is employed.

River and therefore have mixed fresh and tidal water sources. Racine Island gully receives most of its water influx from the Eagle River during the summer. The two remaining sites represent the primary source waters: the Eagle River upstream of where it enters ERF, and the Knik Arm on the coast just north of the Eagle River mouth.

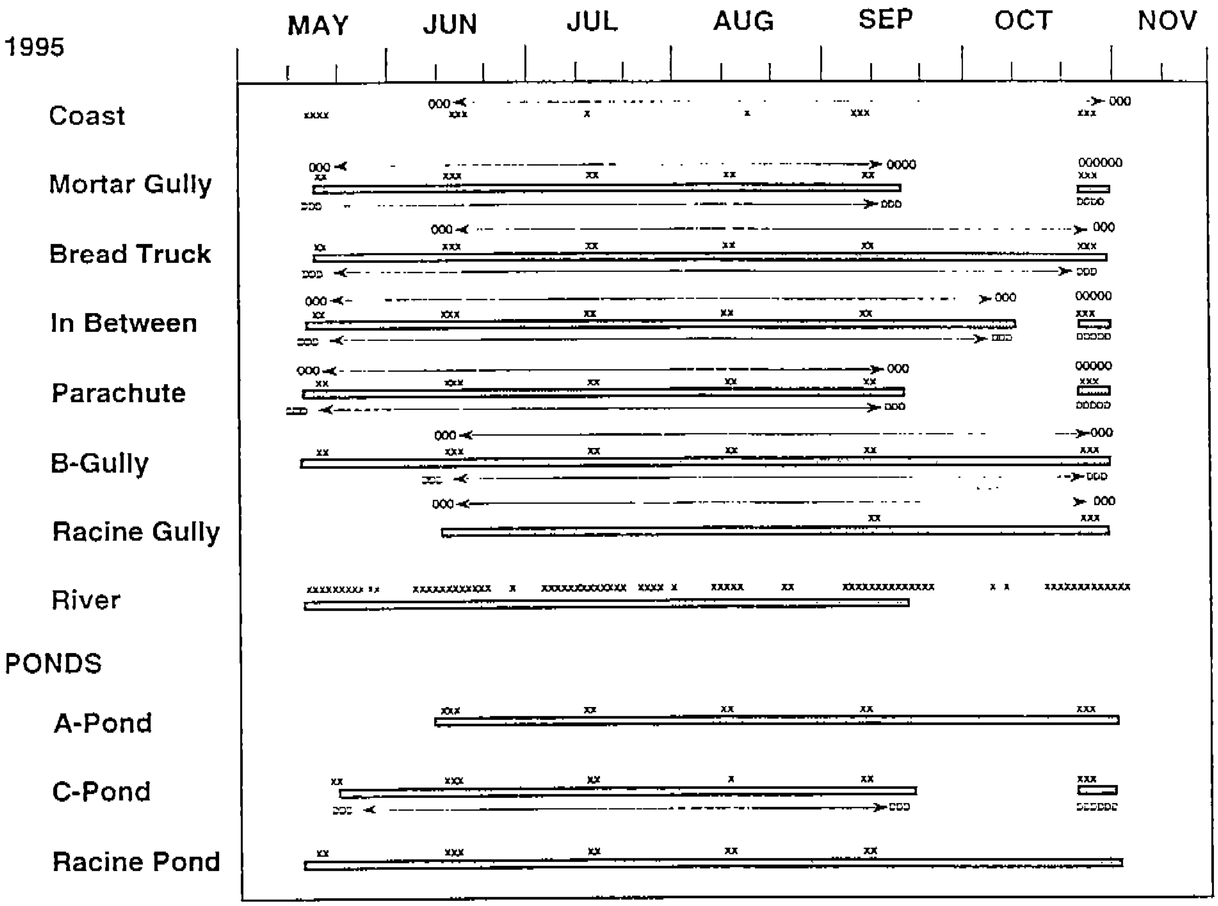
A basic suite of water characterization data was collected at 4-min intervals at each site utilizing the instruments listed in Table II-1-6. These data include temperature (measured by thermistor and/or a Hydrolab H2O multiparameter sensor); salinity, pH, redox and dissolved oxygen (Hydrolab); turbidity (OBS3 optical backscatter sensor); and water surface elevation (Druck pressure transducer). Figure II-1-17 shows the past and present times of data collection since 1993. Water samples were collected with an ISCO suction sampler automatically at various time intervals prior, during and following flood tides. The sampler was pro-



a. 1993 and 1994.

Figure II-1-17. Extent of data collection at hydrostation sites from 1993 to 1995.

grammed to obtain 500-mL water samples at specific intervals through the flood and ebb cycles. These samples were processed for TSS concentration using vacuum techniques and 45-mm glass microfiber filters following procedure 2540D in



a. 1995.

Figure II-1-17. Extent of data collection at hydrostation sites from 1993 to 1995.

Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF 1992). Project modifications to this procedure are described in Lawson et al. (1995b).

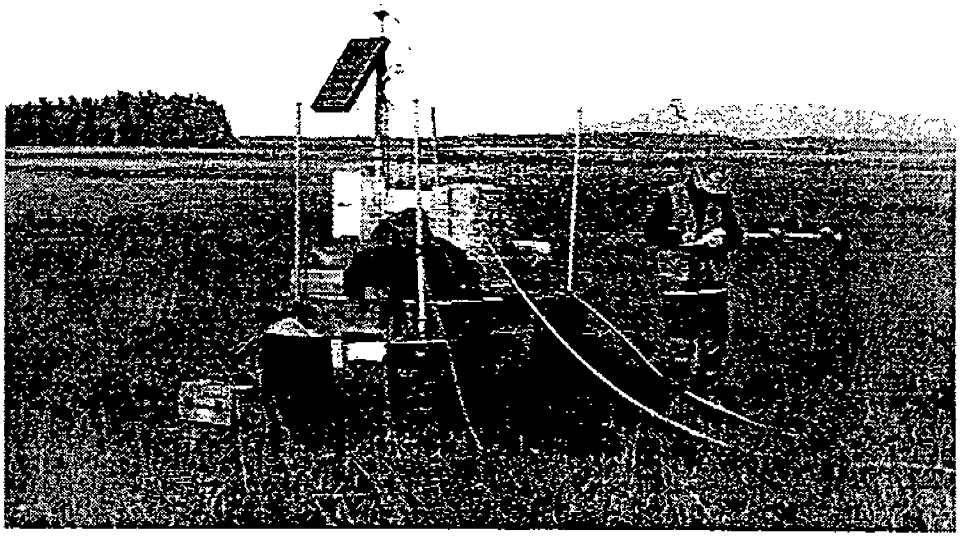
A Marsh–McBirney electromagnetic flow probe was used to measure current velocity during ebb and flood in selected tidal gullies. A unit was also installed in C Pond to measure tidal and wind-generated currents therein. The sensor was mounted about one meter above the bed at the Bread Truck, Parachute, In-Between, Mortar and B gullies (Fig. II-1-16). Ultrasonic sensors were used to measure flooding on the mudflats near the Mortar, Bread Truck, Parachute, In-Between, Racine Gully and Coastal sites.

Water quality parameters were collected at the Knik Arm coastal site using a Seabird SBE 16 Profiler. In addition, a Seabird SBE 26 wave and tide gauge was located here to record water depth and temperature of Knik Arm waters (Table II-1-6). The same location was used in 1993 and 1994 (Fig. II-1-16).

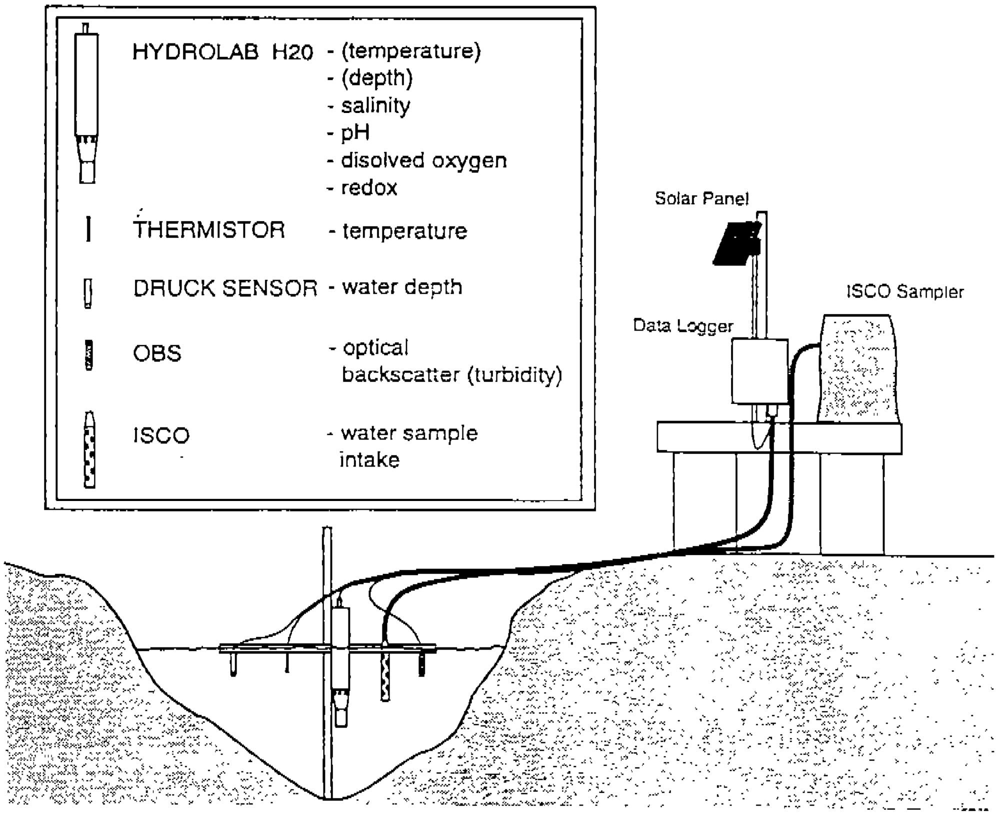
Hydrostation configuration

The instrumentation and samplers for water quality analyses followed an identical configuration at each gully and pond site (referred to as hydrostations). Sensors and the suction sampler intake screen are mounted on a stake driven into the pond or gully bottom under investigation. Mounting hardware was configured identically to permit their precise positioning in the water column. Sensors in gully sites were placed in plunge pools to keep the sensors wet at all times and usually about 15–45 cm above the bed depending on the site's character. Current probes were, however, mounted about 1 m above the bed on separate stakes located downstream of the plunge pool within a reasonably symmetric gully cross section. Ultrasonic sensors are mounted on an arm attached to a metal stake about 10 m from the platform. Each is aimed downward towards the mudflat surface, upon which a plate is pinned to provide a stable, reflective surface.

Instrumentation including the ISCO sampler was located on a floating platform located either on the mudflat next to gully sites or in ponds (Fig. II-1-18). Each platform was constructed of a 4- × 4-ft plywood deck mounted on a 2- × 8-in. wood frame. Large metal eyehooks were screwed into the frame on each corner. Five-foot sections of 0.75-in.-diameter steel pipe were mounted vertically in 20-gal. cans filled with concrete, and the eyehooks mounted on the platform's wood frame lowered over them. Foam filling the inner space of the deck framework provided flotation so that the platform could move vertically up and down the steel pipes during tidal flood and ebb. The platforms allowed us to establish monitoring stations without setting stakes or foundations in the ordnance-bearing mudflat sediments; however, the platforms main task is to keep the datalogger and related devices dry during the highest flood levels. Dataloggers were installed in NEMA plastic enclosure boxes mounted on 2-in. vertical steel pipes. Solar panels of 18-W output are fastened to the pipes above the dataloggers to recharge the 12-V external battery.



a. Platform and instrumentation at Bread Truck Gully.



b. Schematic showing layout of intrumentation in water and collection devices on a flotation platform.

Figure II-1-18. Hydrostation layout at a gully location.

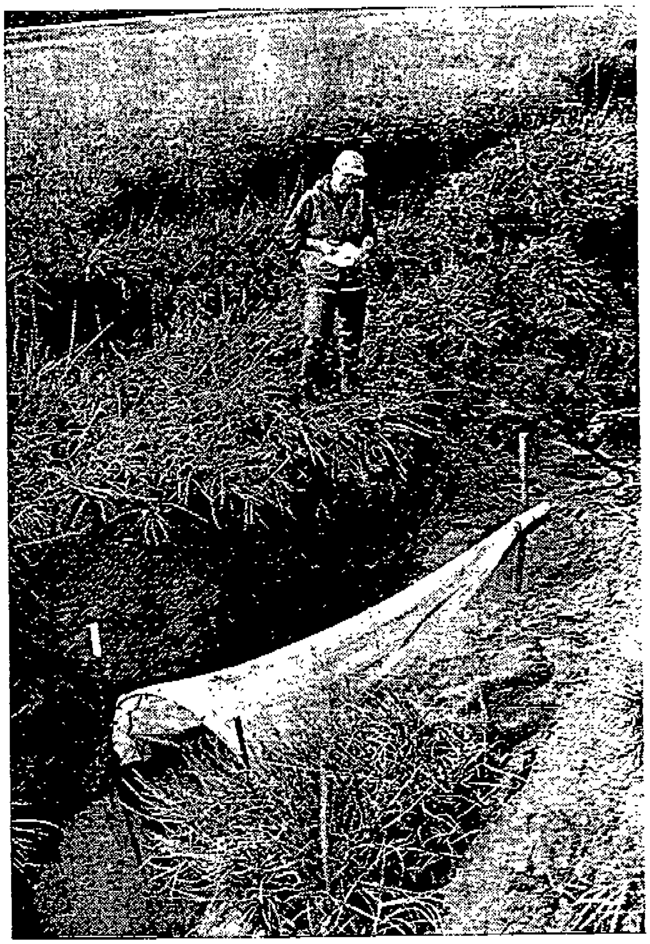


Figure II-1-19. Plankton net used for WP collection in transport at B-Gully.

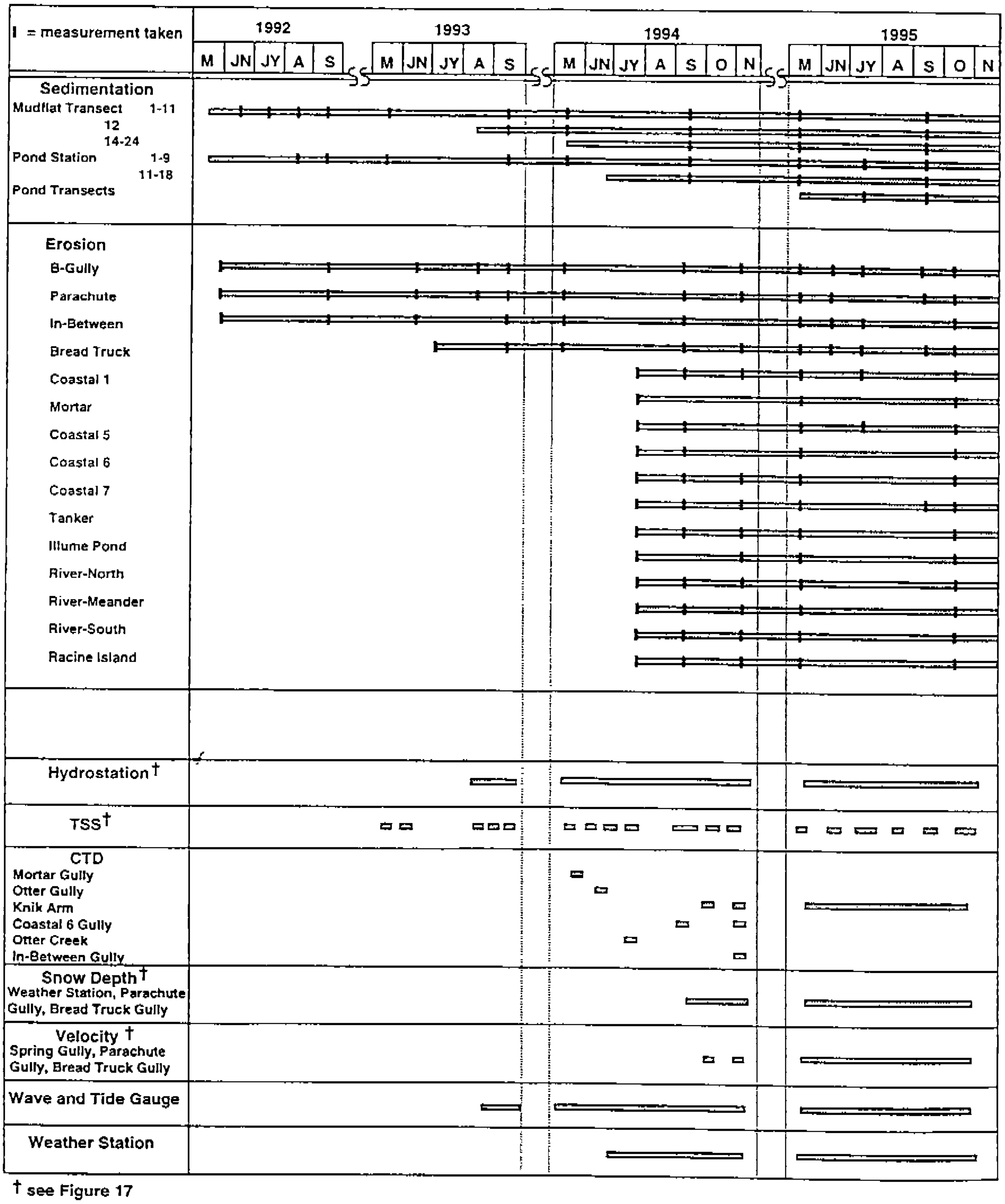
WP transport and resuspension

A plankton net of 3-m length with an opening of 1 m and a mesh size of 80 µm was placed at four gully sites, three of which were previously occupied in 1994 (Fig. II-1-16). The plankton net was tied to stakes driven into the gully bottom and extended down-channel in the direction of ebb (Fig. II-1-19). A cup at the apex of the net collected sediments that were transported into it. Each net was in place during multiple flooding tides each month (Fig. II-1-20). Sediment was collected following each ebb tide during a monitored tidal cycle and analyzed for WP following standard laboratory methods.

