GEOMORPHOLOGY AND HYDROLOGY OF THE COLVILLE RIVER DELTA, ALASKA, 1992

First Annual Report

Prepared for

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INTRODUCTION

The Colville River drains 29% of the North Slope of Alaska and its delta is the largest in arctic Alaska. The river's volume and heavy sediment load produces a dynamic deltaic system with diverse geomorphic, hydrologic, and ecological systems. Recognizing these characteristics and in preparation for exploration work on the Colville River Delta, ARCO Alaska, Inc. contracted Alaska Biological Research, along with Arctic Hydrologic Consultants, to conduct both this study on geomorphology and hydrology and a companion study on wildlife.

This report investigated the geomorphology and hydrology of the Colville River Delta (CRD) by characterizing the morphology of selected channels, mapping the distribution of terrain units, analyzing the flooding regime, and quantifying the rate of landscape change. This information is essential for the engineering design of bridge and pipeline crossings and for locating roads and pads to minimize problems associated with flooding and terrain stability.

The report is divided into four sections. The first two sections describe the physical setting of the delta, and the last two analyze the dynamic nature of its flooding regime and changing landscape. Part I describes channel morphology by presenting information on channel cross sections, riverbed characteristics, and permafrost occurrence at six locations. Part II describes a classification system that integrates landforms, surface forms, and vegetation into a system that identifies terrain units of differing development, age, and flooding regime. This classification system was used to map integrated terrain units across the entire floodplain of the CRD. Part III investigates the flooding regime of the delta by establishing stage-velocity-discharge relationships, analyzing the flood-peak frequency, and mapping distribution of flooding in 1992 within three small pilot-scale study areas. This information and information on elevation relationships obtained from the channel cross sections was used to develop a preliminary model of flooding frequency across the delta. Finally, Part IV assesses surface stability by measuring the amount of landscape change that has occurred between 1955 and 1992 within the three study areas. Each part includes a review of previous studies to provide background information related to each task.

The remarkable environment of the CRD has been the subject of numerous studies conducted over the last four decades. The most information on the geomorphology and hydrology of the delta was gathered by Hugh Walker and his associates during the 1960's and 1970's (Walker 1983). Additional, major research efforts include the study of nearshore aquatic and marine environments by the University of Alaska (UAF 1972), the investigation of the coast and shelf of the Beaufort Sea by numerous organizations during the early 1970's (Reed and Sater 1974), and numerous multi disciplinary studies conducted under the Outer Continental Shelf Environmental Assessment Program of the National Oceanic and Atmospheric Administration. Pertinent information from these and other studies are included in the background portions of each section.

OBJECTIVES

The broad scope of this project was divided into a number of tasks with discrete objectives listed below.

Channel Morphology (Part I)

(1) Measure ground- and water-surface elevations, distribution of integrated terrain units (ITUs), and gradation of bed material at six channel crossings.

(2) Determine the depth to permafrost along these six channel cross sections.

Integrated terrain Units (Part II)

(1) Classify landform, surface form, and vegetation characteristics of the landscape into ITUs.
(2) Map the distribution of ITUs to provide the basis for analyzing flood distribution and landscape change.
(3) Describe the soil stratigraphy at representative locations, to compare depositional environments and surface stability.

Flooding Regime (Part III)

(1) Develop stage-velocity-discharge relationships at the head of the delta to estimate the magnitude of the 1992 flood peak, and to provide an estimate of main channel velocities.

(2) Develop a flood-peak frequency relationship to estimate the magnitude of the discharge associated with specific recurrence intervals at the head of the CRD.

(3) Map the distribution of flooding within three small study areas and determine the percentage of each ITU covered by flood water.

(4) Provide a preliminary estimate of flood frequency of the ITUs, and use the ITUs as the basis for mapping flood frequency across the CRD.

(5) Characterize the occurrence and distribution of storm surges by reviewing the historical record, estimating the magnitude and frequency of storm surges, and mapping the distribution of salt-killed tundra.

Landscape Change (Part IV)

(1) Measure the areal change in integrated terrain units in three small study areas between 1955 and 1992 to identify areas of erosion and deposition.

STUDY AREA

The Colville River is the largest river on Alaska's North Slope and is one of eight major rivers with significant freshwater input to the Arctic Ocean (Walker 1983). The Colville enters the Beaufort Sea just west of Oliktok Point and the Kuparuk Oilfield, about midway between Barrow and Kaktovik. The native village of Nuiqsut, established in 1971, is near the head of the delta.

The Colville River drains approximately 20,700 mi^2 (about 29%) of the North Slope of Alaska. Most of the watershed is situated in the foothills (64%), with smaller amounts situated in the Brooks Range (26%) and coastal plain (10%) (Walker 1976). The head of the CRD is located about 2 mi upstream from the mouth of the Itkillik River (Arnborg et al. 1966). The CRD is bounded on both sides by old alluvial terraces that are traceable from the coast to above the mouth of the Itkillik River (Carter and Galloway 1982). Materials in the terraces ranged from sand to gravelly sand. The deposits are interpreted as alluvium because marine fossils have not been found in them. Fossil wood collected at the base of exposures at three locations yielded ages of 48,000-50,600 years before present (ybp), suggesting that the terraces and underlying deposits were formed during the last interglacial period (Carter and Galloway 1980). Underlying these deposits is the Gubik Formation (Black 1964), a series of unconsolidated deposits that record a complex marine and alluvial history spanning perhaps 3.5 million y (Carter et al. 1986). Overlying the alluvial deposits of the terraces is a cap of eolian silt derived from the delta.

The CRD has two main distributaries, the Nechelik (western) Channel and the Colville (eastern) Channel (Fig. 1). These two channels together carry about 90% of the water through the delta during flooding and 99% during low water (Walker 1983). Several smaller channels branch from the Colville channel, including the Sakoonang, Tamayayak, and Elaktoveach channels. In addition to river channels, the delta is characterized by numerous lakes and ponds, sandbars, mudflats, sand dunes, and low- and high-center polygons (Walker 1976). Most of these water bodies are shallow (< 6 ft deep) ponds that freeze to the bottom in winter and thaw by June. Lakes larger than 10 ac are common and cover 16% of the delta's surface (Walker 1978). Some of these lakes are deep (up to 33 ft) and freeze only in the upper 6 ft. Ice remains on these deep lakes until early or mid-July (Walker 1978).

The CRD study area has a typical arctic maritime climate. Winters last about eight months and are generally cold and windy. Summers are cool, with temperatures ranging from 12°F in mid-May to 60°F in July and August (Simpson et al. 1982, North 1986); summers also are characterized by low precipitation, overcast skies, fog, and persistent winds from the northeast. The occasional northwesterly storm systems usually bring storms, with high, wind-driven tides and rain (Walker 1964, North 1986).

Landcover maps (1:30,000 scale) of the CRD have been generated by the U.S. Fish and Wildlife Service [USFWS] (Rothe et al. 1983). In addition, the USFWS also has mapped wetlands (1:63,360 scale) with the National Wetlands Inventory classification. The North Slope Borough has mapped the delta for vegetation, surface form, and landforms (1:250,000 scale). The vegetation-soil-landform associations have been described for the Prudhoe Bay region east of the CRD (Walker et al. 1980).

The CRD, with its abundant wetlands, has long been recognized as one of the most productive delta for fish and wildlife on the Arctic Coast of Alaska (Gilliam and Lent 1982, Divoky 1983). The area is important for Tundra Swans, Brant, Yellow-billed Loons, and Greater White-fronted Geese (Rothe et al. 1983). Two species of whitefishes, arctic and least cisco, overwinter in the delta (NOAA/OCS 1983) and support the only commercial fishery on the North Slope. Caribou from both the Central Arctic Herd and the Teshekpuk Herd use the delta (Gilliam and Lent 1982). Finally, the area's resources are important to the subsistence economy of the Nuiqsut villagers.

Within the CRD, three study areas were chosen to represent different erosional and depositional regimes for intensive study of the flood distribution and patterns of landscape change (Fig. 1). The Kupigruak Study Area, located on the eastern channel, represents the highest energy regime of the three study areas and encompasses active braiding channels at the lower end of the delta. The Tamayayak Study Area, located in the middle of the delta, represents a low-energy environment that is dominated by thaw-lake processes. Finally, the Nechelik Study Area, which encompassed tidal flats along the western portion of the delta, represents areas dominated by coastal processes.

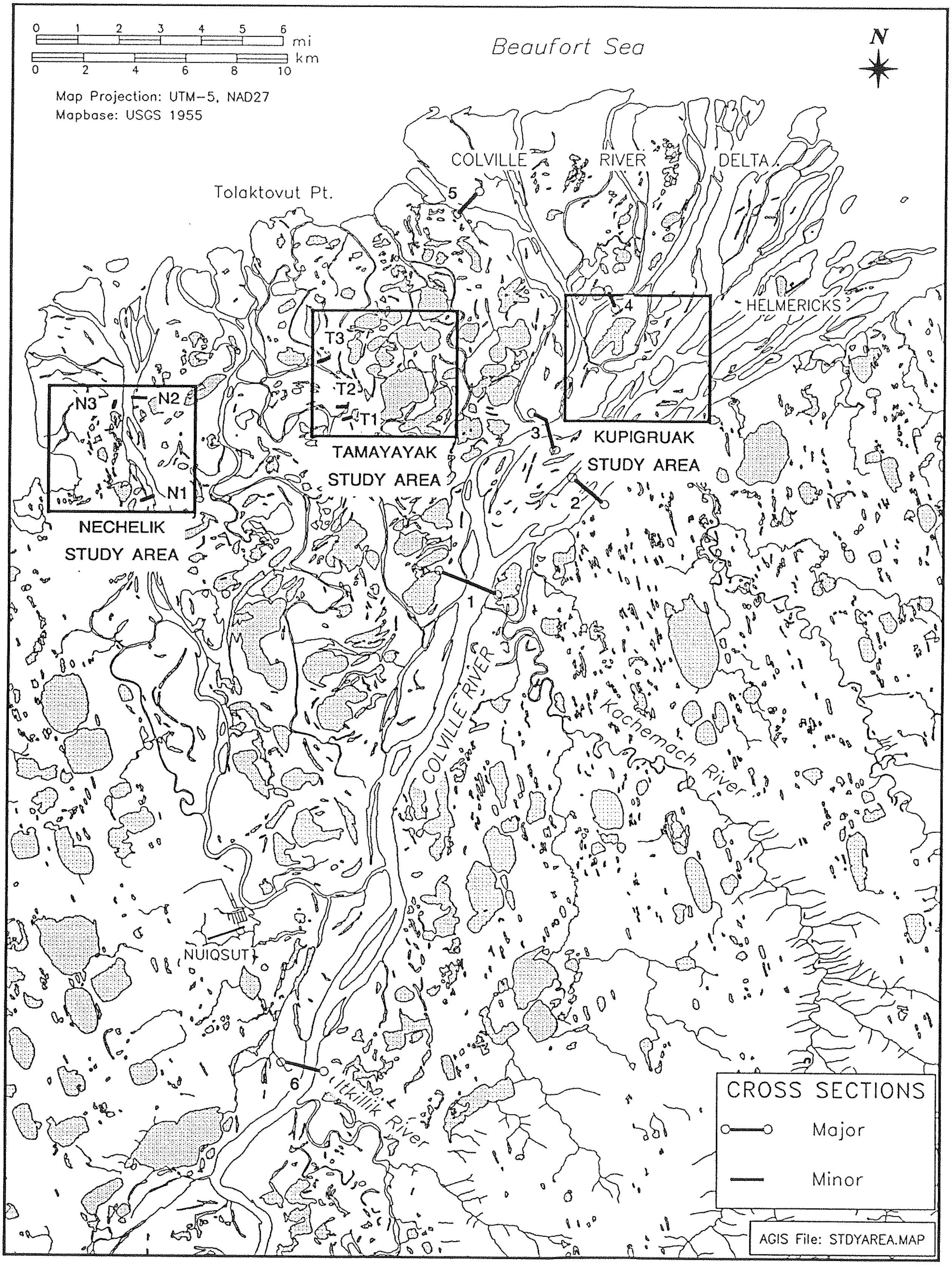

Figure 1. Map of study area showing locations of cross sections and pilot study areas within the Colville River Delta, 1992.

PART I. CHANNEL MORPHOLOGY

METHODS

CHANNEL CROSS SECTIONS AND BED MATERIAL

Six channel cross sections were surveyed, and samples of bed material were taken at five of the cross sections. The portion of each cross section located above the water surface was surveyed with a Leitz Set 2 total station, which uses electronic distance measuring and trigonometric leveling techniques. The portion of each cross section located below the water surface was surveyed by recording the elevation of the water surface and using a sounding reel and 75 lb sounding weight to determine the depth of the water at selected intervals across the channel. The boat containing the sounding reel was placed on a line by the boat operator, who lined it up with two rows of flags on each shore, and was placed at the proper station along the cross section with the electronic distance measuring capabilities of the Leitz Set 2. To relate the elevations at the cross sections to mean sea level, each cross section was surveyed to the nearest available NOAA survey monument.

Temporary bench marks were placed on each side of the river, and generally consisted of an 18-in-long piece of "rebar" that was driven to within about 0.1 ft of being flush with the top of the ground surface. Locations of the temporary bench marks were marked with lath and flagging.

Samples of bed material were taken from sand bars at the edge of the water on the day of the sampling. The samples were taken at a depth of 0-1 ft and were analyzed for gradation. Grain-size determinations were conducted using the washed-sieve analysis method. The tests were run in accordance with the standard method for particle-size analysis ASTM D-422-72 (Particle Size Analysis of Soils). When more than 15% of the sample was less than the size of a number 200 U.S. Standard Sieve, a hydrometer analysis was used to analyze the finer fraction of the sample, following ASTM D-422-72.

In addition to the major cross sections mentioned above, elevations also were measured along six minor cross sections (872- to 1824-ft long) to determine the topographic sequence of integrated terrain units along each transect. Transects were measured along riverbanks beginning at the water edge and continuing to the highest terrace. Elevations were measured with a rod and transit (Leitz Model 20). The one-time measurement of water level at each transect (approximately sea level because sites were within 3 mi of the coast) was used for the elevation datum. Data from the minor cross sections are not presented graphically in this report but were used for calculating relative elevations of integrated terrain units.

PERMAFROST

The depth to permafrost was measured at subjectively chosen locations along each cross section, to determine the edge of the permafrost-thaw boundary. Measurements were made on the riverbanks first and then proceeded towards the middle of the river. To locate the permafrost boundary, a ½ in diameter steel tile probe equipped with 4-ft threaded sections was driven into the sediment with a 10-lb sliding hammer. At each sample site, water depth, the depth of thawed sediment, and the number of hammer blows were recorded. Thaw depth was determined when the probe could no longer be driven into the sediment or when there was an abrupt increase in the number of blows required to drive the probe further. Although there occasionally was some uncertainty about when the permafrost boundary was encountered, in most instances refusal of the probe was obvious. In shallow water and on shore, probing was done using waders, whereas, in deeper water probing was done from a boat. When using the boat, it usually was anchored at three points for stability. For presentation, the thaw-depths were rounded to the nearest foot because determination of thaw depths in deep water to within 0.1 ft was not reliable.

RESULTS AND DISCUSSION

CHANNEL CROSS SECTIONS AND BED MATERIAL

Locations of the surveyed cross sections are presented in Figure 1. The cross sections are presented in Figures 2-7 and include notes regarding the integrated terrain units traversed by the cross sections and the NOAA monuments used to reference the cross sections to mean sea level. A list of the data points along the cross sections is presented in Appendix Table A-1.

Although elevations of the NOAA monuments are reported to the nearest 1 ft, discussions with state surveyors familiar with the area suggested that the actual elevations may deviate from the published elevation by more than 0.5 ft. In particular, we suspect that the published elevation for the KNIK monument may be 1-2 ft low. Thus, at some point, it would be desirable to perform a level-loop survey between the NOAA monuments.

The grain-size analysis for the riverbed material are presented in Figure 8 and Appendix Table A-2. The samples from cross sections 1 and 2 were classified as poorly graded sand, the samples from cross sections 3 and 4 were classified as silty sands, and the sample from cross section 5 was classified as inorganic silts (no sample was collected at cross section 6). Thus, the bed material appears to be primarily sand and becomes finer from the head of the delta to the mouth of the delta. Results from the grain-size analyses of the riverbed material can be used for preliminary analysis of scour depths in the future.

PERMAFROST

The depth to permafrost was measured at a total of 54 locations along the six cross sections. At all cross sections except one (cross section 4), thaw depths under the river exceeded the depth to which we probed (10-22 ft). At cross section 4, where no thaw bulb was found, the maximal water depth was 5 ft at the time of the survey. Occasionally, it was difficult to distinguish whether probe refusal was due to the presence of permafrost or that of compacted sediments or gravel. This uncertainty is noted on the cross sections.

To help analyze the effect of water depth on the absence of permafrost, water depths were correlated with thaw depth (Fig. 9). Overall, where water depths were less than 6 ft, permafrost was present at depths less than 4 ft below the surface of the riverbed. When water depth was greater than 6 ft, permafrost usually was not encountered, although there were a few exceptions. The lack of a thaw bulb at cross section 4 probably was due to the shallow water depth.

Where permafrost was encountered in deep water, the sample locations were near shore. Two factors probably contributed to these occurrences of deep-water permafrost. First, the permafrost may be relic and the river channel may have recently cut over the permafrost, or alternatively, the permafrost may be in equilibrium and is maintained by the cold temperatures found at depth under the nearby riverbanks. The intrusion of salt water under the ice may reinforce the two factors mentioned above by allowing water temperatures to drop below 32°F and transferring heat from the sediments.

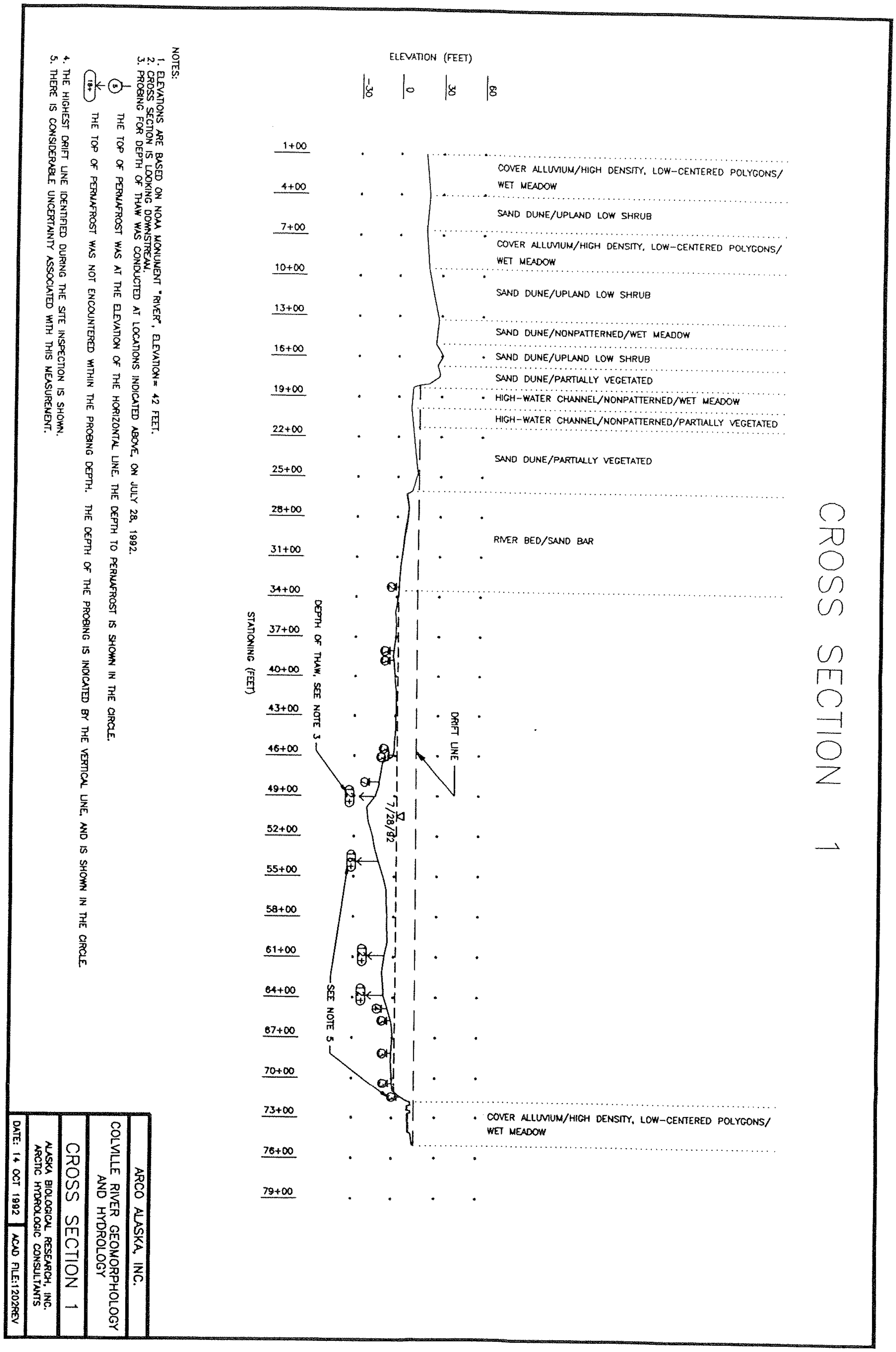

Figure 2. Profile of cross section 1 showing ground-surface elevations and depths to permafrost, Colville River Delta, 1992.

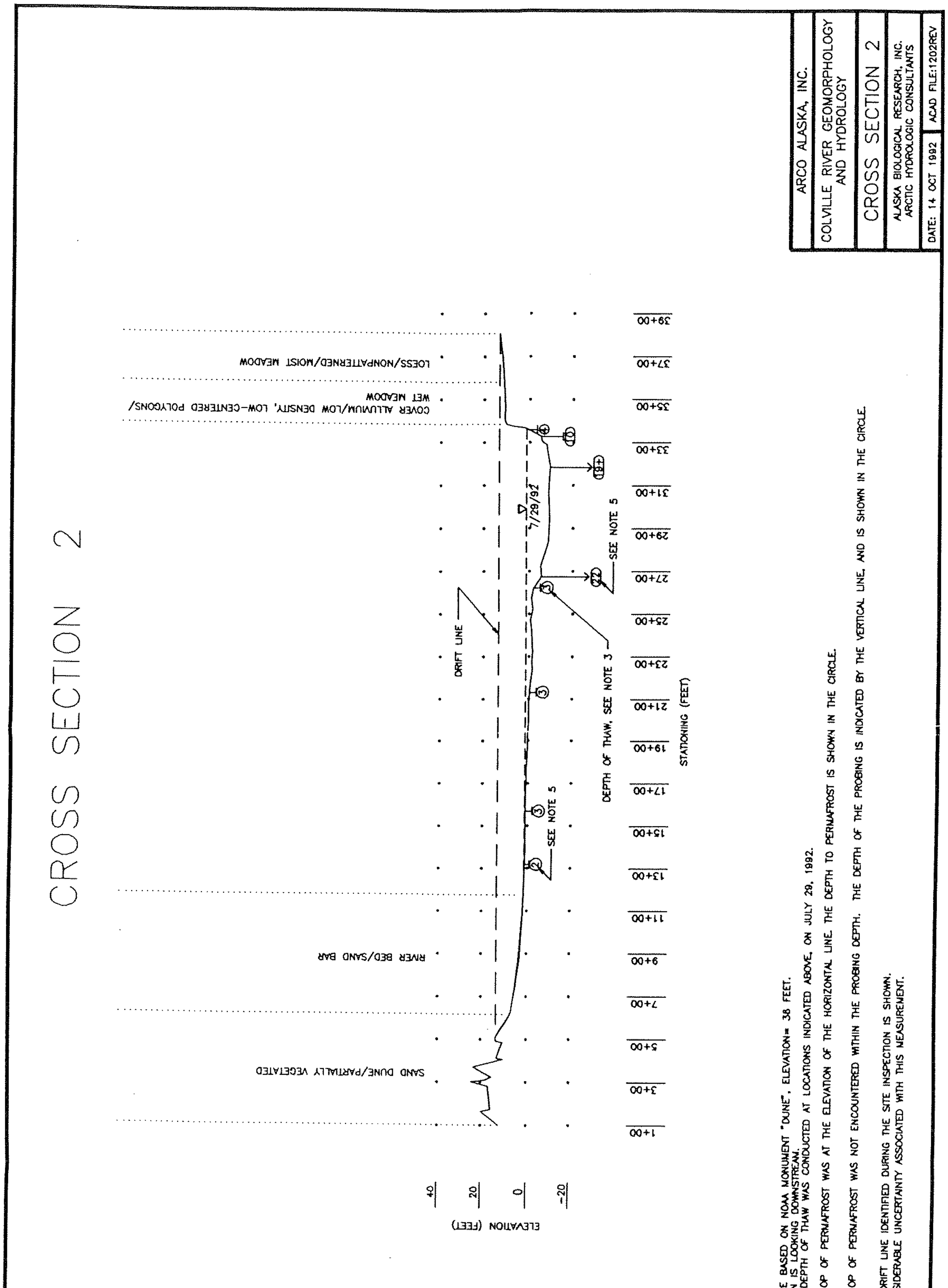

Figure 3. *Profile of cross section 2 showing ground-surface elevations and depths to permafrost, Colville River Delta, 1992.*

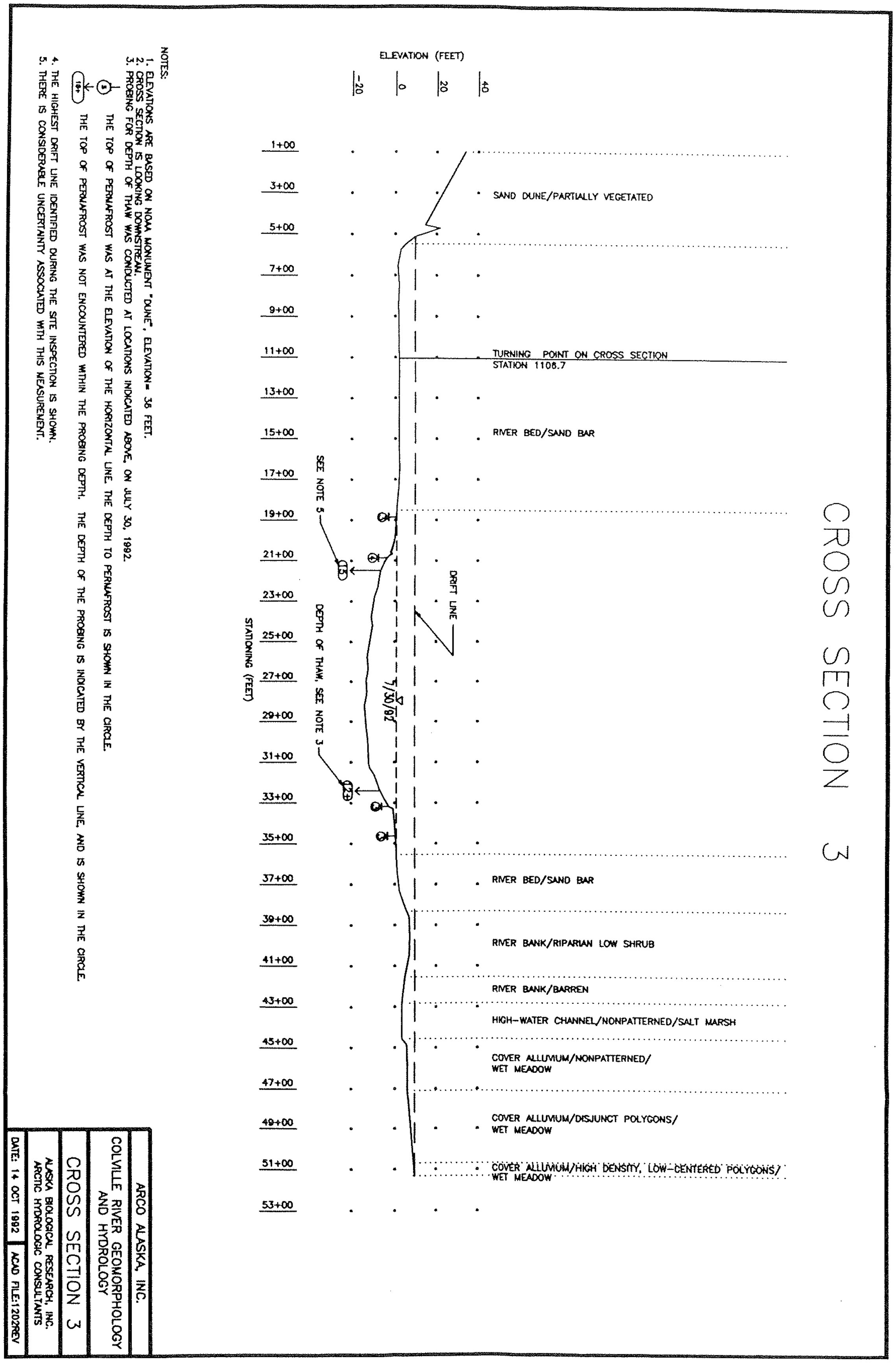

Figure 4. Profile of cross section 3 showing ground-surface elevations and depths to permafrost, Colville River Delta, 1992.

