SUSITNA RIVER ICE PROCESSES: NATURAL CONDITIONS AND PROJECTED EFFECTS OF HYDROELECTRIC DEVELOPMENT

VOLUME I

SUSITNA RIVER ICE PROCESSES: NATURAL CONDITIONS AND PROJECTED EFFECTS OF HYDROELECTRIC DEVELOPMENT

DRAFT REPORT

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April 5, 1985

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I. SUMMARY

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II. INTRODUCTION

A. PURPOSE

The Susitna River system is dominated by river ice for more than half of each year. The processes of ice formation in the late fall, ice development and evolution thoughout the winter, and decay of ice in the early spring have large effects on the river's morphology and fish and wildlife habitats, as well as patterns of human use. The purpose of this report is to summarize all that has been learned to date regarding natural river ice processes in the Susitna River, the predicted alteration of those ice processes by the proposed Susitna Hydrolelectric Project, and the effects of altered ice processes on aquatic and terrestrial habitats, fish, wildlife, and vegetation, and man's use of the Susitna basin.

This assessment is an integral component of an overall environmental investigation of the effects of the Susitna Hydrolelectric Project on fish, wildlife, and the human environment. This report is part of a series, called the Instream Flow Relationships Report Series (IFRS), which summarize aquatic environmental studies.

This report incorporates the work of many groups over the past five years, all of whom contributed directly or indirectly to this effort. Especially notable are the efforts of the following organizations:

R&M Consultants, Inc, who performed river ice observations and analyses every winter;

Harza-Ebasco Susitna Joint Venture (H-E), who carried out computer simulation modeling and analyses of natural and with- project river ice processes;

The Alaska Department of Fish and Game (ADF&G), who performed winter field work in terrestrial and aquatic studies;

The Arctic Environmental Information and Data Center (AEIDC), Univ. of Alaska, who carried out instream temperature simulations by computer model and performed fish and aquatic habitat analyses;

LGL Alaska Associates, Inc., who performed studies of wildlife and terrestrial habitat in the Susitna Basin;

The Agriculture and Forestry Experiment Station (AFES), Univ. of Alaska, who carried out riparian vegetation studies along the river system.

The report is organized into two volumes. The first volume includes text and tables; the second volume contains all figures and appendixes. Figures are not collated into the text because many of them will be in 11 by 17-inch format in the final report. For the draft version of the report, all figures and maps have been reduced to 8 1/2 by 11-inch size.

B. SCOPE

This report analyses river ice processes under both natural and with-project conditions, and describes the expected effects of project-altered ice conditions on the biological environment, for the entire Susitna River system including the proposed impoundment areas. Specifically addressed are the following subjects:

1. Natural river ice processes in the Susitna River as observed for the past five years, including freezeup, mid-winter ice development, and breakup processes;

2. Predicted alterations of river ice processes by the proposed Susitna Hydroelectric Project, produced by computer simulation modeling of with-project instream temperatures and ice processes (SNTEMP and ICECAL). These include predicted ice conditions in the proposed Watana and Devil Canyon reservoirs, and river ice regimes under various operational scenarios including Watana filling, Watana alone on line, and both Watana and Devil Canyon on line. Each of these scenarios is tested against varying climatic conditions, for which the climatic years 1971-72 (cold), 1976-77 (very warm), 1981-82 (average), and 1982- 83 (warm) are used;

3. Predicted effects of altered river ice processes on terrestrial and aquatic habitats, fish, wildlife, and vegetation, and public use.

Many of the conclusions reached in Chapter VI of this report are necessarily speculative, as few studies have been carried out regarding the effects of natural ice processes on fish, wildlife, or vegetation. Also, little information exists on the effects of river ice processes altered by other northern hydroelectric facilities on fish and wildlife habitats. The statements of fact or conclusions contained in this report have been derived from several sources. These are:

1. Field observations and interpretations by investigators contractually involved with determining the environmental effects of the Susitna Hydroelectric Project;

2. Information on the Susitna River basin and its resources and environs contained in both accredited journals and in gray literature;

3. Information on the physical and biological effects of river ice processes learned from studies performed in other river systems,principally reported in accredited journals.

Wherever possible, statements in the report purporting to be factual are documented as to source. Conclusions or expressions of professional opinion are similarly documented unless they are the opinions of the authors.

Additional relevant winter studies in the Susitna Basin are now in progress by ADF&G, but these results were not available in time for inclusion in this report.

Conclusions regarding the effects of altered ice regimes on fish and wildlife and their habitats rest entirely upon the with- project river ice scenarios predicted by computer simulation models. These simulation models, while state-of-the-art, have limited predictive capabilities. For example, the ICECAL model is one-dimensional in scope, limiting its capabilities to predict ice processes in peripheral parts of the river where important fish habitat often occurs. Also, the model is incapable of modeling spring ice breakup processes; conclusions about spring meltout are based on professional judgement using ICECAL- predicted ice regimes.

This report, therefore, serves to give project planners the best view of with-project river ice conditions and their effects on the biological environment that is possible with present predictive technology. The authors believe that the scenarios discussed herein are the most likely to result from the project.

C. BACKGROUND

The Susitna River drains an area of 19,600 square miles, the sixth largest river basin in Alaska. The Susitna flows 320 miles from its origin at Susitna Glacier to the Cook Inlet estuary. Its basin is bordered by the Alaska Range on the north, the Chulitna and Talkeetna mountains on the west and south, and the northern Talkeetna plateau and Gulkana uplands to the east. This area is largely within the coastal trough of southcentral Alaska, a belt of lowlands extending the length of the Pacific mountain system and interrupted in Alaska by the Talkeetna, Clearwater, and Wrangell mountains.

Major Susitna tributaries include the Talkeetna, Chulitna, and Yentna rivers (figure 1). The Yentna River enters the Susitna at river mile (RM) 28 (28 miles upstream from the mouth at Cook Inlet). The Chulitna River rises in the glaciers on the south slope of Mount McKinley and flows south, entering the Susitna River at RM 99 near Talkeetna. The Talkeetna River originates in the Talkeetna Mountains, flows west, and joins the Susitna at RM 97 near Talkeetna.

Tributaries in the northern portions of the Susitna basin originate in the glaciers of the eastern Alaska Range. The east and west forks of the

Susitna and Maclaren rivers join the mainstem Susitna River above RM 260. Below the glaciers the braided channel traverses a high plateau and continues south to the Oshetna River confluence near RM 233. There it takes a sharp turn west and flows through a steeply cut canyon which includes the Watana (RM 184.4) and Devil Canyon (RM 151.6) damsites. In this predominantly single-channel reach the gradient is quite steep, averaging approximately 10 feet per mile (Acres American 1983). Below Gold Creek (RM 137) the river alternates between single and multiple channels until the confluence with the Chulitna and Talkeetna rivers (RM 97), below which the Susitna broadens into widely braided channels for 97 miles to Cook Inlet.

The proposed project consists of two dams to be constructed over a period of about 15 years. The Watana dam would be completed in 1994 at a site 3 miles upstream from Tsusena Creek (RM 184.4). This development would include an underground powerhouse and an 885-foot high earthfill dam, which would impound a reservoir 48 miles long with a surface area of 38,000 acres and a usable storage capacity of 3.7 million acre feet (maf). The dam would house multiple level intakes and cone valves. Installed generating capacity would be 1020 megawatts (Mw), with an estimated average annual energy output of 3460 gigawatt hours (gwh) (Acres American, Inc. 1983).

The concrete arch Devil Canyon dam would be completed by 2002 at a site 32 miles downstream of the Watana damsite. It would be 645 feet high and would impound a 26 mile-long reservoir with 7,800 surface acres and a storage capacity of .36 maf. Installed generating capacity would be about 600 Mw, with an average annual energy output of 3450 gwh (Acres American, Inc. 1983).

Construction and subsequent operation of the Susitna dams are expected to alter the normal flow and thermal regimes of the river. Mainstem flows downstream of the project would be higher in the winter than they are naturally. Mainstem water temperatures downstream from the project would be cooler in the summer and warmer in the winter than under natural conditions. A change in the river ice regime downstream from the project is expected due to these altered flows and temperatures.

III. SUSITNA RIVER MORPHOLOGY AND CLIMATE

The Susitna River drainage basin, sixth largest in Alaska, is located in the Cook Inlet subregion of southcentral Alaska. The drainage basin covers 19,600 square miles. It is bordered on the west and north by the Alaskan Range, on the east by the Talkeetna Mountains and the Copper River lowlands, and on the south by Cook Inlet. The river is 320 miles long from the mouth at Cook Inlet to the headwaters at Susitna Glacier. Major tributaries include the Chulitna, Talkeetna, and Yentna Rivers, all located downstream of the proposed project. Extensive glaciers in the headwaters contribute substantial suspended sediment loads during summer months. Streamflow is characterized by high flows between May and September and low flows from December to April.

The headwaters of the Susitna River and the major upper basin tributaries are characterized by broad, braided, gravel floodplains emanating from glaciers on the south flank of the Alaskan Range. Below the West Fork tributary confluence, the river develops a split-channel configuration with numerous gravel bars, flowing south between narrow bluffs for about 55 miles. Below the confluence with the Oshetna River, the Susitna River flows west for 96 miles through steep-walled canyons before reaching the mouth of Devil Canyon. This reach contains the Watana and Devil Canyon damsites at River Miles (RM) 184.4 and 151.6, respectively, as measured from Cook Inlet. River gradients are quite high, averaging nearly 14 feet/mile in the 54 miles above Watana damsite, 10.4 feet/mile from Watana downstream to Devil Creek, and 31 feet/mile in the 12-mile stretch between Devil Creek and Devil Canyon. Below Devil Canyon, the gradient decreases from about 14 feet/mile to 8 feet/mile above Talkeetna. The river in this reach is generally characterized by a split-channel configuration, with numerous side-channels and sloughs. About 4 miles above the confluence with the Chulitna River, the Susitna River begins to braid, and remains braided the remainder of its length to Cook Inlet. Numerous islands and side channels appear. The gradient continues to decrease, ranging from 5.5 feet/mile for the 34-mile reach below Talkeetna to 1.6 feet/mile for the last 42 miles.

In order to facilitate morphological descriptions, this report refers to three distinct and easily identifiable river reaches labelled the upper, middle and lower reaches. These river reaches have been referred to in other reports concerning a variety of specific studies. This report deals with ice, the formation of which is primarily controlled by air temperature but to a great extent is affected directly by solar radiation as well. For the following discussions regarding river ice, the "upper river" will refer to the initial reach which is subjected to colder air temperatures due to the higher elevation and latitude of the headwaters, but also receives a substantial amount of solar radiation during the freezeup period because of the north-south orientation and lack of major topographic features (figure 2). The "middle reach" is the section of river that flows generally east to west, from the vicinity of the Oshetna tributary confluence, through the Watana and Devil Canyon impoundment areas, then southwest past Gold Creek and ending at the Chulitna River confluence. This reach flows through a mountainous area where steep canyon walls shade the turbulent water surface for much of the year (figure 3). Downstream of the Chulitna River confluence the river morphology changes suddenly from essentially a narrow confined channel with a steep gradient to a broad channel containing a braided flow pattern. This configuration is retained through this final "lower reach" to Cook Inlet (figure 4).

Identification of specific sites on the river is best done with place-names. However, in some areas the lesser features have no names or the cartographers have failed to attach one, so a substitute system of river mile (RM) numbers was developed with a common reference point (Cook Inlet, RM 0) so that all those concerned with the river study could mutually orient themselves. Photomosaic river maps showing the Susitna from Cook Inlet to the proposed Devil Canyon dam site are included in Appendixes A and B. No maps are available of the river upstream of Devil Canyon except for the standard U.S. Geological Survey (USGS) topographic sheets at 1:63,360 scale. The entire USGS map set showing the Susitna River from Cook Inlet to the Susitna Glacier has been compiled and reproduced with river mile numbers in the Susitna River Mile Index (R&M, 1981a).

The Susitna River originates in the continental climatic zone, flowing south into the transitional climatic zone. Due to the maritime influence and the lower elevations, temperatures are more moderate in the lower basin than in the upper basin. Freezing temperatures occur in the upper basin by mid-September, with frazil ice generated in the reach from Denali through Vee Canyon by early October.

Several meteorological stations have been installed along the river since 1980. Records from these stations, located at Susitna Glacier, Denali, Kosina Creek (between Vee Canyon and Watana), Watana, Devil Canyon and Sherman, together with records from the National Weather Service (NWS) at Talkeetna, illustrate the sharp difference in freezing degree-days along the length of the river (figure 5). In general, the meteorology within the Susitna River basin is highly variable between weather station sites. This is due, in part, to the movement of storm systems, the topographic variance, and the change in latitude, but the major reason for the temperature variance between Denali and

Talkeetna is the 2,400-foot elevation difference. Of the seven weather stations currently in operation, only three will be considered in this report as providing representative data for describing ice processes in the upper, middle, and lower reaches. These stations are located at Susitna Lodge on the Denali Highway, at Watana Camp, and at Talkeetna.

The following sections discuss the specific morphological and climatological characteristics unique to each section and how they relate to river ice formation.

A. UPPER RIVER

The waters flowing through this reach originate primarily from four major glaciers and to a lesser extent as runoff via numerous tributaries. Meltwater and runoff drain from the West Fork, Susitna and East Fork Glaciers, flow through broad gravel floodplains and merge into a single channel, to flow through a narrow pass between the Clearwater Mountains on the east and an unnamed range to the west. The Denali Highway bridges the river at this point (RM 291). The U.S. Geological Survey records daily river stages at the bridge. This gage provides information for computations of daily flow, which averages 2,759 cubic feet/second (cfs) from a drainage area of 950 square miles. During freezeup, or between October and December of any given year, the flow drops rapidly from about 2,000 cfs to under 400 cfs. The lowest flow occurs in March, and is usually estimated at less than 300 cfs. Just to the south and east of the highway bridge, at Susitna Lodge, R&M Consultants operates a weather recorder. This station monitors air temperature, wind speed and direction, solar radiation, humidity and precipitation. Along the Susitna River, freezing air temperatures are generally first recorded at the Denali weather station.

Downstream of the Denali area, the river develops a split-channel configuration with many gravel bars but few vegetated islands. The route meanders through a broad plain, with the channel generally confined by low bluffs. The Maclaren River enters from the northeast about 31 miles downstream of the Denali Highway Bridge. Average annual discharge of the Maclaren River is 979 cfs. During freezeup the flow drops from about 700 cfs in October to 200 cfs by the end of December. This river drains the Maclaren Glacier and a large portion of the Clearwater Mountains. Fourteen miles further downstream the non-glacial Tyone River enters the Susitna from the southeast, draining the lakes Louise, Susitna and Tyone, as well as hundreds of square miles of muskeg and black-spruce bogs. The last major tributary entering this reach is the Oshetna River (RM 233). This river flows north into the Susitna, draining the north flank of the Talkeetna Mountains. Several tributaries to the Oshetna are glacial, the largest being the Black River which emerges from a sizeable unnamed glacier.

The climate in this upper river reach is characterized by being colder, drier and sunnier than in the lower reaches. Figure 6 shows a comparison plot of air temperatures recorded at Talkeetna, Watana, and Denali during the 1984 freezeup. Storm systems usually pass to the west of this river reach, funneled northward through the lower Susitna Valley and over Chulitna Pass. The Talkeetna Mountains rise to over 8,000 feet and cause much of the water in the warm maritime air masses to precipitate out, so that the region to the north and east of this range is in a rain shadow.

B. MIDDLE RIVER

This reach description focuses on the general east-west course of the Susitna River beginning at approximately RM 233.

The unique characteristics of this reach are the steep gradient of the channel and the steep-walled canyon through which the river flows. The elevation drops from about 2,150 feet down to 350 feet in roughly 140 miles, for an average gradient of 13.4 feet/mile. This contrasts considerably with the upper river gradient of 5.9 feet/mile and the lower river gradient of 3.6 feet/mile.

Downstream of the Oshetna River confluence the Susitna enters Vee Canyon, the site of a U.S.G.S. streamgage. This gage measures flow draining an area of 4,140 square miles. The average annual flow is 6,404 cfs. From October to December, the flow drops from roughly 5000 cfs to under 1400 cfs. The middle reach is primarily either a single channel or a split channel with intermittent vegetated islands and gravel bars. The water is very turbulent through the entire reach.

The river valley or canyon is generally quite deep, averaging about 1000 feet at the proposed Watana damsite, and the mountainous terrain along the south bank shields the river from direct sunlight for much of the year. This causes an air temperature gradient between the cold canyon bottom and the warmer plateau adjacent to the river. This gradient is especially evident during the winter, when sun angles are lowest and dense cold air settles in the canyon. In December, 1984, temperature deviations of over 10 C were measured between the Watana weather station and a thermograph located near the water surface. The average monthly deviation, however, measured between 2-3 C (figure 7).

The weather recorder at Watana Camp is similar to the recorder at Denali. Winter precipitation is not generally measured at the weather stations except for what snow may accumulate on the ground. However, at Watana a Wyoming gage has been operating since October 1981, giving daily precipitation readings when a heated tipping bucket was operating. Since October 1983 monthly totals have been measured from an accumulating snowgage charged with an antifreeze mixture. These data allow a comparison between winter precipitation at Talkeetna and Watana. Figure 8 summarizes precipitation data over the winters of 1982-1983 and 1983-1984. The effects of storm patterns is illustrated by the large volumes of snowfall at Talkeetna compared to Watana.