Sediments collected in sediment traps from transects in C, A, Racine Island, C/D and Lawson's pond were also analyzed for the presence of white phosphorus. These analyses provide data on resuspension of WP by wind, tidal currents and waterfowl activity.

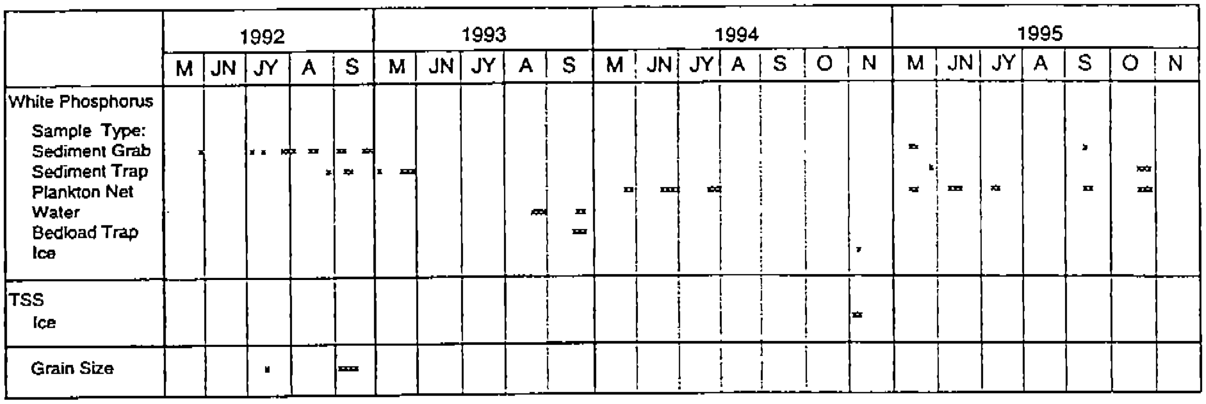
Data acquisition record

Figure II-1-20 summarizes the periods when various types of field data were acquired. The multiple starting dates for acquisition reflect both the implementation of new methods and expansion to additional sites within ERF. Gaps in the records of water quality sensors, other than during the winter period, resulted from either instrumentation failure or disruption by natural processes.



a. Continuous data.

Figure II-1-20. Sampling coverages for various types of field data.



b. Discontinuous data.

Figure II-1-20. Sampling coverages for various types of field data.

INTRINSIC REMEDIATION: POND DRAINAGE BY GULLY EROSION, RECESSION AND EXTENSION

Erosion is one of the most visible mechanisms by which the physical system is currently modifying and reshaping the Flats. Dynamic changes are critical because our initial assessments (Lawson et al. 1995a, b) suggested gully extension could drain contaminated ponds and create conditions conducive to in-situ WP degradation and attenuation within a relatively short time frame. The length of time for drainage to occur will be a function of several factors and may vary spatially across the Flats. The 1964 Alaskan earthquake appears to have had the single greatest effect on ERF, significantly altering the hydrologic system, which in turn has initiated major changes in drainage, gully erosion and extension, and pond and mudflat sedimentation.

External forcing

Drainage system expansion is thought to be a complex response to changes in the base level, tidal inundation and other physical changes caused by the 1964 Alaskan earthquake, and subsequent responses as both external and internal factors have changed since that event (Table II-1-1). Leveling profiles in the Anchorage area indicate that co-seismic subsidence was on the order of 60–70 cm (Brown et al. 1977). This subsidence has been followed by post-seismic uplift that was on the order of 20 cm by 1975. However, tide gauge data indicate that this uplift record has been very erratic in the Anchorage area, and did not reach a reasonably linear response until after 1973 (Savage and Plafker 1991). Savage and Plafker suggest that the oscillatory uplift pattern observed at Anchorage may be caused by creep of rock up the fault plane. Their data also indicate that net uplift, once adjusted for eustatic sea level rise, is nearly negligible (~1.0 + 2.2 mm/yr). It is difficult to compare the results of Brown et al. (1977), with Savage and Plafker (1991); however, it appears as though post-seismic uplift is not as rapid as we had believed in previous reports (Lawson et al. 1995b). The importance of this for ERF is that more water than expected is able to flood the Flats during spring tides, and therefore there is a greater volume of flood waters moving out the drainageways and gullies during ebb tide.

The physical responses to subsidence will occur for an extended time into the future while isostatic recovery continues. Our data indicate significant responses in the physical system since 1964. Sedimentary subsidence of pond bottoms, similar to that of Turnagain Arm (Ovenshine et al. 1976b), probably modified ERF hydrology and affected sedimentation and erosion within them. A lag in response to the earthquake and the various changes since that time can be different at locations across ERF. This lag will be primarily a function of site-specific intrinsic factors (e.g., vegetation cover, peat layers, craters, scattered debris) that control local thresholds for changes in processes or their responses.

Hydrologic changes have led most visibly to increased gully erosion, as is evident by the historical increase in gully entrenchment and their progressive extension into the tidal flats (Lawson et al. 1995a). Knickpoints are locations of abrupt slope change in the longitudinal channel or gully profile that indicate system disequilibrium: the most prominent ones are the near-vertical headwalls that bound plunge pools and mark the upper limit of each gully. In addition, sedimentation in the ponds remains high, as recovery to the subsidence by infilling of the pond bottoms.

Table II-1-7. Summary of gully velocity and discharge data.

Gully	*Tide stage*	*Monthly range in ave. velocity (cm/s)*	*Peak velocity (cm/s)*	*Average TSS (mg/L)*	*Peak TSS (mg/L)*	*Monthly range in ave. water discharge (m^3/s)*	*Monthly range in ave. sediment discharge (kg/s)*
B-Gully	Flood	8.50-15.83	42.39	280-780	2251	0.50-0.94	0.14-0.53
	Ebb	9.04-75.41	207.5			0.54-4.47	0.20-1.81
Parachute	Flood	7.63-26.67	66.96	422-972	2518	0.96-3.36	0.30-1.99
	Ebb	4.56-52.47	96.02			0.57-6.60	0.18-2.79
In-Between	Flood	2.23-15.45	75.16	292-999	2787	0.16-1.11	0.08-1.04
	Ebb	3.46-25.07	97.29			0.25-1.81	0.12-1.62
Bread Truck*	Flood	22.6-29.9	71.1	170-1186	2152	1.24-1.64	0.23-1.95
	Ebb	74.0-81.0	146			4.07-4.46	1.95-3.60
Mortar	Flood	2.75-3.26	15.34	251-856	1973	0.12-0.15	0.03-0.12
	Ebb	7.75-9.93	31.62			0.35-0.45	0.08-0.30

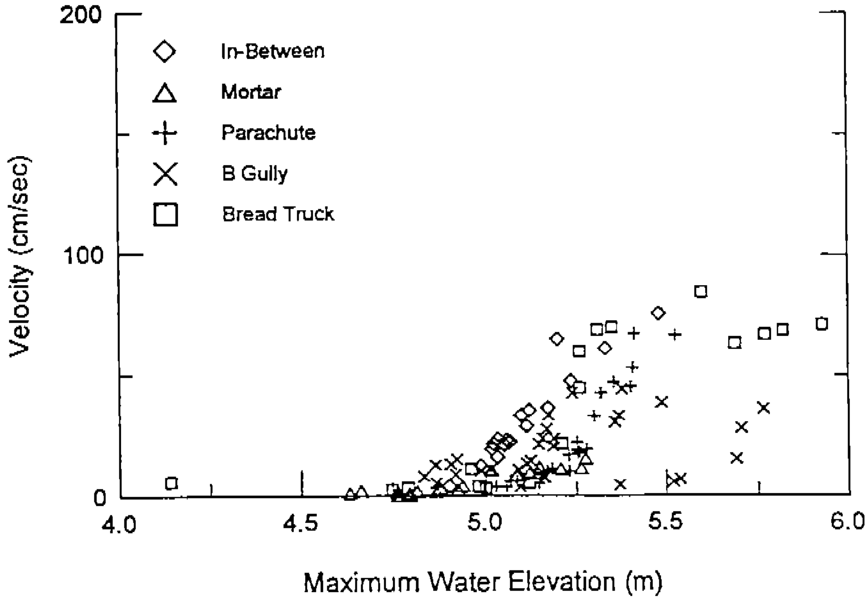
* Based on 1994 measurements

Gully erosion and discharge

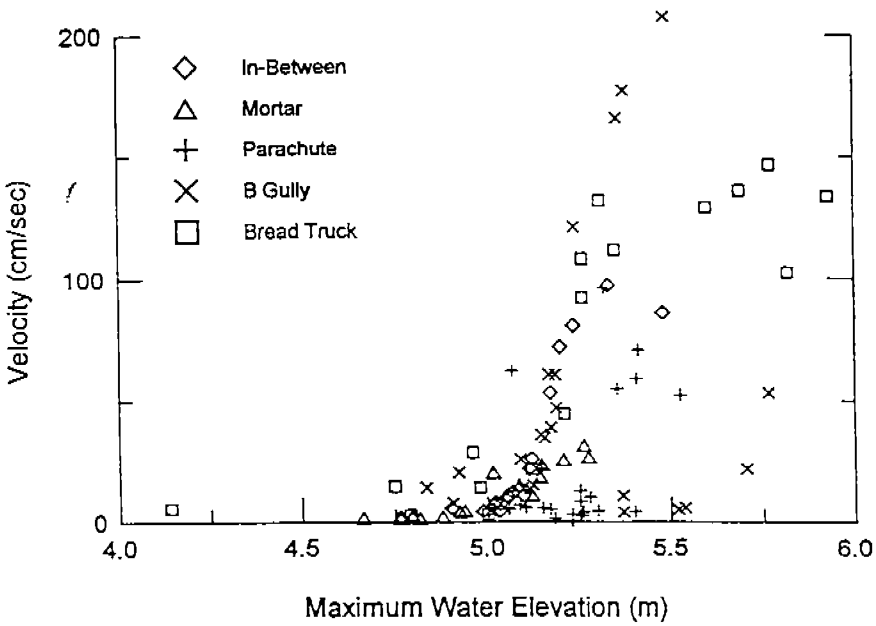
The volume of water that flows through each gully is mainly a function of the height of tidal flooding, as supplemented by river discharge and the additive effects of wind, ice and other factors. The range and magnitude of ebb current velocity is critical to determining both the flux of sediment and water into and out of the ponds and mudflats, and the ability of those currents to scour and resuspend pond, mudflat, and gully sediments.

The velocity of tidal flood and ebb currents at the Mortar, Bread Truck, B, Parachute, and In Between gully sites ranges between 0.75 and 2.07 m/s (Table II-1-7). The peak velocity at each site changes with the height of flooding (Fig. II-1-21), the lower peak and range in velocities occurring during the lower elevation flooding tides. Flow velocities are greatest at B-Gully, with moderate values recorded at Bread Truck, In-Between, Mortar and Parachute gullies.

Peak ebb velocity is greater than peak flood velocity (Table II-1-7, Fig. II-1-21). This asymmetry in flow velocities and therefore discharge determines when erosion and sediment transport will occur and to what magnitude. During tidal flooding, gully water levels rise passively before spreading out onto the mudflats. The suspended sediment load is directly related to the volume of sediment suspended in Knik Arm, except where river water is the primary source of flood.



a. Flood currents



b. Ebb currents

Figure II-1-21. Relationship between peak velocity and maximum water elevation at selected sites.

In contrast, higher velocities during ebb dictate an increase in turbulence and the potential for transporting greater amounts of sediment. Perhaps more importantly, additional energy is available to cause scour and entrain sediment. Thus, drainage and gully erosion are more active during ebb, and it is likely that tidal currents generated on the mudflats or in ponds will also be more erosive.

Discharge (Q) has been estimated for each monitored gully using the peak and mean velocities by:

$$Q = VA$$

where V is velocity and A is the cross-sectional area.

Average discharge values calculated for each gully range from 0.12 to 3.36 m^3/s during flood and 0.25 to 6.60 m^3/s in ebb (Table II-1-7). Peak ebb discharge at each site ranged from 1.16 to 12.30 m^3/s.

Peak and average TSS concentrations collected over the same time intervals as the current velocity and discharge data provide rough estimates of flood and ebb sediment fluxes. Average monthly sediment flux ranged from 0.03 to 1.99 kg/s during flood and 0.08 to 2.79 kg/s during ebb (Table II-1-7).

Ebb sediment flux is greater than the flood sediment flux. This flux is related to the difference in turbulence in the water column during flood and ebb stages; however, the significance is not as clear. These data indicate that over time, there is a net transfer of sediment out of ERF into Knik Arm. Sedimentation rates in ponds and mudflats suggest contradictorily, however, that erosion is localized to drainageways and gully walls and therefore only reflect conditions within them. On the other hand, sedimentation elsewhere may be mainly the system's response to earthquake-induced pond subsidence.

Gully erosion and recession—Modern rates

The amount of recession of scarp crests is highly variable within a particular gully, as well as among all gully sites (Tables II-1-8 and II-1-9). Maximum recession rates ranged from 0.3 to 3.2 m during the May–September 1992 period, 0.1 to 1.3 m during the period September 1992 to June 1993, and 0.1 to 3.3 m during June to September 1993. During the winter of 1993, erosion rates ranged from 0.1 to 5.0 m, 0.1 to 2.0 m in the summer of 1994, 0.1 to 11.7 during the winter of 1994,

Table II-1-8. Seasonal summary of scarp recession

Site name	Summer 92 H	Summer 92 L	Winter 92-93 H	Winter 92-93 L	Summer 93 H	Summer 93 L	Winter 93-94 H	Winter 93-94 L	Summer 94 H	Summer 94 L	Winter 94-95 H	Winter 94-95 L	Summer 95 H	Summer 95 L	Total H	Total L
B-Gully	---	0.1-0.3	---	0.2-0.3	---	0.3-0.8	---	0.1-0.6	---	0.1-1.1	---	0.1-0.8	---	0.2-0.8	---	1.0-5.3
Parachute	0.3-3.2	0.2-0.5	0.5-1.3	0.6-0.7	0.1-3.3	<0.1-0.2	0.6-2.7	0.6-0.7	1.7-2.0	0.7-1.2	0.3-1.7	0.1-2.3	0.1-3.4	0.3-0.6	1.1-12.1	1.3-1.8*
In-Between	<0.1-1.0	<0.1-0.5	<0.1-0.8†	<0.1	<0.1-0.8	0.8	0.1-0.3	<0.1	0.1-0.6	~0.8	<0.1-0.2	<0.1-0.5	<0.1-1.2	<0.1	0.2-2.8	0.2-1.2
Tanker									<0.1	0.1-0.8	<0.1	<0.1-0.3	<0.1-0.5	<0.1-0.5	<0.1-0.5	0.3-0.9
Bread Truck							0.3-5.0	0.1-0.3	0.1->1.1	0.1-2.2	1.0-11.7	0.1-0.3	0.3-20.0	0.1-2.0	2.0-33.3	0.6-3.0
Coastal 5									0.3-1.5	<0.1-0.6	0.4-6.4	0.6-1.0	0.3-16.9	0.5-0.7	0.6-25.9	1.0-1.7
Mortar											0.3-1.7	0.5-1.1	0.3-1.3	<0.1-1.2	~1.1-1.6	0.5-2.2
Coastal 6									~0.9	1.0-1.8	~0.3	0.3-.04	0.7-1.2	0.9-1.1	~1.9	1.1-2.7
Coastal 1									1.5-1.7	<0.1-0.3	0.5-0.8	<0.1-0.7	1.1-1.4	<0.1-0.3	0.8-3.1	<0.1-0.7
Coastal 7									1.0-1.2	0.3-1.0	0.4-0.9	~0.6	0.2-0.8	~0.5	1.3-2.4	0.9-1.1
River-North									---	~3.2	---	3.6-4.6	---	1.1-2.5	---	3.3-7.4

H = Headward; L = Lateral

* Maximim total erosion measured from scarp outline of 5/92; local lateral erosion was greater associated with lateral expansion accompanying headward migration of headwall