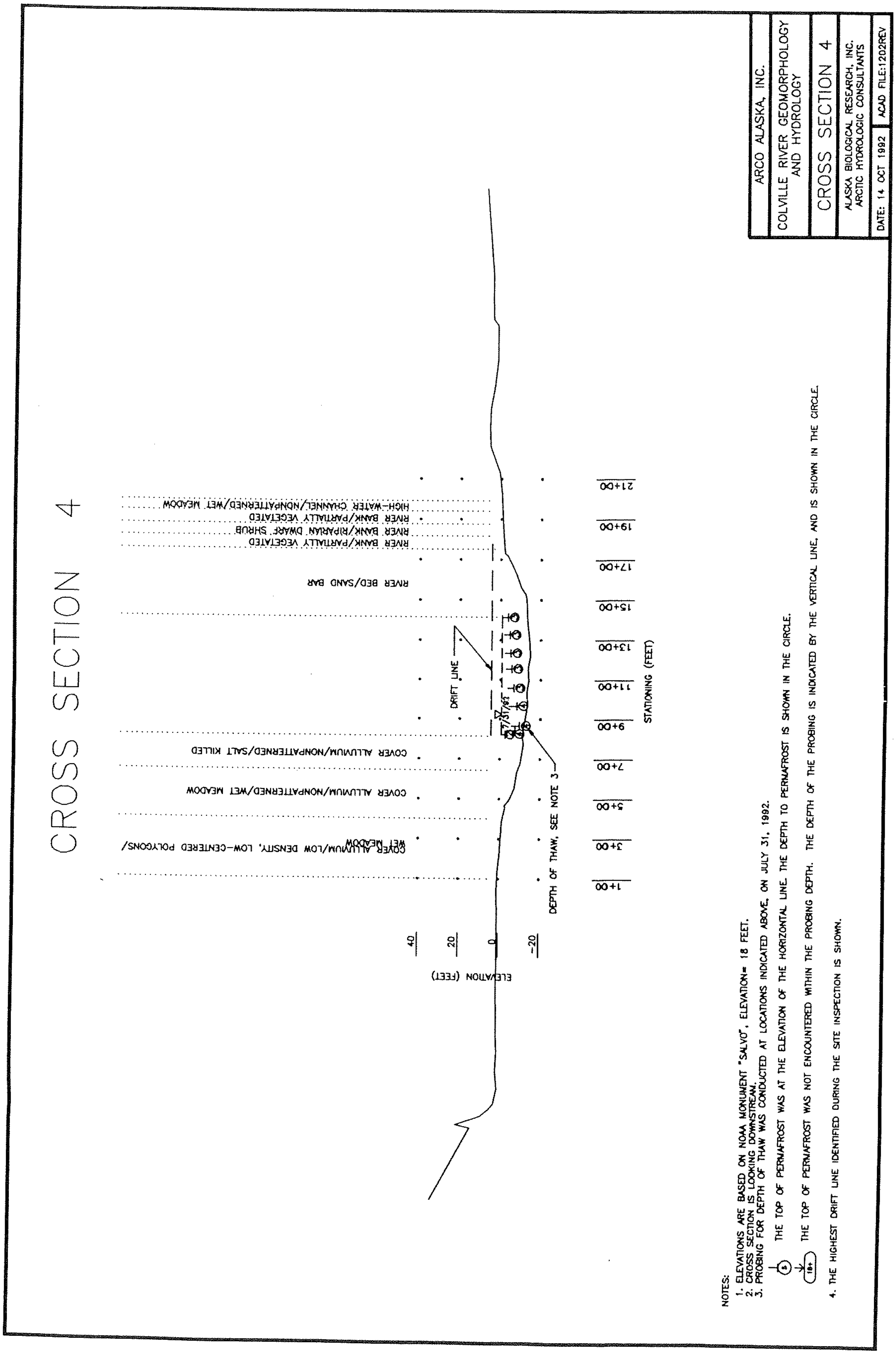

Figure 5. Profile of cross section 4 showing ground-surface elevations and depths to permafrost, Colville River Delta, 1992.

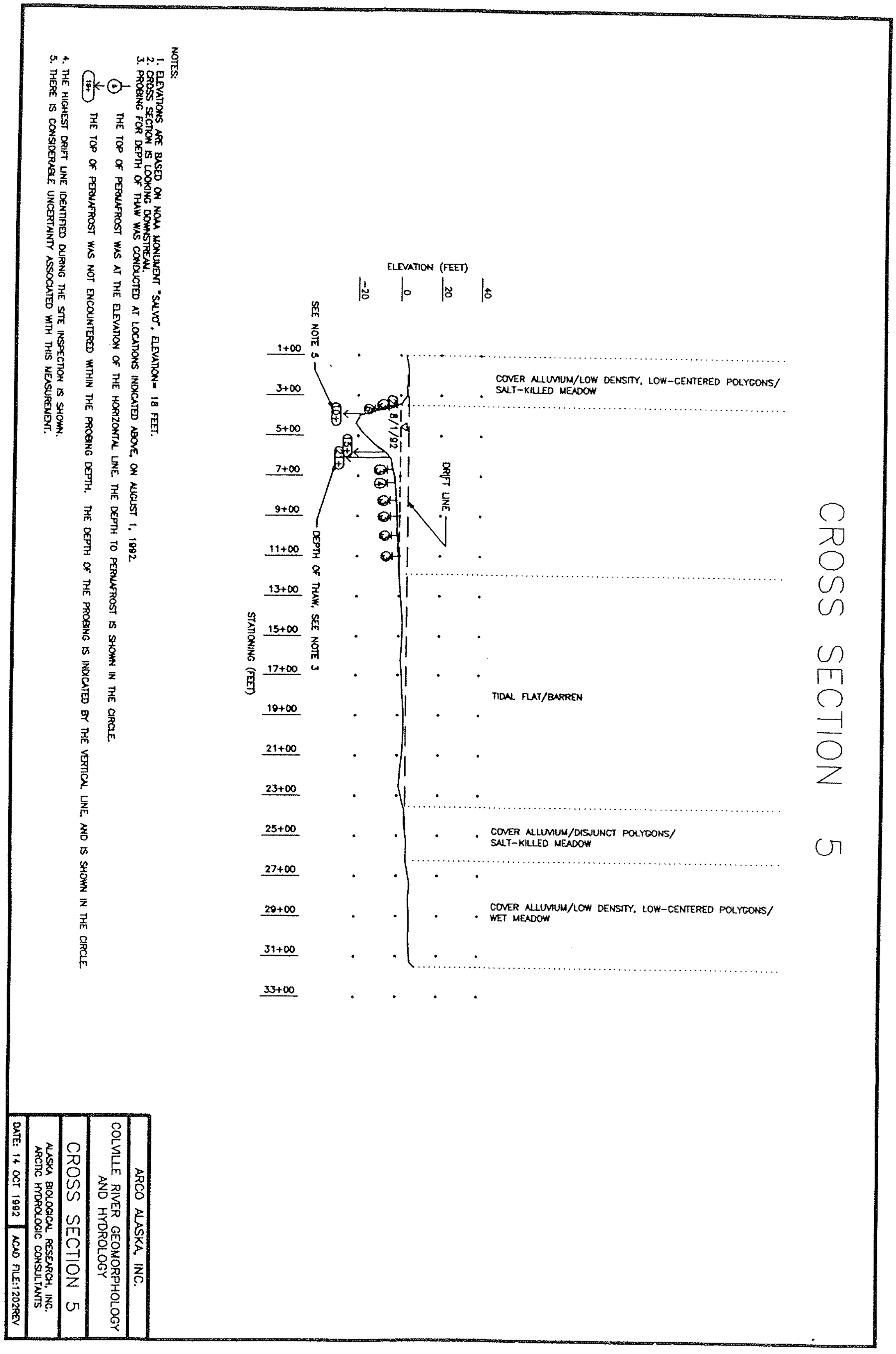

Figure 6. Profile of cross section 5 showing ground-surface elevations and depths to permafrost, Colville River Delta, 1992.

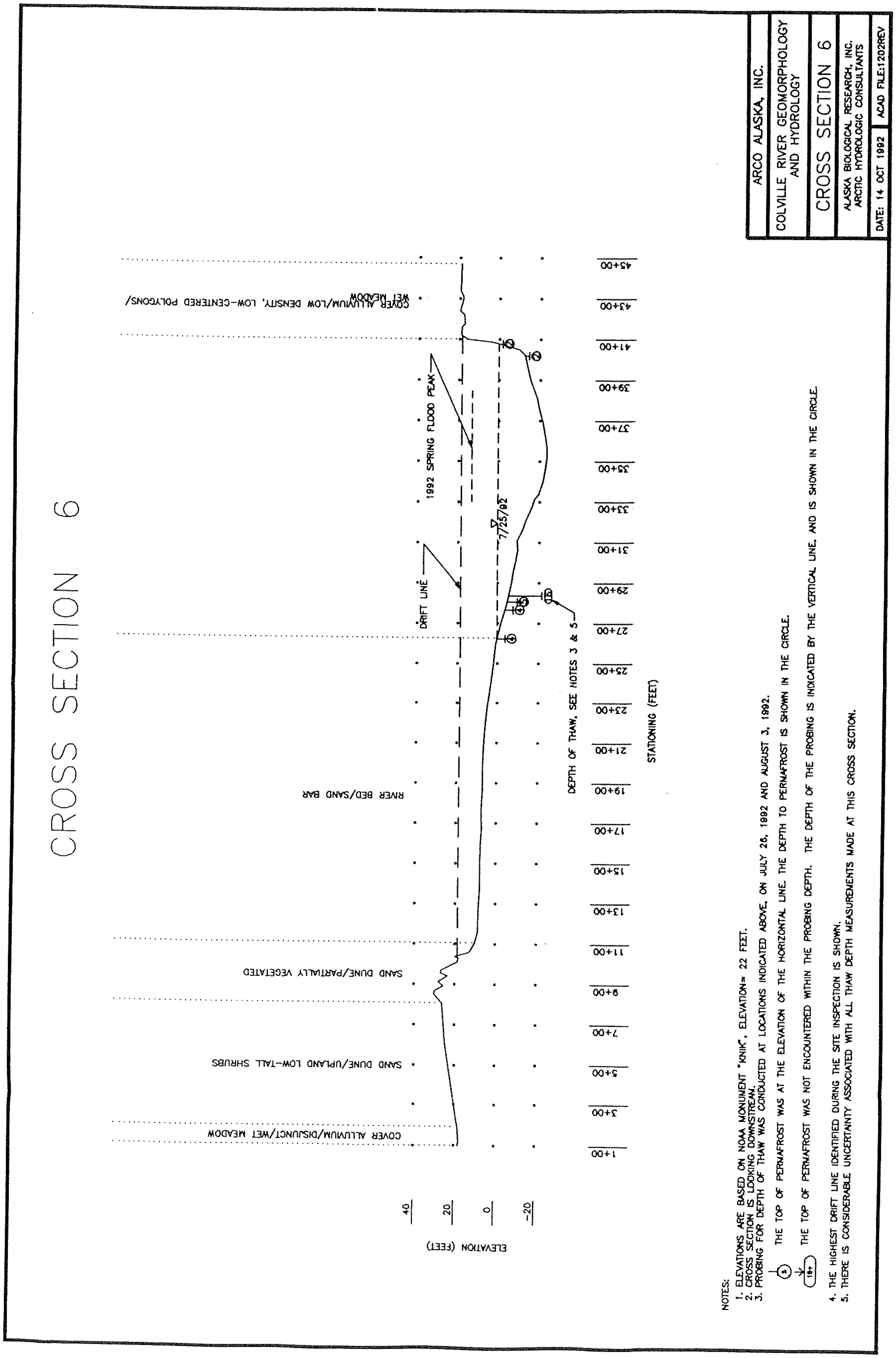

Figure 7. Profile of cross section 6 showing ground-surface elevations and depths to permafrost, Colville River Delta, 1992.

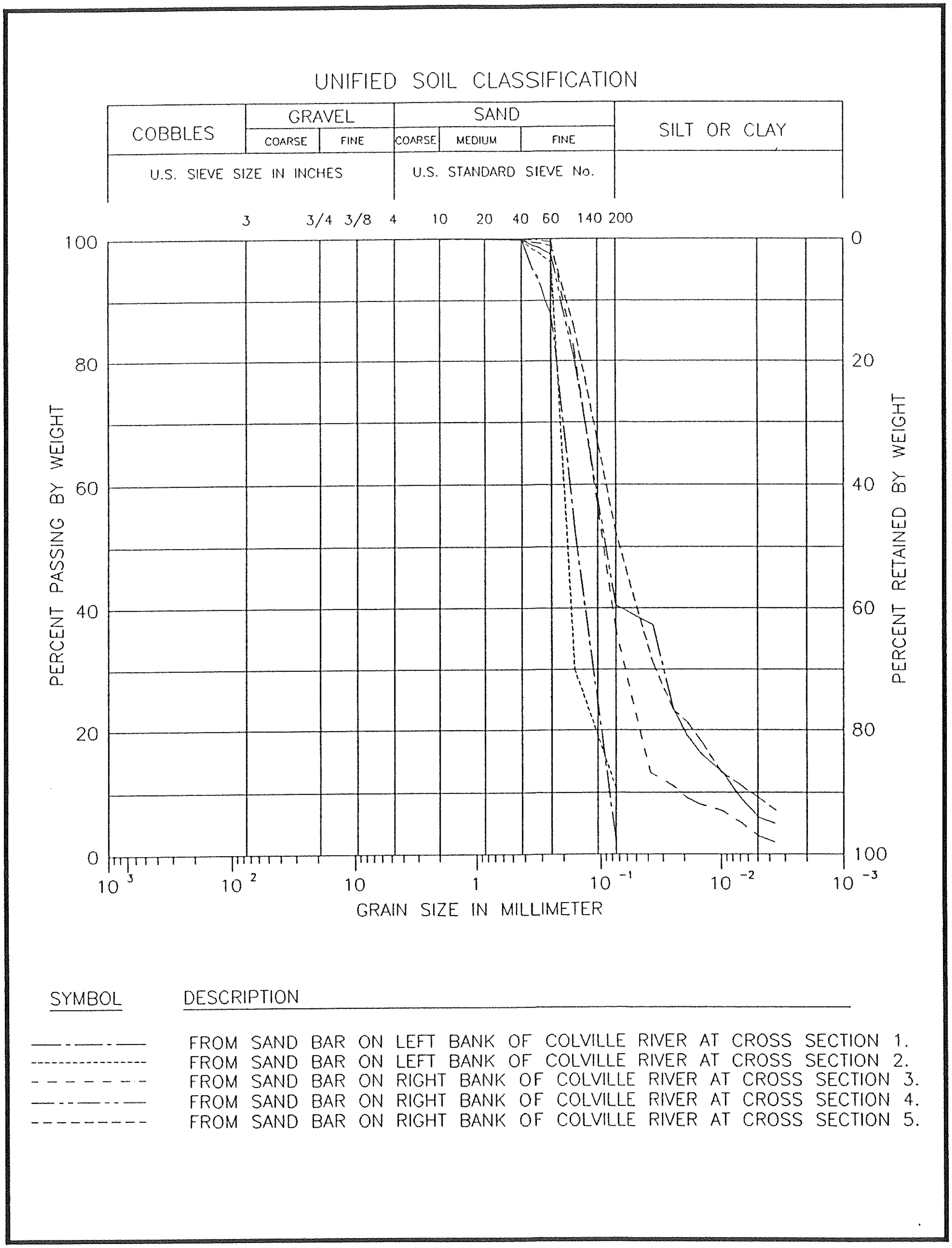

Figure 8. Size gradations of riverbed samples from cross sections, Colville River Delta, 1992.

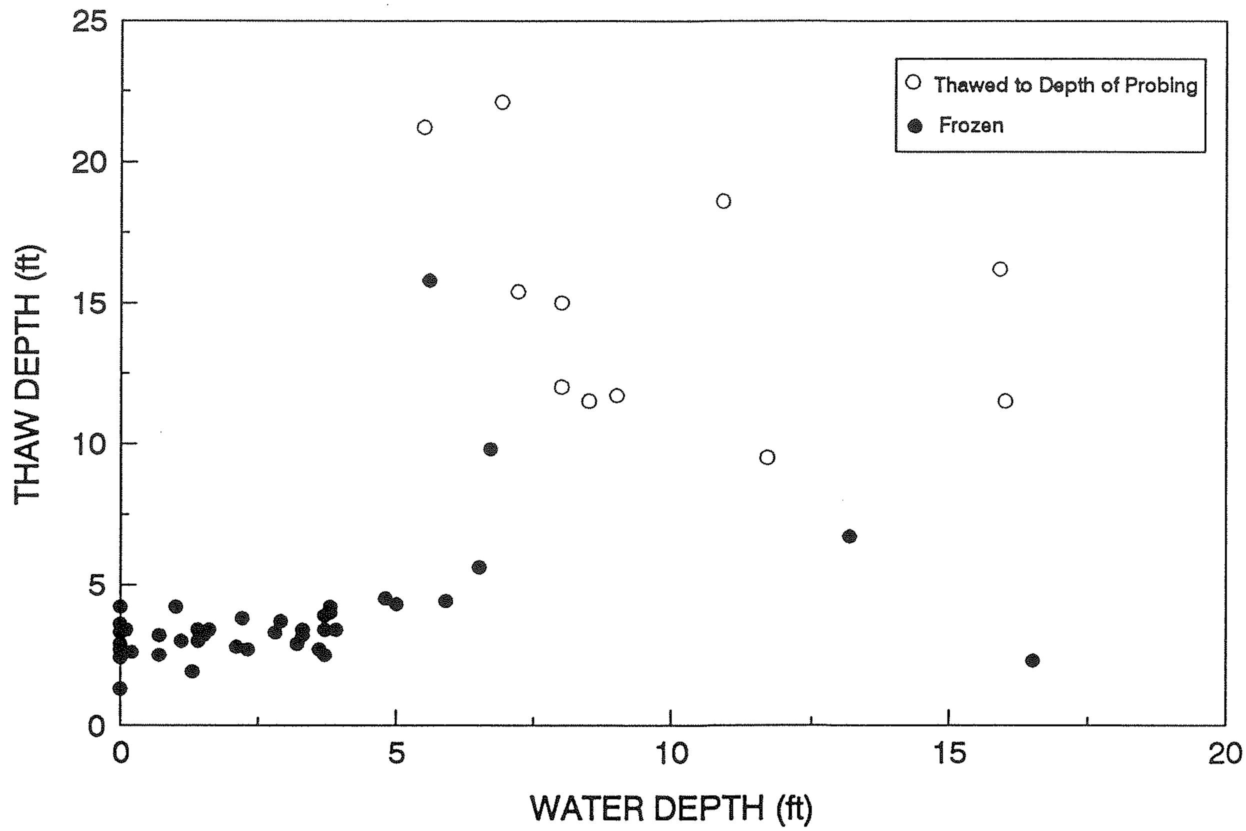

Figure 9. Relationship between thaw depths and water depths, Colville River Delta, 1992.

PART II. INTEGRATED TERRAIN UNITS

BACKGROUND

Integrated terrain units (ITUs) were mapped across the entire delta in order to analyze the flooding regime and landscape change. The maps use a classification system that integrates landforms (surficial deposits), surface forms (ice-related features), and vegetation information into a flexible system that is useful for a wide range of analyses. Landform information is useful for delineating areas with different soil genesis and engineering properties. Surface forms, particularly those that show various stages of ice-wedge development, indicate areas with different ice content that may be related to age and have different elevations. Areas with high ice content may also indicate areas that will be sensitive to disturbance or exhibit surface instability. Vegetation, which is sensitive to flooding and salinity, is useful for differentiating areas with different sedimentation rates and areas of inundation by storm surges. In developing the classification we were able to rely heavily on previous studies in the delta. Some of the more pertinent available information is discussed below.

The CRD is a complex environment that is similar to most deltas around the world. It has migrating distributary channels, water bodies of various origins, natural levees, sand dunes, sand bars, and mud flats (Walker 1976, 1983). Unlike most deltas, however, it is greatly influenced by two other factors: (1) low temperatures that preserve most of the annual precipitation until spring breakup, and (2) the presence of permafrost (Walker 1976). Because of permafrost, the delta also includes ice wedges, ice-wedge polygons, frost mounds, and pingos. Permafrost also alters the character of river discharge and the nature of the delta's erosion (Walker 1976).

In additon to the numerous distributaries, dominated by the East and Nechelik channels, the CRD also contains a maze of lakes and ponds that are distinguished by their origin: oriented thaw lakes, ponds associated with ice-wedge polygons, abandoned channel lakes, point-bar lakes, and perched ponds associated with sand dunes (Walker 1976, Walker and Harris 1976). Many of the delta's tapped lakes are connected to channels, due to meandering of the river and expansion of thaw-lakes (Walker 1978).

Landforms within the delta are highly interspersed as a result of fluvial deposition, eolian transport, and the development of thaw lakes and marine processes. Riverbed and alluvial cover deposits are composed of various materials, including silt, sand, gravel, peat and ice. Most riverbanks average 6.0-14.8 ft above mean water level, although some banks that cut into sand dunes and the Gubik Formation are 23-30 ft high (Ritchie and Walker 1974). Sandbars occupy a large portion of the delta and, generally, the size of bars increases and texture decreases in a downstream direction. Gravel bars are few, except for a few patches of gravel and boulders that occur along the Nechilik Channel where it has eroded into the Gubik Formation (Walker 1976). Many mid-channel bars are large and support their own dune systems.

Both stabilized and active dunes, which are composed mainly of fine sand, are present in the CRD (Walker 1976, Walker and Matsukura 1979). Stabilized dunes generally are long, narrow, vegetated ridges with a smooth, rounded surface and few wind-eroded areas. Most of the stabilized dunes are oriented parallel to and on the west side of former river courses. Active dunes, in contrast, generally form on the western and southwestern sides of river channel bars and along the inner edge of tidal flats in response to the prevailing winds from the northeast.

Marine processes are active primarily during the short ice-free period and contribute to the build up of tidal flats along the fringe of the delta (Walker 1974). The nearly flat, barren mud or sand undergo periodic inundations by tidal waters. Much of the material in the tidal flats has accumulated during spring breakup. Because river flooding and breakup is initiated prior to the breakup of sea ice, floodwater from the river deposits sediment as it progresses over the sea ice.

In addition to these depositional processes, the accumulation of peat has contributed substantially to deltaic deposits, thus raising the surface of the floodplain. At selected sampling sites along the Arctic Coastal Plain, Schell and Ziemann (1983) measured depths of peat accumulation of 1.7-9.7 ft with the thickest deposit having a basal peat age of 12,610 years before present (ybp). Although formation of ice wedges and development of polygons can alter and erode the peat mat, the ubiquitous layer of peat throughout the coastal plain has contributed to the development of the arctic landscape.

Along with sediment deposition, hydraulic and thermal erosion have contributed to the evolution of the deltaic landscape. Although breakup may normally be the largest annual flooding event, the frozen active layer limits the effect of the flood. However, water during both the breakup flood and at lower stages contributes to thermal erosion of the banks. Thermal erosion of material at and below the water surface often leads to the collapse of large blocks, which may be the predominant factor in bank erosion within this area (Walker and Morgan 1964, Walker 1966, Ritchie and Walker 1974).

Strong relationships among landforms, surface forms, and vegetation have been found in permafrost-dominated tundra ecosystems and have formed the basis for many mapping classifications (Walker et al. 1980, Walker and Acevedo 1987, Jorgenson 1986). Some relationships among landforms, surface forms, and vegetation within the CRD have been described by Rothe et al. (1983). Similar relationships have been found on the floodplain of the Meade River (Peterson and Billings 1978, 1990) and the delta of the Sagavanirktok River (Walker et al. 1980).

METHODS

CLASSIFICATION

A classification system was developed that integrates information about landform, surface forms, and vegetation. The landform classification we used was developed by Kreig and Reger (1982), and has been adopted by the Alaska Division of Geological and Geophysical Surveys for their engineering-geology mapping scheme. The surface form classification was developed by Walker (1985). The vegetation classification was adapted from a habitat classification system for arctic tundra (a landform-surface form-vegetation based system) developed by Jorgenson et al. (1989). A numeric coding system was used for the classes to allow rapid key entry and recoding during analysis (Table 1).

MAPPING

ITUs were classified and delineated using color infra red (CIR) photography (1:18,000 scale) acquired by AeroMap, Inc. (Anchorage, AK) on 8 July 1992. The mapping was done on acetate overlays of the photos using a mirror stereoscope. Minimal mapping size for features was 1 ac, although water bodies as small as 0.5 ac occasionally were mapped to provide additional geodetic reference points. Lines and codes then were digitized and encoded using Atlas GIS software (Strategic Mapping, Inc., Santa Clara, CA) on a PC desktop computer. The photos were registered to UTM coordinates obtained from prominent features on USGS topographic maps (1:63,360 scale) for digitizing. To compensate for distortion caused by tilt, the digital features on each photo were geometrically rectified by performing a 3-point transformation (rubber-sheeting) of the vectors to prominent features on a SPOT multi-spectral image (20-m pixel size). The image also was ortho-corrected and geo-referenced by SPOT Corporation. After rectification, the features were joined between adjacent photos to create a seamless map of the entire delta.

SOIL STRATIGRAPHY

A field survey conducted from 8 July to 3 August characterized soil stratigraphy, surface forms, and vegetation within ITUs traversed by the channel cross sections (Fig. 10). The stratigraphy of the near-surface soil was described from soil cores or soil pits to determine the occurrence of flood deposition. In most cases, descriptions were limited to the active layer (i.e., the zone of recent deposition). However, numerous profiles also were described from cutbanks after unfrozen material was removed with a shovel to expose undisturbed frozen sediments. Descriptions for each profile included the texture of each horizon, the depth of organic matter, and the depth of thaw. Samples were collected from each profile (generally one per profile) for analysis of particle-size distribution, pH, and electrical conductivity. Laboratory analyses were conducted by the Soil Testing Laboratory at Colorado State University (Fort Collins, CO) according to standard methods (Klute 1986).

To establish minimal ages for the older ITUs, samples for radiocarbon dating were collected from the base of the organic layer at some of the deeper profiles. In a few instances, fragments of wood stems were collected for dating. Laboratory analyses were performed by Beta Analytic, Inc. (Coral Gables, FL). The dates were reported as radiocarbon years before 1950 A.D. and include the error (one standard deviation) associated with each analysis.

RESULTS AND DISCUSSION

CLASSIFICATION

Seventy-one ITUs within the CRD were mapped, revealing the wide number of combinations that can occur among landform, surface form and vegetation classes (Table 2). Because this large number of classes does not represent substantial differences in terms of the flooding regime, numerous classes were grouped together. For example, all ITUs representing loess were grouped into one class because they occurred above the floodplain. In addition, many units on thaw lake deposits were grouped because they occur

Table. 1. Classification and coding system for integrated terrain units that incorporates landform, surface form, and vegetation features of the Colville River Delta.

Code	Class	Code	Class
LANDFORM[1] (Surficial Deposit)		**VEGETATION**[3]	
1000	Loess	00	Barren
2000	Eolian Sand	10	Partially Vegetated
3000	Tapped Lake Delta Deposit (not used)	20	Emergent vegetation (not used)
4000	Braided Floodplain Riverbed Alluvium	30	Meadow (wet, moist, dry)
5000	Mid-channel Bar	31	Wet Meadow
6000	Riverbed - Sandbar	32	Moist Meadow
7000	High-water Channel	33	Dry Meadow
8000	Braided Floodplain Cover Alluvium	40	Basin Wetland Complex (not used)
10000	Thaw Lake Deposit	51	Riparian Low-Tall Shrub
11000	Beach Deposit (not used)	52	Riparian Dwarf Shrub
12000	Tidal Flat Deposit	55	Upland Low-Tall Shrub
13000	Organic Deposit (not used)	56	Upland Dwarf Shrub
14000	Colluvial Deposit (not used)	61	Salt Marsh
15000	Man-mad Deposits	62	Salt-killed Meadow
		80	Vegetated
SURFACE FORM[2] (ice-related)		81	Vegetated, Wet (not used)
		82	Vegetated, Moist (not used)
000	Nonpatterned	83	Vegetated, Dry (not used)
100	Disjunct Polygon Rims		
200	Low-centered Polygons, Low Density	**WATER BODIES**	
300	Low-centered Polygons, High Density		
400	High-centered Polygons, Low Relief	90	River or Stream Channel
500	High-centered polygons, High Relief	92	Channel Lake
600	Mixed high and low polygons	93	Point Bar and Terrace Flank Lake
700	Pingo	94	Dune Depression Pond (not used)
800	Hummocky terrain	95	Unconnected Thaw lake
900	Frost Scars	96	Connected Thaw Lake
		97	Brackish Pond
		98	Nearshore Water
		EXAMPLE OF CODING SYSTEM	
		Landform (1000s)	
		Surface form (100s)	
		Vegetation or Water bodies (10s)	
		8031 =	Cover Alluvium/Nonpatterned/Wet Meadow

[1]Adapted from Kreig and Reiger 1982 and Walker 1976
[2]Adapted from Walker (1985)
[3]Adapted from Jorgenson et al. 1989

Figure 10. Locations of soil sampling sites, Colville River Delta, 1992.

Table 2. Integrated terrain units mapped within the Colville River Delta, 1992.