The combination of turbulent water, cold air temperatures and little solar radiation creates conditions where massive volumes of ice can form. This reach of river is therefore a major source of ice during freezeup compared to the upper and lower reaches. The upper reach has cold air temperatures but lacks the turbulence necessary to generate large volumes of ice. In October the sun shines directly on the water surface for much of the day, raising the effective water temperature, if not the air temperature, sufficiently to prevent further ice from forming. In the shaded middle reach, freezing air temperatures are sustained, allowing ice to form over a longer period of time. In contrast, the lower river has neither the cold air temperatures in October nor the turbulence to generate much ice.

The reach between Devil Canyon and the Chulitna River confluence has received considerable attention during the project environmental studies. Project impacts would be most evident in this reach because no major tributaries enter the Susitna River to offset the effects of flow regulation. Smaller tributaries include Portage Creek, Indian River, Gold Creek and Fourth of July Creek. The U.S.G.S. maintains a streamflow recorder and conducts monthly measurements of discharge at the Gold Creek Bridge, where the Alaska Railroad crosses the Susitna River (RM 136.6). This gage measures the flow from a drainage area of 6,160 square miles. The average annual discharge is 9,724 cfs. Freezeup flows range from about 10,000 cfs in October to under

TABLE 1
SLOUGH AND SIDE CHANNEL STUDY AREAS
IN LOWER AND MIDDLE SUSITNA RIVER

Name	Location (River Mile)	Observed Freezeup Ice Effects	Year of Observation	Threshold Elevation (Feet)
Hooligan Side Channel	35.2H	None	1984	Unknown
Eagles Nest Side Channel	36.2H	Some flooded snow	84	Unknown
Kroto Slough Head	36.3H	None	84	Unknown
Rolly Creek Mouth	39.0M	None	84	Unknown
Bear Bait Side Channel	43.0H	None	84	Unknown
Last Chance Side Channel	45.4H	None	84	Unknown
Rustic Wilderness Side Ch	59.5H	Overtopped	83,84	Unknown
Caswell Creek - Mouth	63.0M	None	84	Unknown
Island Side Channel	63.2M	Flooded snow	84	Unknown
Mainstem West Bank	74.4M	Some flooded snow	84	Unknown
Circular Side Channel	75.6H	None	84	Unknown
Goose 2 Side Channel	75.8H	Overtopped	83,84	Unknown
Sauna Side Channel	79.8H	None	84	Unknown
Sucker Side Channel	84.5M	None	84	Unknown
Beaver Dam Slough	86.3M	None	84	Unknown
Sunset Side Channel	86.9	None	84	Unknown
Sunrise Side Channel	87.0	None	84	Unknown
Birch Creek Slough	88.4M	None	83,84	Unknown
Trapper Creek Side Channel	91.6	None	83,84	Unknown
Whiskers Slough	101.5H	Overtopped	80-84	367
Side Channel at Head of Gash Creek	112.0	Overtopped	82,83,84	Unknown
Slough 6A	112.3M	Backwater	80-84	U
Slough 8	114.1H	None	83	476
Side Channel MSII	115.5	Overtopped	82,83,84	482
Side Channel MSII	115.9H	None	82,83,84	487
Curry Slough	120.0H	None	84	Unknown
Moose Slough	123.5H	None	84	Unknown
Slough 8A-West	126.1H	Overtopped	81,82,83,84	573
Slough 8A-East	127.1H	Overtopped	81,82,83,84	582
Slough 9	129.3H	Some flooded snow	81,82,83,84	604
Side Channel Upstream of Slough 9	130.6	None	82,83,84	Unknown
Side Channel Upstream of 4th of July Creek	131.8	None	82,83,84	Unknown
Slough 9A	133.7H	None	83,84	651
Side Channel Upstream of Slough 10	134.3	None	82,83,84	657
Side Channel Downstream of Slough 11	135.3	None	82,83,84	Unknown
Slough 11	136.5H	None	82,83,84	687

TABLE 1 (Continued)
SLOUGH AND SIDE CHANNEL STUDY AREAS
IN LOWER AND MIDDLE SUSITNA RIVER

Name	Location (River Mile)	Observed Freezeup Ice Effects	Year of Observation	Threshold Elevation (Feet)
Slough 17	139.3H	None	82,83	Unknown
Slough 20	140.5H	None	82,83	730
Slough 21-Entrance A6	141.8H	None	82,83	747
Slough 21	142.2H	None	82,83	755
Slough 22	144.8H	None	82,83	788

H - Indicated location represents the head of the slough or channel.
M - Indicated location represents the mouth of the slough or channel.
U = "Upland" slough with no upstream head or berm.

3,000 cfs by the end of December. Downstream of the Gold Creek Bridge, the river gradually resumes a more southerly flow direction, retaining the steep gradient and mostly split channel configuration. R&M Consultants operates a weather station at Sherman, which together with the Watana Station provides representative data for the middle river reach.

Downstream of Devil Canyon there are a series of sloughs and side channel habitats that are particularly sensitive to changes in the mainstem flow regime. The project-name given to these sloughs for identification, and the river mile location of the upstream entrances are included in table 1. The majority of these habitats have both an upstream entrance and a downstream exit. During high water events in the mainstem, flood flows overtop the entrance and spill into these overflow channels. The upstream entrances are often protected to some extent by a low gravel berm. These berms have been observed to form when ice floes are pushed laterally from the mainstem by forces usually generated in ice jams. The floes contact the channel bottom and shove gravel, cobbles or soil before them, ultimately forming these berms.

A critical mainstem stage must be achieved before overtopping of the berms occurs. These critical elevations are also listed in table 1. At low mainstem flows the berms are not overtopped and the sloughs often convey clear water from small tributaries and upwelling groundwater.

C. LOWER RIVER

This final reach begins at the confluence of the Susitna and Chulitna Rivers at RM 98.5. During the spring, summer and fall the Chulitna River contributes most of the sediment to the lower river. The large material is deposited as the river gradient decreases. The deposition of sediment eventually causes the unconfined river channel to shift. This on-going process results in numerous interlaced channels. Upstream of ots confluence with the Susitna, the Chulitna River currently has two major channels. The larger one flows along the northeast (left) bank, while the other flows along the extreme right bank. During freezeup the right bank channel usually de-waters at flows under 4,000 cfs, and the left bank channel contains all the Chulitna flow. The exact confluence of this channel and the Susitna varies from year to year. At the Chulitna Canyon, the USGS maintains a gage measuring streamflow from a drainage area of about 2,570 square miles. The average annual discharge is 8,798 cfs. This is about 90% of the average annual flow measured at Gold Creek, although the drainage area is less than half (approximately 40%) the size. To some extent this is due to the higher percentage of the basin that is glaciated, but otherwise indicates the high volume of precipitation this region receives compared to the Watana and Denali area. The Chulitna River flow decreases rapidly during freezeup from about 10,000 cfs in early October to about 2,000 cfs by the end of December.

The lower river has been subdivided into five reaches, each with distinct characteristics: Segment 1, RM 98.5 at the Chulitna confluence to RM 78 near the confluence with Montana Creek; Segment 2, RM 78 to RM 51, which is approximately the upstream end of the Delta Islands; Segment 3, RM 51 to RM 42.5 through the Delta Islands; Segment 4, RM 42.5 to the Yentna River confluence at RM 27; and Segment 5, the remaining reach from RM 27 to Cook Inlet.

The following discussion presents brief descriptions of each river segment including pertinent data based on photo-interpretation and field observations.

1. SEGMENT 1: RIVER MILE 98.5 TO RIVER MILE 78

The Talkeetna River flows into the Susitna from the northeast, upstream and adjacent to the town of Talkeetna. This river is also gaged by the USGS at a site about 3 miles upstream of the Susitna confluence. The streamflow is measured from a drainage area of about 2,006 square miles. The average discharge is 4,055 cfs. The typical range of flow during freezeup is from about 6,000 cfs in early October to about 1,000 cfs by the end of December. The relative flow contributions from the Susitna, Chulitna and Talkeetna Rivers have been summarized in table 2.

Downstream from the three-river confluence area, the Susitna continues through a broad, low floodplain with multiple, interlaced channels. This network generally consists of the main channel and a series of secondary channels. The main channel meanders irregularly across the wide floodplain, occasionally contacting the steep bluffs of the surrounding terrace. Secondary channels are usually flooded during the spring and summer high water period only, since their thalweg elevation is higher than the main channel. They are generally located near or against vegetated islands or directly along either bank, and usually on the opposite side of the floodplain from the main channel. The main channel flow continues all year while most of the secondary channels normally de-water at some time during the winter, not necessarily prior to freezeup.

The floodplain consists mostly of gravel bars and some partially vegetated islands. Several complex side channel systems exist but these are generally flooded only at flows exceeding 13,000 cfs at Sunshine. Some side channels have a separate source of water, either from a tributary or groundwater seeps, and are considered side sloughs at lower discharges. These side channels are separated from the mainstem by large heavily vegetated islands, and may occur along either the left or right bank. Birch, Sunshine,

TABLE 2

RELATIVE CONTRIBUTION OF FLOWS
AT CHULITNA-SUSITNA-TALKEETNA CONFLUENCE
(PRE-PROJECT)

	Flow Contribution by (cfs)			Total Flow D/S(cfs)	Percent Flow by		
	Chulitna(1)	Talkeetna(1)	Susitna(1)	Talkeetna	Chulitna	Talkeetna	Susitna
October	4859	2537	5639	13035	37%	20%	43%
November	1994	1187	2467	5648	35%	21%	44%
December	1457	838	1773	4068	36%	21%	43%
January	1276	671	1454	3401	37%	20%	43%
February	1095	565	1236	2896	38%	19%	43%
March	976	492	1114	2582	38%	19%	43%
April	1158	557	1368	3083	38%	18%	44%
May	8511	4176	13317	26004	33%	16%	51%
June	22540	11910	27928	62378	36%	19%	45%
July	26330	10390	23853	60573	44%	17%	39%
August	22190	9749	21479	53418	42%	18%	40%
September	11740	5853	13171	30764	38%	19%	43%
Annual	8748	4086	9567	22401	39%	18%	43%

(1) Discharge data from U.S.G.S. records up to September, 1981.

Source: Bredthauer and Drage, 1982.

Rabideux and Whitefish sloughs are the most extensive and significant side channel systems along this reach.

Six tributaries enter this reach, including the Chulitna and Talkeetna rivers. Lesser contributions are added by Trapper, Birch, Sunshine, and Rabideux creeks.

The Susitna River downstream of Talkeetna is confined to only one channel at few places, most notably at the Parks Highway Bridge area called Sunshine, and immediately below the Yentna River confluence at Susitna Station. The USGS monitors streamflow at both sites. At Sunshine the gage measures the cummulative flow from the Chulitna, Susitna and Talkeetna rivers, a drainage area of about 11,100 square miles. The mean annual discharge at this site is about 24,000 cfs (unofficial estimate) with the flow usually diminishing from about 25,000 cfs in early October to about 5500 cfs by the end of December.

2. SEGMENT 2: RIVER MILE 78 TO RIVER MILE 51

This reach is characterized by extensive side channel complexes along the entire reach. These consist of a network of interconnecting channels which are normally flooded only at high flows or during the elevated stages induced by an ice cover. Many of the outermost channels in the complexes are fed by one or more tributaries which keep water flowing in a small portion of the side channel regardless of the mainstem flow. Six significant tributaries enter this reach, although only Montana Creek enters the Susitna mainstem directly. Goose Creek, Sheep Creek, Kashwitna River, 197 Mile Creek and Caswell Creek enter side channels which are isolated from the mainstem except at high water stages.

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The gradient through this segment starts out at 6 feet/mile and decreases near the Delta Islands for an average of 5.6 feet/mile. This segment has the steepest slope on the lower river and subsequently has the highest velocities. Due to mechanical thickening (shoving), this reach also has the thickest ice cover. The mainstem (excluding the side channel complexes) appears similar to the main channel in Segment 1, with a broad expanse of gravel and sand bars exposed at low flows when the mainstem is generally confined to one or two channels. The maximum width of the flood plain is 6,000 feet and the minimum is 1,000 feet. The majority of the gravel bars are devoid of vegetation. High summer flows generally inundate the gravel bars, with debris carried along by the flow often piling up on the islands as log jams. At high flows, the water breaches the entrances to side channels and spills into these systems. The side channels seem to function primarily as overflow channels, diverting water away from the mainstem during floods.

3. SEGMENT 3: RIVER MILE 51 TO RIVER MILE 42.5 (Delta Islands)

This reach runs through an intricate system of islands. The mainstem at some high flows becomes diffused and is difficult to differentiate from side channels. Only at the low flows prior to freeze-up can the thalweg be defined. Even then it is split into two channels flowing along both the extreme left and right banks. The majority of the side channels are dewatered at these low flows. The maximum channel width is 4,500 feet at RM 51, with the narrowest portion of 700 feet at RM 42.5. RM 42.5 also marks the joining or convergence of the two main channels emerging from the Delta Islands and the end of this segment. Field investigations documented ground water seeps entering several of the side channels, providing these with a separate source of water isolated from the mainstem. The groundwater seeps are probably related to the mainstem stage since the contribution of flow by groundwater in the side channel seems to diminish with lower water levels in the mainstem.

Two tributaries enter this reach along the east bank. Little Willow Creek and Willow Creek initially flow into a side channel, which then enters the east mainstem at RM 52 about 1,000 feet downstream of the Willow Creek confluence.

The river gradient reduces substantially from 5.6 feet/mile in Segment 2 to 2.9 feet/mile in Segment 3. This may provide an explanation for the complex morphology of this reach. The lower gradient results in reduced water velocities which could result in less degradation and perhaps some aggradation, causing the channels to meander and intertwine.

The east channel conveyed the majority of the flow in 1984. However, this could shift to the west channel if the controlling gravel deposits at the upstream end of the Delta Islands are eroded. The multiple channels of the Delta Islands are forced together by terraces just upstream of the Deshka River at RM 42.

4. SEGMENT 4: RIVER MILE 42.5 TO RIVER MILE 27

This reach is similar to Segment 2, with a well defined mainstem and numerous side channels along both the left and right banks. The Deshka River, at RM 40.6, is the only major tributary entering this segment.

Kroto Slough represents one of the major side channel complexes in this segment. The upstream entrance is located about one-half mile below the confluence of the Deshka River. Although this side channel has several branches which connect with the Susitna mainstem, one channel continues on separately to the Yentna River. This side channel system dewaters at flows less than 13,000 cfs (USGS at Sunshine). However, when the mainstem is ice covered, the stage increases enough to flood the channel, so for a major portion of the year this side channel flows with Susitna and Deshka River waters.

The gradient through this reach continues to decrease with respect to preceding segments. The gradient average of 2.6 feet/mile is also reflected in the lower surface water velocities. Velocities from 3 to 4 fps have been measured when Sunshine flow is 10,000 cfs. Channel widths range from a maximum of 5,500 feet at RM 32.2 to the narrow section of 800 feet at RM 38.5. The side channels through this reach are strictly overflow channels at high water, are generally dewatered at flows below 13,000 cfs, (USGS at Sunshine), or usually between October and April.

At RM 28 the Yentna River joins the Susitna. This is a major tributary draining an area over 6,200 square miles. The Yentna River contributes approximately 40 percent of the annual flow measured at Susitna Station (RM 25.9) by the USGS. However, this is not consistent at all flow ranges. The proportion may vary greatly depending on storm system movement and the glacier mass wasting characteristics of each system. The Yentna discharge approximates the flow on the Susitna measured at Sunshine during low flow periods but often does not respond simultaneously to the same hydrograph peaks. The average annual flow in 1983 was 18,214 cfs. During freezeup the discharge typically drops from about 20,000 cfs in October to under 4,000 cfs by the end of December.

5. SEGMENT 5: RIVER MILE 27 TO RIVER MILE 0

Just downstream of the Yentna River confluence the USGS maintains the last streamflow gage on the Susitna at RM 26. This gage, located at Susitna Station, measures essentially the total flow of the entire Susitna River watershed, an area of about 19,400 square miles. The average discharge is

49,940 cfs, but typically during freezeup the flows drop from about 60,000 cfs to 9,000 cfs during freezeup.

The river reach downstream of Susitna Station represents an area of transition from a river system to an estuary. A dominating feature of this segment is Alexander Slough, also called the Susitna west channel. This represents a major side channel at most open water flows but dewaters just prior to freezeup. When mainstem water enters this side channel the flow essentially becomes isolated and does not re-enter the mainstem except at flood stages. Then an interconnecting channel at RM 9.7 floods. At low flows, such as just prior to freezeup, the side channels are generally dewatered and the mainstem is confined to one channel, although encompassing many exposed sand bars.

The slope through this reach was determined from USGS topographic contours to be about 1.5 feet/mile. Surface velocities average about 2 to 3 fps.

Tributaries entering this reach include Alexander Creek and Fish Creek. Alexander Creek enters Alexander Slough and continues out to Cook Inlet without joining the mainstem. Fish Creek drains the swamplands adjacent to, and east of, the Susitna east channel and enters a side-channel at RM 8. As can be expected, the gradient is so low here that flow from this tributary is greatly restricted by backwater created by mainstem stages.

The National Weather Service has operated a weather station in Talkeetna since 1941. The data from this site are fairly representative of the lower river area and provide good baseline climatic trends for the entire basin. Air temperatures are known to vary considerably between Talkeetna and Cook Inlet, with extremely low winter air temperatures observed between the Delta Islands and Susitna Station. In 1984 R&M Consultants placed a thermograph at

RM 48 in the Delta Islands in order to quantify the air temperature deviation from Talkeetna. These data are plotted in figure 7. Statistical information presented in this section have been summarized and are listed in table 3.