† Shallow trough (<0.5 m deep) extended ~ 40 m

Table II-1-9. Annual summary of scarp recession

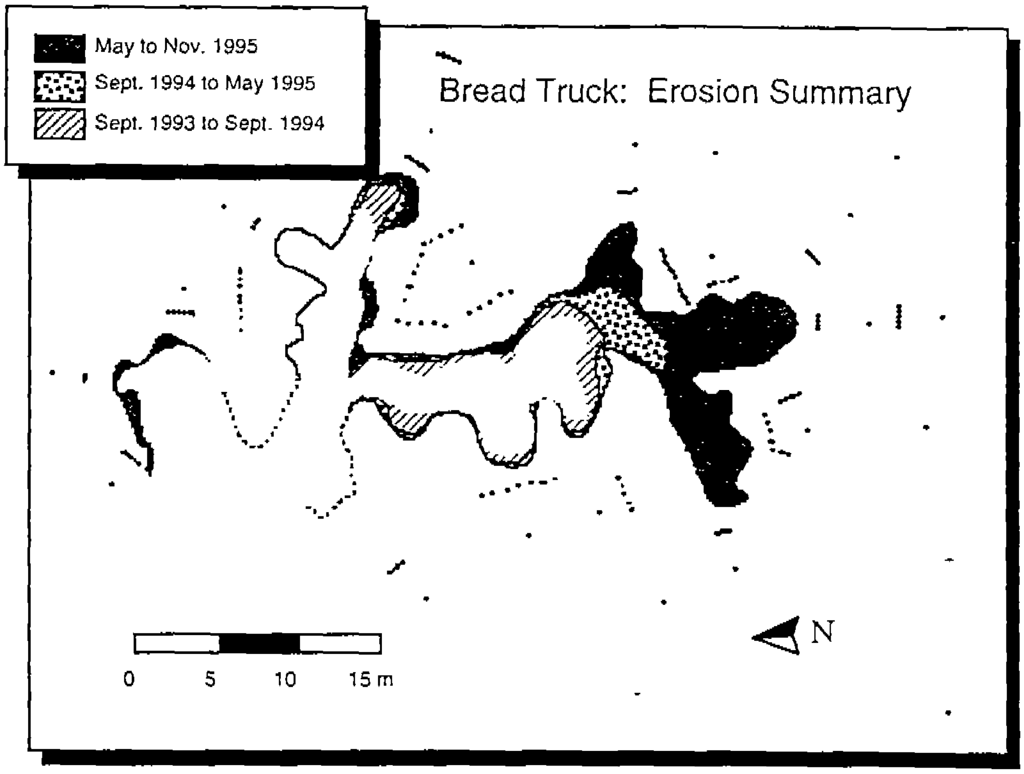
Site name	1992-1993 Headward	1992-1993 Lateral	1993-1994 Headward	1993-1994 Lateral	1994-1995 Headward	1994-1995 Lateral	Total to 11/95 Headward	Total to 11/95 Lateral
B-Gully	---	0.1-1.5	---	0.1-1.1	---	0.2-0.8	---	1.0-5.3
Parachute	0.8-4.5	0.3-0.7	0.4-2.8	0.6-1.0	0.3-2.0	0.6-3.2	1.1-12.1	1.3-1.8*
In-Between	<0.1-1.1	<0.1-0.5	0.1-0.8	0.1-1.1	<0.1-1.3	~0.1	0.2-2.8	0.2-1.2
Tanker				<0.1-0.5	0.3-0.7	<0.1-0.5	0.3-0.9	
Bread Truck		0.3-5.0	0.2-2.2	0.8-31.7	0.3-1.3	2.0-33.3	0.6-3.0	
Coastal 5				0.4-7.6	0.9-1.0	0.6-25.9	1.0-1.7	
Mortar				1.1-1.6	0.5-2.2	~1.1-1.6	0.5-2.2	
Coastal 6				0.6-1.0	1.0-1.8	~1.9	1.1-2.7	
Coastal 1				0.8-2.0	<0.1-0.7	0.8-3.1	<0.1-0.7	
Coastal 7				0.8-2.0	~1.0	1.3-2.4	0.9-1.1	
River-North				1.1-7.4	---	3.3-7.4		

* Maximim total erosion measured from scarp outline of 5/92; local lateral erosion was where greater associated with lateral expansion accompanying headward migration of headwall

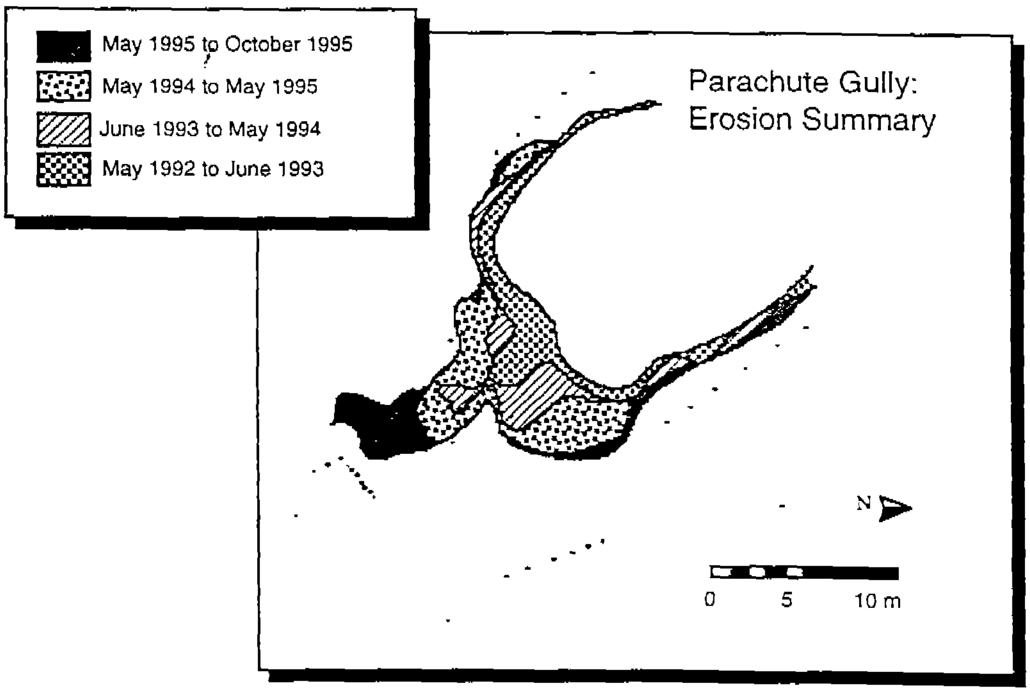
† Shallow trough (<0.5 m deep) extended ~ 40 m

and 0.1 to 20.0 m during the summer of 1995. Net headward recession has ranged from 0.1 m to about 33 m between 1992 and 1995, with a maximum of 33 m occurring since the spring of 1994 at Bread Truck Gully (Fig. II-1-22a).

At each site, however, some parts of the scarp crests did not retreat at all, and in fact, extension was measured where tension cracks developed at an early stage of collapse (Fig. II-1-23). Extension was particularly evident in May 1995 following the first tidal flooding cycle (15 to 17 May 1995) after thawing of the ground began. The winter of 1994 saw an unusually low snowfall early in the season, which allowed for deep frost penetration. Intermittent flooding and subsequent pond drainage produced conditions favorable to ice growth in the gullies themselves (Fig. II-1-24). We feel that jacking caused by freezing of interstitial water and growth of needle ice, as well as ice shove caused a reduction in the cohesiveness

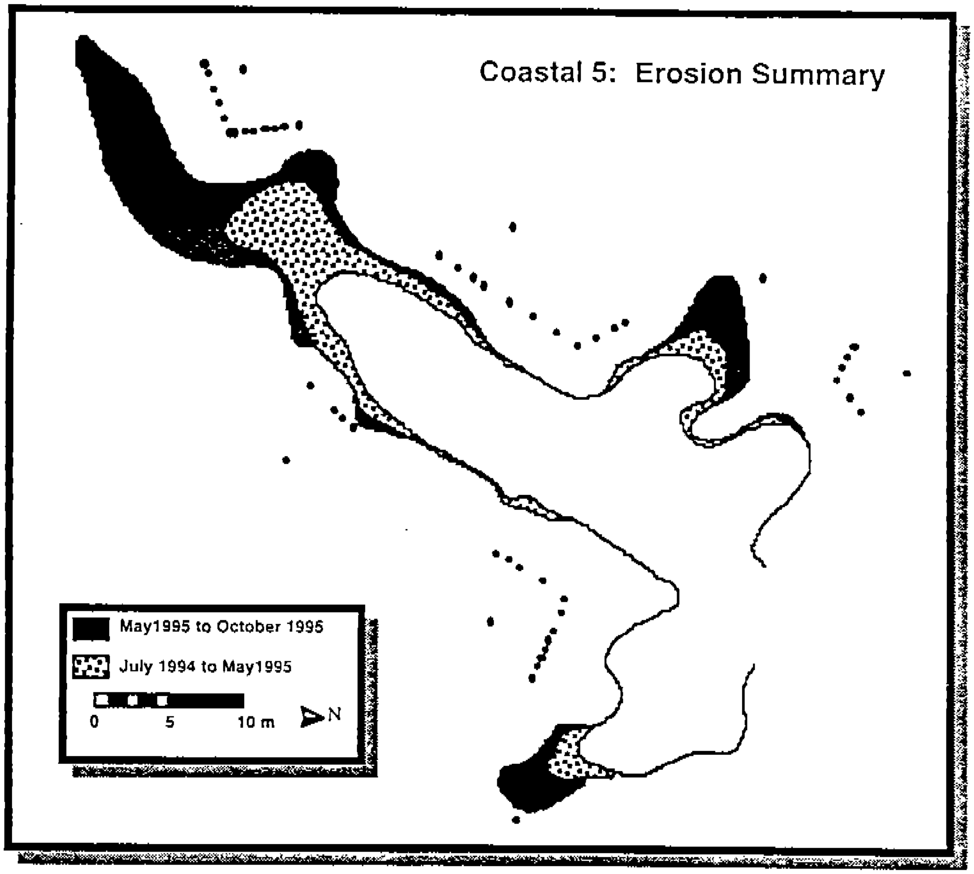


a. Bread Truck Gully.

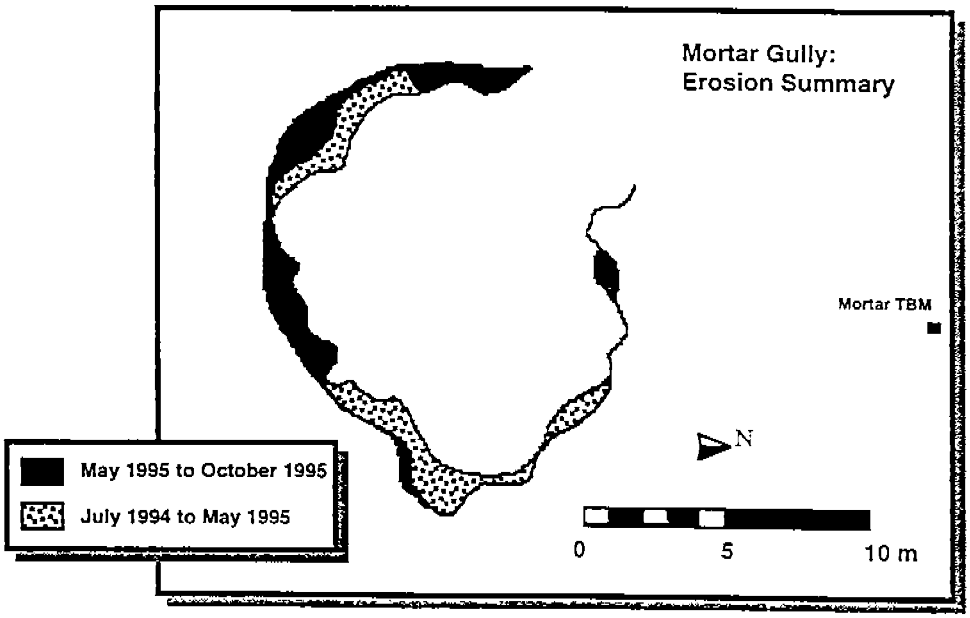


b. Parachute Gully.

Figure II-1-22. Summary of gully scarp recession.

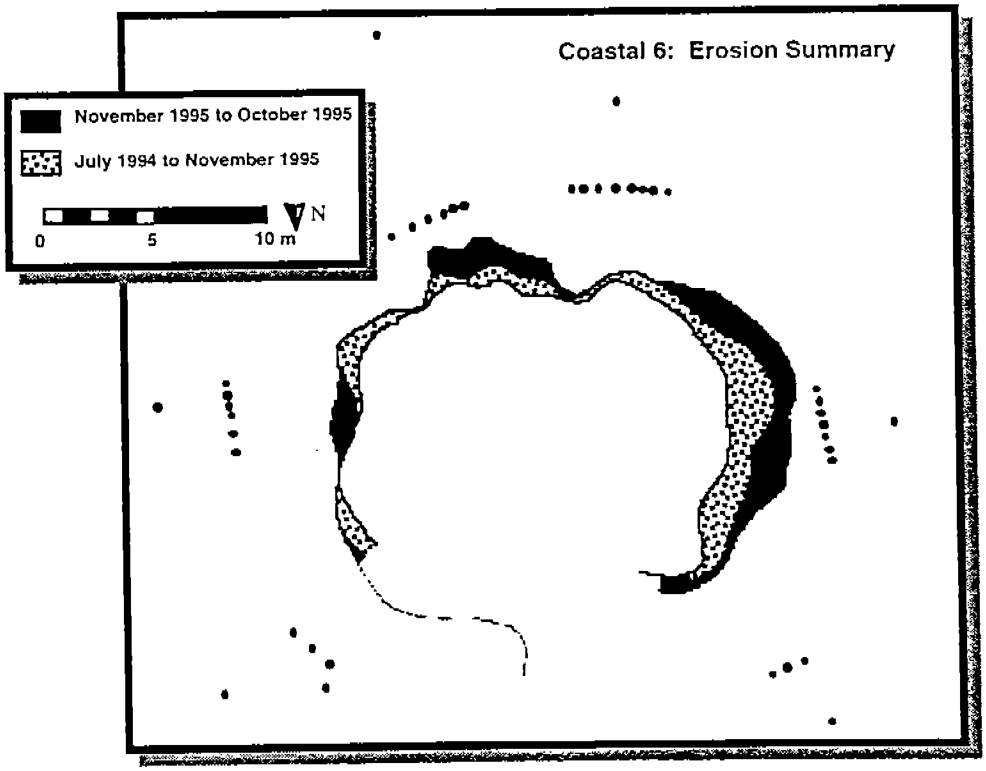


c. Coastal 5 Gully.

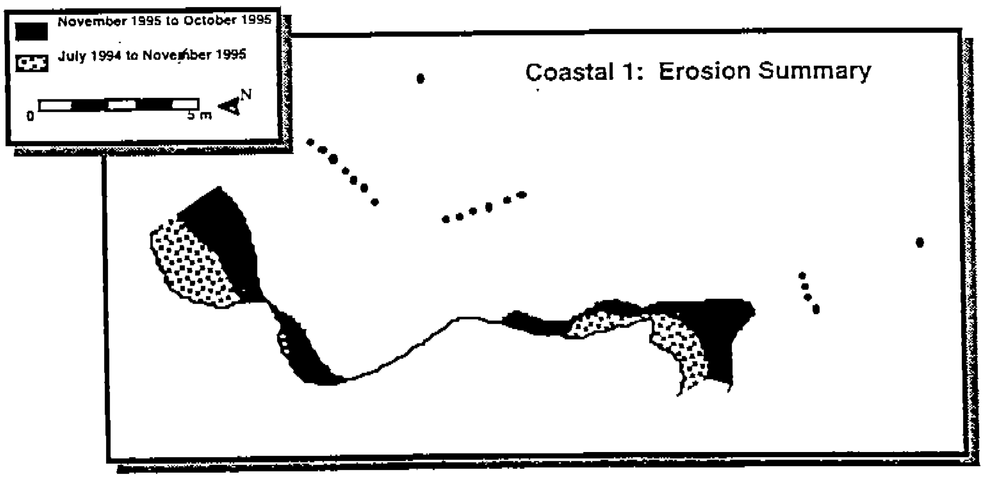


d. Mortar Gully.

Figure II-1-22 (cont.). Summary of gully scarp recession.

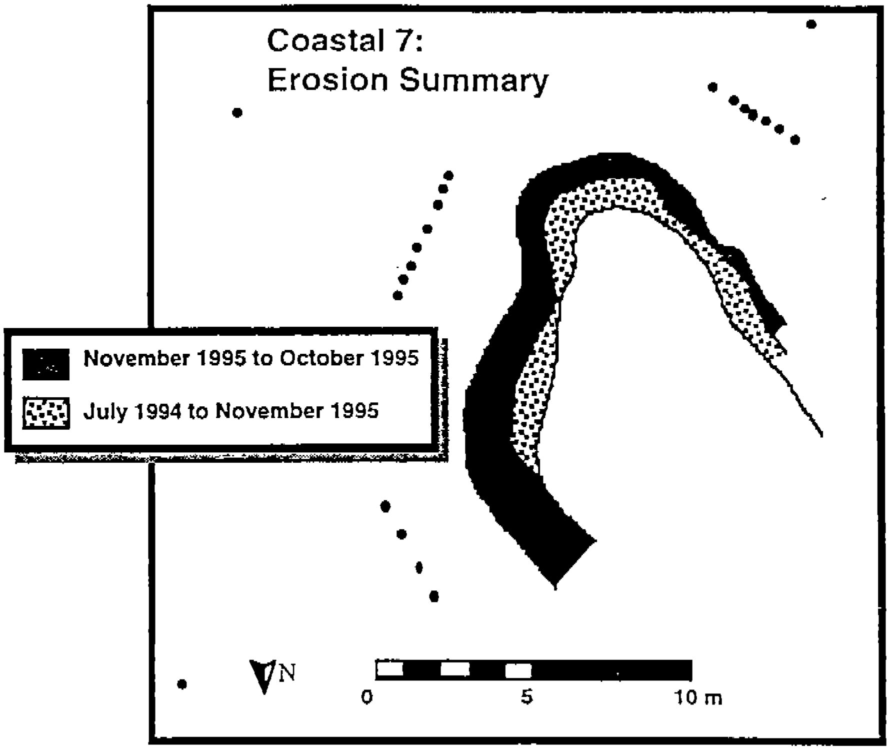


e. Coastal 6 Gully.