Unit Code	Grouped Units	Description
LOESS		
1031	1000	Loess/Nonpatterned/Wet Meadow
1131	1000	Loess/Disjunct Polygons/Wet Meadow
1231	1000	Loess/Low-centered Polygons, Low Density/Wet Meadow
1331	1000	Loess/Low-centered Polygons, Low Density/Wet Meadow
1432	1000	Loess/High-centered Polygons, Low Relief/Moist Meadow
1455	1000	Loess/High-centered Polygons, Low Refief/Low Shrub
1532	1000	Loess/High-centered Polygons, High-Relief/Moist Meadow
EOLIAN SAND		
2010	2010	Sand Dune/Partially Vegetated
2031	2080	Sand Dune/Wet Meadow
2032	2080	Sand Dune/Moist Meadow
2055	2080	Sand Dune/Upland Low-Tall Shrub
2056	2080	Sand Dune/Upland Dwarf Shrub
FLOODPLAIN RIVERBED ALLUVIUM		
5000	6000	Mid-channel Bar/Nonpatterned/Barren
5010	6010	Mid-channel Bar/Nonpatterned/Partially Vegetated
6000	6000	Riverbed-Sandbar/Nonpatterned/Barren (includes lateral and point bars)
6010	6010	Riverbed-Sandbar/Nonpatterned/Partially Vegetated
6051	6051	Riverbed-Sandbar/Nonpatterned/Riparian Low-Tall Shrub
6052	6051	Riverbed-Sandbar/Nonpatterned/Riparian Dwarf Shrub
6061	6061	Riverbed-Sandbar/Nonpatterned/Salt Marsh
7010	7010	High-water Channel/Nonpatterned/ Partially Vegetated
7031	7030	High-water Channel/Nonpatterned/ Wet meadow
7051	7051	High-water Channel/Nonpatterned/Riparian Low-Tall Shrub
7061	7061	High-water Channel/Nonpatterned/Salt Marsh
7062	7062	High-water Channel/Nonpatterned/Salt-killed Meadow
7131	7030	High-water Channel/Disjunct Polygons/Wet Meadow
7132	7030	High-water Channel/Disjunct Polygons/Moist Meadow
7161	7061	High-water Channel/Disjunct Polygons/Salt Marsh
7162	7062	High-water Channel/Disjunct Polygons/Salt-killed Meadow
BRAIDED FLOODPLAIN COVER ALLUVIUM		
8031	8030	Cover Alluvium/Nonpatterned/Wet Meadow
8032	8030	Cover Alluvium/Nonpatterned/Moist Meadow
8062	8062	Cover Alluvium/Nonpatterned/Wet Meadow
8131	8130	Cover Alluvium/Disjunct Polygons/Wet Meadow
8132	8130	Cover Alluvium/Disjunct Polygons/Moist Meadow
8151	8151	Cover Alluvium/Disjunct Polygons/Low-Tall Shrub
8162	8162	Cover Alluvium/Disjunct Polygons/Salt-Killed Meadow
8231	8230	Cover Alluvium/Low-Centered Polygons, Low Density/Wet Meadow
8232	8230	Cover Alluvium/Low-Centered Polygons, Low Density/Moist Meadow

Table 2. Continued

Unit Code	Grouped Units	Description
BRAIDED FLOODPLAIN COVER ALLUVIUM (cont.)		
8251	8251	Cover Alluvium/Low-Cent. Poly., Low Density/Riparian Low-Tall Shrub
8262	8262	Cover Alluvium/Low-Cent. Polygons, Low Density/Salt-killed Meadow
8331	8330	Cover Alluvium/Low-centered Polygons, High Density/Wet Meadow
8332	8330	Cover Alluvium/Low-centered Polygons, High Density/Moist Meadow
8351	8351	Cover Alluvium/Low-cent. Poly., High Density/Riparian Low-Tall Shrub
8362	8262	Cover Alluvium/Low-cent. Poly., High Density/Riparian Low-Tall Shrub
THAW LAKE DEPOSIT		
10000	10000	Thaw Lake Deposit/Nonpatterned/Barren
10010	10010	Thaw Lake Deposit/Nonpatterned/Partially Vegetated
10031	10030	Thaw Lake Deposit/Nonpatterned/Wet Meadow
10032	10030	Thaw Lake Deposit/Nonpatterned/Moist Meadow
10051	10051	Thaw Lake Deposit/Nonpatterbed/Low-Tall Shrub
10061	10061	Thaw Lake Deposit/Nonpatterned/Salt Marsh
10131	10030	Thaw Lake Deposit/Disjunct Polygons/Wet Meadow
10132	10030	Thaw Lake Deposit/Disjunct Polygons/Moist Meadow
10151	10051	Thaw Lake Deposit/Disjunct Polygons/Low-Tall Shrub
10161	10061	Thaw Lake Deposit/Disjunct Polygons/Salt Marsh
10162	10162	Thaw Lake Deposit/Disjunct Polygons/Salt-killed Meadow
10231	10231	Thaw Lake Deposit/Low-centered Polygons, Low Density/Wet Meadow
10251	10251	Thaw Lake Deposit/Low-centered Polygons, Low Density/Riparian Low-Tall Shrub
10262	10262	Thaw Lake Deposit/Low-centered Polygons, Low Density/Salt-killed Meadows
10756	10756	Thaw Lake Deposit/Pingo/Upland Dwarf Shrub
MARINE DEPOSITS		
12000	12000	Tidal Flat/Barren
12010	12010	Tidal flat/Partially Vegetated
12052	12010	Tidal flat/Riparian Dwarf Shrub
12061	12061	Tidal Flat/Salt Marsh
MAN-MADE DEPOSITS		
15000	15000	Gravel Fill
WATER BODIES		
90	90	River or Stream Channel
92	92	Old Channel Lake (Channel Lake)
93	92	Point Bar and Terrace Flank Lakes (Channel Lake)
94	95	Dune Depression Pond
95	95	Unconnected Thaw Lake/Pond (Thaw Lake-Pond)
96	95	Connected Thaw Lake (Thaw Lake-Pond)
97	98	Brackish Pond (Nearshore Water and Brackish Ponds)
98	98	Nearshore Water (Nearshore Water and Brackish Ponds)

in a similar situation. This grouping reduced the number of classes to 40 for map presentation. However, if future analyses revealed the importance of a particular class or the need to present particular ITUs, the original data were maintained in the database. Descriptions of the landform, surface form, and vegetation units are provided in Tables 3-5.

MAPPING

The ITU maps are presented separately in Appendix C. These maps are presented at 1:50,000 scale to provide larger coverage per map sheet, although the original mapping was done at 1:18,000 scale. To aid in pattern recognition, the colors differentiate landform/surface form combinations, and the hatching is keyed to vegetation classes.

The maps help identify several features that can be useful to facility planning. The highest floodplain steps (cover alluvium/low-centered polygons, high density/wet meadow) are of particular interest because they are the least prone to flooding. The riverbed-sandbar/barren unit (includes both lateral bars and point bars) covers large areas of the floodplain along the East Channel that are frequently flooded. Cover alluvium that supports riparian low-tall shrubs is particularly common at the head of the delta and appear to be areas where flooding tops the banks. However, the lack of riparian willow on higher floodplain steps in the lower delta does not necessarily indicate that those surfaces are not flooded. Other significant features include the presence of older, high-water channels, the abundance of salt-killed tundra along the fringe of the delta, and the presence of salt marshes along riverbanks far inland from the coast.

SOIL STRATIGRAPHY

The soil stratigraphy of representative profiles within each major landform unit was used to help characterize the landforms and to provide evidence of recent fluvial depostion (Figs. 11-14). Overall, they reveal complex interbedding of materials of different genesis, particularly in the older units, where organic horizons are interbedded with many layers indicative of changing fluvial regimes. They may be capped by wind-deposited silts or fine sand. Included on the profiles are results of laboratory analyses of particle-size distribution, pH, electrical conductivity (EC), and radiocarbon dates of samples taken from the profile. There are occasionally minor differences between the texture described in the field and the results of the textural analyses. Inclusion of the textural analyses provides an indication of the accuracy of the field identification.

During field sampling of sand dune deposits, there was a notable decrease in particle-size from fine sand to silt with increasing distance downwind from barren riverbars that were source areas for these deposits. This depositional gradient resulted in a progression of mapping units from partially-vegetated sand dunes to sand dunes that were stabilized by upland low or dwarf shrubs or moist meadows. At the farthest downwind areas, a thin layer of loess frequently covered or masked the alluvial cover deposits. In more active areas (profile N14) the sand dunes were composed of fine sand (Fig. 11). In older, less active areas, dune stratigraphy was more complex (profile LS1), with numerous interbedded layers of sand, silty sand, sandy silt, and organics. In profile LS1, much of the profile had a fibrous organic matrix that indicated concurrent organic development and eolian deposition.

In contrast, loess (profile N16) deposits typically were capped by a moderately thick organic horizon and ranged from silts to organic silts (Fig. 11). In some profiles, one or two thin layers of silt or fine sand interbedded in the surface organic horizon was attributed to eolian deposition during storm events. The sediments from the ancient alluvial deposits that underlie the loess were not encountered during our sampling.

Riverbed alluvium was characterized by frequent deposition of sediments of slightly varying texture and an absence of thick layers of organic material (Fig. 12). Textures ranged from fine sand to silty clay. At the head of the delta, a trace of gravel was mixed with these finer sediments. Fibrous organic material occasionally formed thin bands marking periods when organic drift (shredded peat from eroded banks) accumulated on the surface of the sandbars. Accumulation of fine organic drift occurred on the surface of many sandbars and provided a unique marker for identifying riverbed deposits. Clayey silts were diagnostic of fluvial deposits in slow-water environments.

Cover alluvium was characterized by complex interbedding of fluvial and organic deposits (Figs. 13 and 14). Thin caps of eolian material occasionally occurred at the surface; the loess was distinguished by the lack of clays and the lack of bedding during the depositional process. The underlying alluvial material ranged from fine sand to silty clay, and the frequency of interbedded layers was high. Organic accumulations

Table 3. Descriptions of landform units mapped within the Colville River Delta (CRD).

Landform	Description[1]
Loess	Loess is a homogenous, nonstratified, nonindurated deposit consisting primarily of silt, with subordinate amounts of fine sand and/or clay. This type of sediment frequently displays well-developed vertical parting. Within the CRD, loess deposits usually are found along the eastern and western edges of the delta, where they cap ancient alluvial deposits. Typically, loess deposits are overlaid by a moderately thick organic layer (4-8 in), are ice-rich, and highly susceptible to thermal erosion.
Sand Dune	Eolian sand consists of unconsolidated, wind-deposited accumulations of primarily very fine and fine sand that may take the form of sand sheets or hill-like masses of sand, referred to as sand dunes. Surface patterns associated with ice-aggredation are generally absent. These active sand dunes are being built by deposition of sand from adjacent sandbars and are prone to wind erosion, giving them distinct, highly dissected patterns. Active dunes are found in distinct locations; at the inner edge of extensive mudflats, at the front of the delta, and along the western and southwestern sides of river channel bars. Because of active processes on the Sand Dune/Partially Vegetated Units, vegetation is absent to sporadic (<30% cover), whereas on Sand Dune/Upland Dwarf or Low, Tall Shrub units, the dune has developed a nearly continuous cover of vegetation that has stabilized the dune.
Braided Floodplain Riverbed Alluvium	These units are composed of coarse- to fine-grained riverbed or lateral accretion deposits laid down in areas of channeled flow from the bed load of a river. Riverbed alluvium is extensive and highly varied within the CRD and range in type from mid-channel bars to broad riverbank-sandbars exposed during low water and high-water channels that are flooded only during high water. In general, texture of the sediments decreases in a seaward direction along the distributaries and in a bankward direction from the thalweg. Organic matter, including driftwood (mostly small willow), peat shreds, and other plant remains, frequently is found interbedded in the sediments. Riverbed deposits have been subdivided into three types that have different erosional/depositional regimes and are described below. Only those riverbed deposits that are exposed at low water are mapped, whereas all areas under rivers are assumed to consist of riverbed deposits. Mid-Channel Bar--Riverbed deposits exposed in mid-channel. Riverbed-Sandbar--This unit consists of riverbed deposits that are exposed during low water and include point bars, lateral bars, and unvegetated high water channels. Riverbed-sandbars bars are usually barren. High-water Channel--This unit consists of riverbed deposits that occur in channels flooded only during high flow. Because of river meandering, these channels no longer are active during lower flow conditions. These older channels show little surface polygonization indicative of ice-wedge development, although there infrequently are high-water channels that are older and have developed disjunct polygon rims. Typically, high-water channels support wet sedge vegetation, although a few recently developed high-water channels are partially vegetated.
Braided Floodplain Cover Alluvium	This unit is composed of the fine-grained cover or vertical accretion deposits of a braided floodplain that are laid down over the coarse-grained riverbed or lateral accretion deposits by streams at bank overflow (flood) stages. In the CRD, cover alluvium generally is overlain and is frequently interbedded with organic horizons. The stratigraphy of cover deposits also is complicated by the deposition of small amounts of eolian silt and fine sand.
Thaw Lake Deposit	Thaw lake deposits result from the thawing of ground ice. Thaw lake or basin deposits typically are fine-grained and organic-rich, and the stratigraphy of the original sediments have been deformed by the subsidence. Only those deposits exposed at low water were mapped, whereas all areas under thaw lake water bodies were considered to have thaw lake deposits. This unit includes delta deposits that form in thaw lakes that have a connection to a river or nearshore water (tapped lake). Most connections occur when a meandering distributary cuts through a lake's bank and, once connected, the lake is influenced by changes in river level. During breakup, large quantities of sediment-laden water flows into the lake, forming a lake delta at the point of breakthrough. Sediments typically consist of fine sands, silts, and clays. This deposit intergrades with thaw lake deposits and has a similar texture.
Tidal Flat Deposit	This unit includes areas of nearly flat, barren mud or sand that alternate between periodic inundations by tidal waters and subaerial conditions. Tidal flats occur on seaward margins of deltaic estuaries, leeward portions of bays and inlets, and at the mouths of rivers. Tidal flats frequently are associated with lagoons and estuaries, and may vary widely in actual salinity, depending on how exposed the flat is to salt-water incursion and the rate of influx of fresh water. In the CRD, tidal flats are similar to riverbed alluvium. In fact, most of the material is deposited during spring breakup (during high flow conditions), and much of the material lies above normal tidal fluctuations. However, the deposits have been classified as tidal flats because of occasional intrusion of salt water that has increased soil salinity and because of the association of these deposits with salt marsh vegetation.

[1] General portions of descriptions are adapted from Kerig and Reger (1982).

Table 4. Descriptions of surface form units mapped within the Colville River Delta (CRD).

Surface Form Unit	Description[1]
Non-patterned	These flat, nonpatterned areas show no evidence of polygonal rims caused by the development of ice-wedges. Ice wedges may be present but are not evident from the surface form. Small, elevated microsites that may be present generally are less than 1 ft high and compose less than 5% of the surface area. Nonpatterned ground represents some of the youngest portions of the tundra landscape, such as recently drained thaw lakes, abandoned river channels, and exposed riverbanks. An exception, however, is old upland surfaces that have poorly-developed, high-centered polygon rims that may be masked by tussock tundra vegetation.
Disjunct Polygon Rims	In areas with disjunct polygon rims, polygon rims resulting from ice-wedge development are evident but seldom are sufficiently developed to create closed polygons. This surface form also is prevalent on young landforms such as low river terraces, drained lake basins, and high-water channels.
Low-centered Polygons, Low Density	This unit has well-developed ice-wedge polygons with a central low "basin," a raised "rim," and (frequently) a "trough" between polygons. Typically, there is a wide range in sizes of polygons. There is a prevalence of polygons that are up to 75-100 ft across, whereas smaller polygons are 30-50 ft across. A characteristic feature is the incipient development of new rims that are starting to bisect the larger polygons, but have not spanned the whole distance across the polygon basins.
Low-centered Polygons, High Density	This unit has the most developed stages of polygon development. Polygon sizes are small (25-50 ft), and relief between the polygon center and rim can be large (up to 3 ft). Many of the polygon basins contain shallow standing water throughout the summer. In the last stages of development, the polygons are so dense and the rims so large that little area is left for polygon basins. The newly-developing rims bisecting larger polygons, which are evident in low density polygon units, are absent. This unit delineates areas with high ice content and generally is found on the highest and oldest terraces.
High-centered Polygons, Low Relief	High-centered polygons are composed of a raised "center" and a relatively low "trough" between centers of adjacent polygons. Most high-centered polygons range between 20 and 40 ft in diameter. In most cases, high-centered polygons result from the thaw settlement of troughs in groups of low-centered polygons. The high-centered polygons have centers that are only slight raised (<2 ft)with respect to the trough or crack areas.
High-centered Polygons, High Relief	These units are comprised of high-centered polygons in which progressive recession of the ice wedge permits subsidence that results in the development of deep (2-3 ft) troughs. This thermokarst process is frequently related to microclimatic changes resulting from changes in drainage adjacent to river and lake banks.
Mixed High and Low Polygons	This unit contains elements of both high- and low- centered polygons. Mixed polygons occur in areas of incomplete topographic adjustment of a primary land surface to a change in base level. This surface form was not mapped within the CRD.
Pingos	Pingos are small, ice-cored hills that commonly form in recently drained thaw lake basins. Sediments beneath lakes remain thawed during the winter in lakes deeper than the depth of ice (about 6-7 ft). When the lake drains, these unfrozen sediments freeze, and cryogenic forces cause doming of the surface to form a pingo.
Hummocky Terrain	This unit contains hummocks composed of organic-rich, fine-grained mineral soil and are typically 0.5 -1 ft in height. This unit typically occurs on the slopes of moderately stable river bluffs and on the steep slopes of pingos. Hummocks are thought to be caused by runoff due to melting of the snow pack combined with thermal erosion. These units were not large enough to map within the CRD.
Frost-Scar Terrain	Frost scars are roughly circular and slightly convex and are composed of fine-grained mineral soil that, under the proper moisture and freezing conditions, undergoes heaving. This process of frost churning recurs at sufficiently frequent interval to prevent the development of an organic mat. Frost scars may occupy 30% or more of a given surface and at higher densities may have a center spacing of 6-8 ft.

[1] General portions of descriptions adapted from Walker 1985.

Table 5. Descriptions of vegetation types found within the Colville River Delta (CRD).

Vegetation Unit	Description[1]
Barren	This unit has less than 5% vegetative cover. Barren areas typically are found on sandbars and mudflats, where annual erosion and deposition are sufficiently frequent to prevent the establishment of vegetation.
Partially Vegetated	This unit has 5-30% vegetative cover. On riverbed alluvium, dunegrass *(Elymus arenarius)*, and tufted hairgrass *(Deschampsia caespitosa)* occur on the upper portions of sandbars, where flooding probably occurs only during spring breakup, thereby giving these pioneer species a chance to become established during the summer. On less active floodplains, scattered shrubs may be present, including feltleaf *(Salix alaxensis)* and grayleaf willows *(Salix glauca)*. On very active sand dunes, the pioneer vegetation may be composed of dunegrass. On less active dunes, Richardson *(Salix lanata)*, grayleaf, and feltleaf willows are common.
Emergent Vegetation	Emergent vegetation, characterized by sedge or grass marshes, occur in permanent water bodies that have water depths of 0.3-3 ft. In sedge marshes, which generally occur at water depths of 0.3-1 ft, water sedge *(Carex aquatilis)* and tall cottongrass *(Eriophorum angustifolium)* dominate. In grass marshes, which generally occur in water depths of 1-3 ft, pendent grass *(Arctophia Fulua)* dominates.
Wet Meadow	Wet meadows are low-lying areas dominated by sedges and can have up to 0.3 ft of standing water during mid-summer. The meadows usually are associated with lake, pond, and river margins, or more commonly, with low-center polygons. Vegetation is dominated by water sedge, tall cottongrass, and russet cottongrass *(Eriophorum russeolum)*.
Moist Meadow	Moist meadows occur on upland areas such as broad ridges and high-centered polygons. Moist meadows include: tussock tundra vegetation dominated by cottongrass tussocks *(Eriophorum vaginatum)*; sedge-willow vegetation dominated by bigelow sedge *(Carex bigelowii)* and willows; and sedge-*Dryas* vegetation dominated by bigelow sedge and *Dryas* dwarf shrub *(Dryas integrifolia)*. Moist meadows generally occur on the oldest portions of the terrain.
Riparian Low-Tall Shrub	Riparian shrublands, which include both low and tall willow shrubs, generally occur on riverbanks that are subject to occasional flooding. The canopy can vary from open to closed and can attain heights of 9 ft. Feltleaf and grayleaf willows are the dominant species. This vegetation occurs in sites where flooding is frequent enough to deposit new sediments and nutrients, but not so frequent that it prevents seedling establishment. Sediment deposition is limited to very thin deposits (approx. 0.1 in) of silt.
Riparian Dwarf Shrub	This vegetation occurs along low riverbanks and is dominated by the dwarf shrub, ovalleaf willow *(S. ovalifolia)*, which is able to withstand annual deposits of sediment up to 1 in thick.
Upland Low-Tall Shrub	This vegetation type is similar to its riparian counterpart, except that typically it is found on dunes. Common species include feltleaf and grayleaf willows.
Upland Dwarf Shrub	This vegetation is found on stable sand dunes. The vegetation is dominated by *Dryas* dwarf shrubs, but the vegetation can be very patchy; lower sites may have moist meadow vegetation, whereas higher tips of dunes may be dominated by grayleaf willow.
Salt Marsh	Salt marshes occur on stable mudflats along the coast and are inundated periodically by brackish water, high tides, or storm surges. Vegetation is dominated by hoppner sedge *(Carex subspathacea)* and creeping alkaligrass *(Puccinellia phryganodes)*. The vegetation is distributed very patchily among ponds and barren mudflats.
Salt-killed Meadows	Salt-killed meadows occur in low-lying tundra areas that originally had wet or moist meadows. The original vegetation developed under non-saline conditions was killed by inundation by brackish water during storm surges. The most notable recent surges occurred in 1963 and 1970.

[1] Descriptions partially adapted from Rothe et al. (1983).

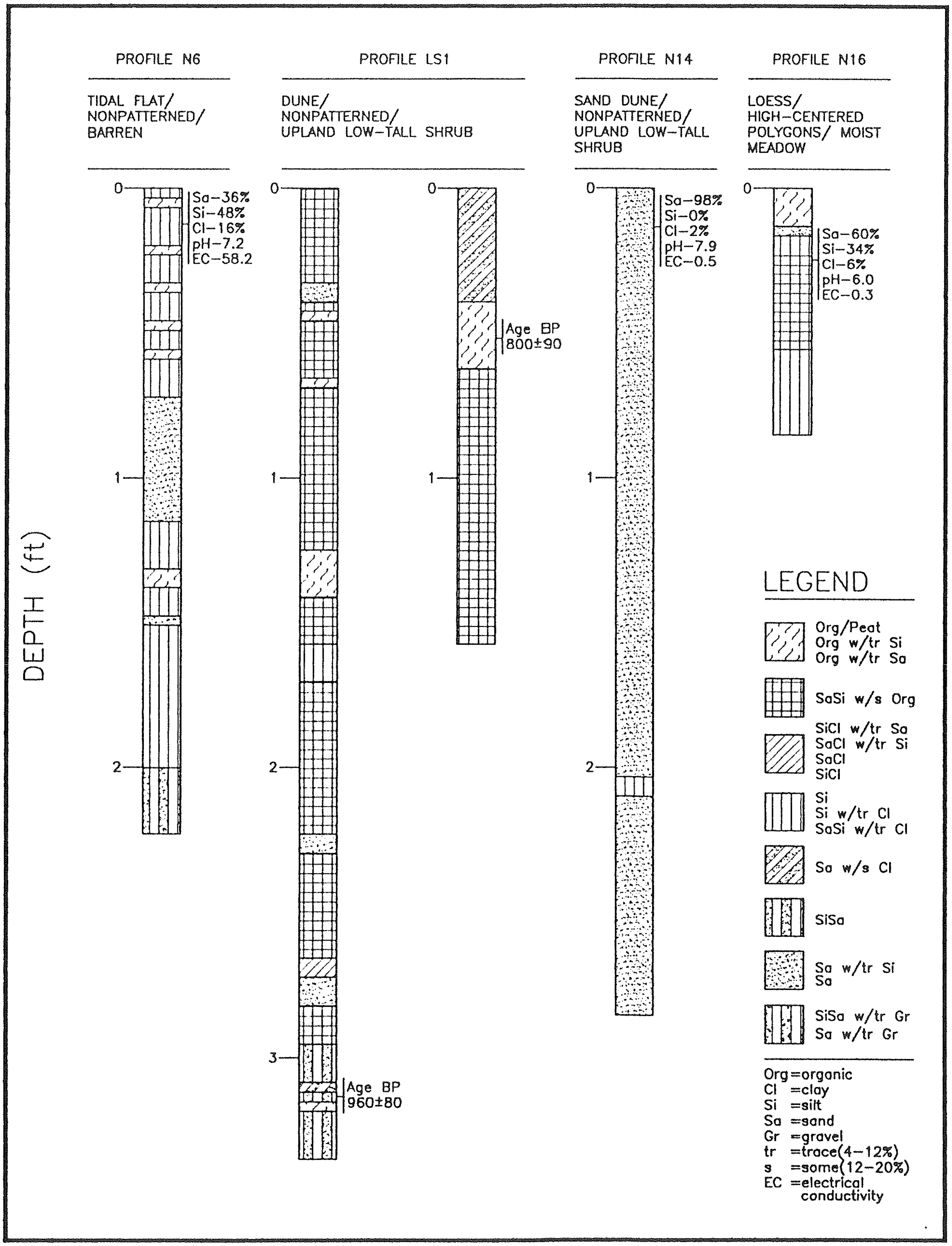

Figure 11. Representative stratigraphic profiles of eolian and tidal flat deposits, Colville River Delta, 1992.

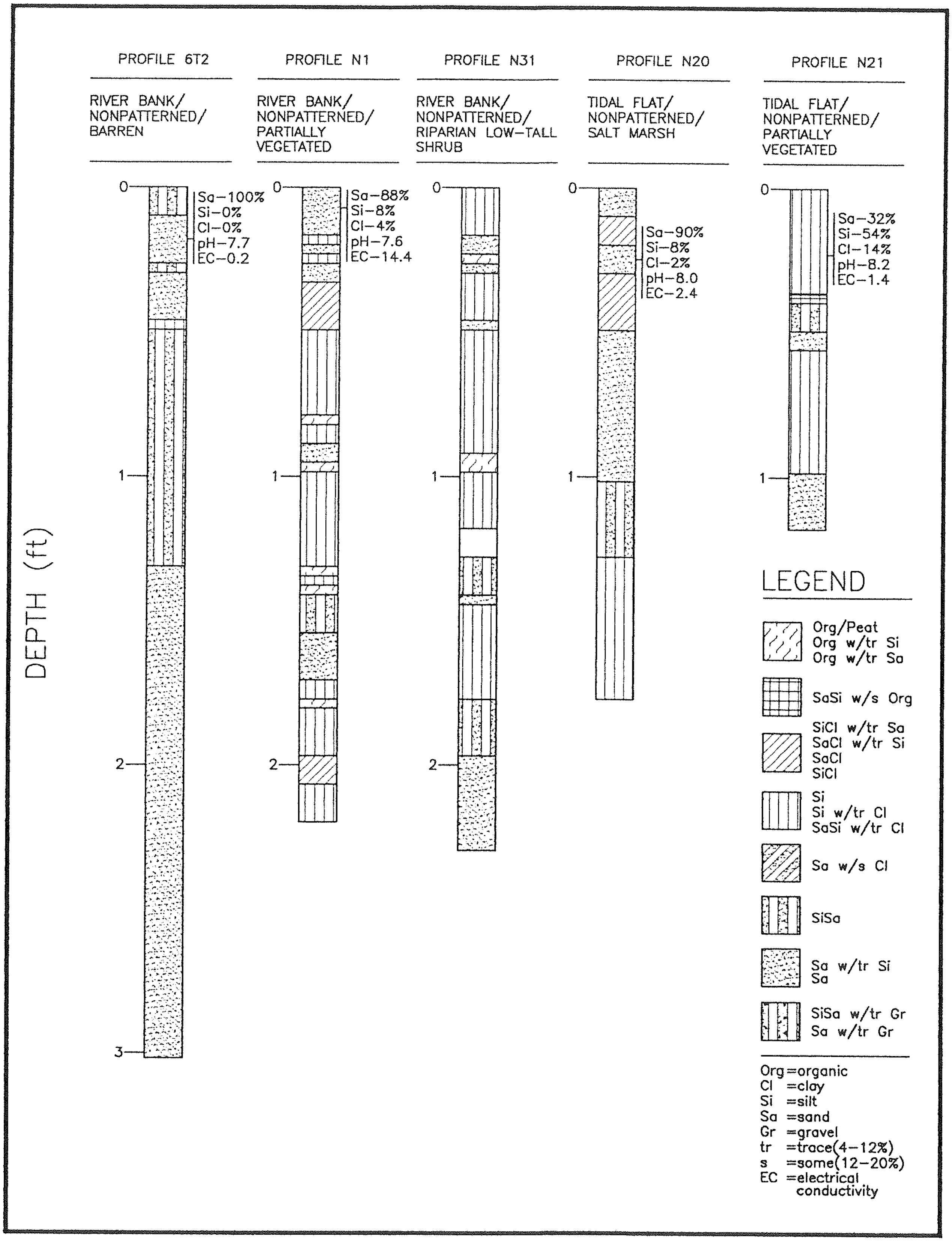

Figure 12. Representative stratigraphic profiles of riverbed alluvium and tidal flat depsits, Colville River Delta, 1992.

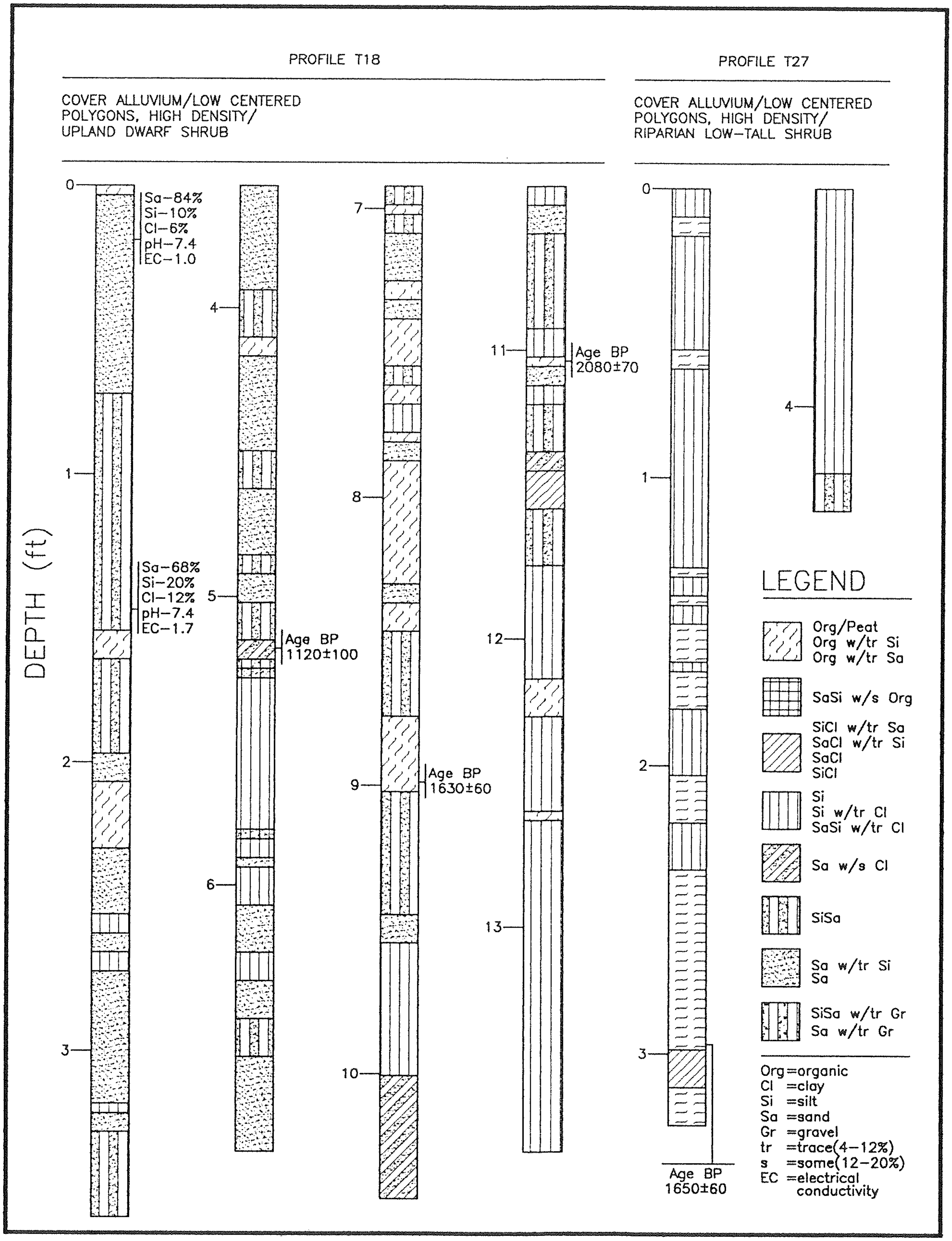

Figure 13. Representative stratigraphic profiles of cover alluvium, Colville River Delta, 1992.