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TABLE 3

SUSITNA RIVER Available Weather Data

Location	Reach Length	Basin Area Gaged (sq.mi)	Gradient (ft/mi)	Annual Average Discharge (cfs)	Major Tributaries	Available Weather * Data
Upper River					West Fork	(R&M)
Denali (RM 291)	27	950	9.3	2,759	East Fork	Denali
					Maclaren	1980-1984
Maclaren River	-	280	-	979	Tyone	
					Oshetna	
RM 233	85	-	5.9	-		
Middle River					Goose	
					Jay	(R&M)
Vee Canyon (RM 223)	10	4,140	25.0	6,404	Kosina	Watana
					Watana	1980-1984
Gold Creek (RM 136)	97	6,160	15.0	9,724	Deadman	Devil Canyon
					Tsusena	1980-1984
RM 98	135	-	13.4	-	Devil	Sherman
					Portage	1982-1984
					Indian	
					Gold Creek	
					Fourth of July	
Lower River						
Chulitna River	-	2,570	-	8,798		
						(NWS)
Talkeetna river	-	2,006	-	4,055		Talkeetna
					Chulitna	1941-1984
Sunshine (RM 84)	14	11,100	5.7	24,000	Talkeetna	
					Trapper	(R&M)
Willow Creek	-	116	-	417	Birch	Delta Island
					Rabideaux	Thermograph
Deshka River	-	592	-	941	Montana	1984
					Goose	
Yentna River	-	6,180	-	18,214	Sheep	
					Kashwitna	
Susitna Station (RM 26)	72	19,400	4.3	49,940	Little Willow	
					Willow	
Cook Inlet (RM 0)	98	-	3.6	-	Deshka	
					Yentna	
					Alexander	
Total	318		8.3			

* Other weather stations operated in the Susitna River basin by R&M Consultants are Glacier 1980-84, and Kosina 1980-84.

IV. RIVER ICE PROCESSES

A. GENERAL FREEZEUP ICE PROCESSES

Previous studies of ice formation on northern rivers have ranged from qualitative descriptions of events to analytical studies of ice cover stability (Newbury, 196). Through these studies a consistent sequence of events has emerged by which an ice cover forms on northern rivers. These events have also been documented on the Susitna River and can be summarized as follows. Generally in October, a continuous trend of cold air temperatures causes the river water temperatures to drop to the freezing point, and frazil ice forms (figure 9). Slush floes appear on the water surface and collect in quiet water, eddies and along the shore, freezing into ice sheets. Anchor ice accumulates on the channel bottom in turbulent shallow reaches. The river current carries the majority of the slush downriver where, on entering the backwater of Cook Inlet, it jams at a constriction to form an ice bridge. From this point the slush packs into an ice cover which accumulates upstream at a rate dependent on the intensity of cold weather, river morphology and the hydrodynamics. Growth of the ice cover continues until the upper and middle river is frozen over and frazil ice is no longer generated. Remaining open water is gradually closed as ice grows laterally from the banks.

1. FRAZIL ICE

The main process of ice development on turbulent northern rivers is the formation and accumulation of frazil ice. Frazil ice forms on open water surfaces when air temperatures are below freezing. Frazil ice is microscopic ice crystals which forms when the river water becomes supercooled. Supercooling occurs when water loses heat to the atmosphere, producing a temperature below the freezing point (i.e. less than 0 C). Supercooling of river water normally does not go below -0.05 C (Michel, 1971). The supercooling of water stops when the heat of fusion of ice formation produces an increase in water temperature. In supercooled water, newly formed frazil ice crystals are very "active" and either agglomerate to form larger grains or adhere to underwater objects. This stage of development may last only a few minutes. Frazil ice takes the shape of flat, circular plates. The frazil ice becomes inactive once the river water returns to 0 C from the supercooled state. The inactive frazil ice grains float to the surface and continue to grow from atmospheric heat exchange.

Frazil ice crystals are continuously changing form. From the initial miniscule crystaline discs they grow rapidly into larger grains (figure 10). The nucleation of frazil is known to be associated with foreign particles such as fine sediments (Osterkamp, 1978). The crystals form around these nuclei, and while the water remains supercooled they grow rapidly in size or stick to other crystals to form ice flocs. The ice flocs have densities nearly equal to water and remain entrained even at low water velocities. If supercooling continues the frazil flocs grow and eventually gain sufficient mass to counteract the turbulence and float to the surface. The frazil slush floes drifting on the surface are agglomerations of highly porous, poorly bonded ice grains that can easily break apart and become re-entrained (figures 11 and 12). The slush is therefore constantly broken up and submerged by turbulence enroute downstream. On the water surface and in close contact to cold air, the slush ice grains grow with the water in the slush pores crystalizing onto the grain surface. Ice particle growth tends towards a spherical shape, suggesting that the flat surfaces grow more ice than at edges or ends. The porosity of the slush decreases as the grain size increases. Measurements of porosity on the Susitna River indicate decreasing values in the downstream direction, which correlates well with the increasing age or residence time of the slush in the downstream direction. (New frazil ice is formed in the colder and more turbulent upstream reaches, then floats downstream.) When flow velocity decreases so that frazil slush remains on the surface, a continuous layer of solid ice forms on the top of the slush floe. Under these conditions the ice grains are no longer being broken apart and the water held in the interstices simply freezes solid, binding the ice particles together in a solid sheet.

The majority of frazil ice is generated at night when air temperatures are usually coldest, and generation is reduced or stopped with sunlight when heat added by solar radiation stops the cooling of the water (Michel, 1971). The variable climatic conditions throughout the Susitna River basin significantly effect the net volume of frazil slush present in the river and, consequently, the rate of ice cover development. The dominating meteorological parameters governing ice formation are air temperature and solar radiation.

2. SHORE ICE

Shore, also called border ice, ice is the first type of ice cover to form over non-turbulent water along a river bank. On many northern rivers an area of laminar flow exists along the banks. Michel (1971) states:

> because in laminar flow there is no intermixing of the top layer with the bottom layers, ... considerable cooling will occur in the top layer while the average water temperature is still far above the freezing point. Ice

is nucleated on the water surface starting in contact with the cold material along the river bank ... forming a clear and solid ice sheet.

Michel also recognizes this as a primary ice cover process, second only to frazil ice accumulation.

Shore ice growth on the Susitna River has not been documented to form exactly the way Michel describes. This is probably due to the high velocity and turbulence of this river. An absolute laminar flow area along the banks is rare on the Susitna and the rapid cooling and subsequent clear ice formation has only occasionally been observed. Shore ice does develop, however, often to extensive dimensions. Flow margins, while not laminar, are relatively slow-moving and water temperatures are close to those at mid-channel. Because the turbulence is less, cooling of the surface does occur, but even a slight amount of mixing prevents the formation of ice on the surface.

Shore ice on the Susitna begins forming soon after frazil ice is first formed, and continues growing towards the channel center until the rate of growth equals the rate of erosion by water velocity (figure 13). Shore ice development begins when frazil slush drifts into the low velocity flow margins along the river banks. Friction against the channel bottom stops the slush, which freezes to the bank. Slush continues accumulating along the flow margins, extending the shore ice out into the channel until flow velocity is high enough to keep the slush moving, preventing it from freezing in place. At this point a shear zone develops where moving slush, carried by the flow, slides along the edge of the fixed shore ice. This usually occurs when the velocity at the shore ice edge exceeds 1.0 fps. The face of the shore ice edge is very rough, consisting of ice grains frozen in place, and the friction on the moving slush ice is enough to slow the velocity of the floes. The slush ice floes are then being forced downstream by the water velocity along their outside edge while also being forced to a standstill along the inside edge by friction against the shore ice. The slush floes then tend to break apart, with the ice grains either being forced underneath the shore ice or deposited along the top edge in a narrow layer. Successive layers are added in this manner, so that the shore ice grows laterally out into the channel and vertically down to the channel bottom by trapping drifting slush ice. This process is known as "buttering" (Lavender, 1981). Low velocity areas subject to this type of frazil slush accumulation include: the inside bank of river meanders; shallow flow margins; eddies downstream of any flow obstruction such as rocks, logs and rapids; backwater areas above flow constrictions; and eddies immediately downstream of a tributary confluence (figure 14). In some reaches the conditions are favorable for extensive shore ice growth from adjacent banks, so that the surface of the flowing water is constricted. In these cases floating slush ice often bridges the narrow gap and freezes in place (see Ice Bridges).

Heavy snowfalls during cold weather often initiate shore ice growth by rapidly covering low-velocity flow margins. If the turbulence is low enough to not entrain the snow layer, then water infiltrated into the snow quickly freezes into a rigid snow-ice cover. Once in place this ice cover continues growing vertically by building up additional layers of black ice. This process has been documented on some shallow areas of the Susitna where velocities are near zero, including backwater zones, sloughs, beaver ponds and lakes.

The growth of shore ice increases the wetted perimeter of the channel while decreasing the cross-sectional area of the channel. This causes an increase in water level. The rising water level often fractures the shore ice, sometimes simply hinging the ice shelf and separating it from the bank. This creates a narrow lead of open water between the bank and the shore ice shelf.

The rate of shore ice growth seems to depend on the channel depth. Shore ice grows quickly over shallow flow margins and slowly in deeper water with high velocities. The gradual decrease in river discharge, therefore, plays an important role in controlling the extent of shore ice growth. If discharge remains high or constant (i.e., the same water level) then shore ice growth is less.

3. ICE BRIDGES

Ice bridges usually initiate an upstream ice cover progression by frazil slush accumulation. This eventually leads to a continuous ice cover on most northern rivers. On the Susitna River, several formation processes have been documented, all of which may occur during the course of one freezeup period. The most important ice bridges to form on the Susitna are those on the lower river, which usually form in the final 10-12 miles upstream of Cook Inlet. In this reach, an ice bridge forms primarily due to low flow velocities induced by a high tide event, allowing the slush floes to accumulate and form a continuous cover from bank to bank that freezes in place. Ice bridges may also form at shore ice constrictions or at shallow riffles where slush ice floes become grounded while having sufficient cohesion to resist breaking apart. Of less significance are ice bridges which form late during the freezeup when water levels rise due to anchor ice (see Anchor Ice) or shore ice growth. The rising water lifts the shore ice away from the river banks. The shore ice fractures into large blocks which are caught by the current and drift downstream until they wedge firmly between a channel constriction or become grounded along the banks. Any type of ice bridge acts as a surface obstruction to slush floes drifting downstream. These floes either contact the ice bridges and submerge, become entrained in the flow and re-emerge further downstream, or accumulate against the upstream edge of the obstruction.

The tide fluctuations in Cook Inlet create a backwater that influences water velocities in the final 15-mile reach of the Susitna River. The tides often fluctuate over 30 feet above the Anchorage reference datum. This datum is 16.4 feet below the local mean sea level. When a high tide of 34 feet occurs at Anchorage the high water line is approximately 17.6 feet above mean sea level. Water velocities are visibly reduced in the 10-mile reach of the Susitna above Cook Inlet.

During the latter half of October, when slush ice floes are drifting downriver and a high tide occurs in Cook Inlet, the floes tend to concentrate in the backwater zone. This accumulation occurs rapidly since the floes are not conveyed through the reach at the same rate as they enter. The accumulations often attain extensive proportions resembling a continuous ice cover but moving at a slow velocity of about 0.5-1.0 fps. When the tide begins to recede the water level drops and flow velocity increases. However, as the surface area of the river decreases it can no longer transport the massive volumes of accumulated ice, resulting in a jam. The ice jam gains stability as the water level continues dropping and more ice floes become grounded. This ice jam prevents incoming ice floes from passing out to sea. At low concentrations of ice floes, a bridge does not develop and the ice accumulation is flushed out to sea. Ice bridges have been observed to form at RM 5 and RM 9 during the 4 years (1981 - 1984) of ice study. The factors which appear to coincide before on ice bridge forms in this reach are cold air temperatures, large volumes of slush ice and a high tide event.

Subsequent to the formation of an ice bridge below RM 10 and the upstream progression of an ice cover, other ice bridges may form above the advancing ice front. The flow velocity is generally reduced in the backwater area upstream of the leading edge. When the slope gradient is low, the flow velocity can be reduced to less than 1 fps for a distance of at least one mile above the ice front. During a cold weather event and with high slush ice discharges, the slush may jam at a channel constriction or river meander upstream of the leading edge but within the backwater zone, leaving an open water reach downstream between the new ice bridge and the old leading edge. Ice cover progression resumes at the new ice bridge. Some slush may break free from the underside of the upstream ice cover, emerge in the open water below the ice bridge, and accumulate along the upstream edge of the old ice front in a thin sheet. This is shown in Figure 14, along with an example of the previously described ice bridges. From 1981 to 1984 river ice bridges have been observed to form at the following river miles:

5	16.5
9	25.9
10	30
12	46.1 (West Channel, Delta Islands)
14	52.1

At low river discharges (i.e., less than 5000 cfs at Gold Creek), several reaches of the middle river between Talkeetna and Gold Creek have a channel configuration that allows wide shore ice development. The shore ice constricts the open water surface area to a narrow lead which becomes plugged by ice floes during a high slush ice discharge. This ice jam freezes in place, and additional ice floes drifting downstream begin accumulating along the upstream edge of the ice bridge. Ice bridges of this type have been documented to form at the following river miles:

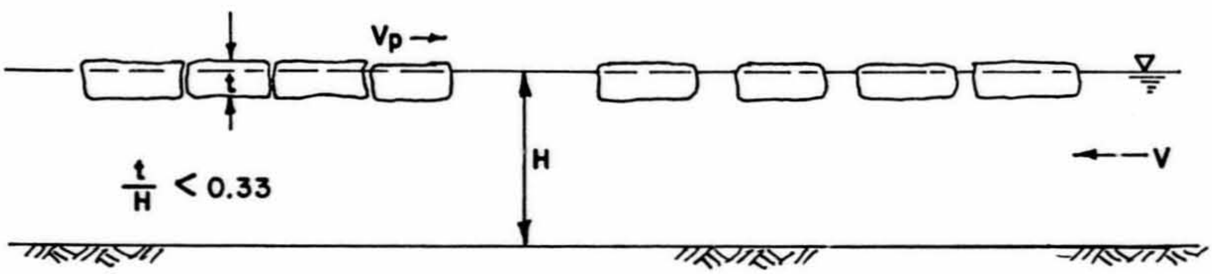
97.4 (lower river)	120.5
98.8	128.5
105.1	135.5

Ice bridge formation is of paramount importance to further development of an ice cover. How or where the bridge forms is not critical, but an obstruction must develop in order to stop the flow of slush out to sea. Once an ice bridge forms the frazil slush rapidly accumulates along the upstream edge by various processes which are dependent on the physical characteristics of the ice and the hydrodynamics of the river. These processes are discussed in the following sections.

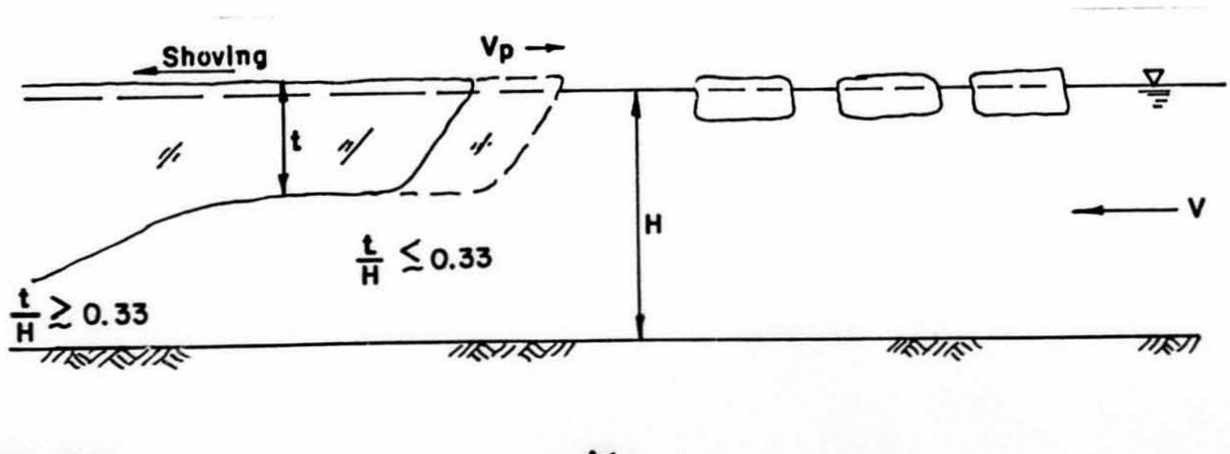
4. ICE COVER PROGRESSION

After the formation of an ice bridge, the upstream progression of an ice cover is controlled by air temperature at the leading edge, the volume of incoming ice discharge, the hydrodynamics of the river flow and the physical properties of the incoming slush ice. Published literature recognizes four conditions for the progression of the leading edge (Calkins, 1983). The following diagrams show the four basic processes of ice cover progression, Vp is ice cover progression rate and V is water velocity, t is ice thickness, and H is water depth.