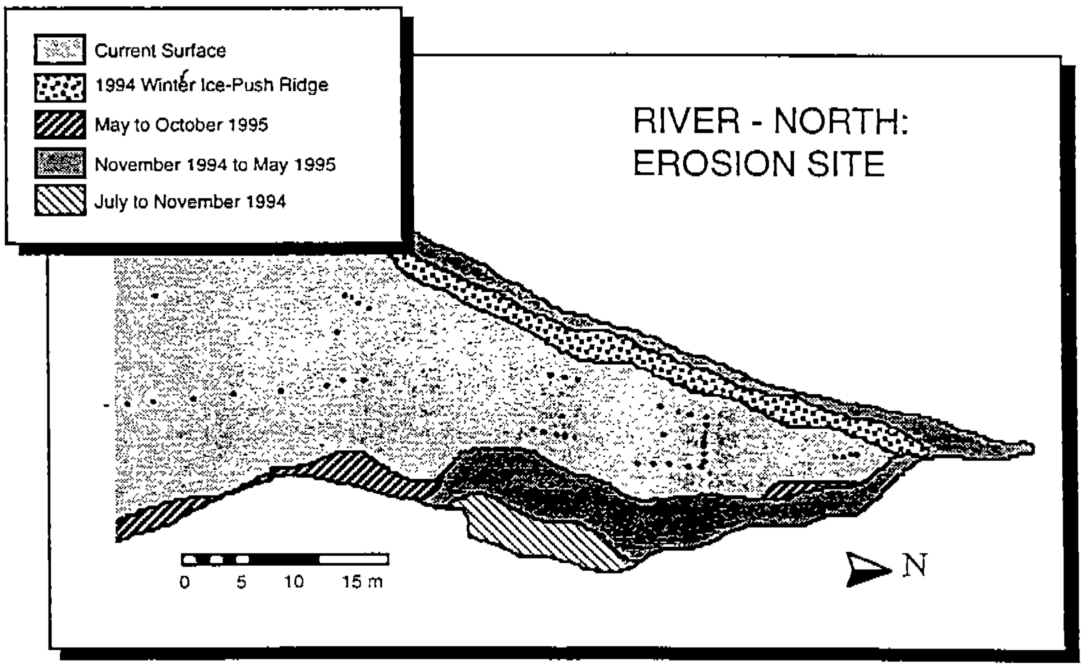


f. Coastal 1 Gully.

Figure II-1-22 (cont.). Summary of gully scarp recession.



g. Coastal 7 Gully.



h. River-North Site.

Figure II-1-22. Summary of gully scarp recession.

a. North view showing extension crack in foreground.

b. Rotational slump blocks visible to right of scarp.

Figure II-1-23. Measurements of bank erosion along Eagle River at the River-North site.

a. Lateral wall view. Ice armor caused by repeated flooding and subsequent freezing in gully.

b. Headwall view showing ice coating formed by freeze-up of waters flowing into gully.

Figure II-1-24. Bank of Bread Truck Gully showing ice growth formation.

Figure II-1-25. Aerial view of Parachute Gully in October 1995 showing accelerated headward recession that has accompanied capture of flow through craters.

of the bank sediments and increased their susceptibility to erosion during the cycle of May tidal flooding.

The spatial variability in recessional rates is evident in the plots showing the sequential recession of scarp crest location through time (Fig. II-1-22). One of the first gullies monitored at ERF is that of Parachute Gully on the west side of Area C (Fig. II-1-14). Since monitoring began in 1992, Parachute gully (Fig. II-1-22b and II-1-25) has undergone up to 12.1 m of headwall recession but only 1.8 m of lateral recession (Tables II-1-8 and II-1-9). Recession has centered around a drainageway that has become incised and enlarged where multiple mortar craters were once situated. In this instance, the craters became hydraulically connected by localized scour during ebb and the direction of gully extension is dictated by their presence. Similar enhanced erosion occurred along drainageways in Area A (Fig. II-1-26a) and B-Gully (Fig. II-1-26b).

Bread Truck and Coastal 5 gullies bracket the mouth of the Eagle River and are the sites with the maximum rates of headward recession (Fig. II-1-14, II-1-22a, II-1-22c). Bread Truck Gully (Fig. II-1-27 and II-1-22a) was first monitored in 1993

a. Area A.

b. B-Gully.

Figure II-1-26. Aerial view of gullies where recession and ebb flow have been modified by surface craters.

Figure II-1-27. Aerial view of Bread Truck Gully in October 1995.

when headward recession ranged from 0.3 to 5.0 m and lateral recession was on the order of 0.2 to 2.2 m (Table II-1-8). In 1995, headward recession accelerated to 11.7 m during the May 1995 flooding tide (representing the winter 94/95 erosion column of Table II-1-8) and an additional 20 m during the 1995 summer season. These rates do not appear to be exceptional or unique; the Coastal 5 gully site experienced 17 m of recession during the summer of 1995 and a total of about 26 m since the hub and line stakes were established in July 1994.

Recession due to lateral erosion is represented by B-gully, a site that has been monitored since 1992. The monitored section lies along the margin of a peninsula between two tributaries to the main gully, about 75 m down-channel of the gully headwall. Gully erosion is characterized by the formation of cuspate embayments that have gradually enlarged since 1992 with a maximum of 5.3 m change (Tables II-1-8 and II-1-9, Fig. II-1-28). This site is significant due to repeated detection of WP in transport within ebb waters (Lawson et al. 1995a), as well as in fauna sampled within the gully (Bouwkamp 1995). The source of this WP may be the erosion and collapse of bank sediments, but at this time, cannot be distinguished from a WP source in C Pond. Data (Tables II-1-8 and II-1-9) indicate that in general, lateral recession is lower (often by an order of magnitude) than headward recession, with the exception of Mortar and Coastal 6 gullies where wide plunge pools below their respective headwalls are expanding laterally through bank collapse and rotational slumping (Fig. II-1-22d, II-1-29).

Figure II-1-28. Eastward view of eroding cuspate embayments at B-Gully.

Figure II-1-22h shows one section of the monitoring network at the River North Site where slope processes are consuming mudflat sediments and introducing material directly into the Eagle River (Fig. II-1-23). Rapid lateral erosion on the order of 3.2 m was recorded at this site between July and November 1994, and up to 7.4 m of recession had occurred by late October 1995. Erosion occurs along large rotational slumps that fail due to river undercutting and removal of sediment supporting the toe of the slope. Prior to failure, large extension cracks develop parallel to the scarp, gradually leading to catastrophic failure. The location of the crack becomes the new scarp of the riverbank (Fig. II-1-23a).

The variability in recession rate is due to the episodic nature of the erosional processes as rapid, short-duration events (Table II-1-2). Recession appears to be caused mostly by currents scouring the lower, unvegetated portion of the gully walls during ebb tide when water velocities are highest. Because the uppermost 20–30 cm of material is consolidated and rootbound (Fig. II-1-30), this soil and root mat are undermined and only fail after an erosional niche of approximately 0.5 m or deeper is cut below it. Within the gullies themselves, current scour during ebb tide removes material from the toe of the slope thereby

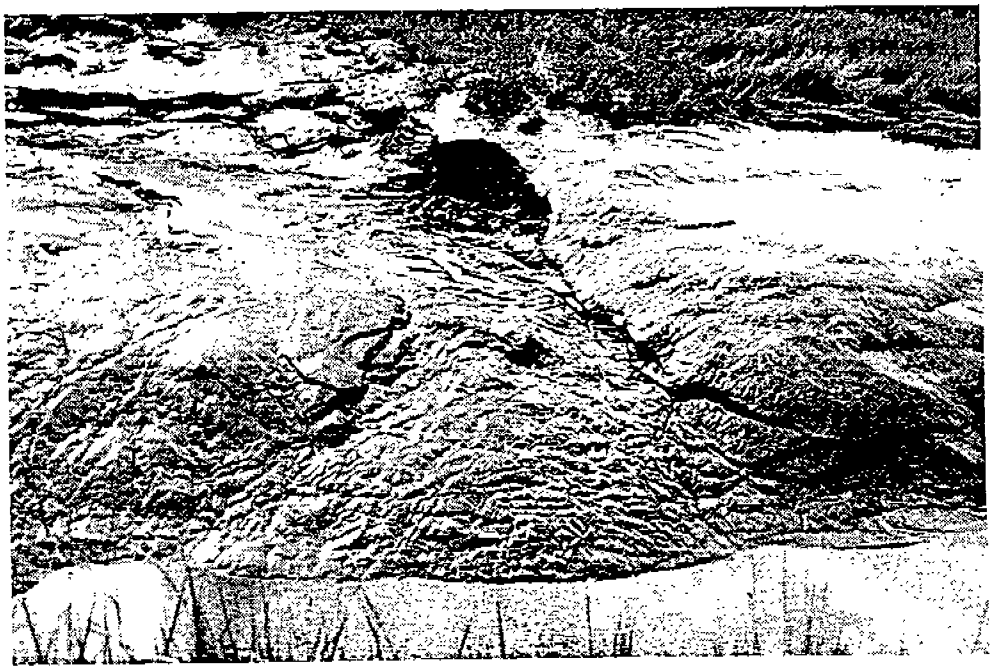


Figure II-1-29. Sediment flow at Bread Truck Gully. Saturated sediment fails when erosion during ebb tide removes material from the slope toe.

Figure II-1-30. Thick laminated peat layer at Coastal 6 forms the threshold to channel downcutting and headward recession.

removing the base of the slope and causing slumping and sediment flow (Fig. II-1-29).

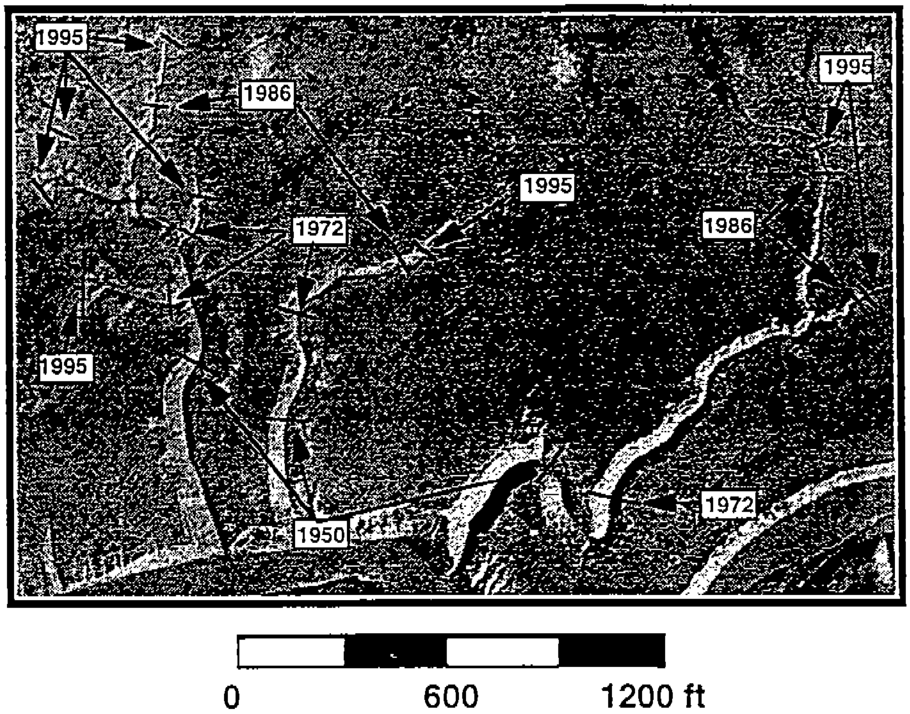
Eroded sediments form deposits in the gullies that are eventually transported into the Eagle River. Along steep scarps the blocks of consolidated sediments bound by roots that fall and roll into the gully bottoms remain intact and block the flow until currents can eventually break them apart as they are forced to roll along the bed. The lateral walls of gullies, which tend to develop low-angle slopes as headwalls recede inland, fail mainly by rotational slump flow, or creeping slowly as a mudflow into the gully channel. On gentler slopes, blocks of root-bound material remain intact as they are transported downslope by slow-moving mudflows that are active in the latter stages of the ebb cycle.

Table II-1-10. Summary of long-term gully erosion rates at selected sites.

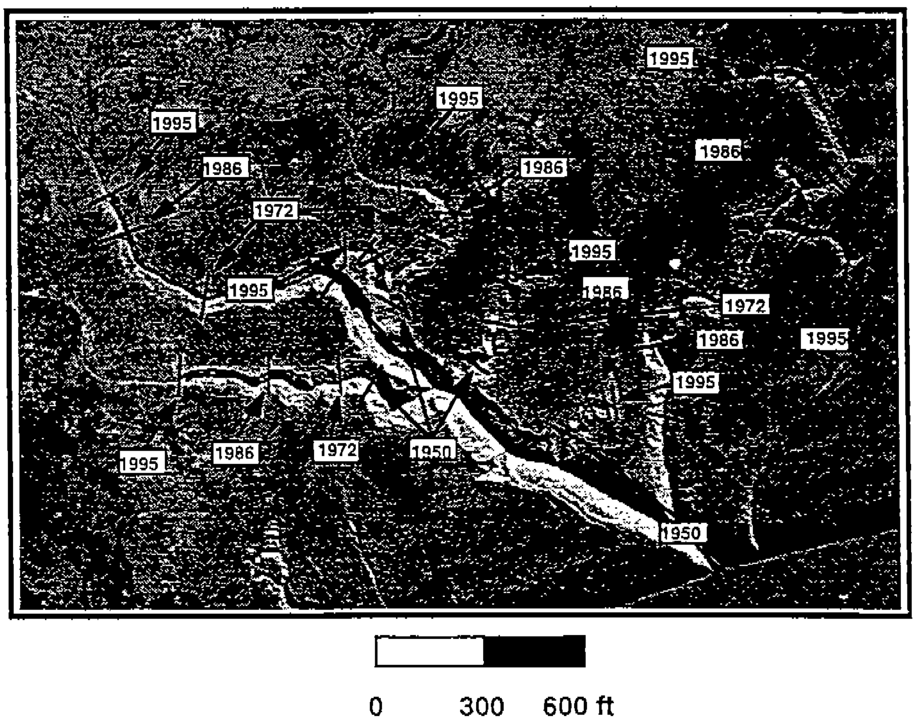
Gully	*Years (19)*	*Duration*	*Distance (m)*	*Rate (m/yr)*
B-Gully	50-60	10	35.4	3.5
	60-72	12	70.8	5.9
	72-86	14	330.4	23.6
	86-95	9	35.4	3.9
	Total	45	472.0	10.5
Parachute	50-60	10	11.8	1.2
	60-72	12	82.6	6.9
	72-86	14	70.8	5.1
	86-95	9	35.4	3.9
	Total	45	200.6	4.5
In-Between	50-60	10	23.6	2.4
	60-72	12	99.1	8.3
	72-86	14	94.4	6.7
	86-95	9	66.1	7.3
	Total	45	283.2	6.3
Mortar	50-60	10	21.4	2.1
	60-72	12	25.2	2.1
	72-86	14	82.0	5.9
	86-95	9	35.3	3.9
	Total	45	164.0	3.6
Bread Truck	50-60	10	34.3	3.4
	60-72	12	34.3	2.9
	72-86	14	251.5	18.0
	86-95	9	194.3	21.6
	Total	45	514.4	11.4
Coastal 5	50-60	10	11.4	1.1
	60-72	12	175.8	14.7
	72-84	12	225.1	18.8
	84-95	11	202.6	18.4
	Total	45	614.9	13.7

Gully erosion and recession—Historic rates

Historic gully recession rates have been reconstructed for B-Gully, Parachute, In-Between, Mortar, Bread Truck and Coastal 5 gullies (Fig. II-1-31, Table II-1-10). Long-term average recession rates over the past 45 years range from 3.6 m/yr at Mortar Gully to 13.7 m/yr at the Coastal 5 Gully. Recession ranged from 1.1 to 3.5 m/yr be-

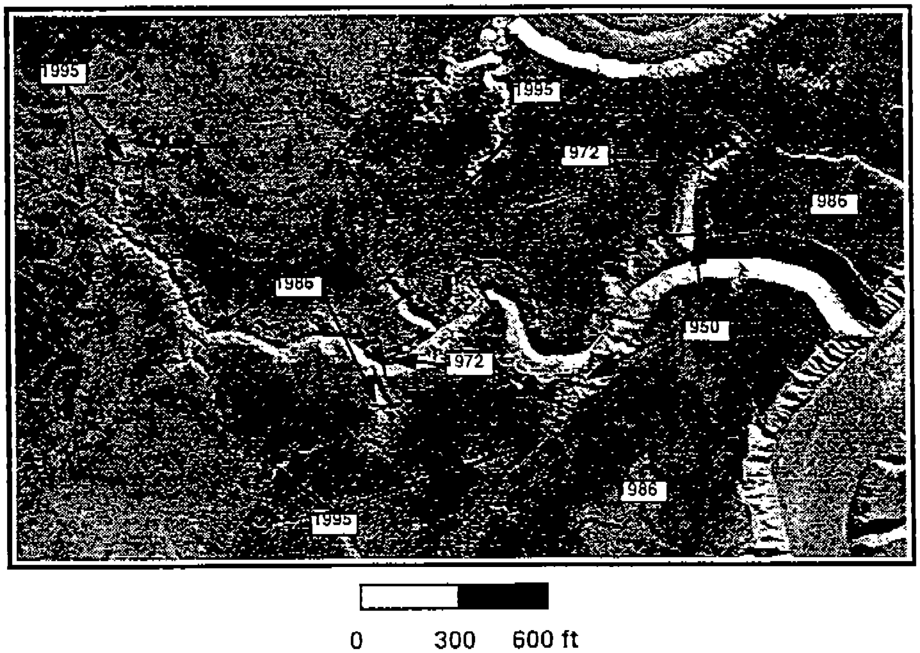


a. B-, Parachute and In-Between gullies.