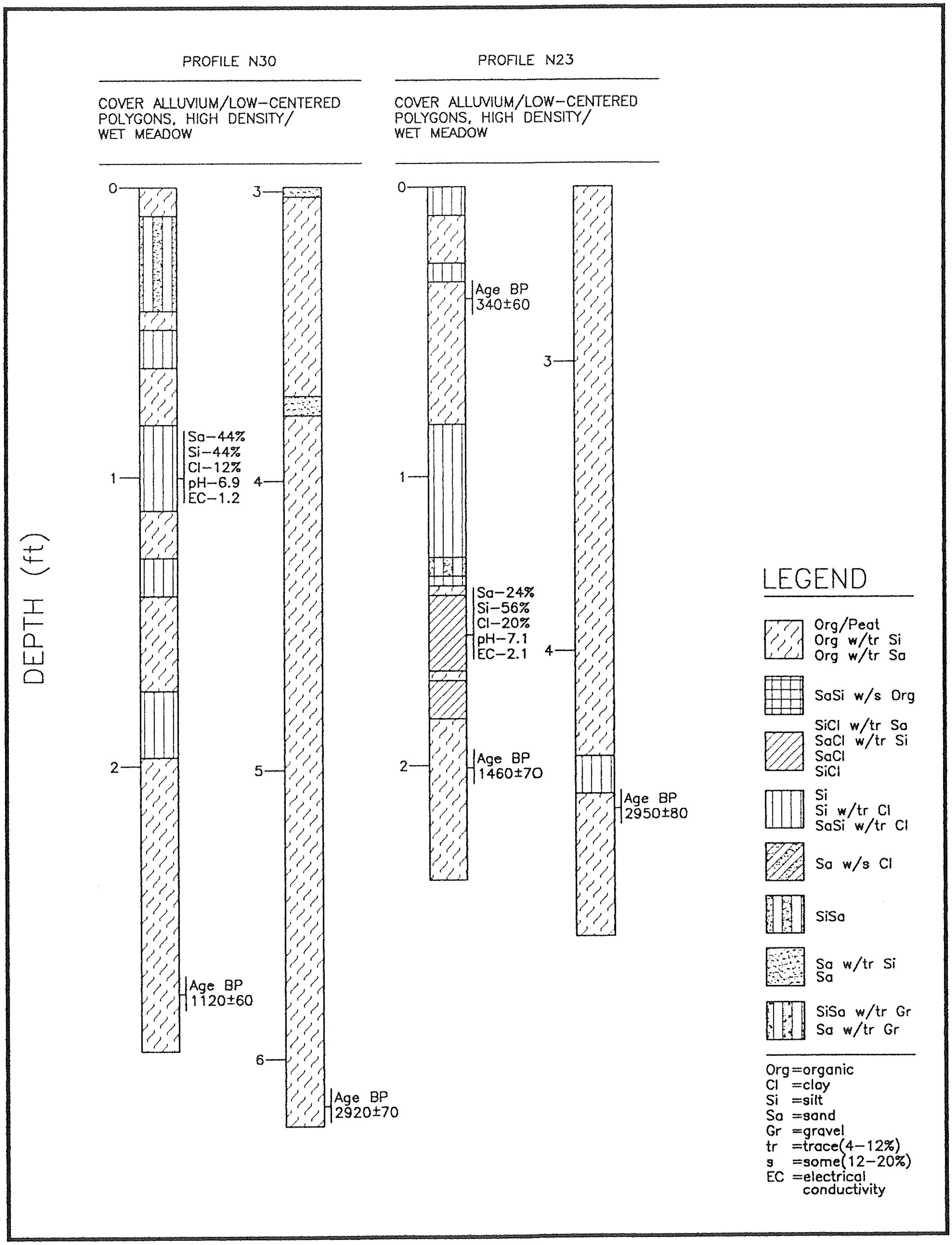

Figure 14. Representative stratigraphic profiles of cover alluvium, Colville River Delta, 1992.

often composed a large portion (e.g., 78% in profile N30) of the profiles. Notable was the frequent alternation of depositional environments from periods of rapid alluvial deposition to relatively stable periods when flooding was infrequent enough to allow the development of vegetation and accumulation of organic material. Another notable feature of the profiles was the lack of alluvial deposition at the surface: all sample sites were capped with an organic layer. Although traces of silt or sand were evident in the surface organic layer, this material was attributed to wind-blown deposition rather than alluvial deposition.

Finally, tidal flat deposits (Figs. 11 and 12) also had a high frequency of depositional layers. These deposits ranged from very fine sand to silty clay that frequently were associated with thin layers of organic drift, similar to that found in riverbed alluvium. In salt marsh areas, where water velocities generally are lower, the tidal deposits frequently had numerous layers of interbedded clayey silts.

To assess the stability of the surfaces, a comparison of the mean depths of the surface organic layer among ITUs revealed there were large differences in thickness of the organic layers. (Fig. 15). Riverbed-sandbars, high-water channels, and sand dunes that were either barren or partially vegetated had no development of an organic layer. Areas with riparian shrubs had modest development of an organic layer. In contrast, the thickest organic layers occurred on cover alluvium deposits that supported wet meadow vegetation. There also was a trend of increasing thickness of the organic layer with increased development of ice wedges, as expressed by surface form, from nonpatterned ground to ground with low-centered polygons.

The lack of any discernable mineral layers near the surface provides evidence that flooding of the highest floodplain steps with the thickest organic layers is infrequent. This is in stark contrast to the amount of sediment that can be deposited on lower areas by one flooding event. Walker (1983) found sediment deposition as thick as 10 in after spring flooding. We observed as much as 1 in of sediment on top of scattered vegetation in riverbed-sandbar/barren units and traces of very thin layers of silt (<0.2 in) in a few riverbed-sandbar/riparian shrub units.

Radiocarbon dating at the base of the profiles from some of the thickest and oldest portions of the delta ranged from 2080 to 2950 ybp (Figs. 13 and 14), indicating a long period of stability. The radiocarbon dates also provide information on the rates of accumulation of alluvial sediments and organic matter. In profiles of cover alluvium that have radiocarbon dates, average rates of accumulation of material in the profiles since the oldest radiocarbon dates ranged from 0.16 to 0.54 ft/100 y. However, there did not appear to be a significant difference between the rate of accumulation at the top of the profile (0.14-0.47 ft/100 y) and the rate of accumulation at the bottom of the profile (0.16 to 0.78 ft/100 y). This suggests that flooding and accumulation of sediments is happening presently at the same rate as it did thousands of years ago.

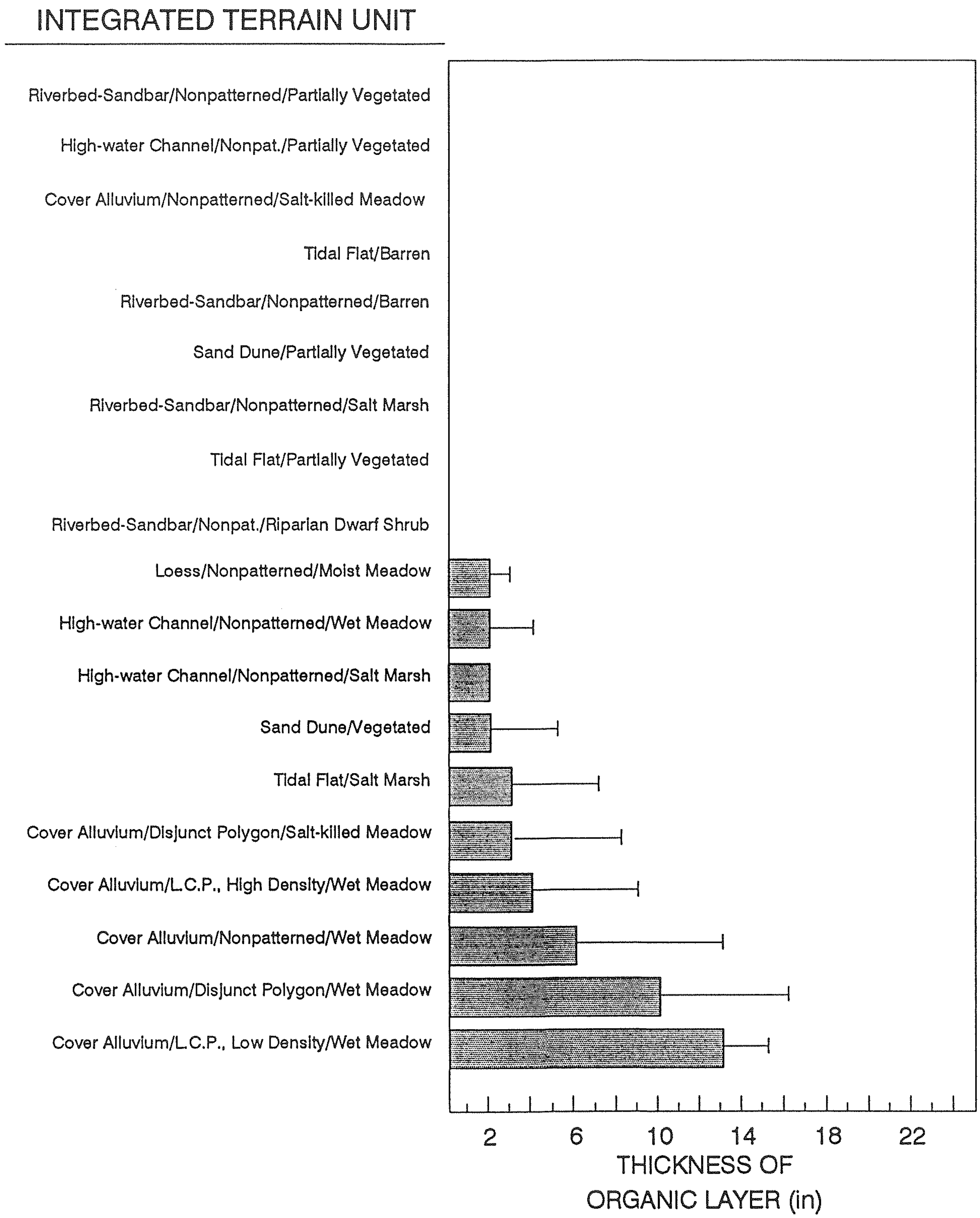

Figure 15. Mean depths (± standard deviation) of the surface-organic layer within integrated terrain units, Colville River Delta, 1992.

PART III. FLOODING REGIME

BACKGROUND

Understanding the flooding regime of the CRD is critical to the designing and placement of potential oil field facilities in the region. Basic information on main channel velocities and stages that might occur are necessary for the design of bridges and pipelines crossing rivers. Similarly, the distribution and frequency of flooding is needed for siting and designing facilities. Finally, information on storm surges is needed to avoid areas that may be inundated.

In the permafrost-dominated landscape of the CRD, seasonal changes in hydrology may be extreme and can be grouped into four distinct seasons (Walker 1974). Winter lasts about 8 mo, and all surface water to a depth of about 6 ft is frozen. Summer, which is less than 3 mo long, occurs between the end of flooding that accompanies spring breakup and the return of low temperatures that set the stage for fall freezeup. In contrast, both spring and fall are short. Of all the seasons, spring breakup is by far the more important in affecting geomorphology, hydrology, and nearshore oceanography.

As river flow decreases during the winter, fresh water within the distributaries gradually is replaced by denser seawater (Arnborg et al. 1966, Walker 1973). Freshwater ice at the surface changes with depth to brackish ice, which in turn blends with saline ice near the bottom, especially in areas near the fringe of the delta (Osterkamp 1972). The depth of river water at freezeup is a major influence on the distance that seawater penetrates upriver, and the degree to which the river is divided into isolated deep pockets of water. Penetration of seawater during late winter has been noted as far as 36 mi upriver (Walker 1973). The thalweg of the East channel (main) reaches a maximal depth of 40 ft. High salinities often occur in isolated pockets upriver (Arnborg et al. 1966, Schell and Hall 1972) and in the lower reaches of the river channel as a result of freezing seawater (Walker 1973).

Spring consists of three periods: (1) pre-breakup, when meltwater accumulates on and flows over and under river ice; (2) breakup, when river ice moves downstream; and (3) post-breakup, which lasts until river flooding ceases (Hamilton and Walker 1974, Walker 1983). A rapid rise in river level usually precedes breakup, which occurs at about the time that the maximal flood stage is reached. During or shortly after breakup, the flood stage drops relatively rapidly. This sequence generally occurs in about 3 weeks, but the actual duration is affected by the rate and nature of snowmelt within the drainage basin. Water usually begins reaching the head of the delta between 23 May and 30 May. Breakup generally occurs between 30 May and 10 June (Walker 1983).

During summer, the river generally continues to drop to a low stage that persists throughout summer and fall. Water comes from delayed snowmelt at higher elevations, precipitation, draw down of lakes, and groundwater stored in the active layer. However, stage also varies with wind conditions and tidal variations. Tides average only 0.5 ft and on a day-to-day basis can be overshadowed by the effects of wind (Reimnitz and Maurer 1979). The dominant winds from the northeast cause low water levels and offshore movements of ice, whereas the westerly winds cause a rise in water levels and onshore movements of ice (Short 1974). The most severe storms have westerly winds and generally occur during September and October.

Despite the numerous studies conducted on the CRD, there still is no long-term record of discharge measurements and flood stages. Previous to this study, only a limited number of discharge measurements had been made at the head of the delta. Arnborg et al. (1966, 1967) collected stage-discharge information in 1962 and the USGS collected stage-discharge measurements in 1977 (USGS 1978). The USGS also collected occassional selected discharge measurements in 1977, 1979, 1980, and 1981 (USGS 1978, 1980, 1981, 1982).

In addition, attempts to characterize flooding in the delta have been limited. A small-scale map of the distribution of the floodwater across the delta on 3 June 1971 was developed by Walker (1974). Relative frequencies of flooding have been mapped on a small scale for the CRD by utilizing geomorphic characteristics to delineate active and inactive portions of the floodplain (Cannon and Rawlinson 1981, Cannon and Mortensen 1982). However, their maps are not of sufficient detail to be useful to this project.

METHODS

STAGE-VELOCITY-DISCHARGE RELATIONSHIPS

Stage-discharge and velocity-discharge relationships were developed for cross section 6, which was located at the head of the delta (Fig. 1). Both relationships were based on a single discharge measurement made by Arctic Hydrologic Consultants (AHC) in 1992 and selected discharge measurements made by the USGS between 1977 and 1980 (see

Appendix Table B-1).

The stage-discharge relationship was developed using the discharge measurements made in the vicinity of cross section 6 and Manning's equation (Henderson, 1966). The exact location of the USGS discharge measurements is not known, however, and it is likely that they were not all collected at exactly the same location. However, we believe that the measurements were all collected within about 0.25 mi of cross section 6.

For each discharge measurement, a value was computed for the slope- roughness term

$$1.49/n * S^{1/2},$$

where

n = hydraulic roughness and
S = slope of the energy gradeline in ft/ft,

in Manning's equation. The water-surface elevation at cross section 6 corresponding to the measured discharge was computed based on trial and error. Using the value of the measured discharge and the associated slope-roughness term, Manning's equation was solved for various water-surface elevations at cross section 6 until the computed discharge equalled the measured discharge. This process was repeated for each of the measured discharges. The water surface elevation associated with discharges higher than those measured, but less than the top of the bank at cross section 6, were computed by using Manning's equation and the slope-roughness term associated with the highest measured discharge. The final stage-discharge curve was developed by plotting the water surface elevation versus discharge points on a graph and fitting a best-fit line through the points associated with the measured discharges. The line was extended above the measured discharges based on the location of the best-fit line and the slope of the points estimated with Manning's equation.

A velocity-discharge curve was computed by simply plotting velocities associated with the measured discharges against measured discharges. Points calculated for discharges above those measured also were plotted based on Manning's equation. The final velocity-discharge curve was developed by fitting a best-fit line through the points associated with the measured discharges. The line was extended above the measured discharges based on the location of the best-fit line and the slope of the points estimated with Manning's equation.

FLOOD FREQUENCY IN THE VICINITY OF CROSS SECTION 6

An estimate of flood-peak frequency was prepared for the CRD, in the vicinity of cross section 6, by extrapolating flood-peak-frequency relationships for each of three North Slope rivers to the Colville River. This extrapolation produced three estimates of the flood-peak-frequency relationship on the CRD. Each relationship was analyzed and compared to estimates of the annual flood peak discharge on the CRD during the years 1962, 1977, and 1992. Based on the relationships and the limited flood-peak data, a flood-peak-frequency relationship was developed for the head of the CRD. A detailed description of each of the phases of the analysis is presented below.

Single-Station-Frequency Analyses

Flood-peak frequency analyses were conducted for the Kuparuk River and the Sagavanirktok River. Discharge data have been collected by the USGS on the Kuparuk River at a location about 10 mi inland from the mouth of the river. Discharge data have been collected by the USGS on the Sagavanirktok River at two locations: near Sagwon between 1969 and 1979, and near Pump Station 3 between 1983 and 1992. Prior to performing the analyses of flood-peak frequency on the Sagavanirktok River data, the data from Pump Station 3 were extrapolated to Sagwon, based on the unit runoff and drainage area. Thus, the flood-frequency analysis for the Sagavanirktok River at Sagwon was conducted based on 21 y of records.

The flood-peak-frequency analyses were performed according to methods presented in "Guidelines For Determining Flood Flow Frequency" (Interagency Advisory Committee On Water Data 1982). As suggested by these guidelines, the station skew was weighted with a regional skew to produce the skew value used in the analyses. The value of the regional skew used for this analysis (0.13) was obtained from Jones and Fahl (1992); the standard error associated with the regional skew was 1.15.

The flood-peak data available for the Kuparuk River, the Sagavanirktok River near Sagwon, and the Sagavanirktok River near Pump Station 3 are presented in Appendix Table B-2. In addition to the estimates of flood-peak frequency prepared for the Kuparuk and Sagavanirktok rivers, an estimate of flood-peak frequency on the Firth River in Canada (Jones and Fahl 1992) also was used to estimate the flood-peak frequency on the Colville River. Drainage-basin characteristics for each of the drainage basins used in the analysis are presented in Appendix Table B-3.

Extrapolation of Single-station Analyses to the Colville River

The analyses of flood-peak frequency prepared for the Kuparuk, Sagavanirktok, and Firth rivers were extrapolated to the Colville River by using regression equations developed by Jones and Fahl (1992) and adjustment factors developed for this project. The original regression equations were developed to estimate flood-peak discharges on ungaged basins based on the area of the drainage basin, mean annual precipitation, percent of the drainage area covered by lakes, and the mean elevation of the basin. Separate regression equations were provided to predict the flood-peak discharge associated with each of the following recurrence intervals: 2, 5, 10, 25, 50, 100, 200, and 500 y.

To use the regression equations to extrapolate the flood-peak frequency data from the three gaged basins to the Colville River, an adjustment factor was added to each of the regression equations. A separate adjustment factor was developed for each of the gaged basins. Thus, three sets of modified regression equations were developed to predict the flood-peak discharge on the Colville River associated with selected recurrence intervals.

The adjustment factor that was added to the regression equations was computed according to the following formula:

$$AF_T = Q_{SSA}/Q_{REG},$$

where

AF_T = adjustment factor applied to Jones and Fahl's (1992) regional regression equation for estimating the discharge associated with the T-year event;

Q_{SSA} = discharge estimate based on the single-station frequency analysis, with an average recurrence interval of T years; and

Q_{REG} = discharge estimate based on the regional regression equations developed by Jones and Fahl (1992) with an average recurrence interval of T years[1].

The modified regression equations and the values of the adjustment factors are presented in Appendix Tables B-5 and B-6, respectively.

Adjustment for Expected Probability

The modified regression equations described above are based on the computed exceedence probabilities associated with each of the gaged basins used to produce the equations. However, the computed exceedence probabilities tend to underestimate the true exceedence probabilities[2] when the record length for the gaged stream is short. Therefore, an expected probability adjustment was made to the discharge estimates that were computed by using the modified equations described above. The expected probability adjustment was computed based on the number of years of record associated with the gaged station used

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1 Example: The adjustment factor for the regression equation to predict the 2-y flood peak, based on the Kuparuk River flood frequency analysis, was developed as follows:

$$AF_2 = Q_{SSA2}/Q_{REG2},$$

where

AF_2 = adjustment factor to use with the 2-y flood peak regression equation developed by Jones and Fahl (1992) when estimating the 2-y flood peak discharge on the Colville River, based on the Kuparuk River flood frequency data;

Q_{SSA2} = estimate of the Kuparuk River discharge with an average recurrence interval of 2 y, based on the single-station frequency analysis for the Kuparuk River; and

Q_{REG2} = estimate of the Kuparuk River discharge with an average recurrence interval of 2 y, based on the regression equation developed by Jones and Fahl (1992).

2 In other words, a discharge with a computed average recurrence interval of T years may actually be equalled or exceeded considerably more frequently than suggested by the computed average recurrence interval, if the record length of the station used to make the etimate is short.

to develop the adjustment factor and was made in a manner similar to that described in "Guidelines For Determining Flood Flow Frequency" (Interagency Advisory Committee On Water Data 1982).

Comparison of Computed Flood-Peak Frequency Relationship to Selected Events

The peak discharge estimates prepared for the Colville River, based on the regression equations developed from the three gaged rivers, were plotted and compared to the average of the peak discharges that actually occurred in 1962, 1977 and 1992. A single flood-frequency relationship was then selected from the three regression estimates, and adjusted to match the average of the estimated peak discharges in 1962, 1977, and 1992.

Although the annual peak discharges were not measured in 1977 or 1992, the discharge on the second day after the peak water surface elevation (WSE) was recorded. To estimate the peak discharge in 1977 and 1992, two assumptions were made. First, it was assumed that the peak discharge occurred on the day with the peak WSE. Second, it was assumed that the percent difference between the peak discharge and the discharge two days after the peak discharge was the same as that inferred from the data reported by Arnborg et al. (1966) for the 1962 spring flood (i.e., the peak discharge was 135% greater than the discharge two days after the peak)[3].

Estimates of the maximum likely annual peak discharge and the minimum likely annual peak discharge were also computed for 1977 and 1992. The maximum likely annual peak discharge was estimated based on the peak stage and a stage-discharge relationship developed for cross section 6. The annual peak stage was recorded in both 1977 and 1992. However, the peak stage in 1977 was affected by backwater from ice (USGS 1978), and no observations were made at the time of the 1992 peak stage to determine if it was affected by backwater from ice. The minimum likely annual peak discharge was estimated based on estimates of the discharge two days after the peak stage.

FLOOD DISTRIBUTION IN 1992

The extent of flood water coverage was mapped within three pilot-scale study areas (Fig. 1) by using aerial photography acquired on 4 and 8 June. Oblique photography was taken on 4 June, two days after the peak stage occurred at the head of the delta, with a 35-mm camera at 500 ft above ground level (agl), just below the cloud ceiling. On 8 June, when weather improved, color vertical photographs (1:17,000 scale) were taken at 11,000 ft agl with a Hasselblad 6 x 7-cm format camera.

The extent of flooding within the study areas was interpreted from the 8 June photography and delineated on the CIR photography (1:18,000 scale) that was used to map integrated terrain units. When possible, the extent of flooding visible on the 4 June photography also was delineated on the CIR photography. The lines were digitized in the GIS and rectified to the ITU map. Finally, the flooding layer was overlain on the ITU map, and the percentage of each ITU covered by flooding determined.

FLOOD DISTRIBUTION MODEL

A preliminary model for predicting flood distribution across the entire CRD was develped by grouping ITUs that were mapped into flood units with similar flooding frequencies. The model correlates flooding frequency to landforms based on the assumption that fluvial landforms are in equilibrium with the flooding regime. This approach was selected because the elevational and hydrologic data requirements for developing either a physical model or mathematical model are non-existent at this time.

To correlate flood frequency with ITUs, we analyzed the relative differences in elevations, flood distribution in 1992, and soil stratigraphy. Initially, the elevations of the highest terraces and riverbed deposits were plotted from elevations measured along the cross section to obtain an elevational profile across the delta. Because of the decrease in elevation from the head to the fringe of the delta, it was necessary to normalize the elevational differences by computing the proportional elevation of each ITU relative to the highest terrace. This normalization of differences was done by calculating the mean elevation of the highest terrace at each transect and then dividing the elevation

[3] Arnborg et. al. (1966) reported the discharge on the day of the peak discharge and four days after the peak discharge. Linear interpolation was used to estimate the discharge two days after the peak discharge.

of each measurement along that transect by that mean. Afterwards, the mean proportional height of each ITU was computed for all transects grouped together. Significant differences ($P < 0.05$) among mean proportional elevations of ITUs were determined by performing a one-way analysis of variance (ANOVA) and comparing differences using the least significance difference multiple comparison test (Zar 1984). Based on differences in relative elevations the ITUs were grouped into flooding units with similar flooding frequencies. Analyses of the flood distribution in 1992 was used to identify ITUs that were covered by the most frequent flood events. Analyses of soil stratigraphy were used to qualitatively assess the amount of flooding of infrequently flooded ITUs. Finally, results from the flood-peak frequency analysis was used to assign tentative recurrence intervals to the flood units.

STORM SURGES

The hazard related to storm surges in the CRD was assessed using four approaches: (1) review of the historical pattern of flooding that has been reported by previous investigations; (2) examination of available literature concerning storm surge magnitude and frequency; (3) analysis of the distribution of salt-killed tundra in the CRD; and (4) analysis of the distribution of the electrical conductivity of water bodies along the fringe of the delta. The mapping of salt-killed tundra was done during the mapping of ITUs. Electrical conductivities of selected water bodies were measured with a portable multimeter between 8 June and 3 August in conjunction with other field studies.

RESULTS AND DISCUSSION

STAGE-VELOCITY-DISCHARGE RELATIONSHIPS

Stage-Discharge Relationship at Cross Section 6

A single-discharge measurement made by Arctic Hydrologic Consultants (AHC) in 1992 and selected discharge measurements made by the USGS between 1977 and 1980 were used to produce a stage-discharge relationship for cross section 6 (Fig. 16).

A check of the stage-discharge relationship was made by using data collected in 1962 by Arnborg et al. (1966). These data are plotted on Figure 16 and suggest that the proposed stage-discharge curve agrees very well with the water-surface elevation and discharge measurements made by Arnborg et al. (1966) in the vicinity of cross section 6. Such close agreement also suggests that the stage-discharge relationship is stable at cross section 6 and might not change dramatically from one year to the next.

The top of the riverbank in the vicinity of cross section 6 varied from 16 to 19 ft in elevation. Thus, based on Figure 16, the bankfull discharge[4] at cross section 6 is between 330,000 and 430,000 cfs. The highest debris line observed at cross section 6 in July 1992 had an elevation of approximately 18.8 ft. Based on Figure 16, the in-channel discharge associated with a water surface elevation of 18.8 ft is approximately 425,000 cfs. It should be noted, however, that the total discharge may have been somewhat higher, as there may have been flow along the floodplain on the east side of the channel.

Velocity-Discharge Relationship at Cross Section 6

A single discharge measurement made by AHC in 1992 and selected discharge measurements made by the USGS between 1977 and 1980 were used to produce a velocity-discharge relationship for cross section 6 (Fig. 17).

A check of the velocity-discharge relationship was made with data collected in 1962 by Arnborg et al. (1966). These data are plotted on Figure 17 and suggest that the proposed velocity-discharge curve agrees fairly well with the velocity and discharge measurements made by Arnborg et al. (1966) in the vicinity of cross section 6. In general, the velocity measurements made by these authors are 0.2-0.3 fps faster than the velocities suggested by the velocity-discharge curve (Fig. 17).

The bankfull discharge in the vicinity of cross section 6 is approximately 330,000-430,000 cfs. Thus, based on Figure 17, the average main-channel velocity at bankfull is probably between 5.6 and 6.2 fps.

The highest debris line observed at cross section 6 in July 1992 had an elevation of approximately 18.8 feet and an associated in-channel discharge of about 425,000 cfs. The average main-channel velocity associated with this event probably was about 6.1 fps. Because larger discharges would flow out across a large floodplain on the eastern side of the river, the average main channel velocity would probably not increase substantially during events considerably larger than bankfull. For instance, if the water surface

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[4] The stage at which water just begins to flow over the banks.

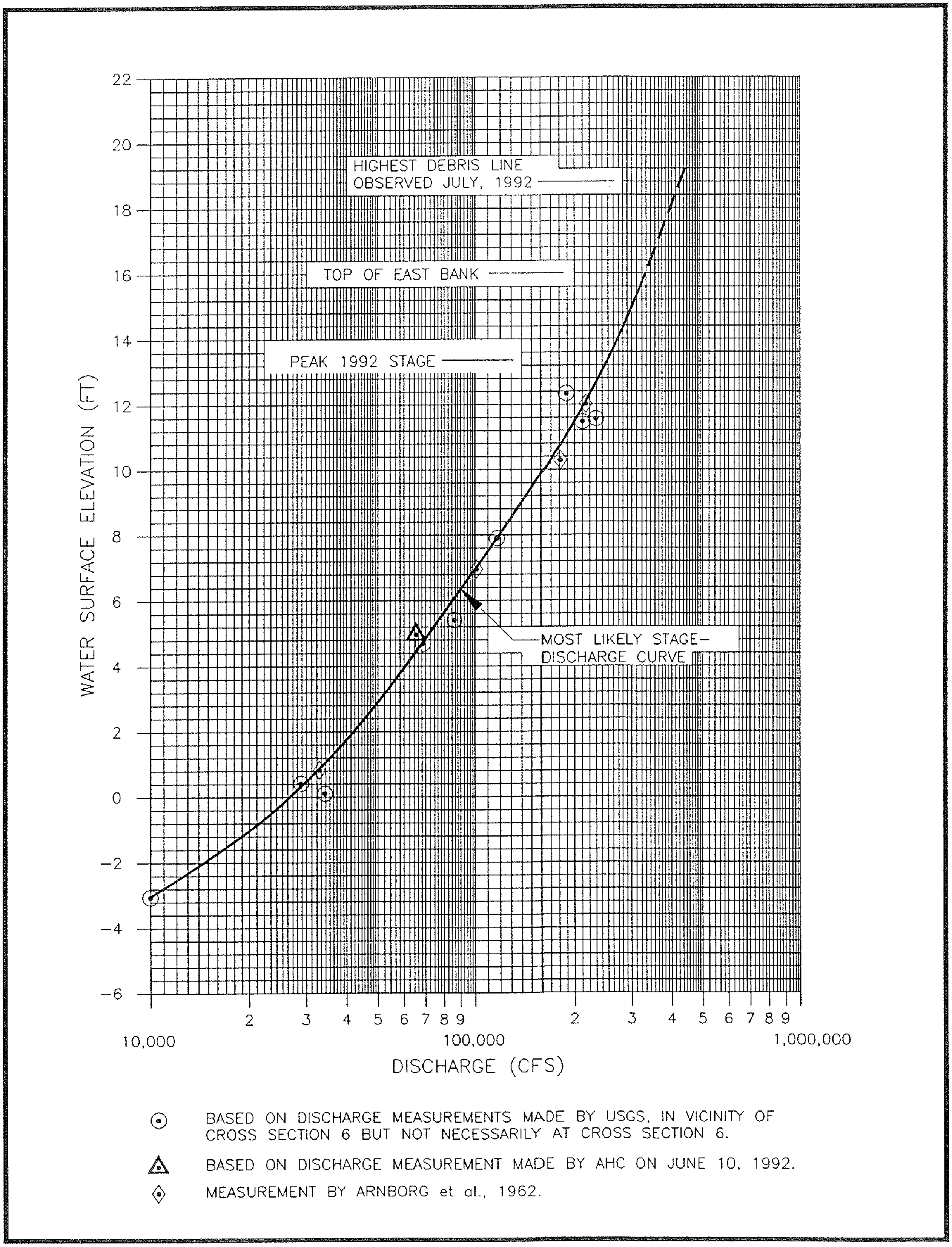


Figure 16. Stage-discharge relationship for the Colville River at cross section 6.