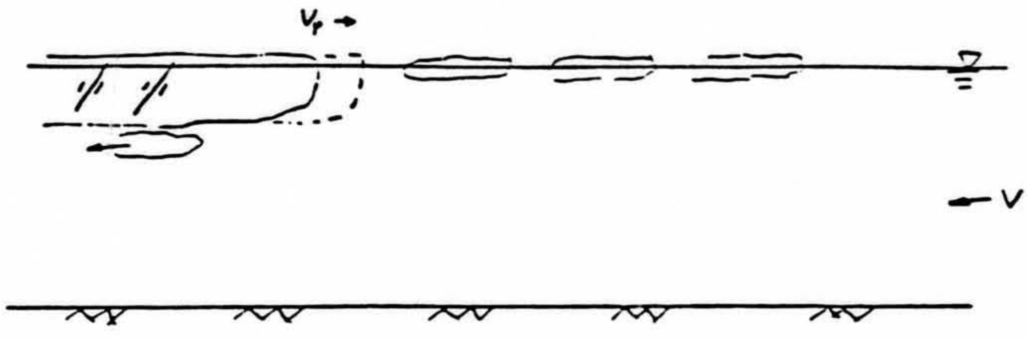
1. Progression by simple juxtaposition of the arriving floes with no subsequent thickening of the ice cover. Ice cover thickness equals initial slush floe thickness.



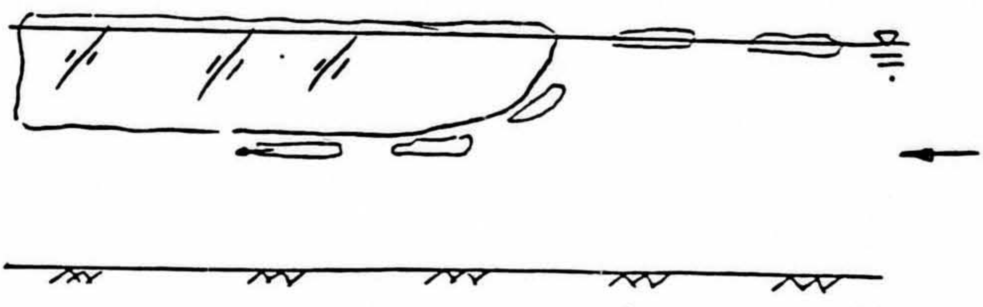
2. Slush floes arriving at the leading edge are compressed to a greater thickness than the original ice floe thickness. This is termed hydraulic thickening and can occur in various degrees when combined with the mechanical thickening process of shoving.



3. Arriving slush ice floes are compressed and added to the cover but some also submerge and break apart, eventually being deposited underneath the ice cover further downstream if lower velocities occur.



4. Arriving slush floes do not accumulate at the ice front but are subducted beneath the cover and may be deposited some distance downstream.



The upstream progression of the ice front by juxtaposition leads to a rapid ice cover development. On the Susitna River this is the predominant process of progression downstream of RM 25. The slush ice floes that drift through this reach have been on the water surface long enough to have formed a solid surface layer. This significantly strengthens the floes so that they resist crushing or breaking apart. Virtually all the floes therefore remain on the surface and come to a stop against the leading edge. The floes pack together and spread across the channel from bank to bank. They accumulate so rapidly during a high ice discharge that voids of open water may remain (figure 15). The shearing stresses of flowing water under the ice cover are not strong enough to compact the ice floes into a tight configuration.

Hydraulic thickening is the primary process of ice cover advance from near RM 25 upstream to the reach near Sherman (RM 130). Even as far downstream as RM 25, the ice floes have not remained continuously on the surface long enough to form a solid layer. The floes therefore lack cohesive strength and deform readily when contacting the leading edge. Hydraulic thickening occurs in various forms, depending primarily upon the water velocity and the cohesive properties of the slush. Generally, with colder air temperatures the cohesion increases. Less ice cover thickening occurs in areas of slower water velocities. Arriving ice floes are plastered along the leading edge to a thickness roughly one-third the water depth in areas where flow velocity is low. Where the river is steeper, the velocity higher, and the cohesion of the slush relatively low, thickening continues by a shoving or compression of the cover. The compression of the cover occurs repeatedly, creating higher upstream water levels and lower velocities until progression can resume. This process is known as staging. Water levels can rise dramatically in a short period of time to many feet above the initial level.

The remaining two processes of undercover deposition are difficult to document, but probably occur to some extent on the Susitna River. However, juxtaposition and hydraulic thickening seem to be the predominant processes.

Air temperatures influence the stability of an accumulating ice cover, thus affecting the frequency and extent of ice shoves and mechanical thickening. Rapid upstream progressions during cold weather periods are due to large volumes of ice being generated upstream and to the fast stabilization of the ice cover as the slush rapidly freezes solid, resulting in fewer and less extensive shoves. Colder air temperatures result in faster stabilization of the ice cover. The equation for estimating solidification of the slush cover is:

$$h\ (t) = \frac{k\ z^{\frac{1}{2}}}{p}$$

where: h(t) = ice thickness at time t in inches

k = empirical coefficient based on snow cover

z = accumulated freezing-degree days (F) since slush floes stopped downstream drift

p = porosity of slush

For example, if the mean daily temperature is 20 F, then in one day the freezing degree-days accumulated equal 12. If no snow lies on the ice then k is about 0.6. With a slush porosity of 0.35, the ice cover on the mainstem would have a solid layer about 1.2 inches thick after 1 hour, about 3.0 inches thick after 6 hours, and 6 inches thick in 24 hours. At 0 F the rate of stabilization would increase so that a solid layer 2.0 inches thick would form in 1 hour and about 5.0 inches thick would form in 6 hours.

Slush ice is relatively weak when compared to black ice, due to the number of bonding surfaces between the small ice grains of slush ice. Black ice, which grows at a slower rate, develops large crystals with fewer boundary surfaces resulting in a substantially stronger material. During warmer temperatures, a solid layer may not form in the slush floes. The compressions then occur concurrently with the arrival of ice floes at the leading edge. This is more difficult to distinguish, as several processes occur simultaneously. The slush ice accumulates in the backwater and rapidly fills the wetted surface area of the open water. The slush floes become grounded along the flow margins, with a shear zone developing where moving slush slides past grounded or fixed shore ice. Slush sliding along the shear zone deposits layers of ice grains along the shore ice, increasing the width of the latter. Additional slush is pushed under the shore ice and fills in any space between the channel bottom and the underside of the shore ice. The slush continues building rapidly onto the shore ice until it has extended out into the channel to some distance where the velocity of the flowing slush prevents further deposition. The shore ice is now in equilibrium for the prevailing flow and temperature conditions, neither building nor eroding. If either the water velocity or air temperature decreases, then the shore ice would begin building out again.

The velocity of slush ice is decreased by friction when contacting the shore ice. This decrease in velocity is transferred to other ice floes further out in the channel. There is generally an increase in velocity from the flow margin to the channel center. Slush therefore tends to accumulate first at the channel perimeter and proceeds towards the channel center, creating a V-shaped leading edge. The fastest flow velocities at center channel are in the notch of the V. Along the sides of the V, the slush floes are compressed and are no longer distinguishable in the resulting ice cover. If air temperatures remain warm enough to prevent the rapid freezing of the surface layer, then the accumulating, unconsolidated ice mass constantly compresses due to the mass of upstream ice and flow friction acting on the ice cover. The momentum of the moving ice is sufficient to compress the cover to thicknesses greater than that necessary for upstream progression. For this reason, ice thickness measurements often detect 10 to 15 feet of slush beneath a solid ice layer of several feet, although the channel gradient or water velocity are not high enough to justify that much resultant staging. Compression or shoving occurs only in reaches of high water velocity (generally greater than 4 fps), but this also depends on the degree of solidification of the slush. Unsolidified slush compresses at lower velocities. The massive bank-to-bank compressions of the entire ice cover usually only occur where water velocities exceed 4 fps.

On the lower river and in some reaches of the middle river, the compressions occur sporadically. The final ice cover shows evidence of compression zones followed by a reach where the floes juxtaposed. At the end of the juxtaposed section, another compression occurs (figure 16). This pattern extends from Cook Inlet to Talkeetna. In constrast, much of the middle river is entirely compressed, with the ice cover shoved laterally until it contacts the surrounding terrace. During a compression the forces within the cover are transmitted to the banks. If the bank slope is low, ice is pushed laterally up the bank well beyond the water level. If the banks are steep, the ice is contained without the lateral spreading. The latter condition is more prevalent on the middle river, with the former more typical of the lower river.

The rapid development of open water leads in the ice cover is evidence of instability between the stable ice and flowing water. The widespread occurrence of the leads suggests that an ice cover, particularly on the middle river, is either eroding or building, but is rarely stable. The rate of erosion is dependent on the air temperature and the water velocity. Open leads can form within 1-3 miles below the ice front, with exceptions noted where leads have developed within a few hundred feet below the leading edge. During extremely cold weather (i.e., below - 15 C) the channel leads begin to form a secondary ice cover by a gradual accumulation of slush at the downstream end. This secondary ice cover progresses upstream until completely covering the open water. If the cold weather ends before a complete ice cover reforms, open water may remain all winter. Erosion of the ice cover is evident by a decrease in water level and a sagging of the ice cover by many feet. This is due partially to a steady but gradual decrease in discharge. However, the primary cause is the erosion or removal of unsolidified slush ice under the solid layer. The entire ice cover between banks settles until the slush contacts the channel bottom along the low flow margins.

5. ANCHOR ICE

In supercooled water, frazil ice crystals have a propensity for adhering to any object in contact with the river flow. When frazil ice adheres to rocks on the channel bottom, it is commonly referred to as anchor ice. Anchor ice generally forms in shallows immediately downstream of a turbulent reach. The turbulence is required to supercool the entire water column down to the channel bottom so that frazil ice forms and is maintained in the active state until it adheres to the substrate. Deeper reaches are generally free of anchor ice because they are less turbulent and the supercooled condition does not effect the entire water column. Anchor ice can accumulate in thick layers in and below shallow rapids where depths do not exceed 4 feet. The greatest accumulations therefore occur in the rapids themselves, often altering the flow regime by either effectively raising the bed surface and increasing the water level, or by restricting the flow and creating a backwater area. Anchor ice "dams" have been documented between Sherman (RM 130) and Portage Creek (RM 149). The thickness of the anchor ice dams can exceed 2 feet. They tend to locally increase water velocity by restricting the cross sectional area, creating turbulence which helps to maintain the supercooled condition of the flow. When supercooling ceases, due to increased air temperature or the formation of an ice cover, anchor ice tends to release from the bottom and float, often taking along material from the channel bottom. Anchor ice is usually readily visible, as it takes on a dark tint (generally appears brown but this varies with depth) from accumulating small sediment particles. The sediment probably was saltating along the bottom until contacting the rough and highly porous surface of the anchor ice. The sediment is trapped between the crystals and is eventually covered by more frazil ice layers.

On clear days, solar radiation or warm air temperatures can raise the substrate temperature sufficiently so that anchor ice breaks away and floats to the surface, often carrying with it accumulations of sediment. The anchor ice floes drift downstream, eventually becoming incorporated in a downstream ice cover.

Studies of anchor ice have shown it to be an important ecological factor relative to lentic macrofauna and fishes (Needham and Jones, 1959). Anchor ice forms only in areas which have no upwelling of relatively warm groundwater through the substrate. When anchor ice releases from the channel bottom it generally dislodges bed material, causing bottom macrofauna to become entrained and made available as food to resident fish species.

B. SUSITNA RIVER ICE COVER DEVELOPMENT

This section discusses ice cover formation on the Susitna River from the mouth at Cook Inlet to the middle river reach near Vee Canyon.

1. COOK INLET TO THE CHULITNA RIVER CONFLUENCE

The initiation of ice cover development on the Susitna River usually occurs when large volumes of slush ice fail to pass through a channel constriction near the river mouth at Cook Inlet. The meander at RM 9 forces the ice floes to contact the outside (west) bank. At a high tide the resulting backwater further reduces the water velocity. With high ice concentrations and cold air temperatures, bridging is likely to occur. Cold air temperatures are necessary to quickly freeze the ice in place. Upstream ice cover progression by accumulating ice floes can begin as soon as the slush ice velocity slows. The higher upstream velocity of incoming slush causes a greater volume of slush to accumulate against the upstream edge than can be expelled from the downstream end. Therefore, with a low channel gradient and slow water velocity the ice cover "advances" upstream by juxtaposing (Figure 15).

A fixed ice cover imparts a frictional resistance to flowing water, causing an increase in water level. The increase in water level, called staging, is required to slow water velocities to such a point that ice floes are not swept beneath the leading edge of the ice cover. The maximum staging level observed below RM 26 is about 2-3 feet, with ice thickness averaging 3 feet. This ice thickness refers to the total of solid surface ice (frozen slush) and the underlying loose slush. Air temperature controls the thickness of the solid ice fraction simply by continually freezing additional slush ice. If the underlying slush ice is removed by erosion, then growth of the solid surface ice layer slows significantly.

Prior to the initiation of freezeup, Alexander Slough is usually dewatered when decreasing mainstem flows drop below the critical level to overtop the entrance. The developing ice cover stages sufficiently to flood the channel. Water usually inundates the snow cover in the side channel and along the flow margins. This quickly freezes solid, producing a shorefast ice cover. The flowing open water in Alexander Slough often requires more than four additional weeks to freeze, primarily because the stage does not increase enough to allow the passage of slush ice. The slush ice rafts are usually 2-3 feet thick. Unless the stage increases by that value above the threshold elevation of the channel entrance, the floes can not drift into the side channel. The depth of water over the channel entrance at Alexander Slough has been observed at 1 foot, so the ice rafts become grounded a short distance from the main channel. No slush ice cover progression has therefore been observed in Alexander Slough. Closure is achieved by border ice growth.

Higher water velocities near RM 26 prevent ice cover progression by simple juxtaposition, and mechanical thickening of the cover begins. This process of thickening occurs after the slush ice cover is in place. The frictional shear between high velocity water and the fixed ice creates an unstable condition, which can cause a portion of the ice cover to shift. This sudden movement upsets the stability of adjacent ice and in seconds the entire local cover is moving downstream and consolidating. A chain reaction of this type has been observed to affect over 2,000 feet of ice cover. Compression of unconsolidated slush ice during this move causes the total thickness to increase. The ice cover may also be shoved laterally onto the banks often above the water line. Several ice compression phases have been timed to last more than 8 minutes, which brought the leading edge downstream about one-half mile and increased the stage about two feet.

Aerial observations noted that the Yentna River often contributes about 50-60% of the total estimated ice volume below the Susitna confluence. When the ice front reaches the confluence it separates and continues up the Susitna River, while another leading edge goes up the Yentna River (figure 16). The progression rate on the Yentna River is faster due to its morphological characteristics and high ice discharge. The Yentna is generally narrower, shallower and has fewer channels compared to the Susitna. The slower water velocities also permits less ice thickening, therefore requiring less ice volume to develop a stable cover.

A stage increase of 3.9 feet has been measured at the entrance to Kroto Slough (RM 40.1). This is sufficient to overtop the slough with a flow depth of 1.5 feet at the entrance, but few ice floes can enter due to a typical thicknesses of about 2 feet. The elevated mainstem stage also effects the Deshka River by creating a backwater zone which extends about 2 miles upstream. The surface water velocities on the Deshka are reduced enough to allow Susitna ice floes to be pushed up the Deshka for about 100 feet. Slush ice drifting down the Deshka River encounters this barrier to flow and an upstream advance by accumulating ice is initiated. The Deshka has low water velocities and the slush ice advances by juxtaposition, eventually freezing into a solid ice cover.

When the ice cover progression enters the Delta Islands the leading edge splits. Ice fronts advance separately up the east and west channels. The east channel ice cover progresses more slowly. The advancing ice cover generally causes stage increases high enough to inundate the snow cover over the Willow Creek gravel fan. This saturated snow eventually freezes into an ice cover. However, the water course from Willow Creek is not usually altered. The stage through this area increases about 3 feet during the ice front advance. Slush ice from the Susitna does not encroach on the creek confluence. In 1983, the stage increase measured on the west channel of the Delta Islands, near RM 48, was about 2.5 feet. This channel was flooded but no slush ice entered. The Susitna ice cover progresses through the Delta Islands and converges near RM 51, then continues to proceed upstream.

The reach above the Delta Islands contains more secondary channels within a broad gravel and sand floodplain. The primary or main channel is relatively shallow at freezeup and when the water level rises a wide area is generally flooded. The ice floes remain contained within the main channel, since water depth is not sufficient to float them laterally out of the thalweg. As the ice cover proceeded through this reach in 1983, a large portion of the flood plain was inundated. The saturated snow eventually froze solid, creating an ice cover but without the hummocked appearance of the main channel slush ice cover.

Many of the lower river side channel complexes are flooded during ice cover progression. When the staged mainstem overtops the channel entrances, existing ice over isolated pools in side channels is immediately broken up and washed downstream. Mainstem slush ice often accompanies the surge through the side channel at RM 60. The slush ice and ice debris occasionally accumulates in small jams a short distance below the side channel entrance, but is usually carried out to the mainstem. A mainstem stage increase of about 3 feet occurs near the mouth of Kashwitna River (RM 60) (figure 17).

The effects of mainstem staging are not evident to a significant degree at the mouth of Sheep Creek. Sheep Creek enters a side channel that extends from RM 62 to RM 67. Through this reach the mainstem is along the west bank. Since the side channel complex is on the east bank, it is not usually affected by backwater or overtopping during ice cover progression.

Goose Creek enters a side channel that runs from RM 69 to RM 72. This side channel was flooded in 1984 but not in 1983 (figure 18).

The mouth of Montana Creek is significantly influenced by the staging process. The existing channel mouth steadily degrades when the mainstem water level recedes. The absence of an extensive backwater area results in higher tributary velocities at the mouth and subsequently more downcutting at low mainstem flows. Montana Creek can therefore become entrenched in the alluvial fan. Heavy anchor ice deposits usually accumulate on the substrate, and a large ice dam has been observed to develop about 200 feet above the confluence. When the ice front approaches RM 73, 2 miles downstream of the tributary confluence, the mainstem stage adjacent to Montana Creek increases by about 1 foot and creates a backwater zone that floods the tributary channel and ice dam. A maximum stage increase of 7.1 feet was measured on November 18, 1983, and most of the confluence area was inundated. The snow cover over much of the alluvial fan was flooded and subsequently formed ice. An additional 2 feet of staging would have been required to completely overtop the alluvial fan.