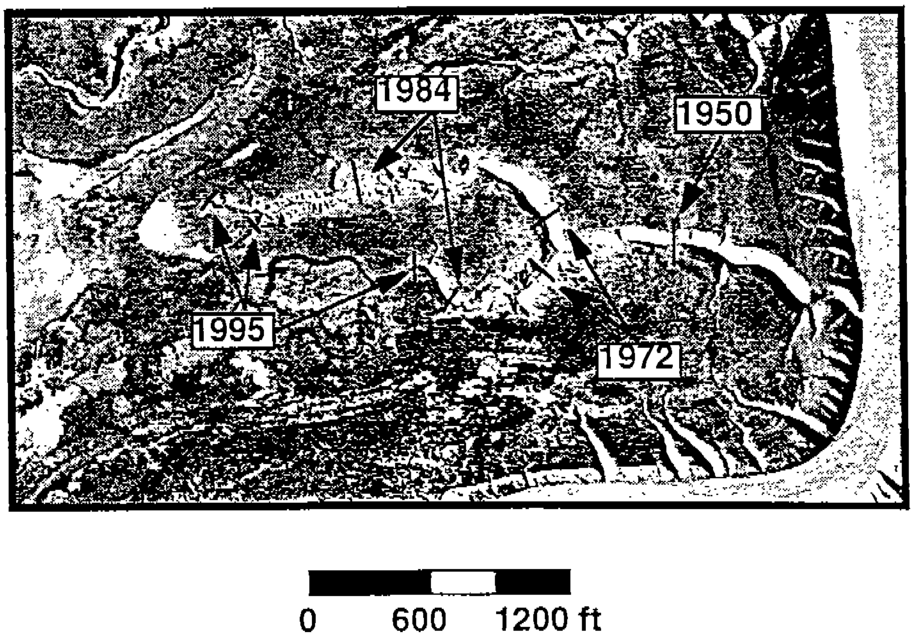


b. Mortar Gully.

Figure II-1-31. Historic gully recession. Refer to Table II-1-10 for corresponding recession rates.



c. Bread Truck Gully.



d. Coastal 5 Gully.

Figure II-1-31 (cont.). Historic gully recession. Refer to Table II-1-10 for corresponding recession rates.

tween 1950 and 1960 and increased to between 2.1 and 14.7 m/yr between 1960 and 1972 following the earthquake in 1964. Recession continued to increase between 1972 and 1986 when rates ranged from 5.1 to 23.6 m/yr. In the decade of 1986 to 1995, recession rates have remained high but have in general slowed slightly, ranging from 3.9 to 21.6 m/yr.

The general pattern appears to reflect a more or less static state prior to the 1964 earthquake. At four of the six locations studied, recession rates reached their peak between 1972 and 1986. The recent high rate of recession at In-Between Gully reflects a rapid, shallow distributary that advanced into the mudflat by about 40 m during the 1992/93 winter (Lawson et al. 1995a), which increases the 9-year average by 4.4 m/yr. Therefore, the last decade of recession at In-Between Gully may be best represented by a rate of 2.9 m/yr (Table II-1-10). The other gullies that have shown a recent acceleration of recession are that of Bread Truck, which has been the site of considerable monitoring (see below), and Coastal 6. Recession at Bread Truck has been accelerating in an unpredictable manner as the gully headwalls have encroached on Bread Truck Pond, and entered into unvegetated mudflats that are intermittently ponded.

Historical analysis of gully extension and drainage

The last 45 years at the Eagle River Flats has seen a progressive change in surface characteristics as the local drainage system has evolved subsequent to the 1964 earthquake. The photographic coverage from 8 August 1950, 27 June 1953 and 30 August 1960 show the surface characteristics of the Flats prior to the earthquake. The overall appearance of the Flats at the time these photographs were taken was one of stability, with the only indication of on-going change being along the incised meanders of the Eagle River where vegetation was absent and some slumping was evident. Small, low-relief channels drained into tidal gullies which were apparently eroding slowly into the mudflats (Table II-1-10).

The Eagle River entered the Flats in 1950 through two well-developed channels that bifurcated about 850 m east of the Route Bravo Bridge (Fig. II-1-32a). North of Racine Island, the channel was straight and confined as it eroded

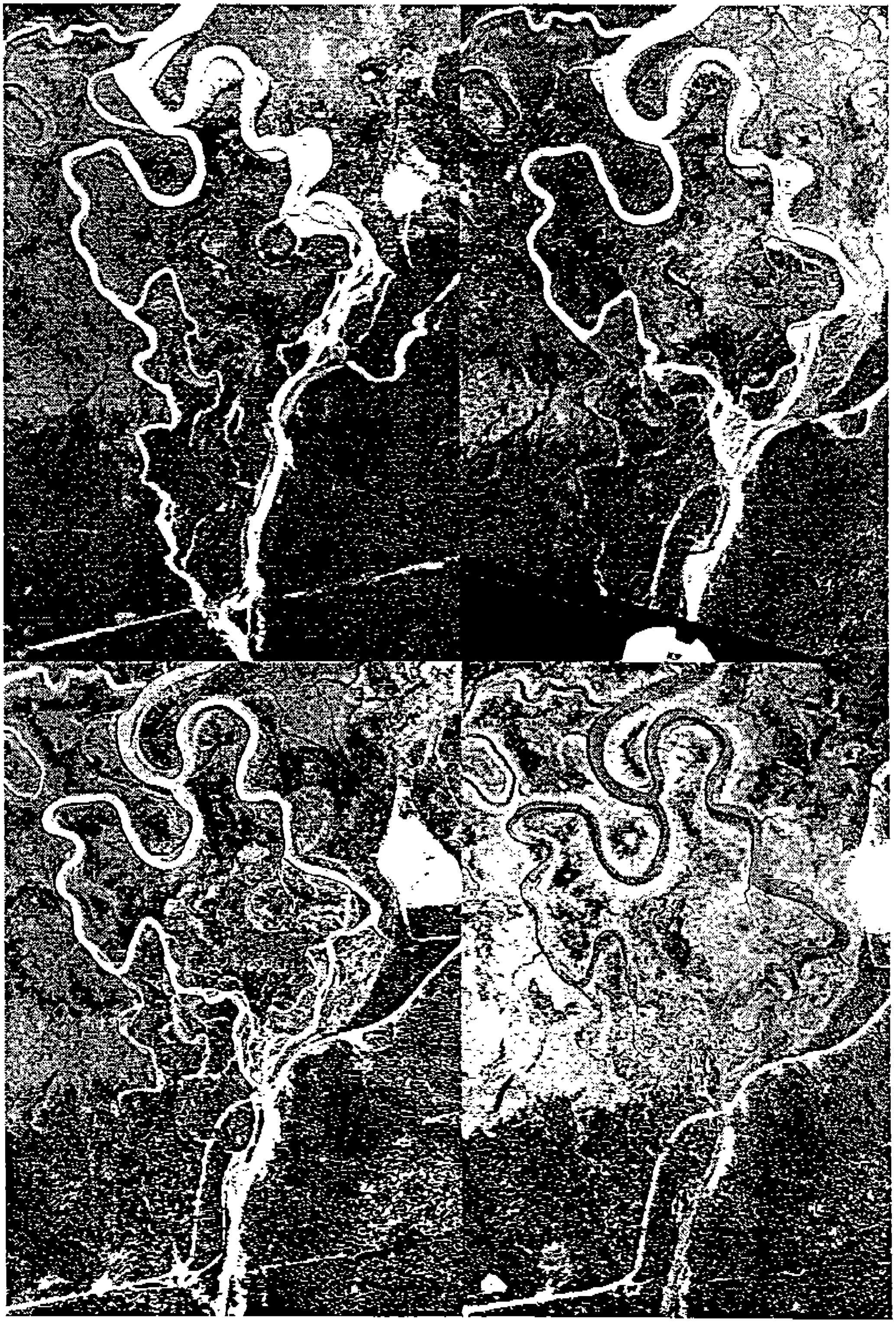


Figure II-1-32. Aerial photographs depicting the morphologic changes in the Eagle River where it enters the ERF. Clockwise from upper left: 1950, 1960,1972, 1993.

into the uplands, while the south channel appears slightly subordinate in discharge volume and exhibited a meandering pattern. Between 1957 and 1960 the south channel had captured all of the flow in the Eagle River and the north channel was inundated only during tidal flooding (Fig. II-1-32b). The southern channel remained the principle discharge until sometime between 1967 and 1972 when flow was reestablished in the north channel (Fig. II-1-32c). Multiple channels then remained active throughout the 1980s and 1990s (Fig. II-1-32d); however, in September 1995 a flood of the Eagle River resulted in the southern channel being abandoned as the northern channel eroded eastward into the upland bluffs.

During the 1950s and early 1960s, the mudflat areas of Racine Island were largely undissected and had a mostly complete cover of vegetation (Interior Sedge Meadow: Racine and Brouillette 1995a). The C, C/D and D areas were mostly vegetated (Halophytic Herb Meadow: Racine and Brouillette 1995), except where dissected by narrow, relict drainageways that extended into freshwater marsh (bulrush) in the areas where the C-, Bread Truck and Pond Beyond ponds now occur (Fig. II-1-2 and II-1-3). Open water can only be observed in the drainageways that feed Mortar, Bread Truck, Parachute and B gullies. In Parachute and B gullies, open water extends down the channels to within about 100–150 m of the Eagle River. At Mortar and Bread Truck, the narrow relict drainages are arranged in a dendritic pattern that penetrates into emergent Sedge Marsh (Racine and Brouillette 1995a). These channels form a tight drainage network along the boundary of what is now Bread Truck and Pond Beyond, where standing water exists currently on the mudflats. Relict drainageways directed water flow through on abandoned meander present in the Bread Truck pond. Small relict pools are also apparent in several of these gullies where present day headwalls and adjacent plunge pools exist, indicating a cyclic nature of stabilization punctuated by rapid erosion.

Open water in the ponds first became visible in 1967 in the areas near Clunie Creek and Clunie Point. There are also several small bodies of water in the C/D and D areas where small sedge bogs are now located. The major gullies of Bread

Truck and Mortar were also actively eroding into the mudflats by 1967 (Fig. II-1-6, II-1-31b, II-1-31c, Table II-1-10). By 1974, areas in C-Pond, the channel in Bread Truck Pond, and large relict drainages in Pond Beyond and C/D Pond exhibited additional open water and by 1984, ponds had dimensions similar to the present. Rapid pond expansion and maximum gully recession rates (Table II-1-10) appear to have been greatest during the late 1970s and early 1980s at a time when isostatic uplift rates were high (~1.5 cm/yr; Brown et al. 1977).

Recent vs. long-term rates of recession

The modern rates of net headward and lateral recession that were measured using the hub and line stake technique are depicted to show the spatial patterns in gully erosion along a transect from the mouth of the Eagle River inland to the head of the Flats (Fig. II-1-33). Nearest the coast, sites Coastal 1 and Coastal 7 have experienced more headward than lateral recession. In the mid-coastal regions, Mortar and Coastal 6 have experienced subequal lateral and headward recession, with a slight lateral erosion dominance as these gullies have been widening by bank collapse and slumping. Slightly inland from the mouth of the river, Bread Truck and Coastal 5 gullies have been experiencing drastic, yet rather symmetric retreat patterns governed by rapid headwall recession. Moving further inland, Tanker and In-Between gully sites have also experienced subequal, yet antecedent headward and lateral erosion and recession. The outer erosion sites (those north of Parachute Gully), appear to be mirrored on either side of the Eagle River to the coast. The mechanisms driving this symmetry are, however, unknown.

Comparison of the recent erosion data (Tables II-1-8 and II-1-9) with historical data (Table II-1-10) indicate dissimilar rates over the short-term, but over the long-term, recent rates are closer to the historical rates. The high rates of headwall recession at Bread Truck (33 m in ~2 yr) and Coastal 5 (26 m in ~1.5 yr) are close to the 11-year average rates of 21.6 and 18.4 m/yr, respectively, as determined from historic photographic analyses (Fig. II-1-31). Similarly, the headward recession of 12.1 m in 3 yr at Parachute Gully (Tables II-1-8 and II-1-9) is almost identical to the 3.9 m/yr average since 1986; the 1.6 m observed at Mortar is close,

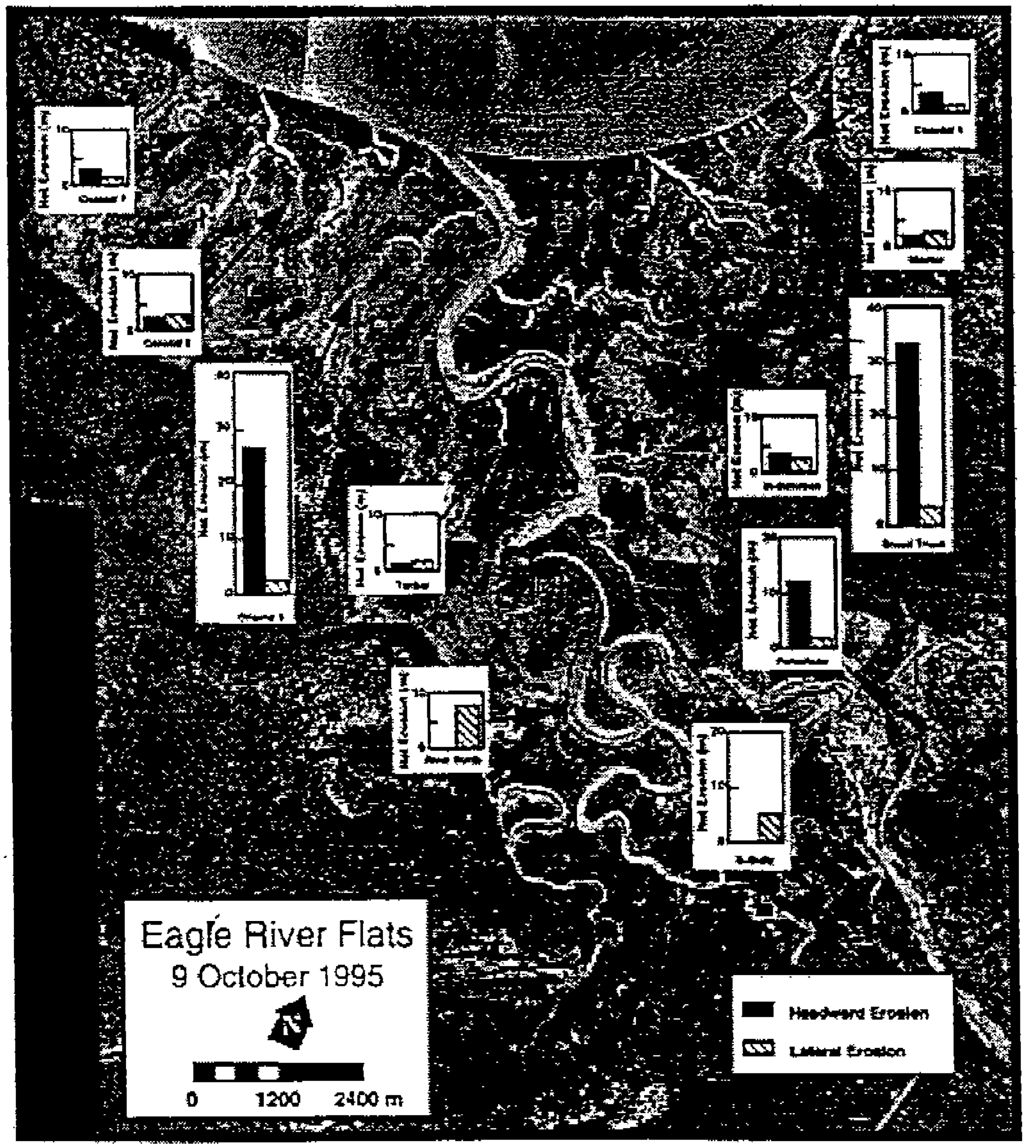
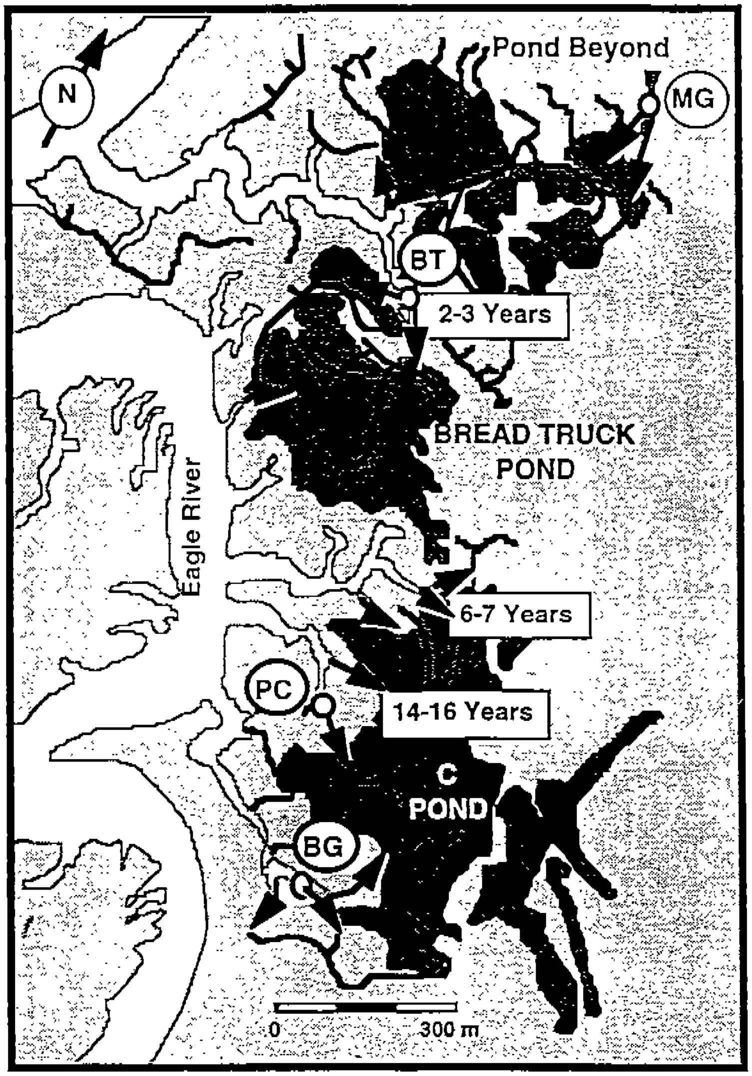


Figure II-1-33. Spatial comparison of headward and lateral recession monitored at selected hub-line stake erosion sites.

but lower than the 11 year average of 3.9 m/yr (Fig. II-1-22d, II-1-31b, Table II-1-9). Since our hub and line stakes at B-Gully record only lateral erosion, the current rates are not comparable to the 11-year average of 3.9 m/yr headward recession.