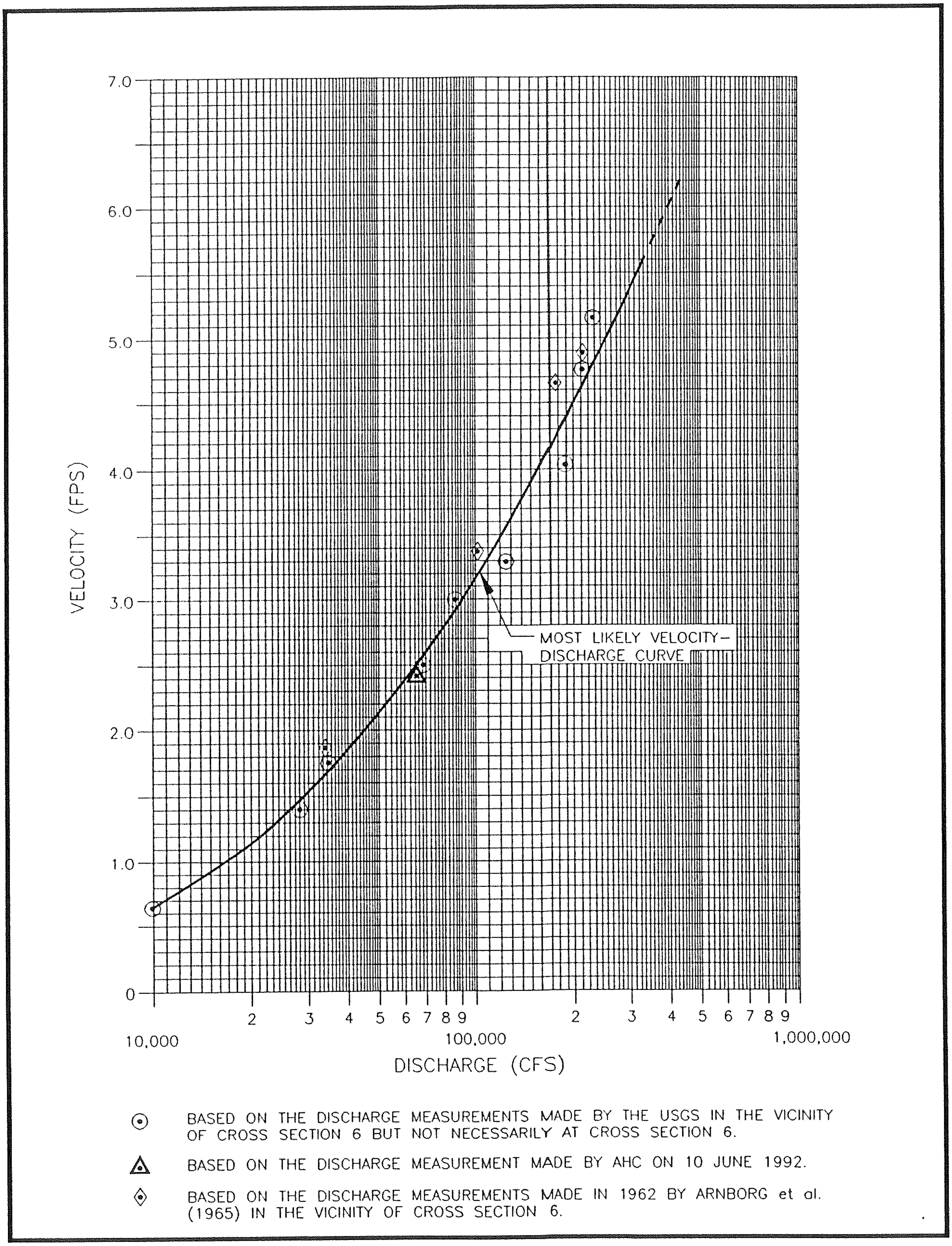


Figure 17. Velocity-discharge relationship for the Colville River at cross section 6.

elevation was 1 ft higher than the highest surveyed point on the eastern floodplain, the average main channel velocity still would be < 7 fps.

Based on the AHC and USGS discharge measurements made in the vicinity of cross section 6, the ratio of the maximum average velocity at any station across the cross section and the average main-channel velocity varies from 1.24 to 1.60, with all but one of the measurements being between 1.24 and 1.40. Thus, the average main channel velocities estimated based on Figure 17 can be multiplied by 1.4 to estimate the maximal likely main channel velocity associated with any given discharge.

FLOOD FREQUENCY IN THE VICINITY OF CROSS SECTION 6

Flood-peak-frequency (FPF) relationships were developed for the Kuparuk, the Sagavanirktok, and the Firth rivers based on stream gaging data. The FPF relationship for each of the three streams then was extrapolated to the Colville River, in order to estimate the FPF relationship on the Colville River.

The data used and the FPF relationships developed for each of the gaged streams are presented in Appendix Tables B-2 through B-4. The equations used to extrapolate these relationships to the Colville River are presented in Appendix Tables B-5 and B-6.

The discharge on the Colville River associated with selected average recurrence intervals, based on each of the gaged streams, is presented in Appendix Table B-7. Also presented in Appendix Table B-7 is the Colville River discharge associated with the average expected recurrence interval, based on each of the gaged streams. As discussed in the section titled "Adjustment For Expected Probability", the expected probability .adjustment attempts to account for the tendency to underestimate the probability of occurrence, when streams with short record lengths are used to estimate the flood peak frequency relationship. A plot of each of the FPF relationships, developed based on the expected exceedence probability and data from each of the gaged streams, is presented in Figure 18.

Extrapolation of the Sagavanirktok River data produced the smallest Colville River discharge estimate associated with any recurrence interval (Fig. 18). Extrapolation of the Kuparuk River data produced the largest Colville River discharge estimate associated with any recurrence interval, and was nearly three times the estimate based on the Sagavanirktok River data.

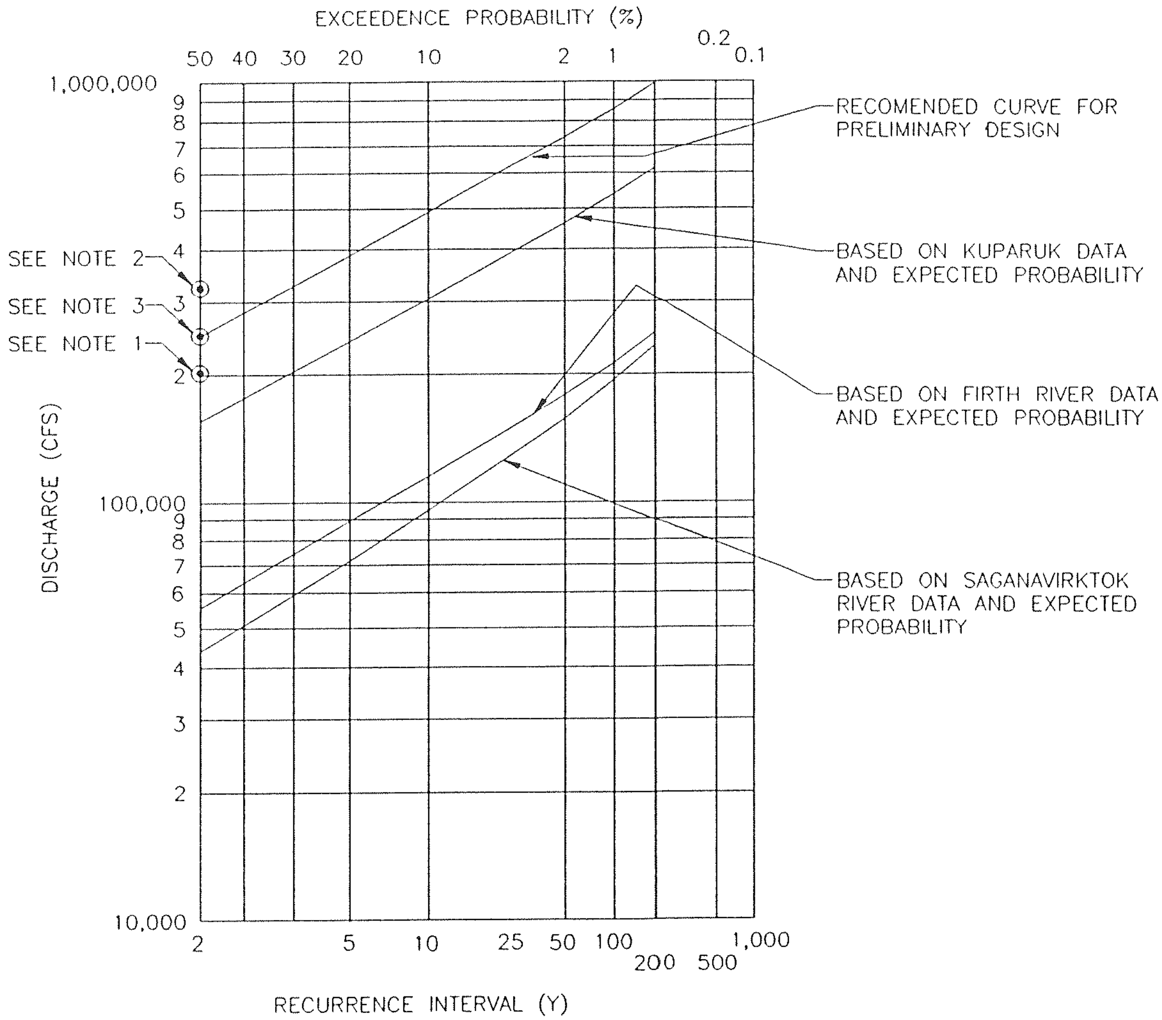
Based on the drainage basin characteristics presented in Appendix Table B-2, there is no clear reason to select one of the gaged basins as being more similar to the Colville River than the other basins. In fact, all three basins are almost an order of magnitude smaller than the Colville River basin. Thus, it was difficult to determine which of the estimates was most similar to the actual FPF relationship on the Colville River.

To select one relationship as being superior to the other two, an independent estimate was made of the magnitude of the 2-y flood-peak discharge based on flood data from 1962, 1977, and 1992. In 1962, the peak discharge in the vicinity of cross section 6 was estimated to be 215,000 cfs (Arnborg et al. 1966).

In 1977 the peak water surface elevation (in the vicinity of cross section 6) was affected by ice, and an instantaneous peak discharge was not reported (USGS 1978). However, the average daily discharge two days after the peak water surface elevation (WSE) was approximately 277,000 cfs (USGS 1978). Based on the percent difference between the peak discharge and the discharge two days after the peak discharge, as inferred from the 1962 data collected by Arnborg et al. (1966), it is estimated that the peak discharge was probably about 374,000 cfs. Thus, the annual peak discharge in 1977 was probably between 277,000 and 510,000[5] cfs, and was most likely on the order of 374,000 cfs.

In 1992, the peak discharge was not observed, therefore it is unknown whether the peak WSE was affected by backwater from ice. The highest WSE known to be unaffected by ice was recorded two days after the annual peak WSE, and was estimated to be associated with a flow of approximately 120,000 cfs. Based on the percentage difference between the peak discharge and the discharge two days after the peak discharge, as inferred from the 1962 data collected by Arnborg it al (1966), it is estimated that the peak discharge was probably about 164,000 cfs. Based on the peak stage recorded in 1992, it is estimated that the maximum likely peak discharge is on the order of 250,000 cfs. Thus, the annual peak discharge in 1992

[5] A discharge of 510,000 cfs is based on the peak recorded stage and the assumption that there was no backwater from ice.



NOTES

1. THIS POINT REPRESENTS AN ESTIMATE OF THE AVERAGE ANNUAL PEAK DISCHARGE, BASED ON THE HIGHEST RECORDED DISCHARGE IN 1962, 1977, AND 1992. HOWEVER, IN 1977 AND 1992, THE HIGHEST RECORDED DISCHARGE MAY HAVE BEEN LESS THAN THE ANNUAL INSTANTANEOUS PEAK DISCHARGE.

2. THIS POINT REPRESENTS AN ESTIMATE OF THE AVERAGE ANNUAL PEAK DISCHARGE, BASED ON HIGH WATER MARKS IN 1977 AND 1992, AND THE ANNUAL INSTANTANEOUS PEAK DISCHARGE IN 1962. HOWEVER, THE HIGH WATER MARK IN 1977 WAS AFFECTED BY BACKWATER FROM ICE, AND THE HIGH WATER MARK IN 1992 MAY HAVE BEEN AFFECTED BY BACKWATER FROM ICE.

3. THIS POINT REPRESENTS AN ESTIMATE OF THE AVERAGE ANNUAL PEAK DISCHARGE, BASED ON AN ESTIMATE OF THE 1977 AND 1992 PEAK DISCHARGES USING DATA FROM 1962 TO EXTRAPOLATE BETWEEN THE PEAK DISCHARGE AND THE DISCHARGE TWO DAYS AFTER THE PEAK, AND THE 1962 PEAK DISCHARGE.

Figure 18. Flood-frequency relationship for the Colville River at cross section 6.

was probably between 120,000 and 250,000 cfs, and is most likely on the order of 164,000 cfs.

Based on the flood peak estimates for 1962, 1977, and 1992, it is estimated that the average annual or 2-year peak discharge on the Colville River is probably between 204,000 and 325,000 cfs, and most likely on the order of 250,000 cfs. A 2-year peak discharge of 250,000 cfs is significantly greater than the 2-year peak discharge estimate based on any of the three gaged basins (see Figure 18). Even the low estimate of 204,000 cfs is significantly greater than the estimates produced based on the three gaged basins.

Therefore, for preliminary design purposes, it is suggested that the flood frequency relationship for the Colville River at cross section 6 be assumed to be similar in slope and form to the estimate based on the Kuparuk River data, but pass through a 2-year flood peak discharge of 250,000 cfs (see Figure 18). Based on the suggested flood-peak frequency relationship presented in Figure 18, it can be estimated that the 50-year flood is on the order of 860,000 cfs[6].

The bankfull discharge in the vicinity of Cross Section 6 is between 330,000 and 430,000 cfs, and probably has a recurrence interval of 3.3 to 6.7 years (Fig. 18). Thus, a discharge equal to or greater than the bankfull discharge is expected to occur, on average, once every 3 to 7 years. The debris associated with the highest debris line, assuming that there was no backwater from ice, is estimated to be at least 425,000 cfs, and probably has a recurrence interval of no more than once every 6.7 years (Fig. 18). The sand bar on the western side of cross section 6 is probably just covered by a discharge of approximately 185,000 cfs. Such a discharge is likely to occur aproximately once every 1.4 years, on average (Figure 18).

It should be noted that the flood frequency relationship presented in Figure 18 applies to the upstream end of the delta, prior to the point where significant distributaries are present. The relationship will change along the delta, due to increasing drainage area and the presence of distributaries. Based on the 1962 measurements made by Arnborg it al. (1966), flood discharges in the East Channel, immediately below the Nechelik River, are on the order of 79 to 88% of those at cross section 6. However, this represents only one event. The percentage may change for flood discharges higher than those observed in 1962 or when ice jamming occurs. The percentage is higher during normal summer flows (Arnborg et al., 1966).

When using the flood peak frequency relationship presented in Figure 18, a distinction should be made between the risk associated with experiencing a flood of a particular magnitude in any given year, and the risk of experiencing a flood of a particular magnitude one or more times over the life of the project. For instance, there is a 1% chance of experiencing a flow equal to or greater than the 100-year event in any given year. However, there is a 26% chance of experiencing a 100-year event (or larger) one or more times over the 30 year life of a project. Thus, the risk associated with experiencing the design flood one or more times over the life of the project, and not the risk of experiencing the flood in any given year, should be used when determining the acceptable level of risk associated with a design event.

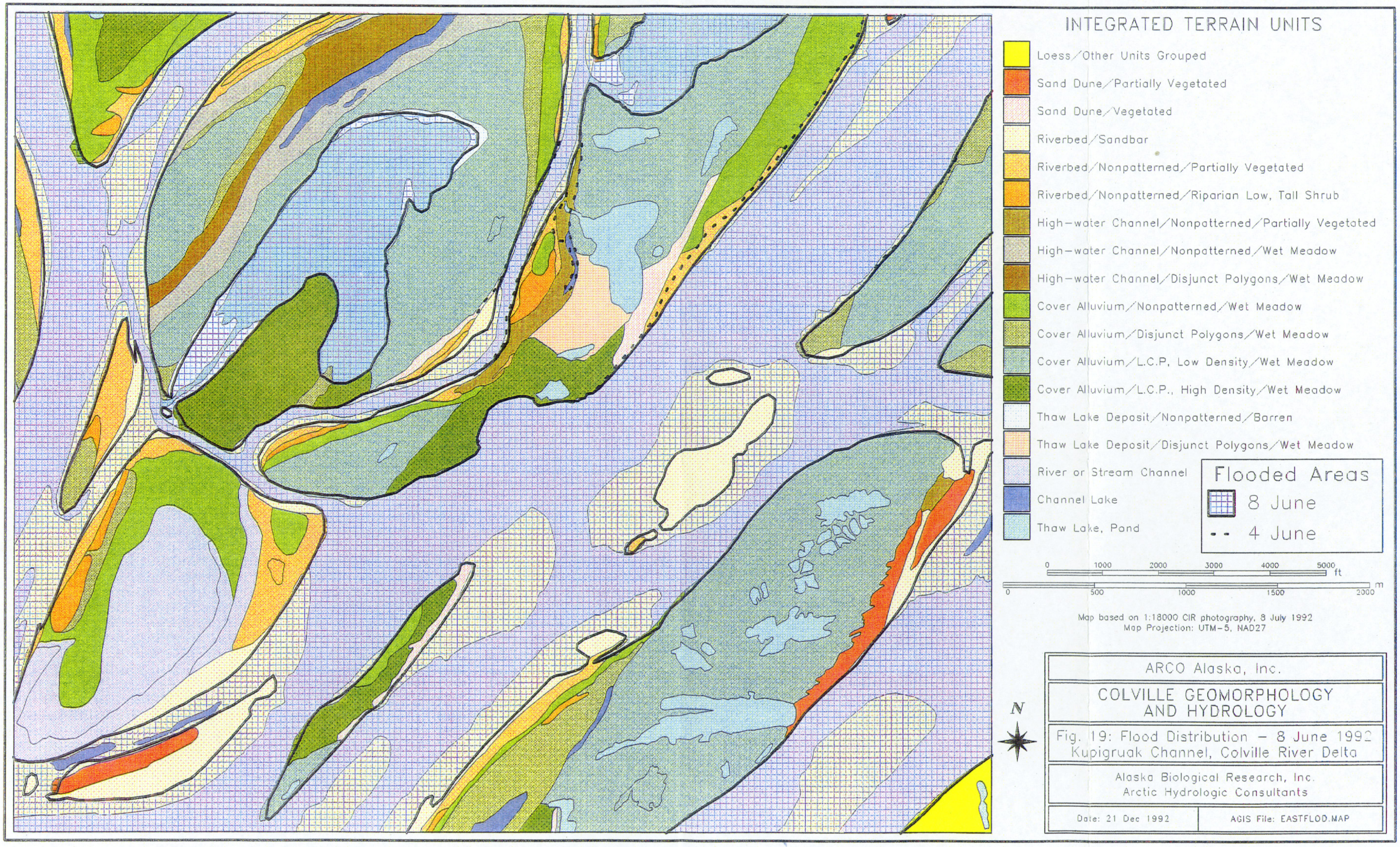
FLOOD DISTRIBUTION IN 1992

Overall, flooding on 8 June 1990 covered 42% of the study areas but varied from 36% in the Tamayayak area (dominated by thaw lakes) to 42% in the Nechelik area (dominated by tidal flats) and 49% in the Kupigruak area (dominated by the main channel; Figs. 19-21). Based on the stage-discharge relationship developed for the head of the delta, discharge at the time when the photography was taken (approximately 73,000 cfs) was substantially less than the flood peak on 2 June (best estimate is approximately 164,000 cfs). The recurrence interval of the flood-peak discharge was probably less than 2 y.

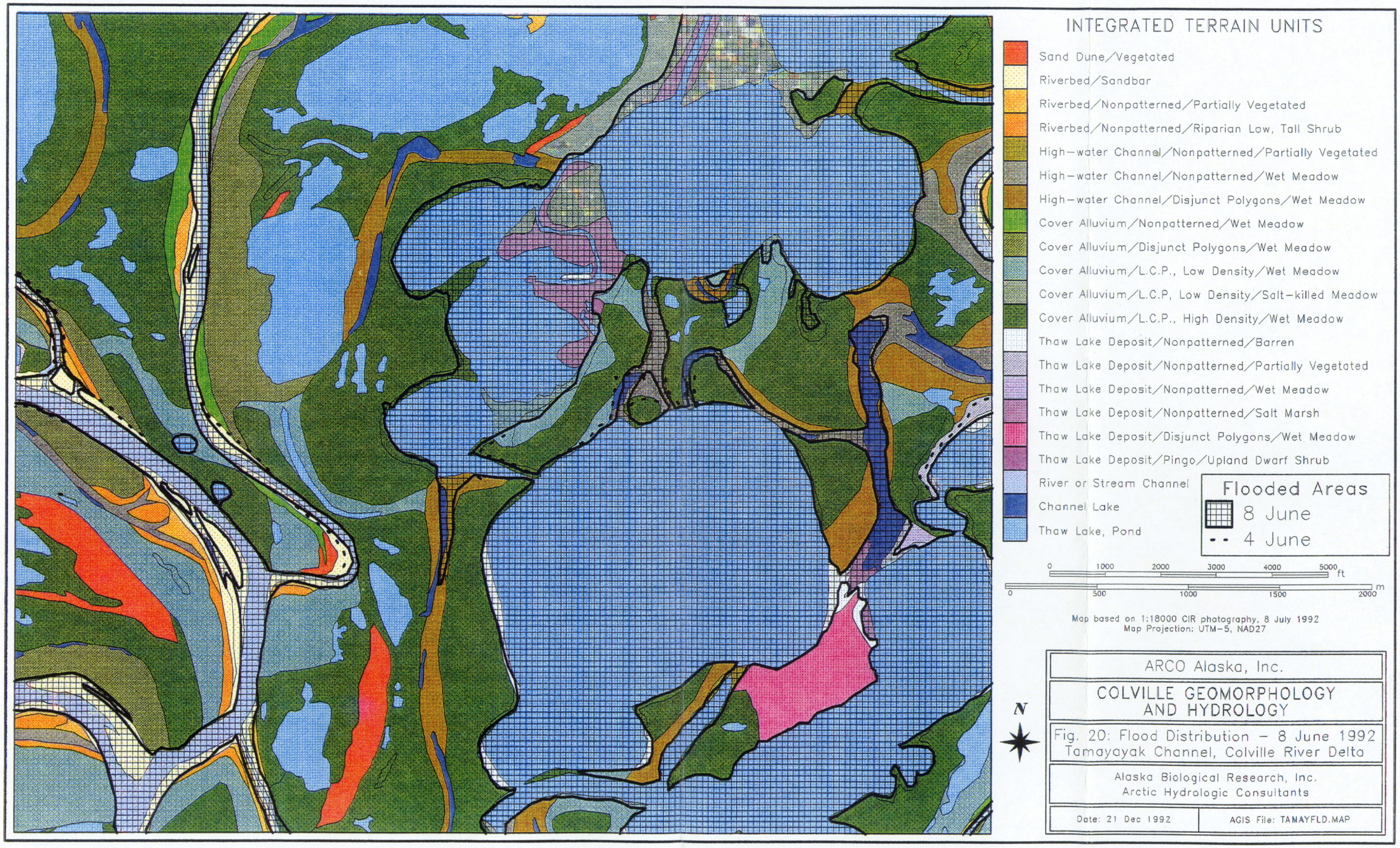
As might be expected, a flood of this magnitude covered only barren, partially vegetated, and salt marsh units on riverbed-sandbars, tidal flats, and thaw-lake deposits (Figure 22). Moderate to low amounts of flooding occurred in areas with riparian shrubs and salt-killed meadows that covered a wide range of landform deposits. Almost no flooding occurred on cover alluvium deposits supporting wet meadows. The negligible flooding (<1%) that was measured in some of these deposits may be due to mapping error.

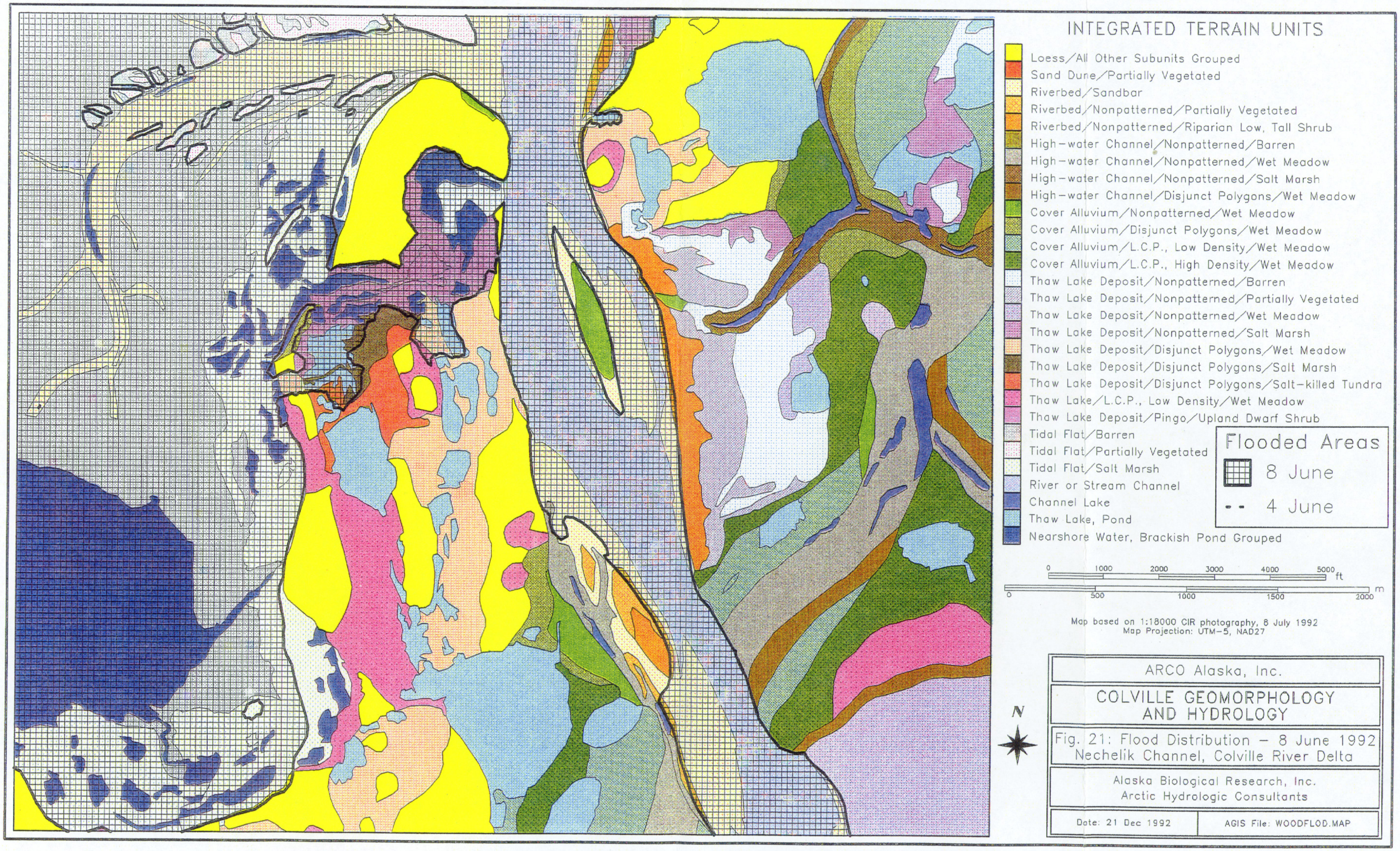
The main areas that were flooded on 4 June were river sandbar/partially vegetated units, although in a couple of small areas there was additional flooding on

[6] It should be noted that the flood peak frequency relationship is very tenuous and therefore, should be refined prior to final design.