Ice thicknesses measured adjacent to the Montana Creek confluence (RM 77) in late January, 1984 averaged 6.8 feet, with a minimum of 1.3 feet and a maximum of 7.0 feet. The channel gradient is relatively steep in this area, with the ice cover usually remaining unstable. After the initial progression through this reach, an open lead appears from about RM 71 to RM 85. This lead eventually freezes over again when entrained frazil ice floats and accumulates at the lower end and along the sides. This secondary progression may not completely close the lead. In March 1984, open water remained from RM 81 to RM 85.

Sunshine Slough and side channels are usually overtopped and flooded. Slush ice has not been observed entering this system due to an insufficient overtopping depth at the entrance. These channels subsequently require an additional 8-12 weeks to freeze over, with many leads existing all winter.

The side channels leading to the entrance of Birch Creek Slough are flooded but the stage does not increase enough to overtop the slough entrance. The maximum observed increase was 3.1 feet in 1983, near the upstream entrance to Birch Creek Slough. An additional foot would have been necessary for overtopping.

Trapper Creek is not affected by Susitna mainstem freezeup. At prefreezeup stages Trapper Creek does not merge with the Susitna until RM 90. No slush ice floes drifted up into the creek mouth, and flow remains unrestricted by ice. With the exception of some backwater, Birch Creek and Sunshine Creek are also unaffected by the ice advance. The flow in Rabideux Creek is low during freezeup (discharge estimated less than 10 cfs) and the staging has been measured to reached 7 feet over the open water level.

Most of the side channels below Talkeetna are flooded to some extent, often only saturating the snow cover. Several side channels, such as Sunshine Slough and Kroto Slough, remain flooded all winter. The maximum staging levels seem to be temporary, and water levels along the entire lower river recede once the leading edge has moved upstream several miles. This may be due to ice cover erosion and the development of leads, or seepage of water into the adjacent banks.

A reduction in mainstem stage may cause the ice cover to sag and eventually collapse. A thinning of the ice cover by erosion has also been measured over high velocity cells along a cross section. Ice thickness measurements along the banks usually reveal thicknesses representative of the original ice cover at the time of progression. Thin covers have been located over fast flowing water, either at mid-channel or along either bank. The thin ice covers are indicative of areas where water velocity (friction) is high enough to erode the underside of the ice cover. Table 4 lists the major open leads documented by aerial photography in 1983 on the lower and middle river. Figure 19 illustrates the general freezeup sequence for the lower Susitna River. Water level fluctuations due to staging at several lower river sites have been plotted and are shown in figure 20. See table 5 for ice thicknesses.

The following sequence summarizes the highlights and general freezeup characteristics of the lower river from Cook Inlet to the Chulitna River confluence.

1. An ice bridge forms at a channel constriction near the mouth of the Susitna during a high tide and high slush ice discharge.

2. A rapid upstream advance of an ice cover by slush accumulation.

3. Thin, unconsolidated initial ice cover forms.

4. Minimal staging (2-4 feet) occurs up to Sunshine, with over 4 feet occurring near Talkeetna.

5. Little telescoping or spreading out of the ice cover occurs due to shoving. Ice cover generally is confined to the thalweg channel.

6. Tributaries generally continue flowing through the winter.

Table 4

Major Annually Recurring Open Leads
Between Sunshine RM 83 and Devil Canyon RM 151
Locations and Dimensions on March 2, 1983

Location of Upsteam End River Mile #	Channel Type	Type of Lead(1)	Approx. Length (Ft)	Widest Point (Ft)	Continuous or Discontinuous
85.0	Mainstem	Velocity	550	80	Continuous
87.1	Slough	Velocity	4,500	50	Discontinuous
87.6	Mainstem	Velocity	700	100	Continuous
89.0	Mainstem	Velocity	1,200	100	Continuous
	Side Channel	Velocity	2,500	40	Continuous
89.5	Mainstem	Velocity	1,400	60	Discontinuous
91.0	Mainstem	Velocity	1,700	80	Discontinuous
92.3	Mainstem	Velocity	1,300	110	Discontinuous
93.7	Mainstem	Velocity	3,500	110	Continuous
94.0	Mainstem	Velocity	3,500	20	Discontinuous
95.2	Side Channel	Velocity	2,400	100	Continuous
96.9	Side Channel	Velocity	5,600	150	Discontinuous
97.0	Mainstem	Velocity	1,100	30	Continuous
102.0	Mainstem	Velocity	2,400	100	Discontinuous
102.9	Mainstem	Velocity	600	100	Continuous
103.5	Mainstem	Velocity	1,850	100	Discontinuous
104.1	Mainstem	Velocity	280	70	Continuous
104.5	Mainstem	Velocity	1,700	110	Continuous
104.9	Mainstem	Velocity	900	150	Continuous
105.9	Mainstem	Velocity	1,050	100	Continuous
106.1	Mainstem	Velocity	200	60	Continuous
106.4	Mainstem	Velocity	370	50	Continuous
106.6	Mainstem	Velocity	350	50	Discontinuous
107.4	Mainstem	Velocity	200	50	Continuous
109.1	Mainstem	Velocity	550	100	Discontinuous
110.3	Mainstem	Velocity	150	100	Discontinuous
110.5	Mainstem	Velocity	290	50	Continuous
110.9	Mainstem	Velocity	450	50	Discontinuous
111.5	Mainstem	Velocity	1,600	100	Continuous
111.7	Mainstem	Velocity	500	90	Continuous
111.9	Mainstem	Velocity	900	150	Continuous
112.5	Mainstem	Velocity	700	100	Discontinuous
112.9	Mainstem	Velocity	500	110	Continuous
113.8	Mainstem	Velocity	600	110	Continuous
117.4	Mainstem	Thermal	780	60	Continuous
117.9	Side Channel	Thermal	1,260	120	Discontinuous
119.6	Side Channel	Thermal	550	50	Continuous
119.7	Mainstem	Velocity	350	50	Continuous

TABLE 4 (Continued)

Location of Upsteam End River Mile #	Channel Type	Type of Lead(1)	Approx. Length (Ft)	Widest Point (Ft)	Continuous or Discontinuous
120.3	Mainstem	Velocity	800	100	Continuous
121.1	Mainstem	Velocity	550	100	Continuous
121.8	Side Channel	Thermal	1,450	30	Discontinuous
122.4	Slough (7)	Thermal	1,850	60	Discontinuous
122.5	Slough (7)	Thermal	380	50	Continuous
122.9	Slough (7)	Thermal	1,950	80	Discontinuous
123.1	Mainstem	Velocity	1,000	80	Continuous
123.9	Side Channel	Thermal	200	50	Continuous
124.4	Side Channel	Velocity	270	40	Continuous
124.9	Mainstem	Thermal	600	90	Continuous
125.3	Slough (8)	Thermal	3,500	50	Discontinuous
125.5	Mainstem	Velocity	2,140	100	Continuous
125.5	Slough (8)	Thermal	800	500	Continuous
125.6	Mainstem	Velocity	350	60	Continuous
125.9	Slough (8)	Thermal	580	50	Continuous
126.1	Slough (8)	Thermal	500	30	Continuous
126.3	Slough (8)	Thermal	250	50	Continuous
126.8	Slough (8)	Thermal	1,500	80	Discontinuous
127.2	Side Channel	Thermal	2,450	50	Continuous
127.5	Mainstem	Velocity	700	80	Continuous
128.9	Slough (9)	Thermal	5,060	100	Continuous
128.5	Side Channel	Thermal	1,210	30	Discontinuous
128.8	Side Channel	Thermal	380	20	Continuous
129.2	Slough	Thermal	4,000	30	Discontinuous
130.0	Mainstem	Velocity	600	90	Continuous
130.8	Side Channel	Thermal	5,000	50	Discontinuous
130.7	Mainstem	Velocity	150	50	Continuous
131.1	Mainstem	Velocity	490	90	Continuous
131.3	Mainstem	Velocity	800	100	Continuous
131.5	Side Channel	Thermal	5,000	80	Discontinuous
131.3	Side Channel	Thermal	900	90	Discontinuous
132.0	Mainstem	Velocity	150	20	Continuous
132.1	Mainstem	Velocity	500	20	Discontinuous
132.3	Mainstem	Velocity	400	80	Continuous
132.6	Mainstem	Velocity	1,350	80	Continuous
133.7	Slough	Thermal	6,000	60	Continuous
133.7	Mainstem	Velocity	1,110	100	Continuous
134.3	Slough (10)	Thermal	4,500	40	Continuous
134.0	Side Channel	Thermal	1,200	50	Continuous
134.5	Side Channel	Thermal	850	100	Continuous
135.2	Mainstem	Velocity	1,580	90	Discontinuous

TABLE 4 (Continued)

Location of Upsteam End River Mile #	Channel Type	Type of Lead(1)	Approx. Length (Ft)	Widest Point (Ft)	Continuous or Discontinuous
135.7	Slough (11)	Thermal	5,500	80	Continuous
136.0	Mainstem	Velocity	230	80	Continuous
136.3	Side Channel	Thermal	2,050	40	Continuous
136.7	Mainstem	Thermal	1,620	80	Continuous
137.1	Mainstem	Velocity	750	60	Continuous
137.4	Side Channel	Thermal	2,500	20	Discontinuous
137.8	Slough (16)	Thermal	1,400	30	Discontinuous
138.2	Mainstem	Velocity	2,000	150	Continuous
138.9	Mainstem	Thermal	2,100	150	Continuous
139.0	Mainstem	Velocity	780	20	Continuous
139.1	Mainstem	Velocity	500	30	Continuous
138.4	Mainstem	Velocity	600	30	Continuous
140.6	Side Channel	Thermal	1,900	100	Discontinuous
	Slough (20)	Thermal	1,100	20	Continuous
142.0	Slough (21)	Thermal	3,850	40	Discontinuous
141.5	Mainstem	Velocity	850	40	Continuous
142.0	Mainstem	Velocity	950	50	Continuous
142.6	Mainstem	Velocity	1,600	150	Discontinuous
142.8	Mainstem	Velocity	850	150	Continuous
143.6	Mainstem	Velocity	550	20	Discontinuous
	Mainstem	Velocity	280	20	Continuous
143.8	Mainstem	Velocity	780	100	Continuous
143.9	Mainstem	Velocity	500	30	Continuous
144.5	Mainstem	Velocity	900	100	Discontinuous
	Slough (22)	Thermal	250	20	Continuous
144.6	Slough (22)	Thermal	300	20	Continuous
145.5	Mainstem	Velocity	1,150	100	Continuous
146.9	Mainstem	Velocity	700	100	Continuous
147.1	Mainstem	Velocity	850	80	Discontinuous
147.7	Mainstem	Velocity	150	40	Continuous
148.1	Mainstem	Velocity	420	50	Discontinuous
148.5	Mainstem	Velocity	680	140	Continuous
149.0	Mainstem	Velocity	400	60	Continuous
149.5	Mainstem	Velocity	500	80	Continuous
150.0	Mainstem	Velocity	350	20	Discontinuous
150.2	Mainstem	Velocity	750	100	Continuous
151.2	Mainstem	Velocity	2,800	100	Discontinuous

(1) Velocity indicates lead kept open by high-velocity flows. Thermal indicates lead kept open by groundwater seepage.

TABLE 5

SUSITNA RIVER ICE THICKNESS SUMMARY 1981-1984

1981

Location	Date	Average Thickness Solid	Slush
Vee Canyon (RM 223)	01/13/81	3.1	30
Deadman Cr (RM 187)	02/27/81	2.6	4.0
	04/04/81	3.0	0
URX-102 (RM 186.6)	03/04/81	2.8	1.3
URX-103 (RM 185.7)	03/04/81	2.5	1.5
URX-104 (RM 185.3)	03/05/81	2.0	3.8
URX-105 (RM 184.8)	03/05/81	2.5	2.1
URX-106 (RM 184.5)	03/06/81	2.4	3.4
URX-107 (RM 184.2)	03/06/81	2.4	2.4
URX-108 (RM 183.6)	03/07/81	2.2	3.3
URX-109 (RM 181.9)	03/07/81	2.5	2.3
URX-110 (RM 182.6)	03/08/81	2.0	2.0
Watana (RM182.3)	04/01/81	2.1	2.1
URX-112 (RM 181.6)	03/08/81	3.0	-
URX-113 (RM 180.1)	03/09/81	3.3	1.9
URX-114 (RM 179.7)	03/09/81	2.5	2.2
URX-115 (RM 178.8)	03/10/81	2.5	2.2
URX-116 (RM 176.8)	03/11/81	1.3	5.5
URX-117 (RM 176.2)	03/11/82	2.6	1.5
URX-118 (RM 173.9)	03/11/81	2.0	3.0
URX-119 (RM 170.0)	03/12/81	2.0	3.0
URX-120 (RM 167.1)	03/12/81	2.0	2.3
URX-121 (RM 162.5)	03/13/81	3.9	-
Portage Cr (RM 148.8)	03/15/81	2.4	1.3
Gold Creek (RM 136.6)	01/14/81	2.1	1.0
	02/27/81	2.3	0.9
Sherman (RM 128.5)	03/05/81	2.1	0.6

1982

Location	Date	Average Thickness Solid	Slush
Deadman Cr. (RM 187)		2.9	4.4
Watana (RM 182.3)	03/11/82	3.0	1.5
Portage Cr (RM 148.8)	03/13/82	2.5	1.7
LRX-61 (RM 148.6)	04/16/82	3.0	3.0
LRX-53 (RM 140.2)	04/13/82	2.0	2.5
Curry (RM 120.6)	03/13/82	3.2	1.5

1983

Location	Date	Average Thickness Solid	Slush
Watana (RM 182.3)	02/04/83	2.4	0
	04/12/83	2.8	0
Portage Cr	02/04/83	2.5	-
(RM 148.8)	04/12/83	3.0	1.1
Gold Cr	02/04/83	1.6	0
(RM 136.6)	04/12/83	2.3	0
Curry	02/04/83	1.9	1
(RM 120.6)	04/12/83	2.2	1
Chulitna Conf	02/04/83	2.9	2
(RM 98.6)	04/12/83	2.8	2

Curry (RM 120.6)	02/27/81	1.8	1.9
Chase (RM 103.3)	03/05/81	2.5	2.0

7. The following major side channel complexes are subject to overtopping during freezeup due to mainstem staging that exceeds the threshold elevation.

   a. Alexander Slough

   b. Delta Islands Side Channels

   c. Rustic Wilderness Side Channel

   d. Goose Creek Side Channel

   e. Sunshine Side Channel

8. Flooded snow forming snow ice along channel margins, with variable widths.

9. High initial freezeup discharges near 16,000 cfs at Sunshine are common, with low final discharges of about 5,000 cfs (based on USGS daily computed values).

10. Gravel bars and islands are seldom overtopped.

11. Flow is often diverted into connecting side channels.

12. Ice cover sags due to a gradual decrease in discharge, bank storage, and erosion of the ice cover.

13. Open leads persist in side channels and high velocity zones through March.

14. Surface area of open water decreases due to steady ice accumulations and decline of water surface.

15. Clear ice builds up under slush ice cover.

16. Minimal shore ice develops, due to relatively warm air temperatures before ice cover advances.

2. CHULITNA RIVER CONFLUENCE TO GOLD CREEK

When an ice bridge forms at the Chulitna confluence, ice progression moves upstream from the confluence to the vicinity of Gold Creek. Depending on climatic conditions, this bridge may form either when ice cover progression in the lower river reaches the confluence, or is well short of it. Depending on the flow rate, ice concentrations and channel morphology, an ice bridge may form in November or December just upstream of the confluence of the Susitna and Chulitna Rivers (figure 21). The flow discharge at Gold Creek during this period is typically about 4,900 cfs. In some years with severe cold periods occurring during ice front progression, one or more secondary bridges may form upstream of the confluence bridge, forming secondary leading edges.

The processes of ice cover telescoping, sagging, open lead development and secondary ice cover progression are the predominant characteristics through this reach (figure 22, 23 and 24). Telescoping, or shoving, occurs during consolidation of the ice cover. When the velocity at the leading edge is low, ice floes drifting downstream contact the edge, remain on the surface, and accumulate upstream by juxtaposition at a rate proportional to the concentration of slush ice and to the channel width. This accumulation zone can be extremely long, generally being governed by the local channel gradient, amount of staging and extent of the resulting backwater. This buildup continues until a critical velocity is encountered, causing the leading edge to become unstable with ice floes submerging under the ice cover. The pressure on a thin ice cover increases as ice mass builds up and higher velocities are reached in conjunction with upstream advance. At an undetermined critical pressure, the ice cover becomes unstable and fails. This sets off a chain reaction, and within seconds the entire ice sheet is moving downstream. Several miles of ice cover below the leading edge can be affected by this consolidation. This process results in ice cover stabilization due to a shortening of the ice cover, substantial thickening as the ice is compressed, a stage increase, and telescoping. The shoving occurs only during each consolidation. As the ice compresses downstream, tremendous pressures are exerted on the ice cover below the accumulation zone and on the river banks. The ice mass shifts to relieve the stresses exerted on it by the upstream cover, often becoming thicker in the process. This tends to further constrict the flow, resulting in an increase in stage. As the stage increases, the entire ice cover lifts. Any additional pressures within the ice cover can then be relieved by lateral expansion of the ice across the river channel. This process of lateral telescoping can continue until the ice cover has either expanded bank to bank or else has encountered some other obstruction (such as gravel islands) on which the ice becomes stranded.