Feasibility of intrinsic remediation by natural pond drainage

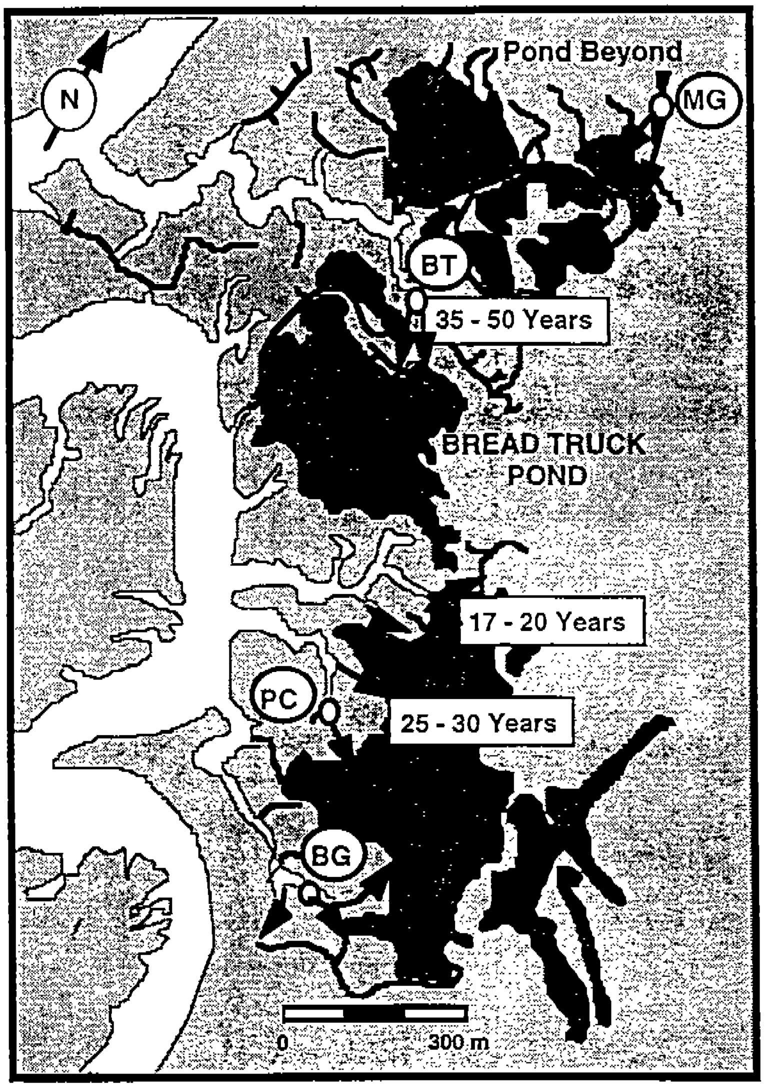
Given that the recent and long-term recession data appear to agree with one another, we revise our 1994 prediction for pond drainages (Lawson et al. 1995). Utilizing these refined recessional data that includes that of the 1995 summer



a. 1995.

Figure II-1-34. Predictions for pond drainage initiation by selected gullies in Areas C, Bread Truck, and C/D.

(Tables II-1-8 and II-1-9) and historical analyses (Table II-1-10), it appears likely that Bread Truck pond will start to drain in 2–3 yr or less. In about 6–7 yr, In-Between gully will drain parts of C and Lawson's pond, and in about 14–16 yr, Parachute gully will drain parts of C Pond (Fig. II-1-34a). Based upon more limited data from 1994, we had previously forecasted that Bread Truck pond would begin to drain in 35–50 years, while the In-Between and Parachute gullies would begin to drain the C Pond area in 17–20 yr and 25–30 yr, respectively (Fig. II-1-



b. 1994.

Figure II-1-34 (cont.). Predictions for pond drainage initiation by selected gullies in Areas C, Bread Truck, and C/D.

34b). The drastic changes in our assessment and predictions reflects the dynamic and variable nature of the erosion processes. By utilizing a greater time span to formulate our assumptions, the predictions for initiating pond drainage are more accurate. Continued monitoring is recommended, however, to document these predicted recession rates and evaluate whether natural processes are a feasible and effective alternative to anthropogenic remediation of the WP contamination.

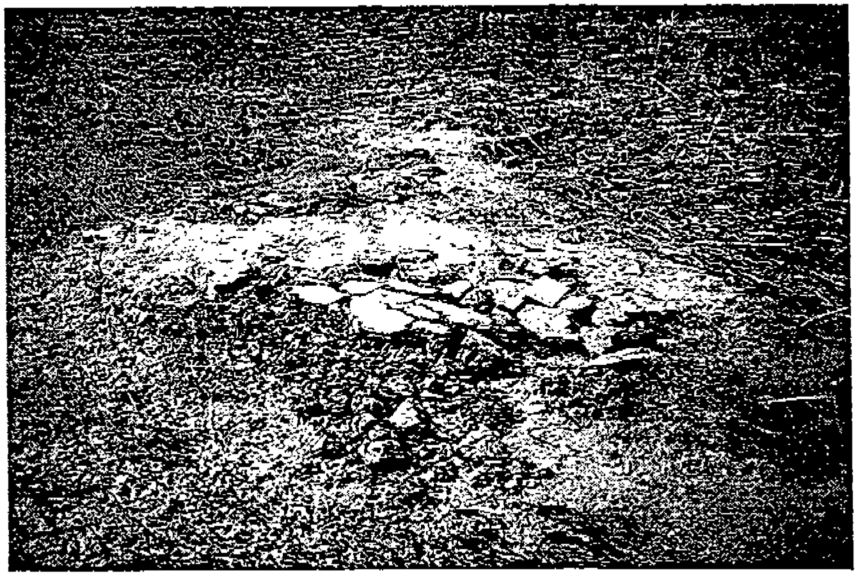
Gullies are routes for pond outflow and therefore potential pathways for WP transport. As the gullies continue headward erosion into WP contaminated areas, fresh sediment will be exposed and introduced into them, potentially increasing the amount of WP in ebb discharge. Gully erosion may also threaten the integrity of other remedial methods. For example, capping measures (i.e., geotextiles and AquaBlock®) may be undercut by erosion, release WP directly, and damage or eliminate the effectiveness of the cap. Similarly, hydrologic and physical changes to the ponds and mudflats may result from dredging and cause rapid extension of the gullies into the dredged areas.

SEDIMENTATION AND NATURAL ATTENUATION OF WP BY BURIAL

Suspension settling through flocculation occurs during slack high tide and through the early stages of the ebb cycle. In ponded areas, it also occurs between tidal flooding when water turbulence is low, allowing fine-grained particles to settle out of the water. Therefore, the longer calm conditions can be maintained, the greater the time over which deposition can occur. The mixing and exchange of flood water with pre-tide pond and marsh water increases the amount of suspended sediment in the ponds and marshes, and provides the primary source for deposition with each flooding tide.

Controls on sedimentation rates at any particular location include elevation, vegetation that traps sediment (e.g. Reed 1995), and the frequency, height and duration of inundations by sediment-laden waters (e.g. Vince and Snow 1984, Reed 1989, 1995, French and Spencer 1993, Reed and Cahoon 1992). The distance from the source also plays a role within some areas, as sediment can be deposited or eroded during flood and ebb, altering its concentration. Large amounts of sediment may be deposited locally from ice rafting of materials plucked from other locations within the Flats (Fig. II-1-35).

a. Sediment layer frozen onto an ice block transported during the November 1994 flooding tides.

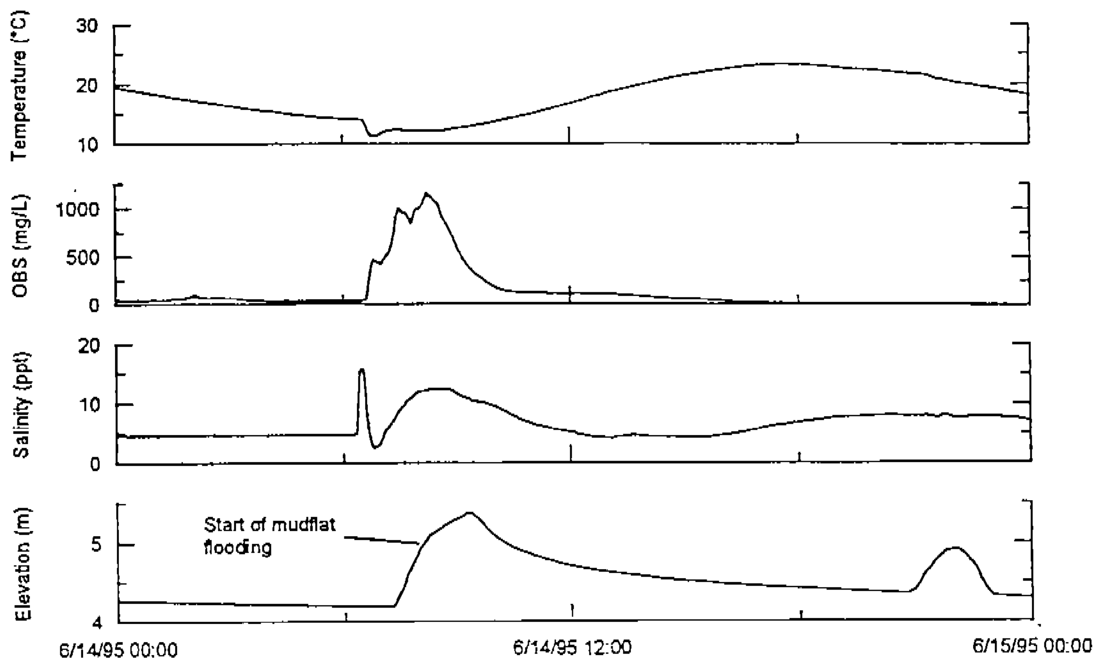


b. Ice-rafted sediment deposited at the head of Mortar Gully.

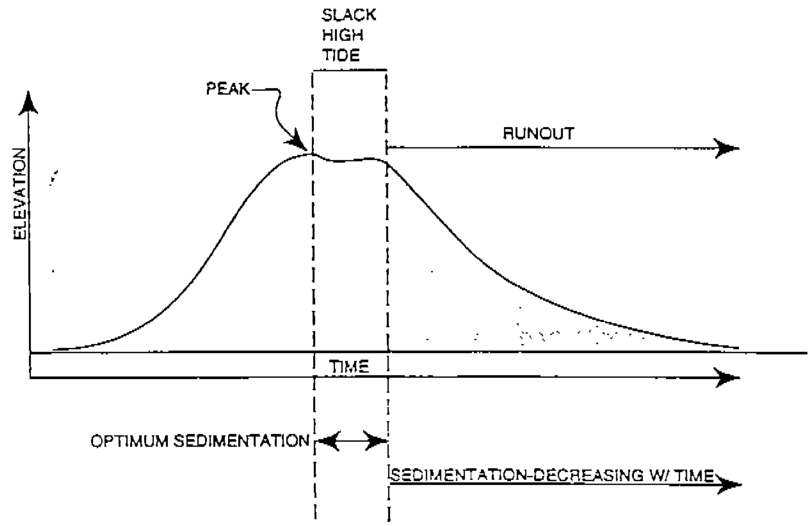
Figure II-1-35. Ice rafting at ERF.

Tidal inundation

Several factors that influence the timing, magnitude and duration of tidal flooding and runoff must be evaluated since flooding drives pond sedimentation and gully erosion, and modulates near-surface soil moisture, thereby affecting the decomposition of WP particles.



a. B-Gully on 14 June 1995.



b. Schematic showing a typical tidal cycle and period of sedimentation during the ebb tide event.

Figure II-1-36. Example of a flooding tide cycle. Note that rate of tidal rise decreases following bankfull stage when water begins to flood adjacent mudflats.

A typical tidal flooding cycle begins with a rise in the water level in the Eagle River and gullies. As the tide reaches its peak, the water floods over the banks of the gullies, displacing the water over a large area, and causing a decrease in the rate of water level rise (Fig. II-1-36). Once the peak is reached, there is a period of

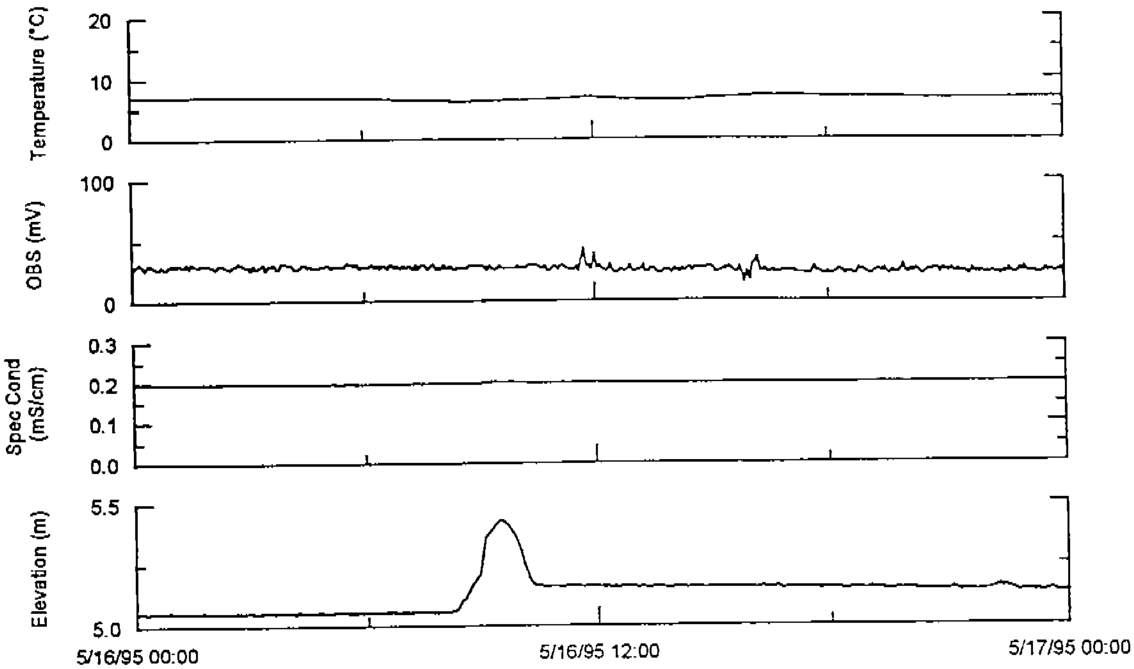


Figure II-1-37. Water quality data from the Eagle River site showing the effect of water damming caused by a flooding tide.

slack high tide when the water is dammed upon the Flats. During ebb the water begins to drain nearest the coast and progressively decreasing water level inland. This effect results in a period of runout that is typically longer than the inundation stage of flooding.

The damming of the river water during the flood tide causes the river to slow, pool, and eventually reverse its direction in the upper Flats (Fig. II-1-37). This damming effect causes the water elevation of the river to rise higher than the elevation of water in the gullies and initiate a reversal in flow direction in the drainage systems, particularly on Racine Island. This damming effect may be accentuated during spring snowmelt or mid- to late-summer runoff peaks caused by glacial melting that increase the amount of water discharged from the Eagle River (e.g. Lawson 1993). Water depths measured at the hydrostations and tidal gauge in Knik Arm show that the peak elevation on the Flats exceeded the predicted tidal height for Anchorage by up to 0.7 m throughout the 1995 summer season (Fig. II-1-38).