INTEGRATED TERRAIN UNITS
Loess/Other Units Grouped
Sand Dune/Partially Vegetated
Sand Dune/Vegetated
Riverbed/Sandbar
Riverbed/Nonpatterned/Partially Vegetated
Riverbed/Nonpatterned/Riparian Low, Tall Shrub
High-water Channel/Nonpatterned/Partially Vegetated
High-water Channel/Nonpatterned/Wet Meadow
High-water Channel/Disjunct Polygons/Wet Meadow
Cover Alluvium/Nonpatterned/Wet Meadow
Cover Alluvium/Disjunct Polygons/Wet Meadow
Cover Alluvium/L.C.P. Low Density/Wet Meadow
Cover Alluvium/L.C.P., High Density/Wet Meadow
Thaw Lake Deposit/Nonpatterned/Barren
Thaw Lake Deposit/Disjunct Polygons/Wet Meadow
River or Stream Channel
Channel Lake
Thaw Lake, Pond
Flooded Areas
8 June
4 June
0 1000 2000 3000 4000 5000 ft
0 500 1000 1500 2000 m
Map based on 1:18000 CIR photography, 8 July 1992
Map Projection: UTM-5, NAD27
N
ARCO Alaska, Inc.
COLVILLE GEOMORPHOLOGY
AND HYDROLOGY
Fig. 19: Flood Distribution – 8 June 1992
Kupigruak Channel, Colville River Delta
Alaska Biological Research, Inc.
Arctic Hydrologic Consultants
Date: 21 Dec 1992
AGIS File: EASTFLOO.MAP


INTEGRATED TERRAIN UNITS
Sand Dune/Vegetated
Riverbed/Sandbar
Riverbed/Nonpatterned/Partially Vegetated
Riverbed/Nonpatterned/Riparian Low, Tall Shrub
High-water Channel/Nonpatterned/Partially Vegetated
High-water Channel/Nonpatterned/Wet Meadow
High-water Channel/Disjunct Polygons/Wet Meadow
Cover Alluvium/Nonpatterned/Wet Meadow
Cover Alluvium/Disjunct Polygons/Wet Meadow
Cover Alluvium/L.C.P., Low Density/Wet Meadow
Cover Alluvium/L.C.P, Low Density/Salt-killed Meadow
Cover Alluvium/L.C.P., High Density/Wet Meadow
Thaw Lake Deposit/Nonpatterned/Barren
Thaw Lake Deposit/Nonpatterned/Partially Vegetated
Thaw Lake Deposit/Nonpatterned/Wet Meadow
Thaw Lake Deposit/Nonpatterned/Salt Marsh
Thaw Lake Deposit/Disjunct Polygons/Wet Meadow
Thaw Lake Deposit/Pingo/Upland Dwarf Shrub
River or Stream Channel
Channel Lake
Thaw Lake, Pond
Flooded Areas
8 June
4 June
0
1000
2000
3000
4000
5000
ft
0
500
1000
1500
2000
m
Map based on 1:18000 CIR photography, 8 July 1992
Map Projection: UTM-5, NAD27
N
ARCO Alaska, Inc.
COLVILLE GEOMORPHOLOGY
AND HYDROLOGY
Fig. 20: Flood Distribution - 8 June 1992
Tamayayak Channel, Colville River Delta
Alaska Biological Research, Inc.
Arctic Hydrologic Consultants
Date: 21 Dec 1992
AGIS File: TAMAYFLD.MAP


INTEGRATED TERRAIN UNITS
Loess/All Other Subunits Grouped
Sand Dune/Partially Vegetated
Riverbed/Sandbar
Riverbed/Nonpatterned/Partially Vegetated
Riverbed/Nonpatterned/Riparian Low, Tall Shrub
High-water Channel/Nonpatterned/Barren
High-water Channel/Nonpatterned/Wet Meadow
High-water Channel/Nonpatterned/Salt Marsh
High-water Channel/Disjunct Polygons/Wet Meadow
Cover Alluvium/Nonpatterned/Wet Meadow
Cover Alluvium/Disjunct Polygons/Wet Meadow
Cover Alluvium/L.C.P., Low Density/Wet Meadow
Cover Alluvium/L.C.P., High Density/Wet Meadow
Thaw Lake Deposit/Nonpatterned/Barren
Thaw Lake Deposit/Nonpatterned/Partially Vegetated
Thaw Lake Deposit/Nonpatterned/Wet Meadow
Thaw Lake Deposit/Nonpatterned/Salt Marsh
Thaw Lake Deposit/Disjunct Polygons/Wet Meadow
Thaw Lake Deposit/Disjunct Polygons/Salt Marsh
Thaw Lake Deposit/Disjunct Polygons/Salt-killed Tundra
Thaw Lake/L.C.P., Low Density/Wet Meadow
Thaw Lake Deposit/Pingo/Upland Dwarf Shrub
Tidal Flat/Barren
Tidal Flat/Partially Vegetated
Tidal Flat/Salt Marsh
River or Stream Channel
Channel Lake
Thaw Lake, Pond
Nearshore Water, Brackish Pond Grouped
Flooded Areas
8 June
4 June
0 1000 2000 3000 4000 5000 ft
0 500 1000 1500 2000 m
Map based on 1:18000 CIR photography, 8 July 1992
Map Projection: UTM-5, NAD27
N
ARCO Alaska, Inc.
COLVILLE GEOMORPHOLOGY AND HYDROLOGY
Fig. 21: Flood Distribution – 8 June 1992
Nechelik Channel, Colville River Delta
Alaska Biological Research, Inc.
Arctic Hydrologic Consultants
Date: 21 Dec 1992
AGIS File: WOODFLOD.MAP

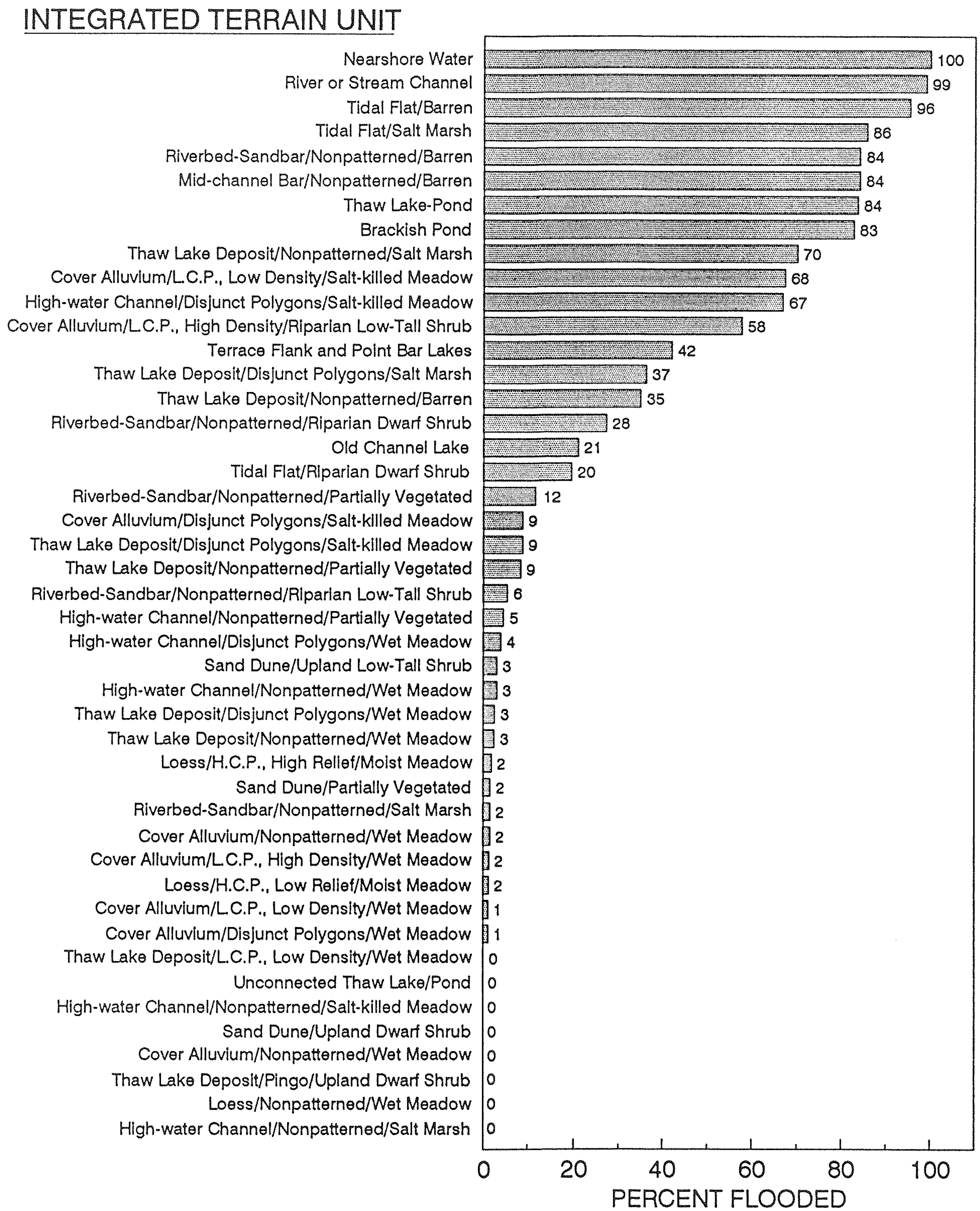


Figure 22. Percentage of each integrated terrain-unit covered by flooding in three study areas in the Colville River Delta, 1992.

high-water channel/nonpatterned/wet meadow units. On this date, disharge at the head of the delta was estimated at 118,000 cfs.

FLOOD DISTRIBUTION MODEL

Three factors were used to relate ITUs to flooding frequency: elevations, observations of percentage of ITUs flooded in 1992, and analyses of soil stratigraphy. Although the period of record is minimal for developing flooding frequency relationships, the model is based on quantitative methods and therefore can be improved as more data are acquired.

The elevation data indicate than mean elevations of the highest floodplain steps (cover alluvium/low-centered polygons, high- and low-density) decrease gradually from 17.8 ft at the head of the delta to 6.1 ft at the coast (Fig. 23). The anomalous elevation at cross section 4 probably occurred because we did not extend the transect to the highest floodplain step in the area. Similarly, mean elevations of barren riverbed-sandbars decreased from 6.3 ft to 0.6 ft in a seaward direction.

Because of differences in mean elevations and amplitudes at flood stage from the head to the fringe of the delta, the elevations were normalized to relative elevations for each cross section. This calculation of relative elevations provides the principal data for examining the correlation between flooding frequency and ITUs (Fig. 24). A comparison of mean relative elevations among ITUs shows that there is a continuum in elevations from the lowest units (riverbed-sandbar/barren) to the highest floodplain steps (cover alluvium\low-centered polygons, high density) and an analysis of variance found that many of these units were significantly different ($P < 0.05$) from each other (Appendix Fig. B-8).

Based on these elevational differences and the results of flood distribution in 1992, we grouped the ITUs into a limited number of flood units (Table 6). Distribution of the flood units is presented in Figures 25 and 26. In 1992, the amount of flooding in flood units 1-5 was 84%, 30%, 2%, 1%, and 2%, respectively.

The greatest uncertainty in the model, however, is assigning a flood frequency the flood unit 4, the highest floodplain steps. Historical observations and measurements we made of the highest driftlines we could find suggest that flooding of unit 4 is infrequent, but can occur at some locations in the lower delta. According to Jim Helmericks, who lives near the mouth of the East Channel, the highest flood that he has observed in 35 years occurred about 1989. During this flood, the water surface at peak stage was about 1.5 ft above the western end of his runway. Based on elevations we measured at that spot, the water level was 5.4 ft above sea level (2 August 1992). The western end of the runway was within a cover alluvium/low-centered polygon, low density/wet meadow ITU (flood unit 4) and therefore indicates that this unit is flooded by high events (at least in some locations).

Similarly, a relatively high driftline was noted along all of the cross sections surveyed in the lower delta (Figs. 3-6). Along the minor cross sections on the Tamayayak and Nechelik channels (not presented graphically), the relative heights of the driftlines ranged from 86% to 96% of the highest floodplain step. In most cases the driftlines were laying on top of the vegetation (slight mortality of underlying mosses) and were estimated to be 3-5 y old. It is possible that the driftlines were related to the event observed by J. Helmericks. At two cross sections there was an additional driftline in close proximity that was estimated to be 15-30 y old due to growth of mosses over portions of the wood. These observations suggest that infrequently floods can overtop or get very close to overtopping the highest floodplain steps in the lower delta. In the upper delta, the flood-peak frequency analysis indicates that flooding of the highest floodplain steps may occur as frequently as 3.3 to 6.7 y.

Although the correlation model is preliminary and is based on a small data set, it shows good potential for predicting flood distribution across the delta. The model can be improved by collecting a more representative sample of the elevations of each terrain unit, by gathering a longer-term record of flood distribution in the spring, and by collecting a longer-term record of peak discharge at the head of the delta. The model already provides a reasonable grouping of terrain units into flood units with similar elevations and flood frequency. The opportunity to observe a major flood event would greatly improve the reliability of the model.

STORM SURGES

The magnitude and frequency of storm surges along the coast of Alaska have been studied by Reimnitz and Maurer (1978, 1979) and Wise et al. (1981). Much of the following discussion is summarized from those publications.

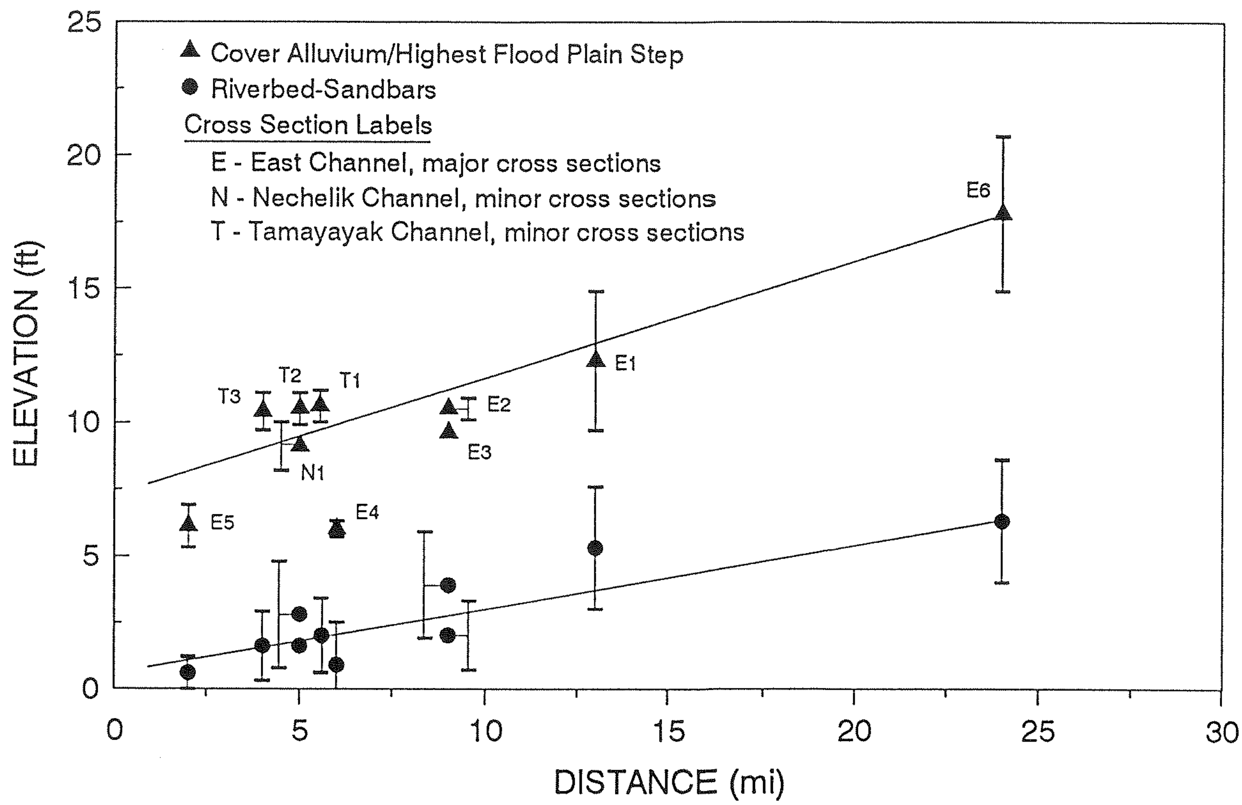


Figure 23. Mean elevations (standard deviation) of highest floodplain steps and barren riverbed relative to distance from the fringe of the delta. Slope is hand fit.

Two important factors associated with the occurrence of storm surges are the hydrographic features of an area and the meteorological characteristics of the storms. Hydrographic features include a gently sloping sea floor near the shore and sufficient open water that results in a long fetch. Flooding requires terrain with a low relief near the shore, which is characteristic of almost all of the arctic coast. From late fall through spring and for most of the summer, sea ice (as shorefast ice, pack ice, or both) covers the entire Arctic Ocean. Because coverage of ice >12% dampens the buildup of waves and surge, damaging storms are limited to the late summer and fall (August-October). Of the 25 examples of flooding discussed by Wise et al. (1981), 16 (64%) occurred in the fall. There have been no recorded spring occurrences of storm surge flooding, and all six summer surges occurred in late summer (August). There have been two recorded instances of cracking and flooding of the ice in mid-winter. The storm most likely to develop a surge is one that moves from west to east and far offshore.

The frequency of major storm surges along the northern coast of Alaska is low, but several major surges have been recorded within the last century (Reimnitz and Maurer 1978, 1979). The two worst recorded cases of flooding occurred in October 1963 and September 1970. The 1963 storm had a surge of 12 feet in Barrow, with lesser surges from Point Lay to Barter Island. The 1970 storm was judged to be as high as any previous storm, based on driftwood lines and eyewitness accounts (Reimnitz and Maurer 1978, 1979). The storm reached its peak with gale-force winds reaching 50 mph and gusting to 120 mph at the DEW-line site at Oliktok Point. The surge height was 9 ft, and deep water waves were as high as 34 ft. Flooding was considerable for settlements at the Colville Delta and Oliktok Point. Saltwater inundation killed tundra vegetation and contaminated freshwater ponds and lakes almost 5 km upriver from the Colville Delta.

The elevation of the highest driftwood line from the 1970 storm ranged from 4.5 to 11.2 feet above sea level, based on measurements taken in August 1977

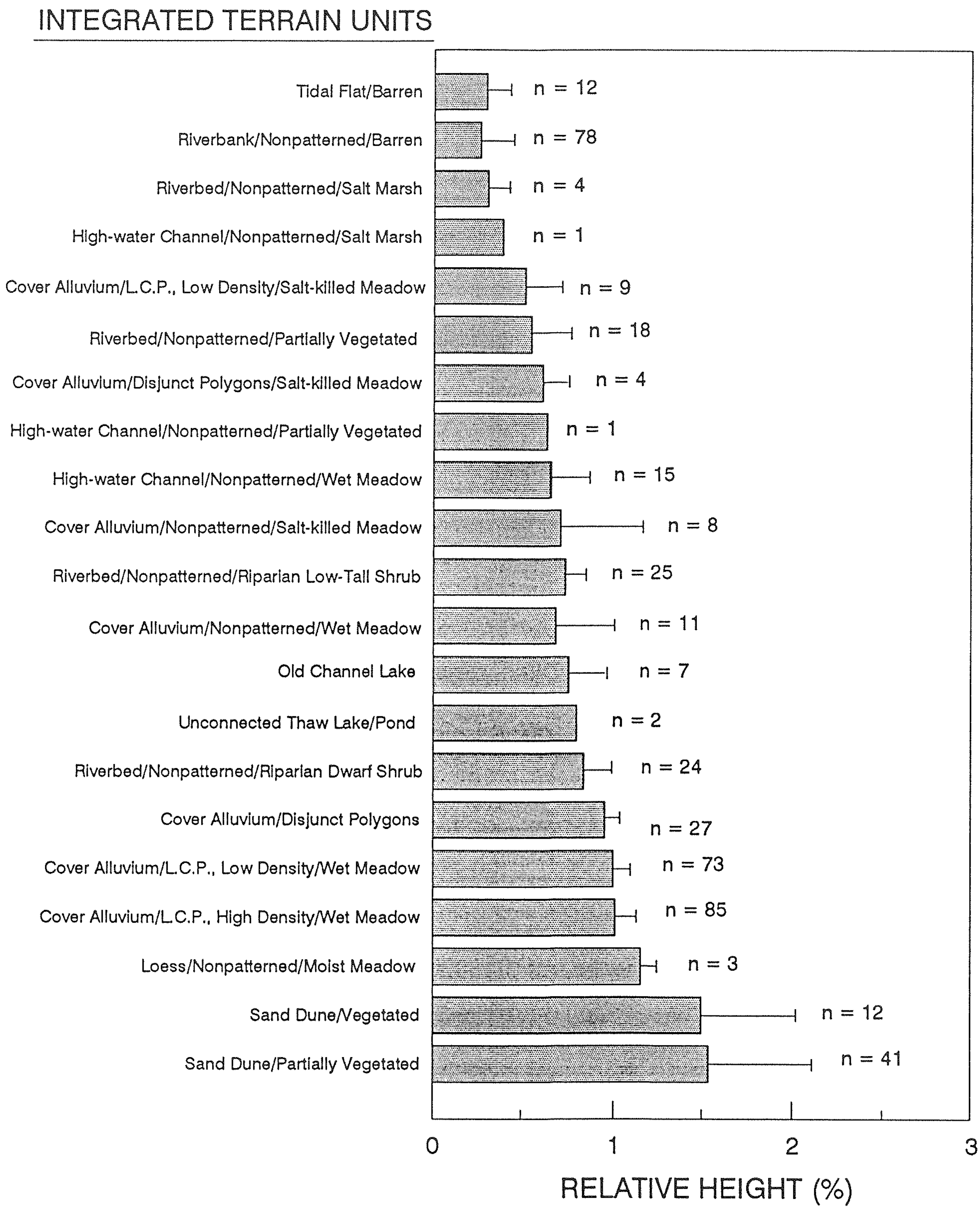


Figure 24. Heights (%) of integrated terrain units relative to the highest floodplain steps occurring along the cross sectional profiles, Colville River Delta, 1992.

Table 6. Grouping of ITUs into flood units that have similar flooding frequencies, Colville River Delta.

Flooding Unit	Integrated Terrain Units	Description
1 High Frequency	90, 93, 96, 97, 98 5000, 6000, 6010, 6061 7010, 7052, 7061 10000, 10010, 10061, 12000, 12010	This unit consists of riverbed-sandbars, high-water channels, and tidal flats that are barren or partially vegetated. Sediment deposition and scouring occur so frequently that little vegetation can become established. The frequency of flooding is estimated to be about once in 2 y.
2 Moderate-High Frequency	92 6051, 6052 7051, 7062, 7162 8062, 8162, 8262, 8362 10161, 10162, 12052	This unit consists of riverbed-sandbars, high-water channels, and floodplain steps that support riparian willows or has been killed by saltwater inundation. The willows grow on areas where occasional flooding provides sediment and nutrients that support productive growth. The amount of sediment deposited is low, allowing development of a thin organic layer. On higher floodplain steps, the riparian willows occur only as a narrow band along the channel. The frequency of flooding is estimated to be on the order of once in 3 to 5 y.
3 Moderate	95, 7031, 7032, 7131, 7132 8031, 8032, 8131, 8132 8251, 8351 10031, 10131, 10231	This unit consists of high-water channels, lower floodplain steps with cover alluvium, and thaw lake deposits that support wet and moist meadow vegetation. The unit's lack of polygonal development indicates that the surfaces are relatively young. A thin-moderate organic layer indicates the unit has been stable for hundreds of years. Included in this unit are areas with riparian, low-tall shrubs along the margins of higher floodplain steps that indicate bankfull flooding. The frequency of flooding is estimated to be on the order of once in 5 to 10 y.
4 Low Frequency	8231, 8232, 8331, 8332	These highest floodplain steps consist of cover alluvium and support wet and moist meadow vegetation. The low-high density of low-centered polygons indicate ice-rich sediments thousands of years old. Thick organic horizons indicate that the surfaces have been stable for a long period. There is little information to assess the flood frequency of this unit. The frequency of flooding is estimated to be on the order of once in 10 y.
5 Very Low Frequency	1000, 2010, 2080 10756	This unit consists of non-fluvial landforms and includes loess caps over ancient alluvial terraces, sand dunes, and pingos in drained-lake basins. There is no evidence to indicate that this unit floods except along the margins, such as at the base of a sand dune or terrace.

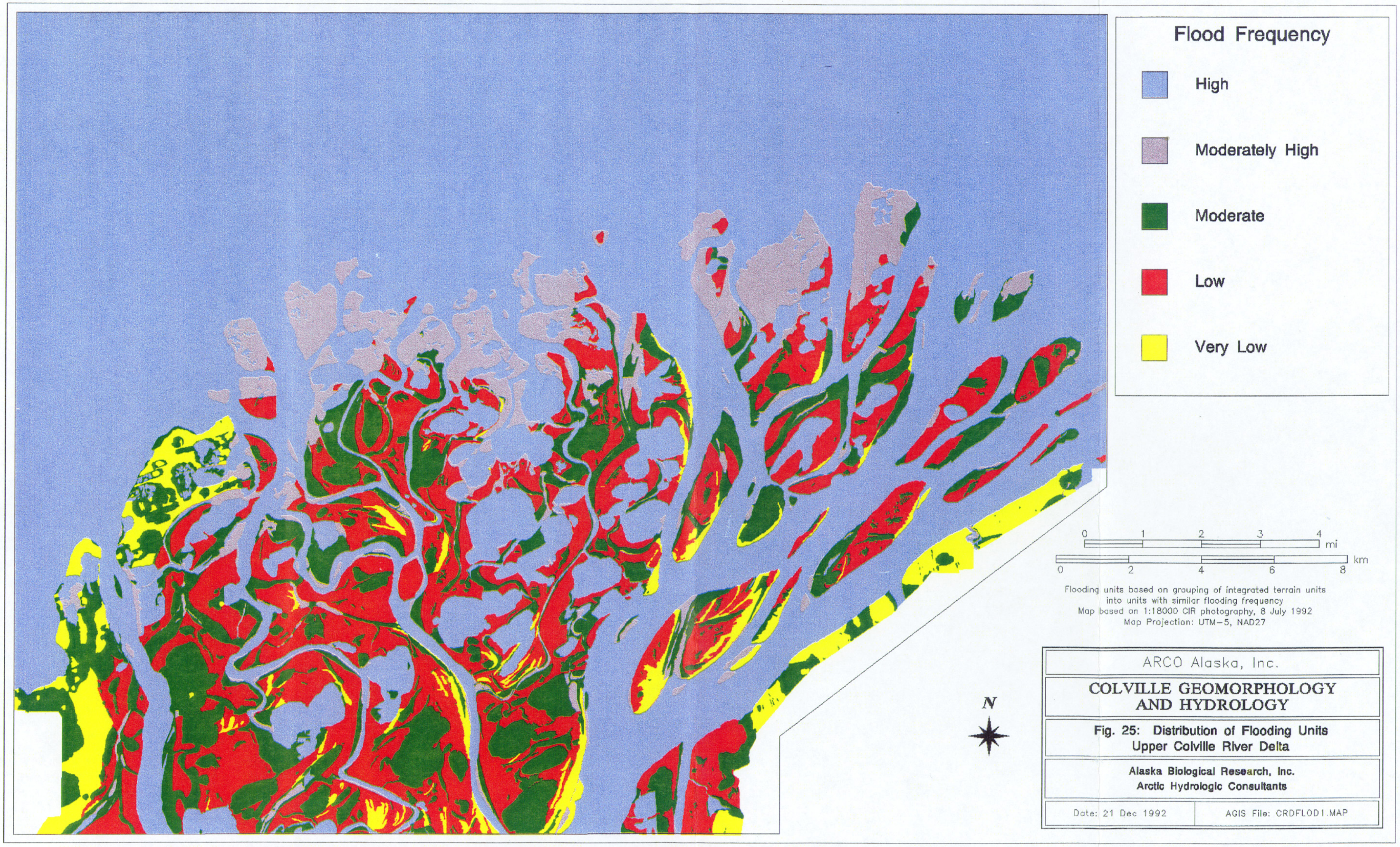
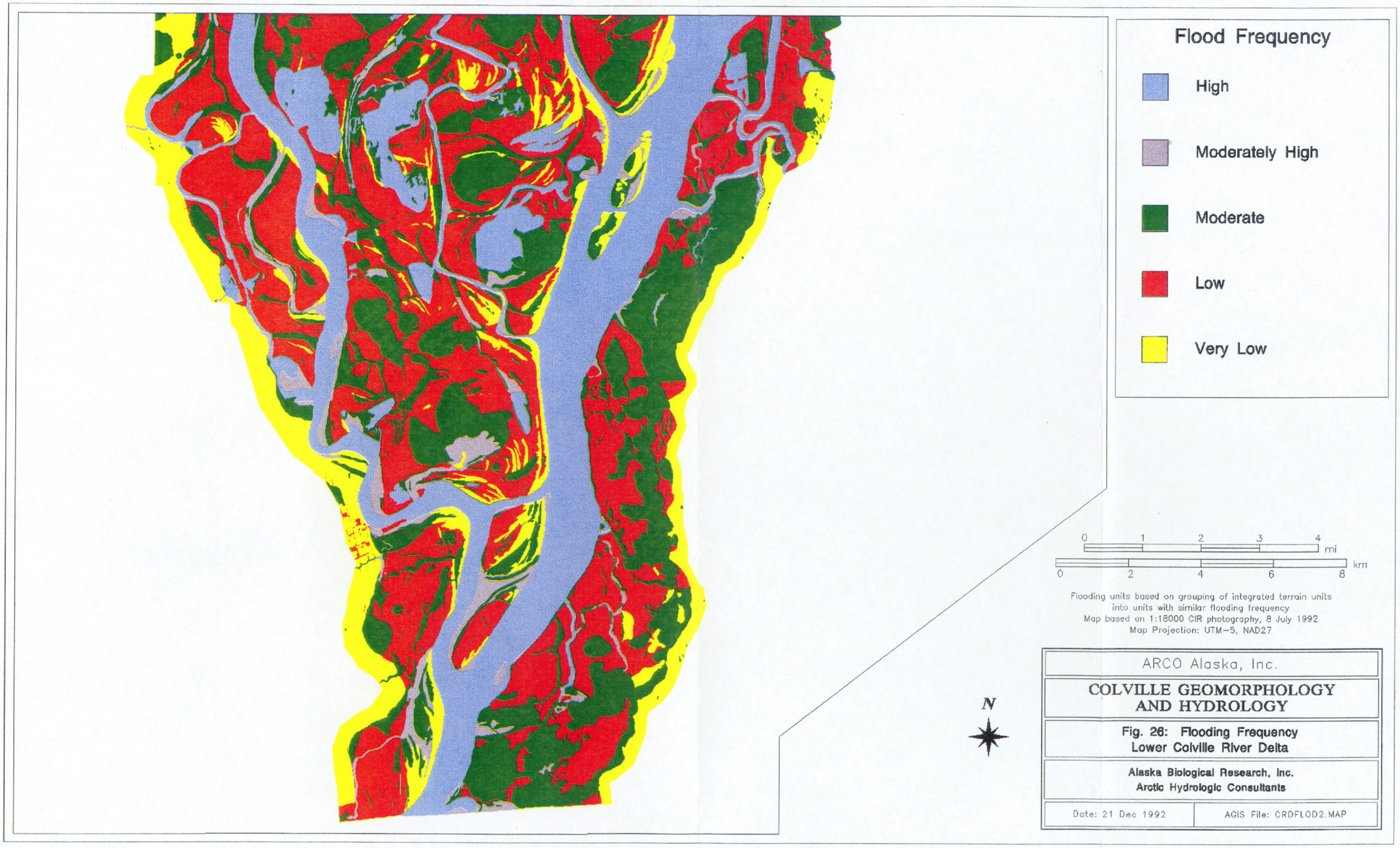


Fig. 25: Distribution of Flooding Units
Upper Colville River Delta


Flood Frequency
High
Moderately High
Moderate
Low
Very Low
0 1 2 3 4 mi
0 2 4 6 8 km
Flooding units based on grouping of integrated terrain units
into units with similar flooding frequency
Map based on 1:18000 CIR photography, 8 July 1992
Map Projection: UTM-5, NAD27
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AND HYDROLOGY
Fig. 26: Flooding Frequency
Lower Colville River Delta
Alaska Biological Research, Inc.
Arctic Hydrologic Consultants
Date: 21 Dec 1992
AGIS File: CRDFLOD2.MAP

(Reimnitz and Maurer 1978). The variation of height is partially due to differences in exposure of the shoreline. Because the onshore winds during the storm were from the west, eastern shores of stream mouths and shallow embayments had higher surges than did western shores. Older driftwood lines were investigated, but none were determined to be higher than the 1970 storm surge.