The ice cover over water-filled channels continues to float during ice cover progression. However, because of constant contact with high-velocity water, the ice cover erodes rapidly in areas, sagging and eventually collapsing. In some reaches these open leads can extend for several hundred yards. A secondary ice cover generally accumulates in the open leads, often completely closing the open water by the end of March. The process is similar to the initial progression except on a smaller scale. Slush ice begins accumulating against the downstream end of the leads and progresses upstream. Generally it takes several weeks to effect a complete closure (figure 25).

Ice cover sagging, collapse, and open lead development usually occurs within days after a slush ice cover stabilizes (figure 26 and 27). A steady decrease in flow discharge gradually lowers the water surface elevation along the entire river. Also, the staging process which had raised the water surface within the thalweg channel tends to seek an equilibrium level with the lower water table by percolating through the gravels of the surrounding terraces.

The ice cover continues to move up the Susitna River, although at a steadily decreasing rate as the channel gradient increases. Since the gradient and the river velocities are increasing, staging levels must increase in order to create sufficient backwater to slow velocities to allow ice juxtaposition. Although flows are only in the range of 3,000-5,000 cfs at this time, the water rises to levels equivalent to open water flows of up to 45,000 cfs. This often causes breaching of upstream berms on many of the sloughs and side channels. Significant quantities of slush ice are swept into these channels, entering the backwater area caused by the downstream staging. The slush ice then consolidates and freezes in the side channel, resulting in ice thicknesses of up to 5-6 feet. This process occurs at different levels in different years and at different locations on the river.

Many of the sloughs have groundwater seeps which persist through the winter. This groundwater is relatively warm, with winter temperatures of 1-3

C(R&M, 1982). This is sufficiently warm to prevent a stable ice cover from forming in those areas not filled with slush ice. This relatively warm flow develops ice along the margins, constricting the surface area to a narrow lead. The leads rarely freeze over, often extending for thousands of feet downstream. Open water was observed all winter in the following sloughs in this reach:

Slough 7
Slough 8A
Slough 9
Slough 10
Slough 11

The ice front progression rate decreases as the ice front moves upriver. In 1982, the progression rate slowed to 0.05 miles per day by the time it reached Gold Creek. The slush ice front progression from the Susitna/Chulitna confluence generally terminates in the vicinity of Gold Creek, about 35 to 40 miles upstream from the confluence, by December or early January. This is probably due to the increase in gradient, and to the reduction in frazil ice generation in the upper river as it develops a continuous ice cover. The upper river freezes over by border ice growth and bridging before the advancing leading edge has an opportunity to reach there. See table 5 for ice thicknesses. Figure 19 shows a generalized schematic of middle river freezeup.

The freezeup characteristics on the Susitna River between Talkeetna and Gold Creek are summarized as follows:

1. Frazil ice plumes appear as early as September, but more commonly in early October.

2. Velocities are generally between fps.

3. Discharges at Gold Creek range from 4,900 cfs on November 1 to 1,500 cfs by the end of March. (USGS estimates).

4. Ice bridge sometimes initiate an independent ice cover progression from the Susitna/Chulitna confluence.

5. The rate of ice advance gradually decreases from 3.5 miles per day near the confluence to 0.05 miles per day at Gold Creek.

6. Flow diversions into side channels and some sloughs occur.

7. Surface ice constrictions are formed by border ice growth.

8. Staging levels of 4-6 feet occur.

9. Ice pack consolidates through telescoping of ice cover laterally across channel.

10. Ice cover sags.

11. Open leads and secondary ice covers are common.

12. Berm breaches at Slough 8A.

13. Staging affects the local water table.

14. Thermal influx by groundwater seepage prevents ice cover formation in sloughs that are not breached and inundated with slush.

3. GOLD CREEK TO DEVIL CANYON

The reach from Gold Creek to Devil Canyon freezes over gradually, with a complete ice cover occurring much later than on the river further downstream. The delay can be explained by the relatively high velocities induced by the steep gradient and by the absence of a continuous ice pack progression past Gold Creek. The river upstream of this reach usually freezes over by late December (figure 28), resulting in an insufficient length of open water remaining to generate the large volumes of frazil necessary to cause the ice cover to progress past Gold Creek (figure 29).

The most significant features of freezeup between Gold Creek and Devil Canyon are wide border ice layers, ice build-up on rocks and formation of ice covers over eddies. Ice dams have been identified at several locations below Portage Creek (figures 30 to 33). Generally, these dams form when the rocks to which the frazil ice adheres are located near the water surface. When air temperatures are cold (less than -10 C), the ice-covered rocks continue accumulating additional layers of anchor ice until they break the water surface. The ice-covered rocks effectively increase the water turbulence, stimulating frazil production and accelerating ice formation. The ice dams are often at sites constricted by border ice. The dams and constrictions create a backwater area by restricting the streamflow, subsequently causing extensive overflow onto the border ice. The overflow bypasses the ice sills and re-enters the channel at a point further downstream. Within the backwater area, slush ice accumulates in a thin layer from bank to bank and eventually freezes.

Since the ice formation process in this reach is primarily due to border ice growth, the processes described for the Talkeetna to Gold Creek reach do not occur. There is only minimal staging. Sloughs and side channels are not breached at the upper end, and remain open all winter due to groundwater inflow. Open leads exist in the main channel, but are primarily in high-velocity areas between ice bridges.

To summarize, the following are the significant freezeup characteristics of the river reach between Gold Creek and Devil Canyon.

1. The reach has a steep gradient, high velocities, and a single channel.

2. A discontinuous ice cover occurs, usually by formation of local ice covers separated by open leads. This results in a late freeze over, generally in March.

3. There is extensive border ice growth, with very wide layers of shore-fast ice constricting the channel.

4. Anchor ice dams create local backwater areas, which form ice covers and cause overflow.

5. Ice covers exist over eddies which form behind large boulders in the channel.

6. Minimal staging occurs. No sloughs are breached, and no flow is diverted into side channels.

7. Few leads open after the initial ice cover. Minimal ice sagging occurs.

8. Thermal influx by groundwater seeps keeps sloughs open all winter.

9. Extensive development of snow ice occurs.

4. DEVIL CANYON (to Devil Creek)

Ice processes in Devil Canyon (RM 150 to RM 151.5) create the thickest ice along the Susitna River, with measured thicknesses of up to 23 feet (R&M, 1981B). The remote, inaccessible canyon has a narrow, confined channel with high flow velocities and extreme turbulence, making direct observations difficult. Consequently, in 1982 a time-lapse camera, on loan from the Geophysical Institute, University of Alaska, was mounted on the south rim of the canyon to document the processes causing these great ice thicknesses.

Large volumes of slush ice enter the canyon from upstream, generated either by upstream rapids or by heavy snowfall. Additional frazil ice is generated in the extremely turbulent flow through the canyon. The slush ice jams up repeatedly in a plunge pool below the canyon and the ice cover progresses upstream, staging the water level over 25 feet above the normal open water level. However, the slush ice has little strength, and the center of the ice cover rapidly collapses after the downstream jam disappears and the water drains from beneath the ice. Some slush ice freezes to the canyon walls, increasing in thickness each time the staging process is repeated. The ice cover forms and erodes several times during the winter.

Two reaches in Devil Canyon were noticed on the Geophysical Institite film. There were a total of 6 ice cover advances observed on the lower reach and 3 on the upper. This difference is due primarily to a steeper gradient, higher velocities and turbulence in the upper section. Only during extreme ice discharges did the upper reach form an ice cover. The initial ice cover developed in October over both reaches, but rapidly eroded away, leaving only remnant shore ice. The second major ice cover event occurred in December, with the final ice cover forming in January. All of the major ice advances seemed to be related to heavy snowfalls. A storm in January left an ice cover on the lower reach which appeared to be stable. The low discharges in January could explain the longevity of this ice cover.

Devil Canyon and the reach between Devil Creek (RM 161) and the Devil Canyon damsite (RM151) are the first areas on the Susitna to form ice bridges and develop an extensive ice cover. Ice covers of one mile in length were observed to form about two miles below the Devil Creek confluence as early as October 12, 1982, despite relatively warm air temperatures. The ice formation process at this point is believed to be similar to that in Devil Canyon.

To summarize the freezeup in Devil Canyon:

1. The narrow, confined channel has high flow velocities and turbulence.

2. There is early formation of ice bridges and loosely packed slush ice covers.

3. Ice covers form and erode several times during the winter.

4. The ice covers are inherently unstable, eventual collapsing long before breakup.

5. There are extreme staging levels and ice thicknesses, with ice accumulations up to 23 ft.

5. DEVIL CANYON TO THE OSHETNA RIVER

Lateral accumulation of border ice layers is the predominant process of ice cover development through this reach. The border ice often constricts the open water channel width to less than 10 feet. The slush ice then jams between the shorefast ice and freezes, forming an unbroken, uniform ice cover across the river channel. However, since this process does not occur simultaneously over the entire reach, a very discontinuous ice cover results. Numerous open leads generally exist until early March.

Upstream of the Devil Creek confluence the Susitna River has a steep gradient, single channel with gradually sloping banks to the vegetation trim line. At this point on a typical cross section the bank slope increases dramatically and rises to nearly 1000 feet above the channel bottom. The gradually sloping banks below water line result in shallow water along the flow margins that abound in large boulders. These boulders provide anchors for slush ice that drifts into and stops along the river banks. Shore ice rapidly develops laterally out into the channel until encountering water velocities greater than 2 fps. Water velocities prevent the slush from adhering to the shore ice fringe or from anchoring to flow obstructions. However, eddies downstream of boulders do fill with frazil ice, resulting in small patches of surface ice with a fluted shape, the upstream tip being the boulder.

An ice bridge usually forms at a flow constriction downstream of the Tsusena Creek confluence at RM 181. Flow is funneled between a vertical rock cliff and a gravel bar. Shore ice grows in the shallow water over the gravel bar and the water depth does not reach the limiting 2 feet until all but 10 feet of the channel is ice covered. The remaining 10 feet of open water plugs up with slush ice, which subsequently freezes solid. The water velocities are too high for an upstream progression, and all the slush from upstream is swept under the ice bridge.

An ice bridge also formed near the mouth of Watana Creek, usually by mid-November. A continuous ice cover advances upstream and in some years reaches the mouth of Vee Canyon at RM 223. Water levels stage to over 10 feet above the initial open water, and slush ice is shoved laterally onto gravel bars and up to the vegetation trim line on both banks between RM 210 and 220.

Anchor ice accumulates on the channel bottom to thicknesses exceeding 2 feet in some areas, raising the water level correspondingly. This usually occurs when shore ice is present, and the rising water either fractures the solid ice or overflows on top. In the latter case, snow laying on the shore ice is flooded and eventually freezes, increasing the overall ice thickness significantly. The lateral growth of shore ice also increases the water level, but this is less noticeable since the discharge is simultaneously decreasing.

By the end of December the reach from RM 170 to RM 210 has a discontinuous ice cover resulting from numerous bridgings between wide shore ice formations. The remaining open leads eventually freeze over if air temperatures remain below -10 C for a long period, but otherwise water velocity and turbulence keeps the leads open. See table 5 for ice thicknesses.

Characteristics of Susitna River freezeup between Devil Creek and the Oshetna River are summarized as follows:

1. Extremely wide accumulations of border ice layers occur, resulting in gradual filling of the narrow open channel with slush ice which freezes and forms a continuous ice cover.

2. There is extensive overflow and flooded snow.

3. Few reaches exist where staging or telescoping occur.

4. Low discharges through the winter result in shallow water and moderate velocities.

5. Minimal ice sagging occurs, with few leads opening after initial freezeup.

6. Extensive anchor ice forms, with high sediment concentrations.

6. THE FREEZEUP OF LOWER AND MIDDLE RIVER SIDE CHANNELS, SLOUGHS AND TRIBUTARIES

To review processes of ice cover development on bodies of open water, black ice develops and grows on the surface of non-turbulent water. Snow can stimulate this by covering and floating on the water surface, effectively decreasing the volume of water that needs to freeze before solidification occurs. An ice cover finally develops by frazil slush accumulation. The side channels, sloughs and tributaries of the Susitna are subjected to one or all of these processes.

Side channels generally have bed elevations higher than the adjacent mainstem, and therefore normally convey water only at relatively high stages such as those associated with spring runoff and summer rain storms. Susitna River side channels vary considerably in length, width and complexity from the relatively short systems on the middle river to the extensive multi-channel complexes on the lower river. Most lower river side channels are de-watered prior to freezeup when mainstem flows drop below 10,000 cfs. Some of these may have separate sources of water such as a minor tributary or groundwater seeps. These contribute enough water to maintain shallow pools. With the advent of cold air temperatures, these pools often develop ice covers by either black ice or snow ice formation. Snow ice obviously forms only after a heavy snow storm. This cools the water surface rapidly and often freezes into a solid but thin ice sheet. The snow can initiate an ice cover many days before it would have frozen without the snow. This ice appears white or opaque and grainy in contrast to the clear and smooth black ice which begins to grow underneath the snow ice.

Staging, or the rising of mainstem water levels due to the accumulation of frazil slush, often increases the water level sufficiently for the side channel entrance to be overtopped. The sudden increase in water volume washes away the snow cover and flushes out the pools, fracturing the ice cover. This often results in small ice jams. The flooding continues until the mainstem water level recedes below the side channel threshold elevation. In some cases overtopping continues all winter long. Depending on the depth of water over the channel entrance, an ice cover then forms by either shore ice growth (shallow overtopping depth) or frazil slush accumulation (deep overtopping depth). In the case of a shallow overtopping depth, mainstem water enters the side channel, but due to the slush floe thicknesses which usually exceed 1 foot, the floes become stranded at the channel entrance and cannot enter. When overtopping depths are greater than 1 foot, then slush ice flows into the side channel and either continues through to the mainstem again, or becomes lodged and initiates an ice progression that develops into a solid ice cover. If a progression does not start, then border ice forms along the banks and continue growing laterally into the channel, eventually closing over the open water. Side channels with separate sources of water generally develop open leads through an ice cover. This is due to thermal erosion by relatively warm water emanating from the ground or tributary. Side channels on the lower river which are usually overtopped during freezeup are:

Alexander Slough
Delta Island Side Channels
Rustic Wilderness Side Channel
Goose Creek Side Channel
Sunshine Side Channel

Side sloughs by definition are side channels with a source of water separate from the mainstem. They generally have an upstream entrance, bifurcating from the mainstem, and an exit which rejoins the mainstem. Upland sloughs have no upstream entrance, only a mouth, but the water level in the mouth is controlled by backwater regulated by mainstem stage. At low mainstem stages the mouth areas of these sloughs are dry except for the contribution of its tributary or groundwater source. Side sloughs that are overtopped during mainstem freezeup behave similarly to the previously described side channels. An ice cover of either snow ice or black ice usually forms over the ponded water by mid-November. As the mainstem ice cover advances upstream, a large volume of water percolates into the substrate and surrounding terraces as bank storage. This has been documented by an increase in the water table adjacent to a developing ice cover. This is also noticeable by an increase in the surface area of the ponds and the subsequent flooding of the surrounding snow (figure 34). The water level rise is not sudden enough to fracture the ice cover. Several sloughs between RM 120 and RM 130 are overtopped by the mainstem during freezeup. The overtopping usually consists only of water and no slush ice enters. An exception to this occurred in 1981 when Slough 8A was breached by an estimated 140 cfs for over 1 week.

Any ice cover that forms over a slough is usually eroded away soon after mainstem ice progression because of the increased heat flux from groundwater flow into the sloughs (figure 35). This source of heat is significant enough to erode through an existing ice cover and keep the open water ice free through the winter. Often the thermal erosion continues out into the mainstem ice cover, which develops an open lead with its source in the slough. Middle river sloughs and side channels that are commonly overtopped during freezeup include:

Lane Slough

Mainstem II Side Channel

Curry Side Channel

Slough 7

Slough 8A

Slough 9

Upland sloughs, such as Sloughs 6 and 10, generally do not develop a continuous ice cover but shore ice will form along the channel fringes.

The major tributaries of the Susitna form an ice cover by surface accumulations of frazil slush. These include the Yentna, Deshka, Talkeetna and Chulitna Rivers. Most of the minor tributaries develop an ice cover by shore ice and anchor ice accumulations. They are generally too shallow and turbulent to form an ice cover by frazil progression. A majority of these tributaries drain basins large enough to contain a sufficient volume of stored groundwater to maintain a flow through the winter. This groundwater flow retains enough heat to erode through an existing ice cover when air temperatures begin moderating in early April. Before breakup these tributaries usually show a discontinuous ice cover and a lead eroded through the mainstem ice cover near the confluence.

7. SUMMARIZED HISTORICAL FREEZEUP CHRONOLOGIES

This section is included for the purpose of consolidating the river ice observations from 1980 to 1984. This will facilititate evaluating the significance of annual variations in the freezeup sequence. Included in this section are tables 6 to 10 and figures 36 to 39, which summarize pertinent information from each year of the study to show how the varying climate conditions control ice cover formation.

a. 1980 Freezeup Chronology

Climate conditions in the Susitna Basin varied significantly from normal during the study period, influencing the processes of ice cover formation and breakup on the river. In early December air temperatures were well below normal. This was followed by unusually warm air temperatures in January after the ice cover had formed over the length of the river. During these early winter months, precipitation was low. Snow survey data showed that the snowpack in the Susitna Basin was 30-50% below normal through January. The combination of these factors resulted in an average ice thickness of 2.5 feet on the Susitna River at Gold Creek in January, close to the historical average at that site.