Because pond sedimentation results mainly from settling-out of sediment

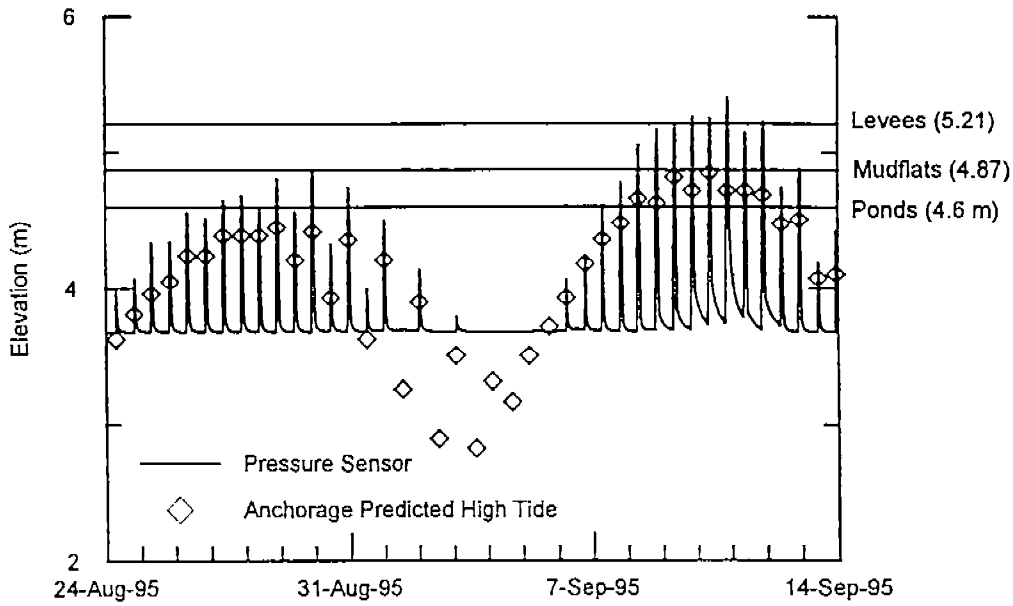


Figure II-1-38. Water elevation record showing elevations required to flood selected landforms and tidal amplification above predicted high tide at Anchorage.

suspended in the water column, sediments are deposited during and immediately following slack high tide (Fig. II-1-36b). The duration, height and mass of water inundating the ponds and mudflats therefore determine the time during which sedimentation will occur. Quiescence is of the essence to suspension setting. Incomplete drainage of pond areas commonly occurs between consecutive tides exceeding 32.4 ft (5.0 m) locally on the Flats. The mixing of flood waters with the pre-tide pond and marsh waters increases the amount of suspended sediment. In those ponds such as Racine Island, which have the highest proportion of fresh river water inundation, suspended sediment concentrations are less than where tidal sources predominate.

The time between the start of water rise and peak high tide was calculated for each gully hydrostation and compared to the peak water elevation at that site. A linear relationship was found between water rise time and peak elevation (Fig. II-1-39). Average elevations for tidal flooding across the Flats were estimated from the surveyed transects (Fig. II-1-8). These data indicate that most ponds will begin to flood at a tidal height of about 4.6 m, mudflats are inundated at 4.9 m and levees are covered at 5.2 m (Fig. II-1-38). Only at Racine Island was there a

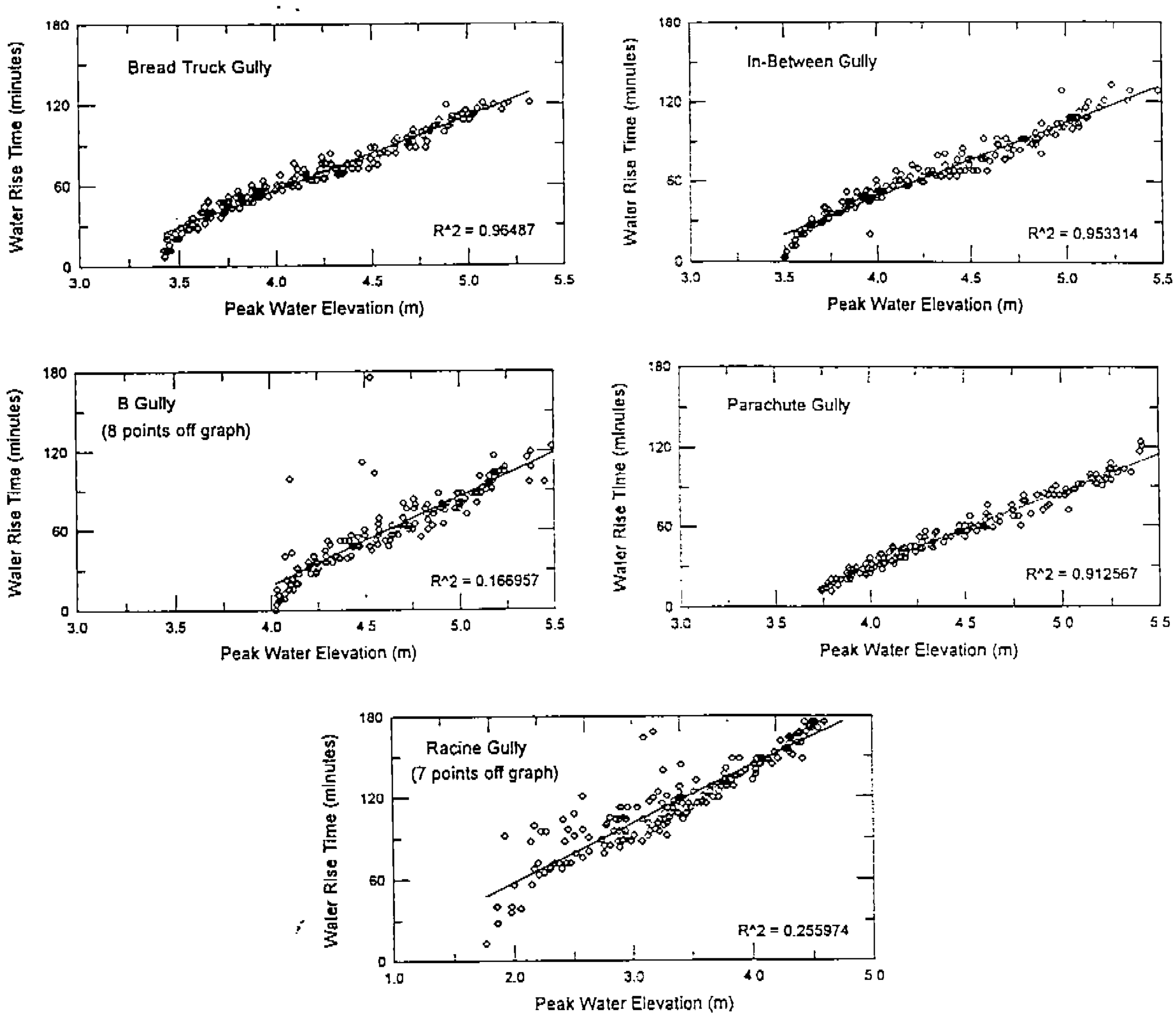


Figure II-1-39. Relationship between water rise time and peak water elevation at several gully sites.

difference; here, survey data indicate a 4.35-m threshold for pond flooding. These former elevations also yielded a linear relationship between the period of flooding (i.e., time when water elevation was greater than 4.6 m) and peak water elevation (Fig. II-1-40). Estimates of how often each landform is flooded in a given time period can be based upon these elevations. The length of time available for sedimentation during tidal inundation is directly related to the peak elevation and each landform's threshold for flooding.

Timing of flooding is a function of the elevation of the levees and mudflats surrounding the gullies, distance of the gully headwall from the coast, and gully length. Water moving down the river can also alter the timing of flooding in-

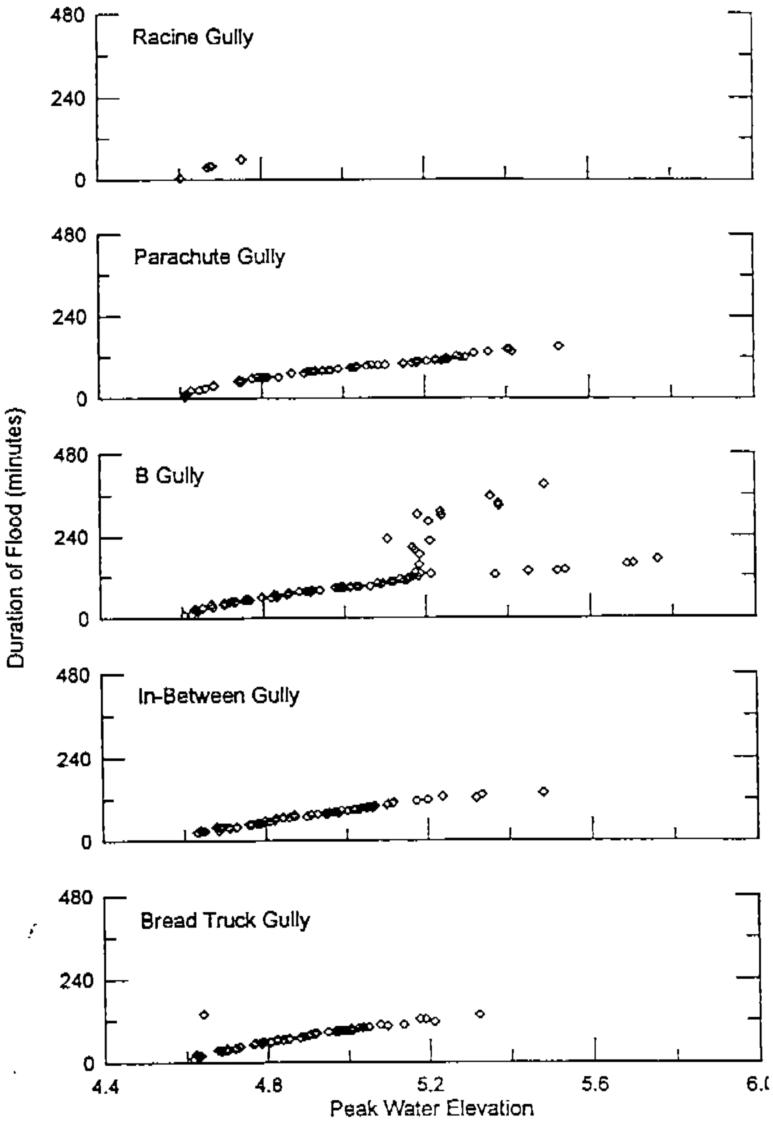


Figure II-1-40. Tidal flooding time as a function of peak flood elevation at selected gullies.

land from the coast, depending upon its volume relative to the volume of tidal waters. Analyses indicate that tidal flooding is best described by a polynomial regression (Lawson et al. 1995a).

Pond drainage is restricted by gully parameters (cross-sectional area, channel roughness, and drainage density) which limit the volume of water that can escape from the pond. This produces a "bottle-neck" effect where water in the pond remains dammed despite turbulent, fast flowing conditions within the gully

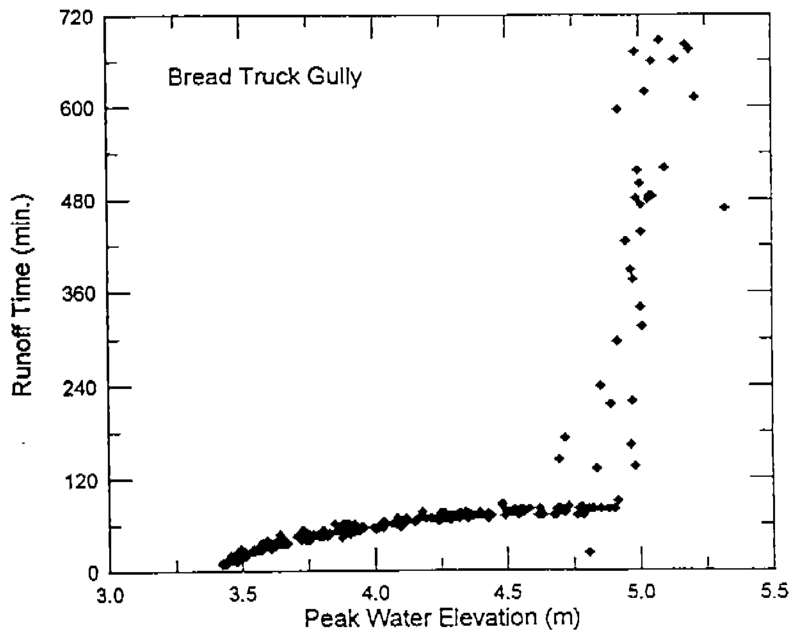


Figure II-1-41. Run-off time versus peak water elevation at Bread Truck Gully. The change in slope reflects the effect of pond drainage where run-off is extended once ponds are flooded.

heads. The response is a non-linear relationship between water elevation and runoff time (Fig. II-1-41) which, in effect, extends the period of time for sedimentation.

Sediment transport and sediment sources

Sediment transported in suspension from Knik Arm is the primary source for ponds and varies seasonally as well as during single tidal cycles (from flood to ebb) (Lawson et al. 1995a). TSS measurements in Knik Arm exceed those at the river throughout the year and show a general increase in sediment concentration through the summer season (Fig. II-1-42). These higher sediment concentrations reflect the high sediment influx from the large glacierized basins of the Susitna, Matanuska and Knik Rivers (Fig. II-1-1). The increase in TSS values during fall and winter probably reflect the colder water temperatures and increased salinity. In the Flats, reduced discharge from the Eagle River minimizes dilution by waters with much lower sediment concentrations, allowing water with greater sediment concentration to enter the ponds and mudflats.

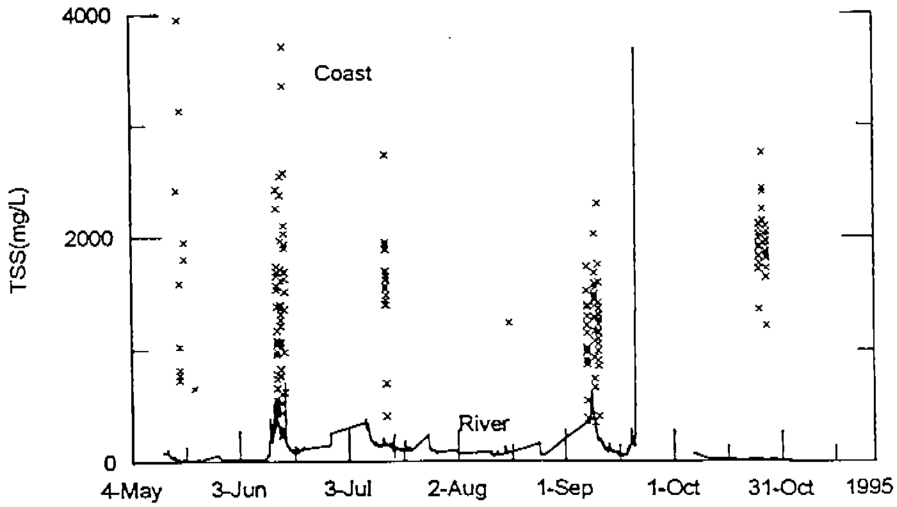


Figure II-1-42. Coastal versus river TSS measurements.

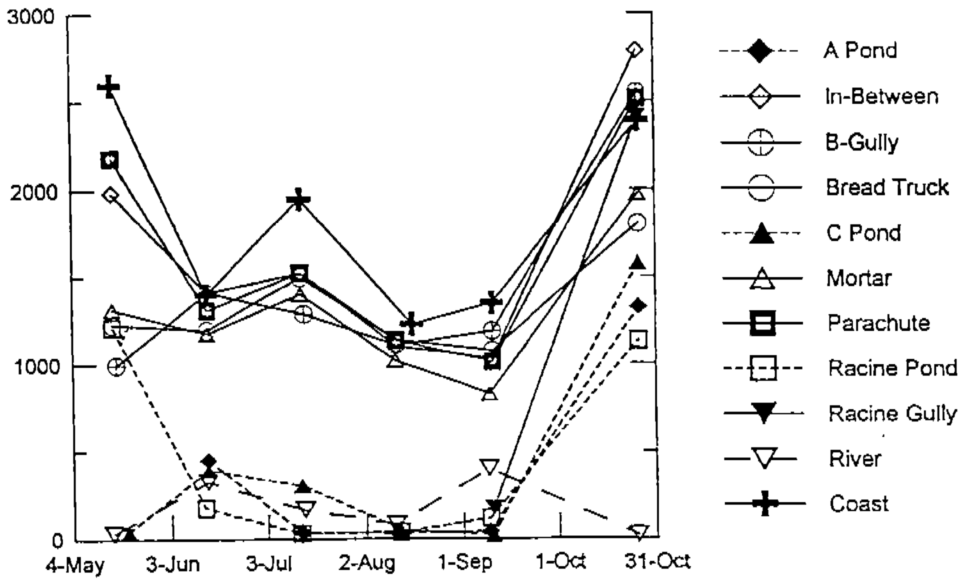


Figure II-1-43. Maximum monthly TSS comparison at all sites.

Sediment flux into and out of the ponds and mudflats varies monthly as tidal height, flood duration and runoff time vary (Fig. II-1-43). Total suspended sediment (TSS) concentrations vary among the gullies through a single tidal cycle and reflect distance inland from the coast, as well as spatial variations in runoff, pond storage capacity and the capacity of the gully to drain water from the ponds and mudflats. These differences in sediment flux into and out of the ponds and mudflats result in the spatial variability in deposition. Other factors determining the rate of sedimentation result in more localized rate differences.