Estimates of the frequency of occurrence associated with specific surge heights along the arctic coast within Sector 1 are presented in Figure 27. The curve was derived from selected wind direction frequencies from Barter Island (west through northwest) during the months of greatest surge frequencies (August, September, and October; Wise et al. 1981). Based on the curve, the height of the 100-y storm surge is approximately 10.7 ft, and that of the 50-y storm surge is approximately 9.1 ft.

During the field investigations conducted in 1992, we interviewed Jim Helmericks about his experience with storm surges at his homestead situated on an island in the East Channel near the mouth of the Colville River. Mr. Helmericks stated that the largest storm surge event he had experienced occurred in 1970 and that it affected the salinity of ponds nearby.

During our field work, we observed two distinct and continuous driftwood lines along the west-facing shoreline at the mouth of the Nechilik Channel on the CRD. Our boat driver (Jobe Wood) attributed the drift lines to the 1963 storm (without distinguishing between the two different lines); however, we believe that these drift lines resulted from the 1963 and 1970 storms based on the differences in the amount of vegetation overgrowing the driftwood and differences in the types of human debris mixed in with the drift. Elevations of these drift lines relative to a one-time measurement at sea level (19 July 1992) were 5.0 ft and 6.6 ft for 1963 and 1970, respectively; one isolated piece of wood was found at 7.6 ft.

Saltwater inundation caused by the storm events have been observed to kill tundra vegetation (Jorgenson et al. 1989). We used the distribution of salt-killed tundra to delineate areas that may have been inundated by the storm surges (Fig. 28). However, mixing of saline water during spring flooding also may cause damage to the tundra. Regardless, areas of salt-killed tundra are areas of concern when planning facility locations.

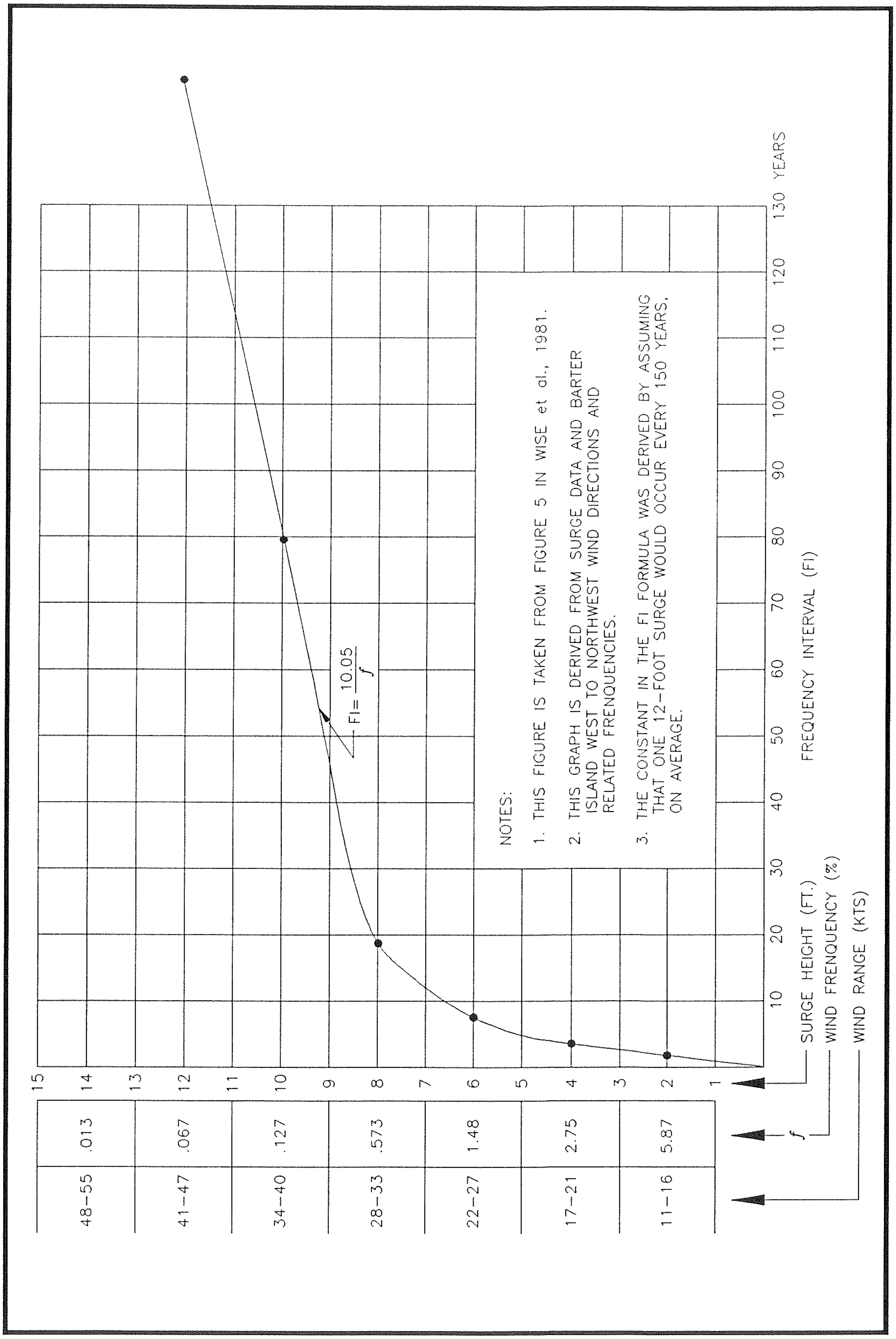


Figure 27. Frequency interval versus storm surge height (adapted from Wise et al. 1981).

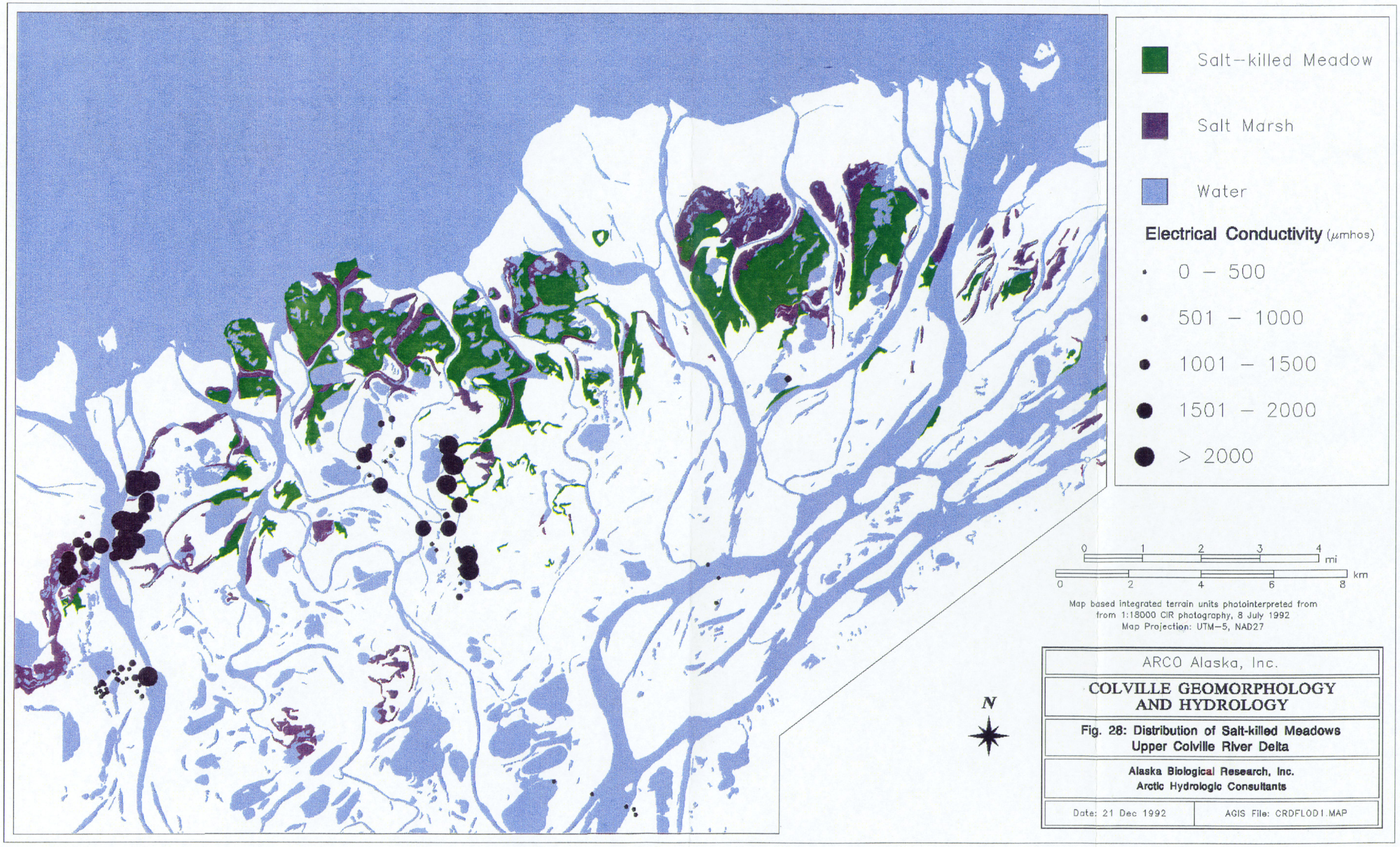


Fig. 28: Distribution of Salt-killed Meadows Upper Colville River Delta

PART IV. LANDSCAPE CHANGE

BACKGROUND

A substantial amount of information about rates of geomorphic change has been collected for areas along the Beaufort Sea coast and has focused on migration of barrier islands, and rates of coastal and riverbank erosion. Knowledge of the rates of erosional and depositional processes is essential for planning the location of facilities.

Rates of coastal retreat along the Beaufort Sea, some of which are so rapid that they pose a serious hazard to man-made structures, have been summarized by Hopkins and Hartz (1978). Coastal retreat along the mainland coast between Demarcation Point and the Colville River averages 5.3 ft/y, although storm-driven episodes may be much higher. At Oliktok Point, for example, 36 ft of shoreline was lost within a 2-wk period. Average rates of retreat are highest from Harrison Bay westward to Barrow (15.5 ft/yr), primarily because coarse sediment is absent from the low bluffs along this stretch of coastline (Lewellen 1977).

Rates of erosion along riverbanks and lake shorelines also can be rapid, although they often are less dramatic. At two sites along the Nechelik Channel, Walker (1966, 1983) measured erosion rates of just over 3 ft/y and 6 ft/y over a 23-30 y period. However, averaging rates over a long period masks the episodic nature of erosion. Walker and Morgan (1964) observed a maximal undercutting of 25-30 ft from a single storm in 1961. He also observed that erosion was greater along the eastern banks in the East Channel because southwesterly winds are most common during summer storms. The East Channel is sufficiently wide for sizable waves to develop, and wind erosion has been observed to be an important factor.

Although these previous studies provide valuable reference, they are of insufficient detail for facility planning and engineering design on the CRD. Erosion rates, which are affected by characteristics of riverbanks, fetch, orientation of the wind and channels, and currents, are site specific. Thus, detailed information in potential areas of development is essential.

METHODS

To analyze the rates of landscape change within the CRD, integrated terrain unit maps were developed using aerial photography from 1955 and 1992 for three pilot-scale areas (approximately 3 x 3 mi). The Kupigruak Study Area, within the East Channel, represents a higher energy environment than the other two sites; the Tamayayak Study Area represents a low-energy environment dominated by thaw lakes; and the Nechilik Study Area represents an environment that is dominated by tidal influence. The maps were based on CIR photographs (1:18,000 scale) taken in 1992 and black-and-white photographs (1:50,000 scale) taken in 1955. Mapping was done on acetate overlays on the photography and rectified to digital files of USGS 1:63,360 scale quadrangles. Analysis of the positional accuracy of the control points used to register the 1955 photography revealed a root mean square error (RMS) of 61, 64, and 65 ft for the three study areas.

To improve the registration of the 1992 photography to the 1955 photography, better control points were established on the two photo bases (60-100/study area) by identifying well-defined geographic features (usually intersections of polygon rims). The lines on the 1992 photos were transferred manually to the 1955 base with an adjustable opaque projector and then matched with the high density of control points. Next, the 1955 and 1992 maps (with a common base) were digitized and the amount of overlap between the years was analyzed with the GIS. The various combinations of features created by the overlay were recoded into six classes that reflect depositional or erosional processes.

The accuracy of our ability to measure change given the errors inherent in photointerpretation, boundary delineation on the acetae overlays, registration, and digitizing, was assessed to qualify the accuracy of the changes that were measured by the analysis. The distances to feature boundaries, relative to the nearest control point, was measured on both the 1955 and 1992 photos with a magnifying reticle scale to the nearest 0.005 in. The photographic distances were converted to ground distances based on the scale of the photography. The distance the boundaries changed on the photographs was then compared to the distance measured for the corresponding area on the landscape change maps (1:20,000 scale). The RMS error (67% of the points less than the value) was calculated at 60 points by computing the difference the amount of change measured by the two methods. The RMS error was 66 ft (mean = 37 ft, SD = 28 ft) and represents 0.03 inch (about the width of a fine line) on the 1:25,000 scale enlargements of the 1955 photography that were used for the base map.

RESULTS AND DISCUSSION

The analysis of landscape change in the three study areas from 1955 to 1992, a 37-y period, revealed that higher floodplain steps (landforms other than riverbed alluvium, thaw lake deposits, and tidal flats) were, for the most part, stable; only 2.2 to 2.9% of their areas had eroded (Figs. 29-31). In contrast, the riverbed was more active; the area of sandbars that had eroded ranged from 0.4% in the Nechelik Channel to 5.4% in the East Channel.

The greatest rates of erosion of the higher floodplain steps (landforms other than riverbed) in the Kupigruak Study Area occurred at the upstream, unprotected ends of narrow islands, where maximal rates of 230-530 ft (7-14 ft/y) were measured. Along the sides of island and along cutbanks in meandering channels, maximal erosion rates of 130-230 ft (3-6 ft/y) occurred. Maximal erosion rates were similar along the shorelines of large thaw lakes in the Tamayayak Study Area, where maximal rates were as high as 230 ft (6 ft/y). However, erosion along most of the shoreline was much lower. Changes in the tidal flats in the Nechelik Study Area were marked by expansion of the tidal flats (up to 825 ft, 22 ft/y), particularly at the mouth of channels emptying into the open sea.

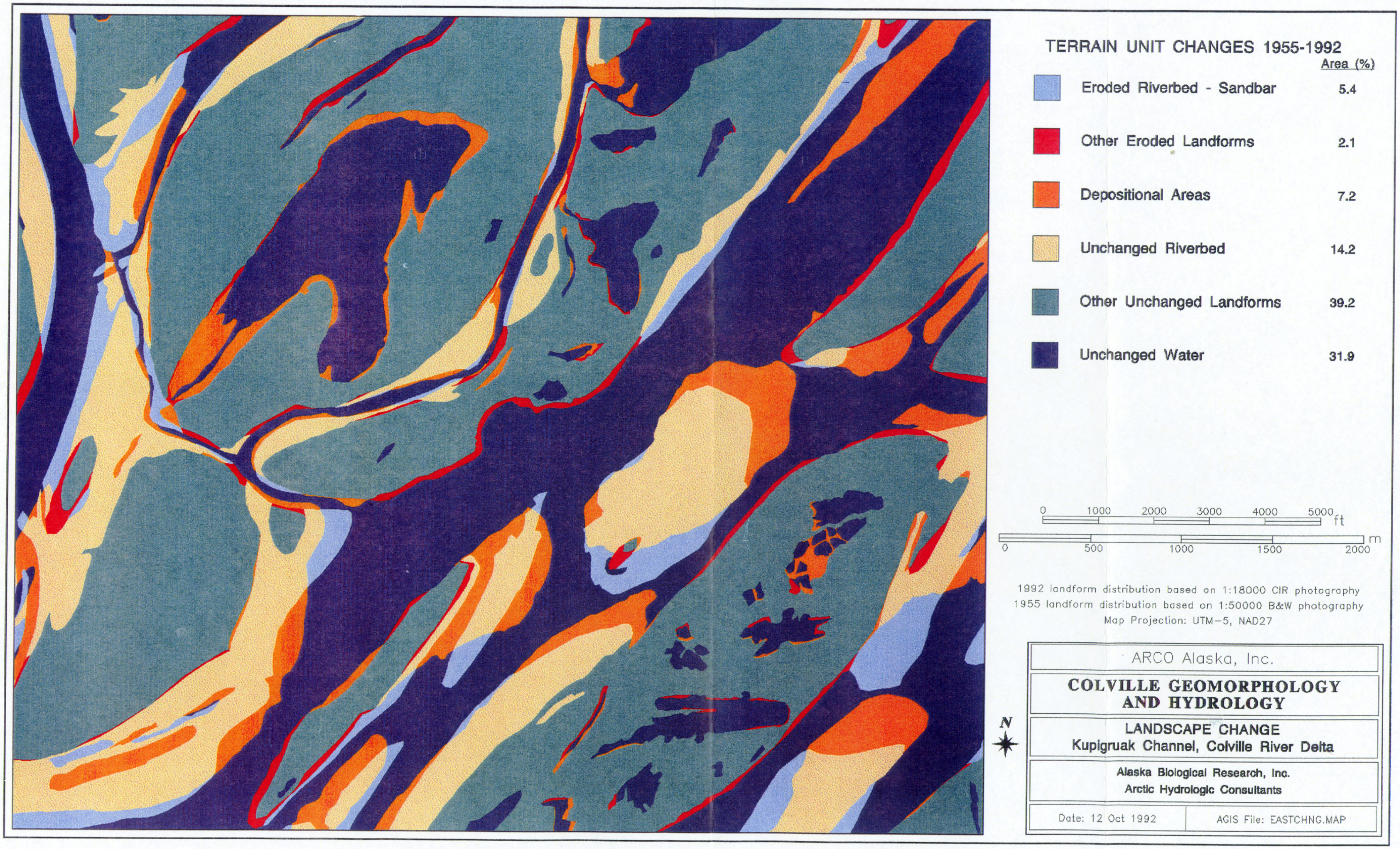
In comparison to the higher floodplain steps, the linear amount of erosion of riverbed materials was much higher. In the Kupigruak Study Area, mid-channel bars within the main channel migrated as much as 1300 ft downstream; material was eroded from the upstream end and deposited below the bar. Other portions of the riverbed along point bars and channel splits showed similar rates of erosion and deposition.

The erosion rates in large thaw lakes that are far removed from river currents demonstrated the importance of wind-driven waves. Thermal and mechanical erosion of ice-rich sediments by the thaw-lake process provides a central paradox regarding the stability of landforms in the delta: the oldest, highest landforms have accumulated such high contents of ice that they have become some of the most unstable areas. Indeed, the high percentage of the surface area in the Tamayayak Study Area (presumably one of the oldest portions of the delta) that is occupied by thaw lakes, indicates how rapidly these ice-rich landforms are changing.

One problem inherent with this approach is the effect of differences in water levels between years when we were delineating water bodies. This problem is illustrated by the numerous "slivers" of areas denoting erosion or deposition around small tundra ponds and lakes in high-water channels. Close examination of the photographs indicated that these supposed changes resulted from changes in water level rather than from erosion or deposition. Similarly, fluctuations in water in the river affect the boundaries of exposed sandbars at any time. The "slivers" around small tundra ponds that did not really change could have been removed after reexamination of each situation, but were included on the map to illustrate the limitations of the analysis.

Overall, the estimates of the rates of change of the landscape roughly agree with the estimates indicated by the radiocarbon dating. In the three study areas, an average of 2.4% of the area that eroded over 37 y consisted of the older tundra surfaces (landforms other than riverbed alluvium). At this rate (0.065%/y), the entire area would be reworked after 1538 y. Despite the variability in the data and the numerous factors that contributed to the data, that rate compares favorably with the radiocarbon dates at the bases of the highest floodplain steps (2080-2950 y).

Although the rates of change are fairly rapid in geologic terms, the data show that for engineering design large portions of the area are sufficiently stable for development. The maps can be used to locate facilities away from locations that are eroding rapidly, thereby providing a sufficient buffer zone so that facilities would not be endangered within hundreds of years.


TERRAIN UNIT CHANGES 1955-1992
Area (%)
Eroded Riverbed - Sandbar 5.4
Other Eroded Landforms 2.1
Depositional Areas 7.2
Unchanged Riverbed 14.2
Other Unchanged Landforms 39.2
Unchanged Water 31.9
0 1000 2000 3000 4000 5000 ft
0 500 1000 1500 2000 m
1992 landform distribution based on 1:18000 CIR photography
1955 landform distribution based on 1:50000 B&W photography
Map Projection: UTM-5, NAD27
N
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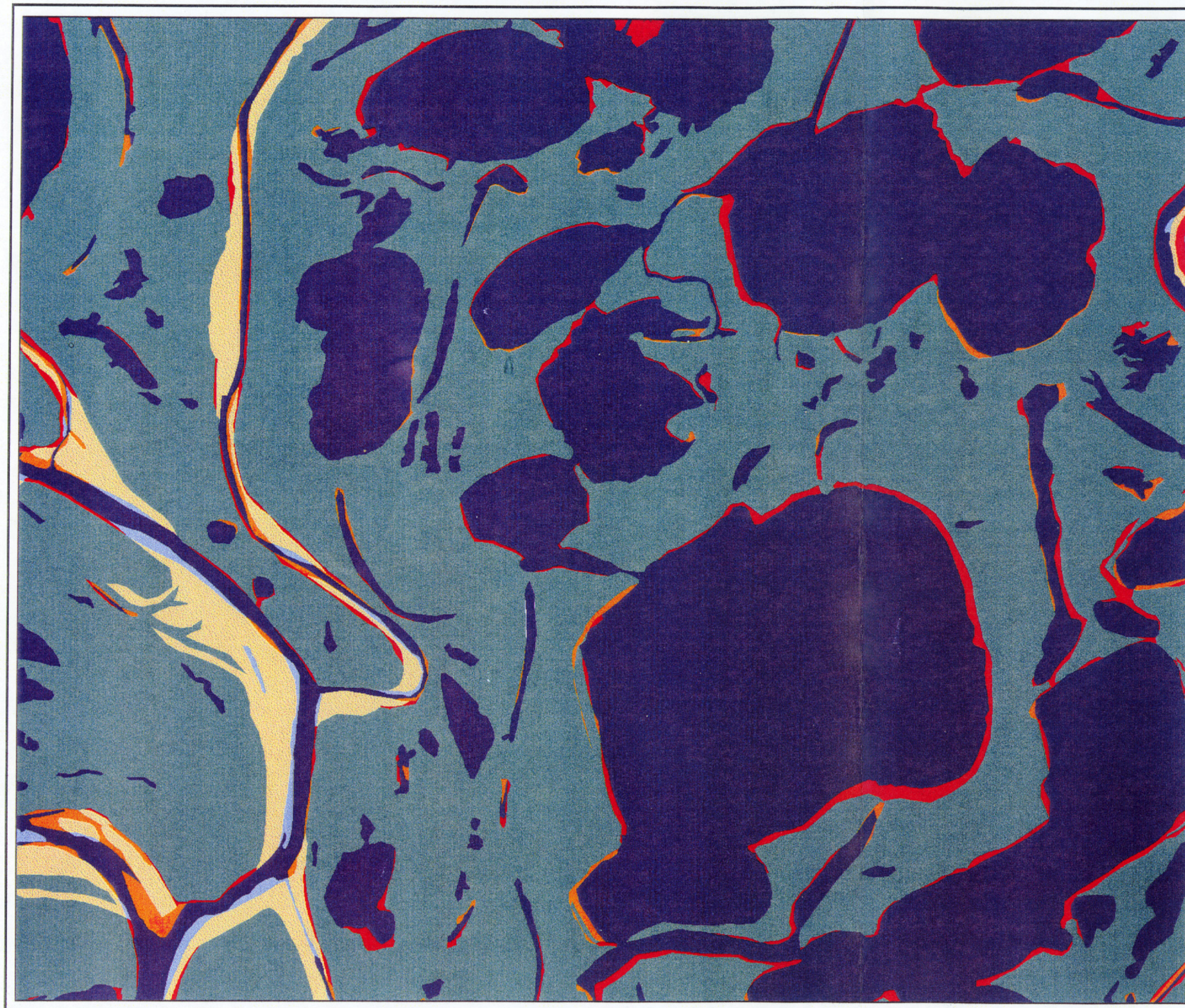
COLVILLE GEOMORPHOLOGY AND HYDROLOGY
LANDSCAPE CHANGE
Kupigruak Channel, Colville River Delta
Alaska Biological Research, Inc.
Arctic Hydrologic Consultants
Date: 12 Oct 1992
AGIS File: EASTCHNG.MAP



TERRAIN UNIT CHANGES

	Area (%)
Eroded Riverbed - Sandbars	0.4
Other Eroded Landforms	2.9
Depositional Areas	4.4
Unchanged Riverbed	3.3
Other Unchanged Landforms	54.6
Unchanged Water	37.7

0 1000 2000 3000 4000 5000 ft

0 500 1000 1500 2000 m

1992 landform distribution based on 1:18000 CIR photography
1955 landform distribution basd on 1:50000 B&W photography
Map Projection: UTM-5, NAD27

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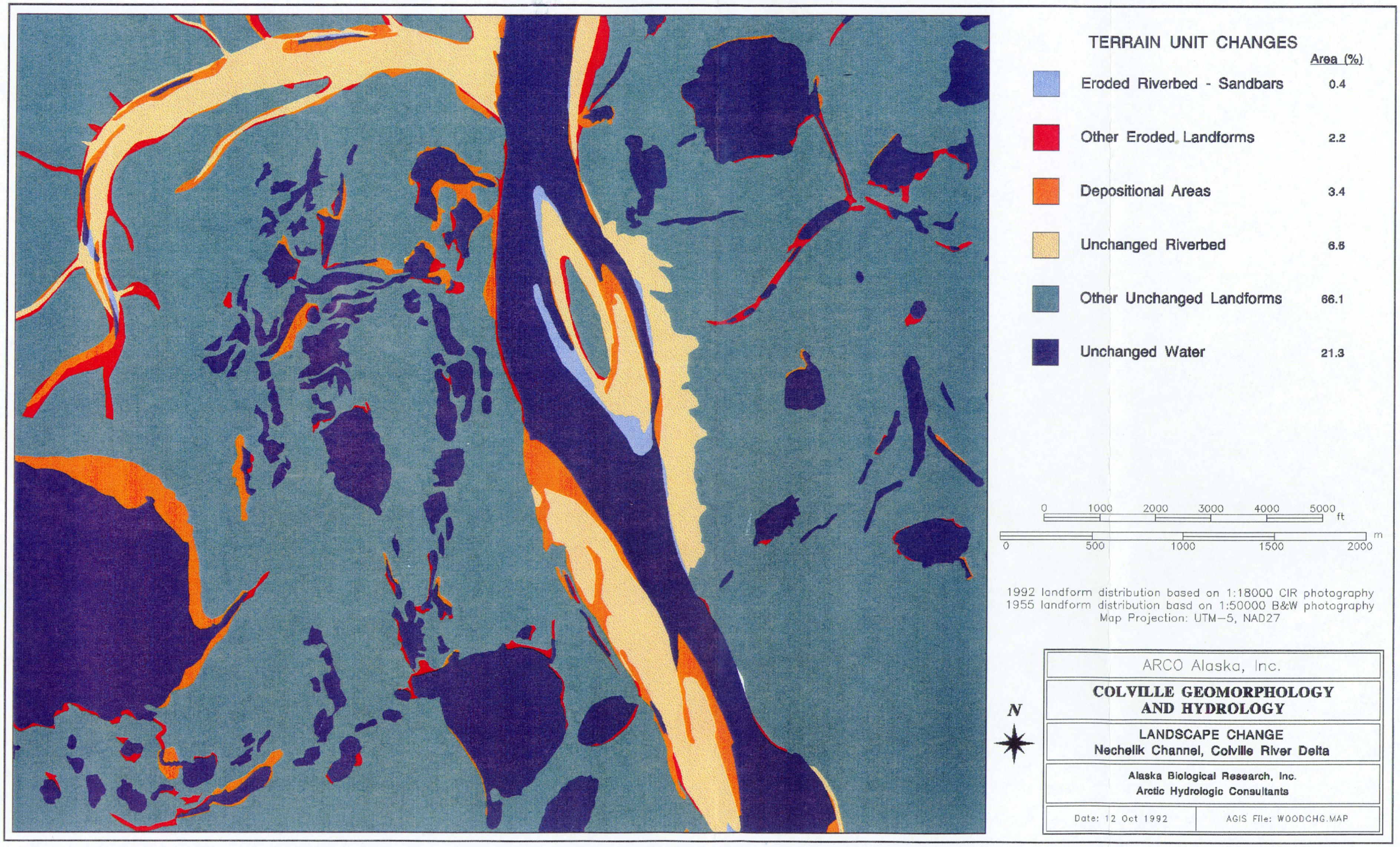
LANDSCAPE CHANGE
Tamayayak Channel, Colville River Delta

Alaska Biological Research, Inc.
Arctic Hydrologic Consultants

Date: 12 Oct 1992 | AGIS File: TAMAYCHG.MAP


TERRAIN UNIT CHANGES
Area (%)
Eroded Riverbed - Sandbars 0.4
Other Eroded Landforms 2.2
Depositional Areas 3.4
Unchanged Riverbed 6.6
Other Unchanged Landforms 66.1
Unchanged Water 21.3
0 1000 2000 3000 4000 5000 ft
0 500 1000 1500 2000 m
1992 landform distribution based on 1:18000 CIR photography
1955 landform distribution basd on 1:50000 B&W photography
Map Projection: UTM-5, NAD27
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ARCO Alaska, Inc.
COLVILLE GEOMORPHOLOGY AND HYDROLOGY
LANDSCAPE CHANGE
Nechelik Channel, Colville River Delta
Alaska Biological Research, Inc.
Arctic Hydrologic Consultants
Date: 12 Oct 1992
AGIS File: WOODCHG.MAP

SUMMARY AND CONCLUSIONS

The complex geomorphic and hydrologic processes on the Colville River Delta provide a challenging environment in which to explore for and develop oil resources. However, through systematic characterization of the physical landscape and analysis of the dynamics of the flooding regime and terrain stability, the information essential for engineering design can be acquired. This report presents the results from one year of field work, and therefore is limited as to how confident estimates can be for some aspects of the study, particularly the flooding regime. Despite such limitations, it forms a solid basis for continuing to acquire the kind of information required to evaluate such a dynamic environment.

The channel cross sections at six locations provide representative profiles of channels that can be used for developing the initial concepts for bridge and pipeline crossings. The cross sections show that the active floodplain is expansive but usually is flanked by high floodplain steps. In addition, permafrost is absent from the near surface of the deeper channels.