On October 11, 1980 in the vicinity of Gold Creek, areal coverage of frazil ice in the main channel was estimated to be 40%. It appeared that frazil was being generated primarily through Devil Canyon. At this time, there were no signs of frazil or shore ice developing in the Chulitna or Talkeetna Rivers.

By late afternoon on October 12th, the leading front of floating frazil ice was approximately 5 miles above the Kashwitna River confluence (approximately RM 66). Frazil ice was flowing in the Yentna River, but no ice was observed in the Deshka (Krotc Creek). Frazil ice coverage in the main channel of the Susitna averaged 30% in the river above Talkeetna. Floes were beginning to accumulate at natural constrictions and in low velocity areas. Shore ice was also beginning to form in the quiet-water areas, but there was no significant constriction of the main channel due to shore ice growth.

The following day, October 13th, first frazil ice was observed in the Talkeetna River, but there was still no sign of frazil ice in the Chulitna River. Ice floes in the Susitna River above the Chulitna/Susitna confluence were more concentrated, with coverage in the main channel estimated at 80%.

The floes varied from 2-5 feet in diameter through more turbulent reaches up to 50-100 feet long in the constrictions below Curry and Portage Creek confluence. A thin ice cover had formed on some quiet-water sloughs and side channels. Tributaries upstream from the Susitna/Chulitna confluence showed no signs of flowing frazil ice.

On October 31st, anchor ice was first observed in the river near Sherman. The ice accumulated in masses 3-4 inches thick over 50% of the cobble bed in the near-shore area. Anchor ice was still present in water depths of 4 feet up to 30 feet from shore in the main channel. Several ice bridges were observed through Devil Canyon and upstream to Devil Creek.

By mid-November, anchor ice could be clearly seen along the length of the river from Talkeetna to Portage Creek. In the main channel, most reaches of shallow, high velocity water had anchor ice over 50-70% of the bed. Spring-fed side channels showed no signs of anchor ice formation. No ice bridges existed below Portage Creek. The most noticeable channel constrictions occurred just upstream of Curry near RM 120.8, at RM 126.1, at the bedrock outcrop near RM 128.5, just upstream of Sherman at RM 131 and at the rock point near RM 135.8.

By November 13, most of the tributaries below Talkeetna had formed ice covers near their confluences with the Susitna. In the lower river, the leading edge of the ice cover was observed at RM 75.5 approximately 8.4 miles below the Parks Highway Bridge. Upstream from this bridge to Talkeetna, flow was confined to the main channel, and side channels were either ice-covered or dry.

On November 29, frazil ice coverage in the Talkeetna River was 40-50%, with most flow through the north channel. There was no sign of an ice cover forming in the Chulitna River near Talkeetna, with approximately 40% frazil ice coverage. The Susitna River at the confluence with the Chulitna showed 80-90% coverage of frazil slush ice, but the channel was still open.

On December 1, an ice bridge was observed across the Susitna River at the Susitna/Chulitna confluence. The Chulitna River was still ice free. Evidence of a rise in water level of 3 to 4 feet occurred between November 29 and the morning of December 1 upstream of the ice bridge.

Over the next two weeks the progression of the ice cover between the confluences and Gold Creek was monitored to determine the rate of ice cover growth upstream. The average rate of ice cover growth was 2.7 miles per day. Overall, there was little observed variation from this rate. It is important to note here that during ice cover formation air temperatures at Talkeetna were far below normal, which would tend to accelerate the rate of ice cover growth.

On December 2nd, the leading edge of the ice cover was at RM 108.5. At RM 110.4, the width of open water was 100 to 125 feet and the edge of shore ice was approximately 80 feet from the toe of the right bank. Upstream from the leading edge of the ice cover, there appeared to be little change in the ice conditions along the river through Devil Canyon. However, from Tsusena Creek upstream, the channel was severely constricted by shore and anchor ice growth. At Watana Creek, an ice cover had formed which extended upstream to approximately 3 miles above the Kosina Creek confluence by the afternoon of December 3. At a few sites there was water spilling into side channels, indicating a rise in water level.

The next reconnaissance trip for ice observations was carried out on December 8. By this time, the ice cover in the river below Talkeetna had progressed as far as RM 93.5. Above the Susitna/Chulitna confluence, the leading edge of the ice cover was observed at RM 126.4.

The final reconnaissance trip for freezeup observations was conducted on December 12. The ice cover extended as far upstream as Gold Creek. Upstream of Gold Creek, there were no ice bridges in the channel until just below Portage Creek, where a small bridge had formed on the upstream side of a constricted bend in the channel.

On December 15th, the ice cover extended upstream past Portage Creek and into Devil Canyon. On December 30, the ice cover extended intermittently through Devil Canyon upstream to 4 miles above Devil Creek. Open water persisted in several turbulent flow reaches. Further upstream there was a discontinuous ice cover with several open leads.

b. 1981 Freezeup Chronology

The 1981 freezeup process was prolonged by the delay of cold weather. This contrasts with the 1980 freezeup, when a November cold snap caused rapid ice formation. Fluctuating air temperatures and relatively heavy precipitation through October precluded the formation of a stable ice cover. By the second week of December the leading edge of ice on the lower river was near Talkeetna, about two weeks later than in 1980. Long before an ice cover formed adjacent to Talkeetna, an ice bridge formed at the Susitna/Chulitna confluence. The ice bridge at the Susitna/Chulitna confluence presented a barrier to ice floes, greatly reducing the volume of ice feeding the downstream ice pack. Consequently, it took over 6 weeks for the confluence area between Talkeetna and the ice bridge on the Susitna to develop an ice cover.

Frazil ice was first observed on October 2, 1981 at RM 110 during a morning flight up the Susitna River on October 2, 1981. No frazil ice was observed in the confluence area.

With air temperatures fluctuating above and below 0 C all through October, no permanent ice formations developed. Between October 12-15, temperatures increased sufficiently to melt much of the remaining border ice. On October 29, border ice was again building along both sides of the river, and most side channels were de-watered. Ice pans and rafts from the Susitna formed 70% of the total floating ice below the confluence with the Chulitna River.

By November 2, mean daily air temperatures had remained consistently low (about -11.0 C) for several days. Above the mouth of Deadman Creek, the border ice had extended into and closed the channel to form an ice bridge. Ice pans were accumulating against this obstruction, causing an upstream advance of the ice cover. Another channel closure was forming just downstream of Bear Creek confluence, about 1 mile below Tsusena Creek. An extensive ice bridge had developed below Fog Creek confluence, but the ice cover was not progressing further than the rapids immediately below the Fog Creek confluence. A continuous ice cover had formed over the two mile long rapids section below the Devil Creek confluence. Many ice bridges were building between RM 155 and RM 160. Devil Canyon had a continuous ice cover from the proposed damsite down to RM 150. The discharge at Gold Creek at the time of these observations was 4,100 cfs. Below Gold Creek, the river channel remained open.

Ice rafts were periodically broken up and reformed by local variations in flow. At RM 115 channel constrictions concentrated the ice rafts, and bridging seemed imminent.

Cold air temperatures continued, and on November 6 the following aerial observations were recorded. Below Talkeetna, the Susitna was ice-covered from Cook Inlet to approximately the Kashwitna River. The channel at the Parks

Highway Bridge was choked with slush ice rafts. The confluence area showed some frazil ice being contributed by the Chulitna and Talkeetna Rivers, but most of the ice was drifting down from the Susitna. In the Chase area 50-60% of the river channel was covered by border ice. An apparently stable ice bridge had formed at RM 105.5. Slush ice rafts were accumulating against it, creating an upstream progression of ice coverage. Channel constrictions were observed at RM 123, at RM 131 at Sherman, at RM 136 below Gold Creek, at RM 145 and at RM 149 just above the Portage Creek confluence. The ice cover and bridges through Devil Canyon remained stable with no significant growth observed. Little further ice formation was reported in the reach from Devil Canyon to Watana.

On November 18, the mean daily air temperatures ranged from -13 C at Talkeetna to -16.0 C at Watana. The leading edge of the ice cover had progressed upstream to within 4 miles of the Parks Highway Bridge. The Chulitna River showed increasing ice formation activity, with moderate concentrations of frazil ice and widening border ice. The Talkeetna River was completely ice-covered and was no longer contributing ice to the Susitna. Slush ice rafts on the Susitna River had consolidated and jammed at a border ice constriction near the confluence. The reach between Curry and Sherman was characterized by extensive anchor ice, giving the water a milky appearance. The ice bridge below Gold Creek remained stable, with no ice progression. No significant ice formation had occured above the Devil Canyon area.

By December 14, the ice cover had progressed to RM 95 below Talkeetna. From there to the Susitna/Chulitna confluence, the river maintained an open channel. At the confluence, an ice cover resumed on the Susitna River and continued to RM 127 with the exception of narrow open leads of varying lengths, usually less than one-half mile long. The open channel above RM 127 was 40-50 feet wide, and contained 70% frazil ice. Extensive patches of anchor ice were also observed. At Gold Creek the channel was 60-70 feet wide with no visible frazil ice. The ice-covered reaches in Devil Canyon and below Devil Creek confluence had developed narrow open leads about ½ and 1 mile long, respectively. Above Devil Creek, the river remained open with extensive border ice formations constricting the remaining open water.

On January 4, the Talkeetna, Chulitna and Susitna rivers were frozen at the confluences with the exception of open leads through the ice cover resulting from high water velocities. The Susitna above the confluence was generally ice-covered, with many reaches of narrow open leads. Near Sherman at RM 127, an open channel about 1 mile long persisted. Above Sherman, the open leads became more numerous and generally longer. Above Gold Creek, the river was essentially open but had many anchor ice dams. Little had changed through the Devil Canyon reach and further upstream.

c. 1982 Freezeup Chronlolgy

Between October 22 and October 26, 1982, slush ice jammed near RM 10 and accumulated upstream 57 miles to the Sheep Creek confluence. Assuming that the ice cover began progressing upstream on October 22, then the progression rate was 11.5 miles per day.

On October 26, the ice cover had progressed past RM 25 but was not continuous. There was no ice cover on the Susitna near the confluence of the Yentna River. The Yentna was also completely free of drifting ice and shore ice. At RM 32, a loosely packed ice cover resumed and continued upstream to RM 67. From RM 67 to RM 97 near Talkeetna, the river remained free of shore ice, even though a large volume of slush ice was continually drifting downstream. All of the major tributaries to the Susitna below Talkeetna were still flowing and remained ice-free.

The leading edge of the ice pack on October 29 was near RM 87, just upstream from the Parks Highway Bridge and adjacent to Sunshine Slough. However, the ice cover remained discontinuous, with long open leads at the Yentna River confluence near Susitna Station, the Deshka River confluence, Kashwitna River, and Montana Creek. These tributaries were still flowing but showed signs of an ice cover beginning to develop. From RM 76 upstream to RM 87 the ice cover was thin and discontinuous, with long open leads adjacent to Rabideux Slough and in a side channel that extended from ½ mile below the confluence of Rabideux Creek downstream for about 1 mile.

By November 2, the leading edge had advanced to RM 95 at a rate of 2.1 miles per day during the previous 4 days. Many side channels had filled with water and the surface of the ice pack was near the vegetation line along the left (east) bank. The channel along the west bank remained dry and snow covered.

An ice bridge formed at the Susitna and Chulitna confluence on November 2, greatly reducing the volume of slush ice flowing into the lower river and slowing the rate of ice cover advance substantially. The formation of this ice bridge was dependent on decreased velocities brought on by the proximity of the leading edge.

A snow storm immediately preceded the formation of the ice bridge at the Susitna/Chulitna confluence. This storm may have caused a substantial local increase in ice discharge which could not pass through the constricted channel at one time. Ice discharge estimates were substantially lower at Talkeetna after November 2. Several ice constrictions were located near Curry (RM 120.6), Slough 9 (RM 128.5) and Gold Creek (RM 135.9). Slush ice had been passing easily through these narrows since October 26, but was now being compressed into long narrow rafts which broke up within several hundred feet downstream. Unlike the confluence area, these constrictions were formed by successive layers of frozen slush ice along the shore.

The rate of ice advance averaged 1.6 miles per day for thirteen days after passing Whiskers Creek. On November 22 the leading edge was situated adjacent to Slough 8A. The ice cover had staged approximately 4 feet and was overtopping the berm at the head of Slough 8A. The estimated discharge through the slough was 138 cfs.

The ice cover was very slow in advancing through the shallow section of river between Sloughs 8A and 9. By December 2, the ice cover had advanced at a rate of only 0.3 miles per day for the previous 10 days, even though high frazil slush discharges were observed at Gold Creek.

On December 9 the leading edge had reached RM 136, just downstream of the Gold Creek Bridge. The ice cover advance stalled here for over 30 days, as the ice needed to accumulate in thickness before it could stage past this high-velocity channel constriction. On January 14, 1983, the leading edge finally crept past the Gold Creek Bridge at a rate of 0.05 miles per day.

d. 1983 Freezeup Chronology

On October 17, 1983, slush ice was flowing through the middle and lower river, depositing along flow margins where it quickly froze into border ice. From October 23 until October 26 slush ice floes were estimated to cover 60% of the open water surface area on the Yentna River and about 40% on the Susitna. On the morning of October 26, 1983 an ice bridge formed at RM 9.

On November 1, 1983 the leading edge was at RM 31.5, having progressed more than 16 miles in five days. By November 4 the ice front had passed the confluence of the Deshka River at RM 40.5. The maximum stage increase measured at the entrance to Kroto Slough (RM 40.1) was 3.9 feet. This was sufficient to overtop the slough with a flow depth of 1.5 feet at the entrance, but no slush ice floes could enter due to their thicknesses of about 2 feet. The elevated mainstem stage also effected the Deshka River by creating a backwater zone which extended about 2 miles upstream.

On November 5 the ice cover progression entered the Delta Islands. The leading edge split, and ice fronts advanced separately up the east and west channels. The east channel ice cover progressed more slowly. The advancing ice cover caused stage increases high enough to inundate the snow cover over the Willow Creek alluvial fan. This saturated snow then froze into an ice cover. However, the water course from Willow Creek was not altered. The measured stage increased about 3 feet during the ice front advance. Slush ice from the Susitna did not encroach on the creek confluence. The stage increase measured at the entrance of a side channel near RM 48 on the west channel was about 2.5 feet. This channel was flooded but no slush ice entered. The Susitna ice cover progressed through the Delta Islands and converged near RM 51.

Most of the major side channel complexes on the lower river were flooded during ice cover progression. Mainstem slush ice was observed to accompany the surge through the Rustic Wilderness side channel. The slush ice and ice debris occasionally accumulated in small jams a short distance below the side channel entrances but usually were carried back out to the mainstem.. A maximum mainstem stage increase of 3 feet was measured near the mouth of Kashwitna River (RM 60) on November 11.

On November 9 the leading edge was at RM 66, but the new ice cover remained unstable due to warm air temperatures that prevented the slush from freezing. This was apparent by the quickly deteriorating ice cover below the leading edge. An open lead had formed from RM 62 to RM 65. The leading edge continued to advance at an average rate of 2 miles per day, even though the channel gradient gradually increases beyond RM 66 and more ice was required to produce a sufficiently stable cover. The effects of mainstem staging were not evident to a significant degree at the mouths of either Sheep Creek or Goose Creek. Sheep Creek drains into a side channel that extends from RM 62 to RM 67. Through this reach the mainstem is along the west bank and since the side channel complex is on the east bank, it was therefore not affected by backwater or overtopping. Goose Creek enters a side channel that runs from RM 69 to RM 72. This side channel was also not flooded or affected by backwater when the mainstem water level staged. The stage at these tributary mouths did increase slightly due to a rise in the local water table.

On November 19 the stage was rising at entrances to Sunshine Slough. The slough and side channels were eventually overtopped and flooded, although no slush ice entered. These channels subsequently required an additional 8-12 weeks to freeze over and many leads remained open all winter. The side channels leading to the entrance of Birch Creek Slough were flooded but the stage did not increase enough to overtop the slough entrance. The maximum increase was 3.1 feet near the entrance to Birch Creek Slough. An additional foot would have been necessary for overtopping. The temporary arrival of the leading edge at RM 95.5 initiated a separate ice progression up the Talkeetna River. This progression on the Talkeetna was so late, however, that the majority of the river had already frozen over with anchor ice and border ice, significantly reducing the volume of frazil being generated. By mid-December the ice cover had reached a position about 300 yards upstream of the railroad bridge and essentially remained there for the rest of the winter.

By December 9 the Susitna River ice front had advanced upstream into the middle reach above Talkeetna. No intermediate ice bridges formed. The ice cover on the lower river remained unstable and was marked by many extensive open water areas, either in mainstem leads or in flooded side channels. The Chulitna River, like the Talkeetna, had frozen over by lateral ice growth at the headwaters and was by this time generating so little ice that no upstream accumulation occurred. The confluence area of the Chulitna did not freeze over until late March, 1984. This was entirely due to anchor ice and lateral growth of surface ice.

On December 22, a second leading edge was observed progressing from an ice bridge at RM 120.7, just upstream of Curry. The river downstream between RM 120 and RM 118 was still open and an ice front was not longer advancing there. Heavy anchor ice deposits were observed within the open lead. This anchor ice had noticeably raised the water level and flooded the surrounding shore ice and snow.

A new leading edge was subsequently started and moved past Curry (LRX-24) probably on December 21, 1983.