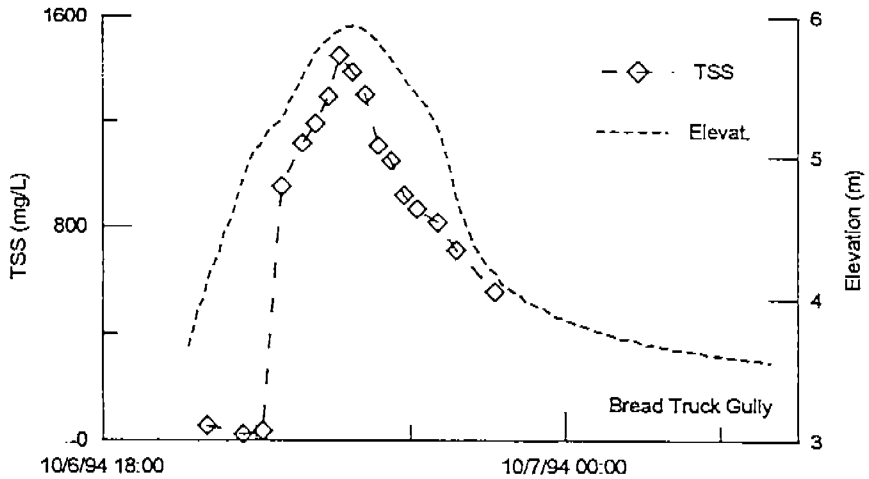


Figure II-1-44. Typical TSS variation through a flooding tide.

A typical pattern in TSS response as measured at the heads of gullies through a flooding cycle is a sharp increase due to the influx of highly turbid flood water from Knik Arm and resuspended gully bed sediment (Fig. II-1-44). TSS values remain high through slack high tide and the start of ebb. An abrupt decrease in TSS occurs during ebb runoff. The duration of ebb runoff is dependent on the ability of the gully or network of gullies to transfer water stored in the ponds and mudflats. The greater the volume of water stored in an area, the longer it will take for gullies to effectively drain the ponds. The decrease in suspended sediment concentration during ebb reflects the loss of material by deposition on mudflats and within ponds, as well as the mixing of the tidal waters with sediment-poor pond and river waters.

Seasonal variability in TSS concentrations occur in the Eagle River, being high through July and August, with sediment peaks occurring in mid-June and early August during the peak periods of snowmelt in the mountains and glacial runoff, respectively (Fig. II-1-42). The relative levels of TSS concentrations in the River are quite low, however, compared with simultaneous values measured in Knik Arm (Fig. II-1-43) and in the gullies during tidal inundations.

Landform transect rates

Sedimentation rates vary with respect to morphology and in a general sense to elevation (Table II-1-11). The overall trend is an increase in rate from levees

Table II-1-11. Gross sedimentation rates. Measurements for seasons through winter 1993-94 are from transect lines 1-12 only, Summer 94 measurements from lines 1-24 (Fig. II-1-4).

	Range (mm)						
Morphological unit	*Sum. 1992*	*Win. 1992-93*	*Sum. 1993*	*Win. 1993-94*	*Sum. 1994*	*Win. 1994-95*	*Sum. 1995*
Levee	1-6	1-12	0-6	0-11	0-15	0-30	0-17
Vegetated mudflat	1-6	1-16	1-14	1-21	1-30	0-31	0-13
Unvegetated mudflat	1-13	7-12	1-8	6-10	1-17	3-21	0-17
Pond - plate	1-4	8-28	6-26	2-17	1-21	1-16	1-37
Pond - cup	2-9	8-26	6-19	1-13	2-20	9-40	1-39
Marsh	ND	ND	ND	ND	1-20	2-10	1-13
Gully	1-77	20-33*	0-19	0-16	1-19	3-50	6-60

* Based on small sample size.

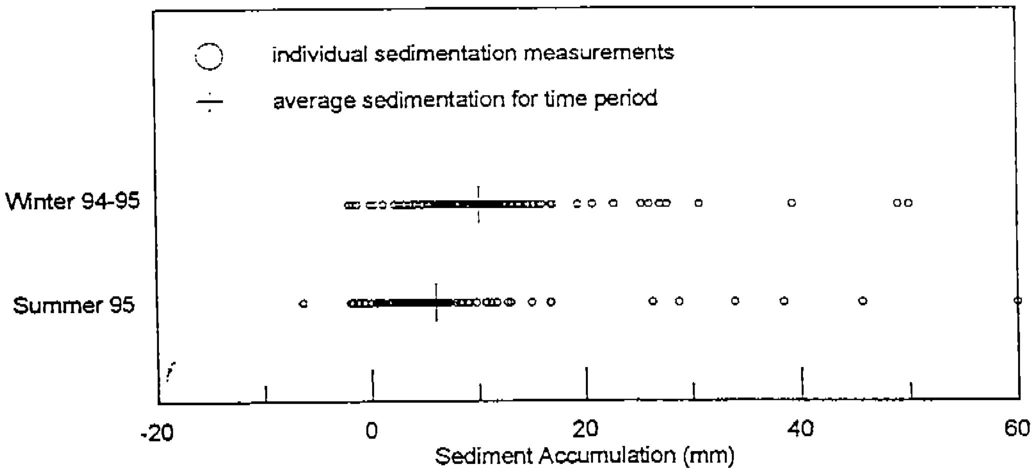


Figure II-1-45. Net seasonal accumulation rates at sites spray-painted in the C and D Areas.

to mudflats, ponds, marshes, and gully bottoms, with the more heavily vegetated areas of mudflats having higher rates of accumulation than those that are not vegetated. Typical annual sedimentation rates range from about 10–30 mm among the various landform types.

Net accumulation rates are generally higher during the "winter" 8-month period from September to May, than during the "summer" 4-month period from May to September. This difference may reflect their respective lengths of measurement, the increases measured in TSS values during the early winter months (Fig. II-1-45), the trapping of sediment by the snow cover, or the number of flooding events. Net accumulation measurements from the paint-layer technique for the period of September 94 through May 95 (winter) and May 95 through September 95 (summer), in Area C and D mudflats and levees vary seasonally. Most winter values fall in the range of 2 to 18 mm (average 10 mm), while the summer values range between –2 and +14 mm (average 6 mm).

The relationship of sedimentation rate to elevation is a response to the number of times the sites are inundated. The number of measured flooding events exceeds that predicted from tidal elevations at Anchorage because of several factors including tidal amplitude caused by the geometry of Knik Arm (e.g. Syvitski et al. 1987, p. 163), river discharge, ice cover and wind. Significantly more tidal flooding occurred at each hydrostation site during both 1994 and 1995, and given this scenario, should far exceed that number again in 1996. During summer, about twice as many floodings occur, but fewer take place in winter, perhaps due to the seasonal reduction in river discharge.

Table II-1-12 depicts on a seasonal basis the number of flooding events that would reach critical elevations to flood different landforms based on predictions using the Anchorage tide gauge. The number of inundations is highest for ponds, being less on mudflats and levees, thereby correlating with the general decrease in sedimentation rates that characterizes this respective sequence of landform types (Fig. II-1-46).

The amount of vegetation cover in the mudflats influences the sediment accumulation rates. Sediment accumulation versus percentage of vegetation cover

Table II-1-12. Comparison of predicted and measured number of flooding events reaching critical heights during summer 1994 and summer 1995. Time periods relate to intervals between sedimentation measurements.

	Number of flooding events				
	*Summer 1994**		*Summer 1995*†		*Summer 1996*
Critical height	*Predicted***	*Measured*††	*Predicted*	*Measured*	*Predicted*
Inundate ponds (4.6m)	16	52	33	38	44
Cover mudflats (4.87m)	8	18	10	22	25
Cover levees (5.21m)	0	4	0	1	2

* Summer 1994 (22 May - 15 Sep)

† Summer 1995 (5 May - 11 Sep)

** Predicted based on Thompson tide table at Anchorage.

†† Measured based on depth transducer at Bread Truck gully.

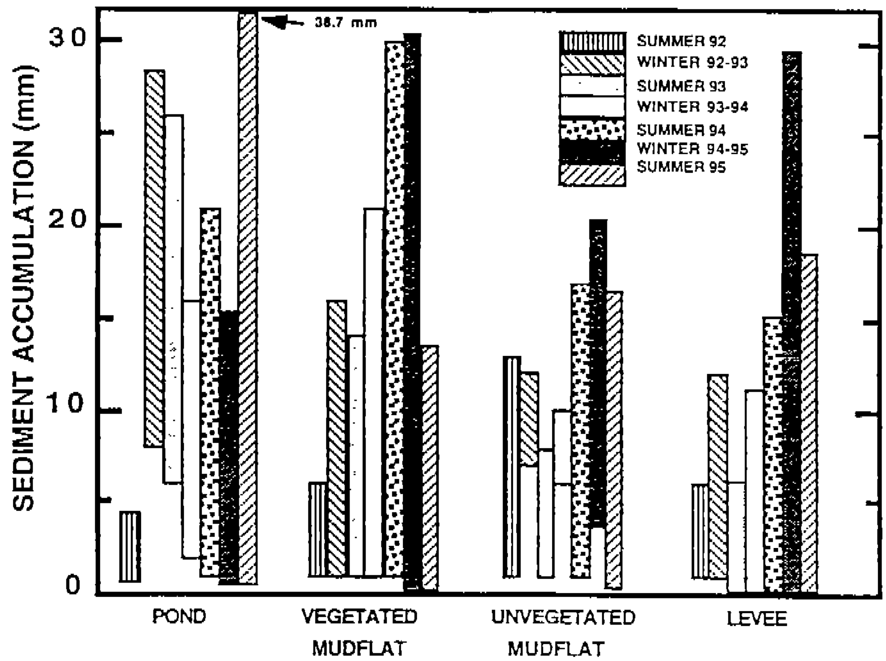


Figure II-1-46. Variations in sedimentation rate as a function of landform type.

at sites first established in 1992 are shown in Figure II-1-47. Gross sedimentation rates had two-year total accumulations of 6–18 mm at sites with less than 60–65% vegetative cover, and 26–32 mm at sites with a vegetation cover of greater than 70%.

Sedimentation rates also vary with distance from source waters. A decrease in sedimentation rate with distance inland is seen along transect 16 (Fig. II-1-48a), which extends southward from Knik Arm in coastal Area A (Fig. II-1-8). Decreased velocities of Knik Arm waters during flooding reduces their ability to transport sediment, causing rapid sedimentation near the coast. The same effect is often seen along

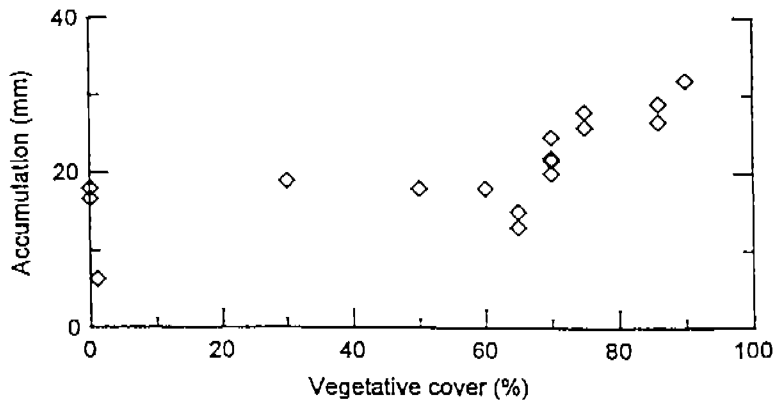
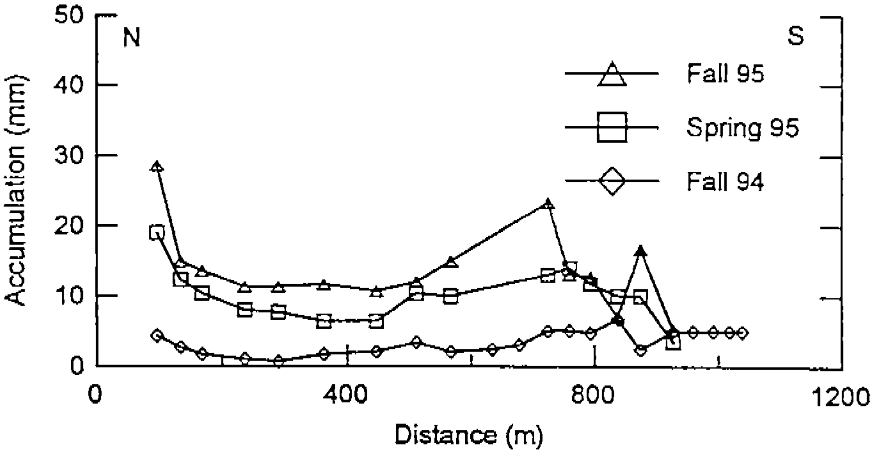
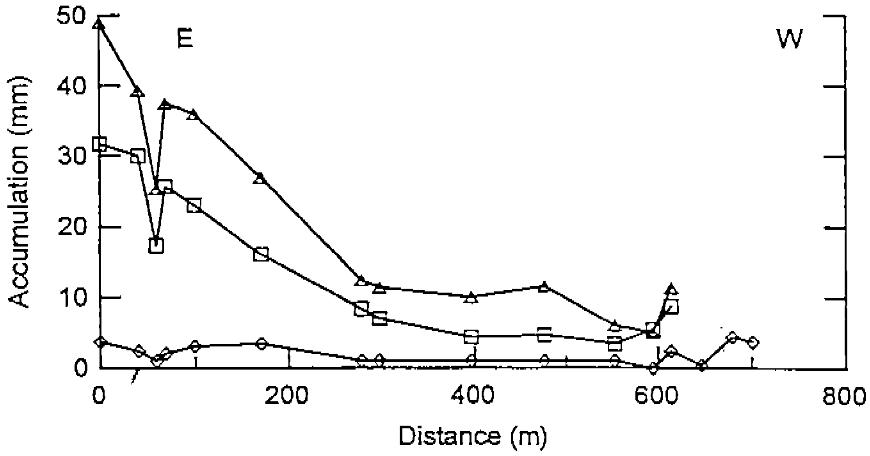


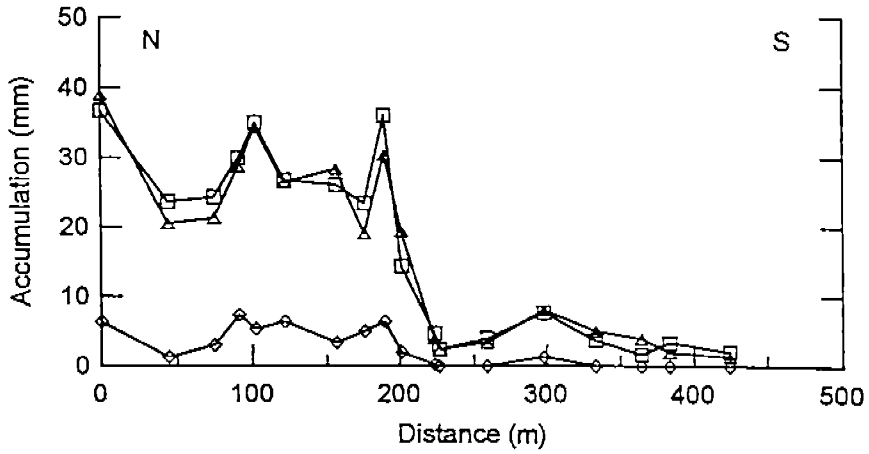
Figure II-1-47. Relation between total sediment accumulation and vegetation cover at sites sprayed with paint in 1992 and measured in the fall of 1994.



a. Transect line 16.



b. Transect line 14.



c. Transect line 19.

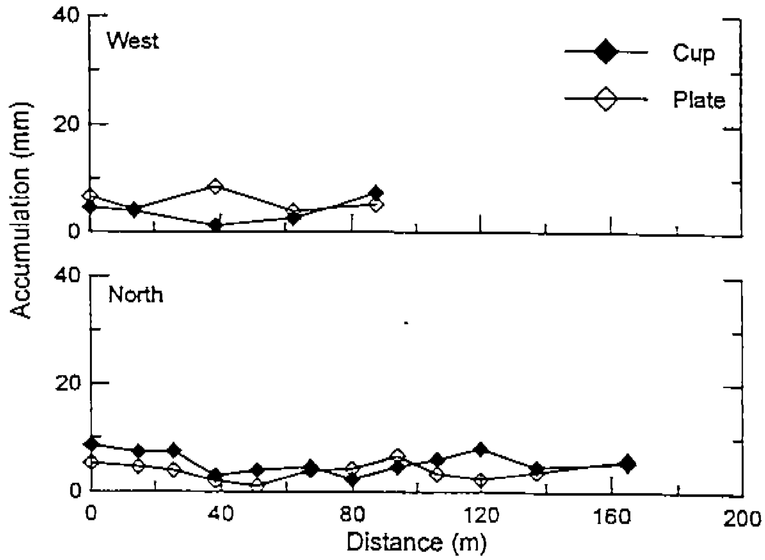
Figure II-1-48. Sediment accumulation along mudflat lines sprayed with paint in early summer 1994 (see Fig. II-1-8).

the scarp of many gullies where flow conditions change rapidly as flood waters overtop gully banks. Sedimentation rates decrease with distance from the Eagle River inland toward the marshes adjacent to the uplands (Fig. II-1-48b). High accumulation rates were also observed at a low elevation oxbow area on Racine Island that floods more frequently (Fig. II-1-48c).

Pond transects and stations

Pond sedimentation transects were newly established in 1995 in Bread Truck, C/D, C, Lawson's, A, and Racine Island ponds (Fig. II-1-9). Measurements on the plates and cups were made in September at each station on these transects; only cup measurements were obtained at C/D pond. The character of the sediment accumulated at the new pond sites during this first summer season is quite liquified. Since it is impossible to differentiate between the mineral and vegetative or organic fraction of accumulated material, the measurement includes both these fractions. At sites where an algal bloom was present in the water column above the measuring devices, the material was either gently removed or moved enough to see the sediment surface and obtain the measurement.

Overall, accumulation amounts were consistent along the transects, ranging from 5 to 20 mm (Fig. II-1-49). There were a few anomalously high readings



a. Bread Truck Pond.

Figure II-1-49. Pond sedimentation measured along pond transects for the period of May to September 1995.