To aid in analyzing the flooding regime and landscape change, we developed a classification system that integrated landforms, surface forms, and vegetation into units that represent different erosional and depositional environments. Sixty-seven integrated terrain units (ITUs) were mapped within the delta, but were grouped into 40 classes to reduce the complexity for map presentation. Descriptions of the soil stratigraphy of many of these units showed a complex depositional environment; the highest landforms were composed of many interbedded layers of riverbed and cover alluvium, organic accumulation, eolian deposits, and marine deposits. The oldest age from one of the deepest profiles was 2950 ybp at the base of a high floodplain step in the middle of the delta.

Stage-velocity-discharge relationships were estimated for the head of the delta. In 1992, the peak discharge was estimated at 164,000 cfs. This was less than the 2-y peak discharge, which was estimated to be on the order of 250,000 cfs. Based on tenuous comparisons with other drainages on the North Slope that have longer records of discharge, the most likely estimate of the discharge during a 50-y flood is approximately 740,000 cfs.

Flood distributio in 1992 was measured in three study areas in the CRD from aerial photographs taken 5 days after peak flow. On 8 June 1990, 42% of the three study areas was inundated. Flooding was limited mainly to barren and partially-vegetated areas on sandbars, tidal flats, and thaw lake deposits. Salt-killed meadows also were flooded in most areas. Walker (1976) estimated that flood waters may extend over two-thirds of the delta, although he did not estimate the frequency of that amount of flooding. The amount of area covered by a 100-yr flood event remains unknown, because the limited amount of data currently available are insufficient for calculating an estimate using quantitative methods.

Using these observations from 1992, measurements of elevations for each ITU collected along the channel cross sections, and analyses of soil stratigraphy, we developed a model that correlated ITUs with flood frequencies. The model then was used to recode ITUs into flooding units for predicting the occurrence of flooding across the delta. Although this preliminary model is limited by the amount of data currently available, it provides a systematic approach to predict flooding across this large and complex area. As the period of record improves, the reliability of the model will improve.

An analysis of the rates of landscape change from 1955 to 1992 showed that higher floodplain steps (landforms other than riverbed-sandbars) within the delta are fairly stable, having lost 2.1-2.9% of their surface areas. Based on these rates of erosion, we estimate that 87.3% of the area of the higher floodplain steps remains stable over a 100-yr period. However, erosion along some riverbanks and lake shorelines was fairly rapid. Erosion rates as high 14 ft/y were measured along some upstream ends of narrow islands within the main channel and as high as 6 ft/y on rapidly-eroding shorelines along thaw lakes. Identification of erosional and depositional areas can be used to avoid such areas when planning structures and facilities.

In summary, this study provides geomorphic and hydrologic information essential to the initial conceptual designs for oil exploration and development in the CRD. The channel morphology information will help in evaluating options for bridge and pipeline crossing. The hydrologic studies developed preliminary stage-velocity-discharge relationships and flood-peak frequency analyses that are needed for design of structures within the floodplain. The ITU maps provide a basis for locating areas that are the most stable and least prone to flooding. Through this systematic approach to analyzing the dynamics of the CRD, we have assembled an initial database that can be used for site specific development applications.

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APPENDIX A. Data File listing for channel morphology section.

Table A-1. Cross Section Data For Cross Section 1.

STATION (FT)	GROUND ELEV (FT)	DEPTH OF THAW (2) (FT)	TERRAIN CODE
100.0	17.5		8331
404.9	20.4		2055
664.6	18.2		8231
944.0	20.2		2055
1324.9	27.6		1231
1504.7	25.7		2055
1597.3	31.1		2055
1669.9	26.9		2010
1732.0	29.0		2010
1753.6	28.2		2010
1804.8	20.9		2010
1811.3	14.5		2010
1825.7	11.0		2010
1833.2	9.4		7031
1984.9	7.9		7010
2475.7	13.5		2010
2510.6	12.3		2010
2576.5	10.6		2010
2607.3	9.2		6000
2629.0	5.8		6000
2731.1	7.0		6000
2830.9	6.3		6000
2943.1	4.9		6000
3047.5	3.9		6000
3152.3	2.9		6000
3250.2	2.0		6000
3324.2		2	
3354.3	1.6		90
3457.7	0.5		90
3513.7	-0.5		90
3564.3	-0.1		90
3616.5	0.1		90
3667.5	-0.2		90
3713.7	-0.4		90
3766.1	-1.0		90
3803.2		3	
3813.3	-1.6		90
3842.5	-2.1		90
3876.2		3	
3876.7	-1.3		90
4041.1	-0.3		90
4102.2	0.3		90
4173.7	0.6		90
4240.5	0.6		90
4306.7	0.5		90
4370.0	0.3		90
4431.2	0.2		90
4497.6	-0.5		90
4559.1	-0.5		90
4592.2		3	
4609.2		3	
4609.7	-2.1		90
4651.8	-9.0		90
4661.7	-10.3		90
4795.2		7	
4795.7	-11.4		90
4822.2	-11.6		90
4903.9	-14.1		90
4904.2		>12	
4985.5	-20.3		90
5087.7	-19.1		90
5199.3	-15.9		90
5283.2	-14.5		90
5389.2		>16	
5407.7	-10.8		90
5498.7	-7.9		90
5598.5	-5.7		90
5692.7	-5.3		90
5798.3	-4.9		90
5888.4	-4.8		90
5982.9	-4.5		90
6091.2		>12	
6091.6	-6.6		90
6213.7	-8.1		90
6349.3	-7.1		90
6386.2		>12	
6386.7	-7.1		90
6482.9	-4.0		90
6483.2		4	
6573.2		3	
6573.6	-1.2		90
6634.4	-0.4		90
6698.0	-0.1		90
6759.5	-0.6		90
6815.2		3	
6815.7	-0.7		90
6874.3	-1.0		90
6932.4	-0.5		90
6986.4	-0.3		90
7040.2		3	
7041.1	-0.0		90
7093.0	0.5		90
7144.2		3	
7174.7	10.1		8331
7183.0	11.8		8331
7207.2	12.0		8331
7208.2	10.2		8331
7242.8	10.0		8331
7246.7	12.0		8331
7264.3	12.1		8331
7270.0	10.4		8331
7405.9	10.7		8331
7413.8	12.1		8331
7504.4	13.3		8331

Table A-1. Cross Section Data For Cross Section 1 (Continued).

STATION (FT)	GROUND ELEV (FT)	DEPTH OF THAW (2) (FT)	TERRAIN CODE

NOTES

1. ELEVATION'S ARE BASED ON NOAA MONUMENT "RIVER", ELEV = 42 FT.
2. DEPTH OF THAW IS DEPTH BELOW GROUND ELEVATION. VALUES FOR DEPTH OF THAW HAVE BEEN ROUNDED TO THE NEAEREST FOOT.
3. CROSS SECTION 1 WAS SURVEYED ON JULY 26 & 28, 1992. MEASURED WATER SURFACE ELEVATIONS VARIED FROM 1.38 TO 1.95 FT.

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Table A-1. Cross Section Data For Cross Section 2.

STATION (FT)	ELEV (FT)	DEPTH OF THAW (2) (FT)	TERRAIN CODE
100.0	11.9		2010
163.6	19.7		2010
174.0	15.6		2010
279.6	16.7		2010
301.6	24.4		2010
309.5	18.2		2010
325.4	15.3		2010
369.6	23.3		2010
370.6	23.2		2010
406.2	10.0		2010
411.8	12.8		2010
484.6	10.2		2010
490.6	13.1		2010
509.9	13.3		2010
616.0	6.9		6000
628.1	6.3		6000
740.8	4.4		6000
862.4	3.1		6000
1009.8	2.4		6000
1063.9	2.1		6000
1089.6	1.9		6000
1175.4	1.5		90
1317.8		2	
1338.1	1.1		90
1390.6	0.9		90
1445.4	1.1		90
1512.7	1.0		90
1569.7	1.1	3	90
1622.2	1.1		90
1676.2	0.9		90
1722.6	0.7		90
1774.4	0.7		90
1827.1	0.4		90
1875.6	0.2		90
1924.6	0.2		90
1978.1	0.0		90
2028.0	-0.1		90
2080.8	-0.0		90
2131.9	-0.3	3	90
2183.9	-0.9		90
2231.9	-1.5		90
2278.1	-1.4		90
2324.3	-1.6		90
2370.6	-1.3		90
2418.7	-1.2		90
2469.9	-0.6		90
2520.9	-1.7		90
2573.4	-1.0		90
2622.5	-2.0	3	90
2674.3	-5.4	22	90
2726.5	-5.1		90
2838.1	-8.7		90
2945.4	-9.1		90
3070.5	-8.7		90
3177.4	-9.3		90
3184.7		>19	
3185.0	-9.5		90
3268.9	-7.8		90
3288.4	-7.7		90
3304.5	-5.4		90
3328.3	-5.2	10	90
3360.3		4	
3366.1	1.8		90
3383.6	10.0		8231
3406.6	10.8		8231
3470.3	10.7		8231
3579.9	11.2		1032
3691.8	11.8		1032
3807.3	13.1		1032

NOTES

1. ELEVATIONS ARE BASED ON NOAA MONUMENT "DUNE," ELEV = 36 FT.
2. DEPTH OF THAW IS DEPTH BELOW GROUND ELEVATION. VALUES FOR DEPTH OF THAW HAVE BEEN ROUNDED TO THE NEAEREST FOOT.
3. CROSS SECTION 2 WAS SURVEYED ON JULY 27 & 29, 1992. MEASURED WATER SURFACE ELEVATIONS VARIED FROM 1.12 TO 1.60 FT.

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Table A-1. Cross Section Data For Cross Section 3.

STATION (FT)	ELEV (FT)	DEPTH OF THAW (2) (FT)	TERRAIN CODE
100.0	33.9		2010
455.7	14.5		2010
471.1	21.4		2010
472.0	21.4		2010
512.1	9.8		2010
547.8	5.5		6000
577.8	3.0		6000
653.7	1.3		6000
744.8	2.1		6000
839.4	1.6		6000
935.1	2.0		6000
1054.9	1.9		6000
1106.7	2.1		6000
1150.0	2.1		6000
1249.4	2.0		6000
1347.6	1.9		6000
1442.7	1.9		6000
1541.3	2.0		6000
1641.5	2.2		6000
1738.7	1.8		6000
1832.8	0.9		6000
1884.8	0.7		6000
1885.5		3	
1912.2	0.3		6000
1984.7	-0.0		90
2056.5	-1.5		90
2067.0	-1.3		90
2085.8	-2.9	4	90
2111.8	-4.3		90
2147.5		15	
2153.2	-6.0		90
2231.7	-7.4		90
2279.2	-8.9		90
2344.9	-9.8		90
2377.3	-10.3		90
2418.1	-9.7		90
2504.5	-11.1		90
2573.5	-12.2		90
2633.9	-11.8		90
2665.5	-12.2		90
2690.2	-12.8		90
2759.7	-12.5		90
2820.5	-13.5		90
2927.5	-12.7		90
2993.1	-11.9		90
3103.9	-11.5		90
3126.3	-11.0		90
3157.6	-8.9		90
3231.3	-6.4		90
3240.1		>12	
3317.5		3	
3319.4	-2.1		90
3327.2	-0.7		90
3371.9	-0.3		90
3463.5		3	
3463.6	0.4		6000
3531.4	0.6		6000
3632.7	1.2		6000
3729.3	2.3		6000
3832.1	5.9		6051
3863.8	7.1		6051
3929.7	7.2		6051
3947.5	7.3		6051
4047.5	7.1		6051
4153.7	5.2		6000
4282.5	3.7		7061
4456.6	3.7		8031
4485.5	5.9		8031
4599.1	6.2		8031
4708.0	6.2		8131
5070.0			8331
5129.0	9.6		8131

NOTES

1. ELEVATIONS ARE BASED ON NOAA MONUMENT "DUNE", ELEV = 36 FT.
2. DEPTH OF THAW IS DEPTH BELOW GROUND ELEVATION. VALUES FOR DEPTH OF THAW HAVE BEEN ROUNDED TO THE NEAEREST FOOT.
3. CROSS SECTION 3 WAS SURVEYED ON JULY 30, 1992. MEASURED WATER SURFACE ELEVATIONS VARIED FROM 0.41 TO 1.06 FT.

FILE: 1202SC3b.WQ1
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Table A-1. Cross Section Data For Cross Section 4.

STATION (FT)	ELEV (FT)	DEPTH OF THAW (2) (FT)	TERRAIN CODE
100.0	5.8		8231
126.8	5.5		8231
169.4	6.2		8231
172.1	5.9		8231
174.0	6.2		8231
192.7	5.8		8231
207.0	6.3		8231
211.0	6.1		8231
215.6	6.7		8231
241.3	5.5		8231
265.5	6.2		8231
268.1	6.0		8231
269.4	6.4		8231
295.4	6.0		8231
326.4	6.3		8231
336.1	5.4		8231
343.0	6.1		8231
362.5	5.6		8231
400.0			8031
484.5	4.9		8031
586.6	5.3		8031
629.8	5.6		8031
631.4	5.2		8031
633.7	5.7		8031
642.0			8062
718.3	5.6		8062
755.3	6.5		8062
776.6	5.9		8062
798.0	6.2		8062
810.2	5.6		8062
814.4	3.9		8062
822.6	0.3		8062
823.3	-0.6	2	90
842.9	-3.5		90
843.3		4	
865.3		4	
865.5	-5.7		90
917.0	-4.9		90
965.3	-4.4	4	90
1013.5	-4.2		90
1057.3		3	
1057.6	-3.8		90
1107.9	-3.2		90
1155.3		3	
1155.9	-2.7		90
1190.3	-2.4		90
1235.3		3	
1235.4	-2.1		90
1283.2	-1.8		90
1327.3		3	
1327.4	-1.6		90
1368.8	-1.2		90
1413.9	-0.7		6000
1414.3		3	
1453.4	-0.5		6000
1554.9	0.7		6000
1648.0	1.8		6000
1748.9	3.0		6000
1751.2	3.1		6010
1780.5	4.4		6010
1815.1	5.3		6010
1815.7	5.2		6052
1851.3	5.8		6052
1851.8	5.7		6052
1876.0			6010
1898.8	5.1		6010
1940.0			7031
1988.8	3.1		7031

NOTES

1. ELEVATIONS ARE BASED ON NOAA MONUMENT "SALVO"; ELEV = 18 FT.
2. DEPTH OF THAW IS DEPTH BELOW GROUND ELEVATION. VALUES FOR DEPTH OF THAW HAVE BEEN ROUNDED TO THE NEAEREST FOOT.
3. CROSS SECTION 4 WAS SURVEYED ON JULY 31, 1992. THE WATER SURFACE ELEVATION WAS APPROXIMATELY 0.65 AT 12:35 P.M. ON JULY 31, 1992.

FILE: 1202SC4b.WQ1
DATE: 10/14/92 14:40

Table A-1. Cross Section Data For Cross Section 5.

STATION (FT)	ELEV (FT)	DEPTH OF THAW (2) (FT)	TERRAIN CODE
100.0	2.9		8262
141.4	3.6		8262
153.5	3.8		8262
186.0	4.1		8262
204.5	3.5		8262
241.7	3.7		8262
257.3	3.2		8262
299.5	3.4		8262
344.2	0.2		8262
344.6		2	
345.2	-0.5		90
356.6		3	
362.2	-3.7		90
365.6		6	
375.7	-12.5		90
392.6		>10	
398.3	-18.9		90
437.0	-21.1		90
476.7	-18.4		90
532.3	-12.6		90
582.6		>15	
583.4	-7.2		90
609.6		>21	
614.0	-4.4		90
668.2	-3.4		90
668.6		3	
703.1	-2.5		90
735.6		4	
736.0	-2.3		90
781.1	-1.9		90
822.6		3	
822.9	-1.6		90
861.0	-1.5		90
902.6		3	
902.7	-1.3		90
948.5	-1.1		90
982.6	-1.3		90
997.6		3	
998.2	-0.8		90
1048.2	-0.7		90
1061.5	-1.0		90
1101.2		3	
1101.3	-0.2		90
1146.5	-0.4		90
1238.2	0.2		12000
1333.8	1.0		12000
1425.8	1.8		12000
1525.0	1.7		12000
1620.6	1.1		12000
1717.7	1.8		12000
1789.2	2.1		12000
1885.5	2.8		12000
1983.7	2.8		12000
2082.4	2.3		12000
2178.5	1.2		12000
2255.9	0.7		12000
2355.7	3.0		8162
2367.6	3.7		8162
2434.4	3.5		8162
2527.7	4.8		8162
2624.9	4.5		8231
2740.0	6.6		8231
2813.7	5.9		8231
2922.1	6.3		8231
3022.3	6.2		8231
3129.8	6.8		8231
3153.9	9.3		8231

NOTES

1. ELEVATIONS ARE BASED ON NOAA MONUMENT "SALVO", ELEV = 18 FT.
2. DEPTH OF THAW IS DEPTH BELOW GROUND ELEVATION. VALUES FOR DEPTH OF THAW HAVE BEEN ROUNDED TO THE NEAEREST FOOT.
3. CROSS SECTION 5 WAS SURVEYED ON AUGUST 1, 1992. MEASURED WATER SURFACE ELEVATIONS VARIED FROM 0.38 TO -0.33 FT.

FILE: 1202SC5b.WQ1
DATE: 10/14/92 14:50

Table A-1. Cross Section Data For Cross Section 6.

STATION (FT)	ELEV (FT)	DEPTH OF THAW (2) (FT)	TERRAIN CODE
100.0	18.0		8031
121.3	17.7		8031
191.5	18.2		2055
232.8	19.0		2055
484.9	22.9		2055
610.9	24.8		2055
807.6	26.2		2010
850.6	30.3		2010
868.2	29.9		2010
891.1	25.7		2010
911.6	28.1		2010
940.3	23.6		2010
953.7	26.8		2010
970.7	26.7		2010
1012.4	18.8		2010
1030.2	18.2		2010
1036.9	20.1		2010
1054.0	13.9		2010
1062.1	12.7		2010
1105.3	10.0		6000
1159.3	8.7		6000
1264.1	8.5		6000
1369.7	7.8		6000
1473.9	7.8		6000
1582.9	7.7		6000
1662.0	7.2		6000
1768.6	7.3		6000
1873.0	6.9		6000
1980.8	6.9		6000
2086.6	6.5		6000
2178.5	5.9		6000
2274.4	4.9		6000
2378.3	3.6		6000
2488.1	2.2		6000
2595.8	1.0		90
2622.6		4	
2707.1	-1.7		90
2754.3	-3.2		90
2765.6		4	
2780.7	-3.9		90
2807.0		5	
2815.7	-4.7		90
2821.3	-4.9		90
2838.3		16	
2851.1	-5.6		90
2904.6	-6.7		90
2949.8	-7.3		90
2951.1	-7.4		90
3009.1	-8.6		90
3062.6	-9.5		90
3110.6	-9.2		90
3164.4	-11.9		90
3210.1	-13.4		90
3273.5	-16.3		90
3315.2	-17.6		90
3338.8	-19.4		90
3401.1	-21.5		90
3446.0	-22.3		90
3512.4	-23.3		90
3570.9	-23.3		90
3624.8	-22.5		90
3686.8	-21.4		90
3691.4	-21.3		90
3755.2	-19.6		90
3812.2	-18.5		90
3897.7	-15.3		90
4018.5		2	
4022.0	-12.5		90
4048.1	-9.8		90
4077.2		2	
4079.7	1.4		6000
4086.8	4.6		6000
4098.4	16.0		8231
4122.4	19.2		8231
4160.4	19.0		8231
4179.4	17.5		8231
4220.4	17.7		8231
4239.4	19.9		8231
4299.4	18.2		8231
4312.4	18.4		8231
4337.4	19.7		8231
4469.4	19.3		8231
4470.1	19.2		8231

NOTES

1. ELEVATION'S ARE BASED ON NOAA MONUMENT "KNIK", ELEV = 22 FT.
2. DEPTH OF THAW IS DEPTH BELOW GROUND ELEVATION. VALUES FOR DEPTH OF THAW HAVE BEEN ROUNDED TO THE NEAEREST FOOT.
3. CROSS SECTION 6 WAS SURVEYED ON JULY 24 & 25, 1992. THE WATER SURFACE ELEVATION WAS APPROXIMATELY 0.35 AT 14:00 HRS ON AUGUST 25, 1992.

FILE: 1202SC6b.WQ1
DATE: 10/14/92 15:00

Table A-2. Riverbed Gradations.

Cross Section Number	U.S. Standard Sieve No.	Size	Cumulative Weight Retained (Grams)	Percent Passing By Weight
1	#40	0.425 mm	0.001	100.0
	#60	0.250 mm	24.200	87.8
	#100	0.150 mm	93.400	53.1
	#200	0.075 mm	194.800	2.2
2	#8	2.38 mm	0.001	100.0
	#10	2.00 mm	0.100	100.0
	#20	0.85 mm	0.300	99.9
	#40	0.425 mm	0.700	99.7
	#60	0.250 mm	9.100	96.2
	#100	0.150 mm	167.400	30.0
	#200	0.075 mm	213.600	10.7
3	#40	0.425 mm	0.001	100.0
	#60	0.250 mm	1.100	99.5
	#100	0.150 mm	36.200	82.0
	#200	0.075 mm	127.600	36.7
		0.0371 mm		13.1
		0.0236 mm		11.1
		0.0188 mm		9.1
		0.0138 mm		8.1
		0.0098 mm		7.1
		0.0069 mm		5.0
		0.0049 mm		3.0
		0.0035 mm		2.0
4	#10	2.00 mm	0.100	99.9
	#20	0.85 mm	0.200	99:9
	#40	0.425 mm	0.300	99.8

Table A-2. Riverbed Gradations (Continued).

Cross Section Number	U.S. Standard Sieve No.	Size	Cumulative Weight Retained (Grams)	Percent Passing By Weight
4	#60	0.250 mm	4.900	97.5
	#100	0.150 mm	39.000	80.4
	#200	0.075 mm	118.400	40.5
		0.0345 mm		37.3
		0.0228 mm		23.2
		0.0182 mm		19.1
		0.0134 mm		16.1
		0.0096 mm		13.1
		0.0069 mm		9.1
		0.0049 mm		6.0
		0.0035 mm		5.0
5	#10	2.00 mm	0.001	100.0
	#20	0.85 mm	0.200	99.9
	#40	0.425 mm	0.500	99.7
	#60	0.250 mm	2.100	98.9
	#100	0.150 mm	28.400	85.7
	#200	0.075 mm	94.800	52.4
		0.0352 mm		31.2
		0.0228 mm		23.2
		0.0181 mm		21.2
		0.0134 mm		18.1
		0.0096 mm		13.1
		0.0068 mm		11.1
		0.0049 mm		9.1
		0.0034 mm		7.1

File: 1202RT1

Notes:

1. Riverbed samples were taken of Cross Sections 1, 2 and 3 on August 2, 1992. A riverbed sample was taken at Cross Section 4 on July 31, 1992 and at Cross Section 5 on August 1, 1992.

APPENDIX B. Data File listing for flooding regime section.

Table B-1. Hydraulic Parameters Based On Discharge Measurements In The Vicinity Of Cross Section 6.

Measured By	Location	Date	X-Sec Area (Sf)	Hydraulic Radius (Ft)	Discharge (Cfs)	Average Velocity (Fps)	(1.49/n)* (s^1/2)
USGS	@ Gage	07-29-77	16132.0	10.9674	9,991	0.619	0.125
USGS	(1)	09-11-79	20368.0	13.8162	28,647	1.41	0.245
USGS	(1)	08-20-79	20170.0	13.2439	34,945	1.73	0.309
AHC	(2)	06-10-92	27182.5	15.2736	65,704	2.42	0.393
USGS	@ Gage	06-18-77	26330.0	15.9272	68,243	2.59	0.409
USGS	@ Gage	06-15-77	28205.0	15.6533	86,325	3.06	0.489
USGS	@ Gage	06-14-77	30690.0	14.6045	112,802	3.68	0.616
USGS	(1)	06-06-80	47572.0	15.1900	190,000	3.99	0.651
USGS	@ Gage	06-12-77	44420.0	14.7959	212,256	4.78	0.793
USGS	@ Gage	06-10-77	44930.0	14.7220	231,940	5.16	0.859

Notes:
1. Measurement made 1 mile d/s of Itkillik River, about 0.25 miles d/s of USGS reference markers.
2. It is estimated that Cross Section 6 is located a few hundred feet upstream of the old USGS reference markers, this could not be confirmed.

Table B-2. Annual Flood Peak Discharge Data.

Year	Annual Flood Peak Discharge (Cfs)		
	Kuparuk River	Sagavanirktok River Near Sagwon	Sagavanirktok River Near Pump Station 3
1969		34,900	
1970		15,200	
1971	77,000	19,300	
1972	45,800	22,200	
1973	82,000	24,700	
1974	24,000	28,900	
1975	22,600	8.340	
1976	55,000	18,700	
1977	66,800	29,600	
1978	118,000	19,800	
1979	24,300	10,800	
1980	40,500		
1981	27,500		
1982	104,000		
1983	68,400	43,900 (2)	37,000
1984	56,800	15,600 (2)	13,100
1985	34,500	18,200 (2)	15,300
1986	38,000	13,800 (2)	11,600
1987	15,500	15,800 (2)	13,300
1988	38,700	10,600 (2)	8,940
1989	75,400	13,700 (2)	11,500
1990	70,000	11,200 (2)	9,440
1991	37,100	19,500 (2)	16,400
1992		40,400 (2)	34,000

Notes:
1. This is a preliminary estimate made by the U.S. Geological Survey.

Table B-3. Drainage Basin Characteristics.

Drainage Basin	Drainage Basin Area (Square Miles)	Mean Basin Elevation (Feet)	Percent Of Area covered By Lakes (%)	Mean Annual Precipi-tation (Inches)	Record Length (Years)
Kuparuk River	3130	900	2	9	21
Sagavanirktok River Near Sagwon	2208	3220	0	22	11
Sagavanirktok River Near Pump Station 3	1860	3580	0	22	10
Firth River	2200	2630	0	18	12
Colville River	20670	1600	3	7	0

Table B-4. Flood Peak Discharge Frequency At Gaged Drainage Basins.

Recurrence Interval (Years)	Kuparuk River (Cfs)	Sagavanirktok River Near Sagwon (Cfs)	Firth River (Cfs)
2	47,400	18,500	20,800
5	74,200	27,300	30,600
10	93,000	33,800	37,000
25	118,000	42,700	45,100
50	137,000	49,900	50,900
100	156,000	57,500	56,700
200	176,000	65,700	62,300
500	203,000	77,400	69,700

Table B-5. USGS Regional Regression Equations With Adjustment Factors.

$$Q_2 = AF_2 * 16.2 * A^{0.894} * P^{0.949} * (L+1)^{-0.209} * E^{-0.345}$$

$$Q_5 = AF_5 * 43.9 * A^{0.843} * P^{0.753} * (L+1)^{-0.206} * E^{-0.305}$$

$$Q_{10} = AF_{10} * 70.3 * A^{0.818} * P^{0.667} * (L+1)^{-0.202} * E^{-0.288}$$

$$Q_{25} = AF_{25} * 112 * A^{0.793} * P^{0.588} * (L+1)^{-0.194} * E^{-0.272}$$

$$Q_{50} = AF_{50} * 147 * A^{0.778} * P^{0.544} * (L+1)^{-0.187} * E^{-0.264}$$

$$Q_{100} = AF_{100} * 185 * A^{0.765} * P^{0.509} * (L+1)^{-0.179} * E^{-0.257}$$

$$Q_{200} = AF_{200} * 224 * A^{0.754} * P^{0.480} * (L+1)^{-0.171} * E^{-0.252}$$

$$Q_{500} = AF_{500} * 275 * A^{0.742} * P^{0.451} * (L+1)^{-0.160} * E^{-0.245}$$

Where:

Q_T	=	Flood peak discharge with recurrence interval of T-years;
AF_T	=	Adjustment factor to be applied to the USGS regional regression equation used to estimate the flood peak discharge with a recurrence interval of T-years (see Table B-5 for a list of AF_T values.);
A	=	Drainage basin area in square miles;
P	=	Mean annual precipitation in inches;
L	=	Percent of the drainage basin covered by lakes and ponds; and
E	=	Mean basin elevation in feet.

Table B-6. Adjustment Factors Developed For USGS Regional Regression Equations.

Recurrence Interval Of Predicted Discharge (Years)	Adjustment Factor Based On		
	Kuparuk River Flood Frequency Analysis	Saganavirktok River Flood Frequency Analysis	Firth River Flood Frequency Analysis
2	3.59	1.01	1.29
5	3.65	1.08	1.33
10	3.74	1.15	1.36
25	3.85	1.24	1.40
50	3.98	1.33	1.44
100	4.08	1.42	1.48
200	4.24	1.53	1.53
500	4.41	1.67	1.57

Table B-7. Colville River Flood Peak Discharge Frequency Estimates Based On Computed and Expected Exceedence Probabilities.

Average Recurrence Interval	Flood Peak Discharge (Cfs) Based On					
	Kuparuk River Data And		Saganavirktok River Data And		Firth River Data And	
	Computed Exceedence Probability	Expected Exceedence Probability	Computed Exceedence Probability	Expected Exceedence Probability	Computed Exceedence Probability	Expected Exceedence Probability
2	156,000	156,000	43,900	43,900	55,900	55,900
5	238,000	242,000	70,700	72,300	86,900	89,900
10	294,000	305,000	90,700	95,000	107,000	115,000
25	368,000	392,000	119,000	129,000	134,000	150,000
50	422,000	460,000	141,000	158,000	153,000	180,000
100	477,000	537,000	166,000	195,000	172,000	214,000
200	533,000	620,000	193,000	236,000	192,000	254,000
500	610,000		231,000		217,000	

Table B-8. Multiple Comparison Tests Of Elevational Differences Among Integrated Terrain Units (ITUs), Colville River Delta, 1992.

ITU Code (Listed Vertically)

ITU Code	Mean Relative Height (%)	90	6000	12000	6061	7061	8262	6010	8162	7010	7031	8031	8062	6051	92	95	6052	8131	8231	8331	1032	2080	2010
90	-.4995																						
6000	.2678	*																					
12000	.3010	*																					
6061	.3075	*																					
7061	.3900	*																					
8262	.5167	*																					
6010	.5500	*	*																				
8162	.6150	*																					
7010	.6400	*																					
7031	.6547	*	*	*																			
8031	.6778	*	*	*																			
8062	.7063	*	*	*																			
6051	.7328	*	*	*	*																		
92	.7486	*	*	*																			
95	.7950	*																					
6052	.8333	*	*	*	*		*	*															
8131	.9483	*	*	*	*		*	*			*			*									
8231	.9951	*	*	*	*		*	*			*	*	*	*									
8331	1.0056	*	*	*	*		*	*	*		*	*	*	*									
1032	1.1467	*	*	*	*		*	*			*												
2080	1.4908	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			
2010	1.5290	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*			