The open water below Curry on the mainstem eventually froze over by border ice growth. Two anchor ice dams were observed in the lead, at RM 120 and RM 119.6. This created some backwater ponding which facilitated faster lateral growth of border ice.

By January 5, 1984 the second leading edge was located at Sherman near RM 130. Since very little slush ice was flowing in the open water, the ice cover progression was relatively slow. By this time the river above Devil Canyon had essentially frozen over and stopped generating substantial volumes of frazil. An ice bridge formed at RM 135.6 and a third leading edge began but progressed only about 1 mile before becoming an indefinite zone of accumulation. The open water area between RM 130 and RM 135.6 eventually covered by border ice closure.

e. 1984 Freezeup Chronology

Unusually mild weather during September and early October delayed the formation of significant volumes of frazil ice until the fourth week in October. The lack of late summer rainfall resulted in low freezeup stages compared to previous years.

Slush ice was first observed flowing down the mainstem at Gold Creek on October 16, 1984, although it had probably started flowing during the previous night. Variable concentrations of ice were observed until the afternoon of October 22, when the air temperatures warmed to 3 C and all ice disappeared. A full 6 feet of accumulated border ice disintegrated at Gold Creek during the following two days. Slush ice concentrations began to increase again on October 25. On October 26, at river mile (RM) 9, near the mouth of the Susitna River, a dense concentration of ice floes had accumulated during the high tide of 32.4 feet (Anchorage reference station) at about 7:30 a.m. At RM 9 the tidal fluctuation was measured to range over 6 feet during this particular cycle. Near the river mouth the top 1-2 inches of the ice pans had solidified, forming a rigid sheet on the surface. Pan size was variable with average diameters ranging from 2 feet to over 6 feet. The water velocity during the high tide was less than 1 foot/sec. and at low tide about 2.5 feet/sec at center channel. The ice floes which drifted into the flow margin along the east bank were barely moving, and became grounded when the tide receded.

The following day, October 27, the ice concentration in the area below RM 9 again increased during high tide. With substantially higher volumes of ice floes coming into this area from upstream due to the cold air temperatures, an ice bridge developed near RM 5.

On October 29, a complex picture unfolded of ice cover development on the lower reach. From RM 5 a somewhat continuous cover extended to RM 19, adjacent to the entrance of Alexander Slough. The predominant process of advance was by juxtaposition. Large areas of open water were present throughout the cover, indicating that little pressure was acting on the ice and no compression had occurred. By 10:30 a.m. on October 29, the leading edge was located at RM 19. However, due to insufficient ice from upstream, the leading edge was no longer advancing, and this ice front was essentially stalled at RM 19. The leading edge consisted of a thin layer of fine slush that was building in diagonal layers across the channel from the area of high water velocity on the outside of the river bend to low velocity on the inside of the bend. Open water with no slush was noted from RM 19 to RM 25.9 at Susitna Station (USGS gage site), where a second ice bridge had formed. A continuous ice cover had developed upstream from RM 25.9 to RM 43 of the east channel through the Delta Islands. The ice cover had also progressed up the Yentna River about 12 miles. The west channel through the Delta Islands was entirely open from RM 42.5 to RM 46. At RM 46 on the west channel a third ice bridge had formed. This obstruction had prevented slush ice from drifting downstream to advance the ice cover above RM 42.5. From the ice bridge at RM 46, the ice cover had progressed up the west channel to RM 51. At this point the main channel bifurcates, creating the west and east channels. The ice cover progression had stopped here, and there was open water up to RM 52. The east channel was open from RM 43 to RM 52. A fourth ice bridge had formed at RM 52. Very little slush ice emerged from under the downstream edge of the bridge, indicating that most of the ice floes were retained by the advancing ice cover near the leading edge. This ice cover had progressed up to RM 55. Visual estimates of slush concentrations at Gold Creek during the 4 days following the initial ice bridge formation were never less than 50% of the total open water surface area.

By November 3, the leading edge of the ice cover, which now originated from the ice bridge at RM 52, had progressed to RM 71.5 at an average rate of 4.1 miles per day. At the three rivers confluence, the Chulitna River and Talkeetna Rivers appeared to be contributing most of the slush ice to the lower Susitna River. The Susitna above this confluence area contained very little slush. At RM 105, slush ice had bridged the river at a shallow reach. This bridge had remained stable long enough to initiate an upstream progression of an ice cover on the middle reach of the Susitna. The consequence of this new progression was a decreased supply of slush ice to the lower river ice front, ultimately delaying ice cover formation below Talkeetna. The leading edge progression rate slowed to under 2 miles per day on the lower river, being entirely dependent on slush from the Chulitna and Talkeetna Rivers and on frazil ice generated below the ice bridge at RM 105.

A warm weather period began on November 5 and lasted until the 10th. Ice concentrations sharply decreased during this period to less than 10% at Gold Creek on November 8. This subsequently decreased the rate of leading edge progression to 0.5 miles per day on the middle river and 0.2 miles per day on the lower river. At this time, an estimated 75% of the slush forming the lower river ice cover above the Yentna River confluence originated from the Chulitna and Talkeetna Rivers.

On November 10, cold air temperatures once again increased the ice concentrations, and on November 13 the surface coverage was estimated at 80% by the Gold Creek observer. The middle river ice front advanced 6 miles (up to RM 121) and the lower river front moved upstream about 2 miles (up to RM 86). The middle river ice front progressed more rapidly due to a larger volume of slush ice generated in the available open water reach from Gold Creek to Watana.

On November 14, the Chulitna and Talkeetna Rivers had formed ice bridges several miles upstream of the Susitna confluence. These ice bridges prevented slush from entering the Susitna, and the ice cover progression on the Susitna stopped at RM 88. An insufficient supply of slush prevented further upstream progression at the rates previously observed.

In Slough 8A, ponds with black ice about 4-6 inches thick began overflowing and flooding the surrounding snow cover on November 16, when the leading edge was located at RM 127. This indicated that groundwater levels were rising. The entrance berm at RM 127 had not yet been overtopped. However, the berm at RM 126.1 had been flooded. The upper entrance to Slough 8A began overtopping on November 19 when the leading edge was at RM 128. This event was not nearly as dramatic as the previous overtopping in 1982. From the air it was difficult to tell that overtopping had occurred. The snow cover was about 1 foot thick at the time, and the mainstem water seeped through the snow pack.

On November 21, the leading edge of the middle river ice front reached RM 129, near the entrance to Slough 9. No overtopping of the entrance berm occurred.

By this time the river upstream of Devil Canyon had become ice covered, severely limiting the volume of frazil capable of being generated. The rate of leading edge advance subsequently slowed to about 0.2 miles per day. Anchor ice had accumulated on the bottom in massive proportions. Thick layers often broke free from the bottom and floated downstream to also become part of the downstream ice cover.

On December 15, backwater from an ice dam at RM 135 caused a fracturing of upstream border ice. A large solid fragment drifted downstream, but instead of floating down to the leading edge at RM 131, it became lodged on the anchor ice dam at RM 135, creating a new ice bridge. This ice bridge accumulated slush ice at the upstream edge. The new ice front prevented slush from continuing downstream and advancing the previous leading edge. By December 20, the river under the Gold Creek bridge had frozen over and the leading edge was approaching RM 137. The open water below the ice dam at RM 135 remained as it appeared a week earlier.

By the final observation flight on December 20, 1984, the leading edge on the Susitna River below the three rivers confluence had reached RM 92, at a rate of 0.12 miles per day. The Talkeetna River was frozen over above the railroad bridge. The Chulitna River was frozen over from about three miles above the Susitna confluence. Extensive open leads existed in the Susitna River ice cover below Talkeetna. Open water still persisted on the east channel of the Delta Islands, although the flow velocity had diminished in many places and border ice was beginning to close the open channel in several areas.

See tables 6 through 10 for yearly river ice summaries.

TABLE 6

1980 - 1981 RIVER ICE SUMMARY

Date	Ice Bridge Location (RM)	Leading Edge Location (RM)	Stage Increase (ft)	Slough or Side Channels Overtopped	Ice Jams (RM)
Nov. 29	97	75.5			
Dec. 1	98.5	104.5	4.0		
Dec. 3		112.8	3.3		
Dec. 5		118.8			
Dec. 8		126.4	4.0		
Dec. 12		136.9			
De. 15	147.6				
May 3					126.1
					135.8
					138.8
					142.3
May 4					138.8
					129.7
					119.3
					112.8
May 6					138.8
					101.8
May 9					Ice Free

TABLE 7

1981 - 1982 RIVER ICE SUMMARY

Date	Ice Bridge Location (RM)	Leading Edge Location (RM)	Stage Increase (ft)	Sloughs or Side Channels Overtopped	Ice Jams (RM)
Nov. 2	186.6				
	181.0				
	176.5				
	150.0				
Nov. 6	105.5	60			
Nov. 18		82			
Dec. 14	98.5	95		Sunshine	
		127			
Jan. 4		137			
May 10					153
					142
					139
					130
May 12					107
May 14					Ice Free

M18/5 3

TABLE 8

1982 - 1983 RIVER ICE SUMMARY

Date	Ice Bridge Location (RM)	Leading Edge Location (RM)	Stage Increase (ft)	Sloughs or Side Channels Overtopped	Ice Jams (RM)
Oct. 22	10				
Oct. 26		57	3	Alexander Rustic Wilderness	
Oct. 28		87	5		
Nov. 2	98.5	95	4	Sunshine	
Nov. 9		106			
Nov. 22		126	4	Slough 8A	
Dec. 2		129			
Dec. 9		136	1		
Jan. 14		137			
April 27					148.8
					145.5
					142.0
					135.9
					131.0
					120.0
					113.5
May 4				Slough 21	141.8
					134.5
					131.4
					129.0
					122.0
					119.5
					113.2
					89.0
					85.5
May 6				Slough 9	183.0
				Slough 8A	131.5
				Slough 7	129.0
					124.5
					122.0
					120.5
					113.0
May 7					183.0
					131.5
					122.0
					112.5
May 8					99.5
May 9					Ice Free

TABLE 9

1983 - 1984 RIVER ICE SUMMARY

Date	Ice Bridge Location (RM)	Leading Edge Location (RM)	Stage Increase (ft)	Sloughs or Side Channels Overtopped	Ice Jams (RM)
Oct. 26	9		2-3		
Oct. 27		15.0			
Nov. 1	27	31.5		Alexander	
Nov. 4		40.5	4		
Nov. 5		50.0	3		
Nov. 9		66.0	3	Rustic Wilderness	
Nov. 10		73.0	7		
Nov. 18		82.5			
Nov. 19		84.5	6	Sunshine	
Nov. 26		95.5			
Dec. 9		98.6	4		
Dec. 22	120.7	118.0			
		124.0	10		
Jan. 5	135.6	130.0	4		
		136.5	2		
May 5					79
May 6					Ice Free

TABLE 10

1984 (FREEZEUP ONLY)

Date	Ice Bridge Location (RM)	Leading Edge Location (RM)	Stage Increase (ft)	Sloughs or Side Channels Overtopped	Ice Jams (RM)
Oct. 27	5				
Oct. 29	26	19		Alexander	
	46	43	3		
	52	55	4		
Nov. 3	105	71.5	9		
Nov. 5		109			
Nov. 10		121			
		86			
Nov. 14		127		Slough 8A	
		88		Sunshine	
Nov. 19		128			
Nov. 21		129			
Dec. 15	135				
Dec. 20		137			
		92			

C. GENERAL RIVER ICE BREAKUP PROCESSES

Breakup is a gradual process of ice cover disintegration that begins with the formation of open leads through the ice cover, the melting of snow in the basin, and subsequent rising water levels that lift and fragment the ice cover. The multitude of resultant ice floes often accumulate in areas where the flow or channel configuration cannot convey the ice volume, and jams may develop. The stability of the jams is dependent on their configuration (floating or grounded) and on the presence of secondary channels that can divert water and relieve pressure from the jam.

Ice jams are not common on channels with broad flood plains since a rapid rise in water level, necessary to lift and shatter the ice cover, is prevented by a greater increase in open water surface area relative to depth with the rising discharge. Jams may still develop upstream of an ice cover on this type of channel, but last only until the cover weakens and collapses.

On confined channels, the river water eventually reaches a level where the ice jam is freed from its anchor and the mass of ice debris is swept downstream with a great enough force to destroy other ice blockages. This breakup drive leaves the channel essentially ice-free, with the exception of ice blocks left stranded above the high water line.

1. CHANNEL LEADS

Open water leads are common in the ice cover on the Susitna. They are either formed shortly after the progression of a frazil cover, exist as a remnant in channels that were flooded but never ice-covered, or indicate reaches of mainstem that were either bypassed by the progression or by the progression ending further downstream. Examples of each case follow.

The upstream progression of a frazil slush ice cover is dependent on a slush accumulation of sufficient thickness to slow the water velocity upstream of the leading edge. Massive thicknesses can thereby be attained in reaches where high water velocities prevail, since the cover continues thickening until the rapids section is essentially drowned out. Slush ice tends to accumulate in thicker deposits near the banks, since water velocities are generally slower in shallow water. The thinnest ice cover can usually be found over the faster flowing water. The ice cover thickness necessary for continued progression only needs to be sustained long enough for the leading edge to move upstream. If progression occurs rapidly, the downstream slush ice cover may have little time to freeze solid, and leads may consequently form through the cover.

After the passing of the leading edge the water stage drops as flow is lost to bank storage and slush ice is eroded from under the cover, thereby increasing the cross sectional area. The elastic properties of the ice cover cause it to sag, conforming to the configuration of the channel cross section in shallow water and floating over the area conveying deeper flow. If the bank slopes are low the ice cover forms an undulating surface with bulges where the slush is grounded on the bottom, and depressions corresponding to areas where the cover still floats. If the bank slopes are steeper, the cover deforms only to a critical angle before failure occurs. In this case the ice cracks and falls into the water, creating an open lead.

Leads also form in areas of high water velocity soon after an ice cover forms. On some reaches of the middle and lower river, leads have formed within hours after the slush stopped moving. This suggests an instability between the ice thickness and the water velocity which causes the unsolidified slush to rapidly erode away, usually only over a narrow portion of the channel where a critical velocity is exceeded.

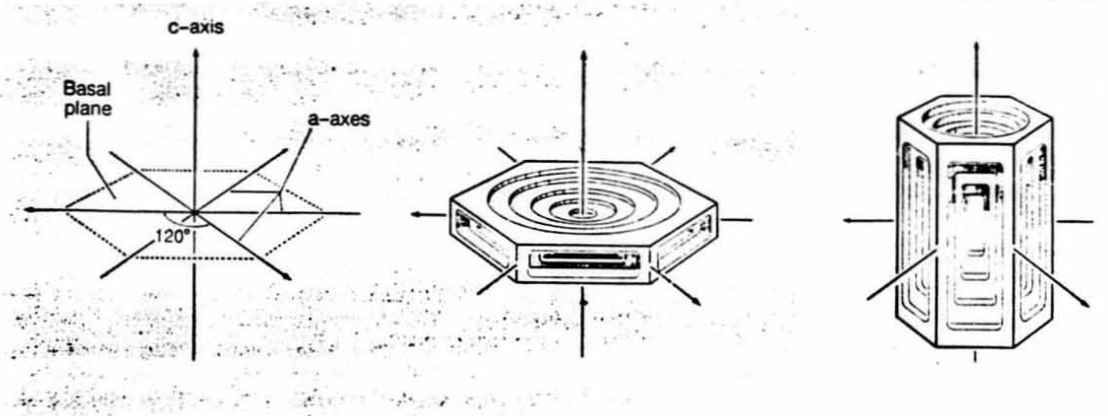
Leads are also prevalent in areas that were bypassed by the slush cover progression or in areas such as upstream of Gold Creek where a continuous progression usually does not reach. Many side channels on the lower river are dewatered prior to freezeup, only to be flooded when the mainstem water level stages upstream of the advancing ice front. The side channels carry water diverted from the mainstem, but often are too shallow to allow passage of the 2-3 feet thick ice floes. Without the entry of slush, the side channels can only freeze over by direct heat loss to the atmosphere. This process requires significantly more time than a slush accumulation, and many side channels have never entirely frozen over in the years of observation.

Leads on the mainstem may grow an ice cover by slush accumulation if a supply can be generated in the open water area and if the resultant frazil can be captured at the downstream end of the lead.

Leads often develope downstream of tributary mouths, side sloughs, or groundwater seeps. Groundwater upwelling in sloughs results in relatively warm water being exposed to the surface. This rapidly erodes any ice cover on the sloughs (if it ever developed) and the thermal erosion continues downstream until the water has lost most of its heat. Thermal leads have been documented on the middle river, with their source emanating from sloughs and extending hundreds of feet into the main channel ice cover. The ice cover often perpetuates the flow of groundwater by raising the local water table so as to increase the rate of upwelling (see Section E, part 4: Groundwater).

2. CANDLING

Ice grows in hexagonal crystals. The crystal structure is described by four intrusive axes, three A-axes and one C-axis (See diagram below). The A-axes lie in the basal plan of the crystal and the C-axis is perpendicular to the basal plane. An ice crystal resembles a pencil with the C-axis as the lead. When ice crystals nucleate on a body of calm water the axes are oriented randomly. The crystals grow more easily along the A-axes and crystals with horizontal C-axes tend to grow faster. Growth along the C-axis also occurs, but at a slower rate. Horizontal growth is usually restricted by a crowding out effect after about 1 cm. During the process of crystal growth, impurities within the water are rejected, and concentrate along the crystal boundaries where they cause a weak bond between adjacent ice crystals. Because of the trapped impurities concentrated at crystal interfaces, solar radiation weakens this bond first when melting begins, causing the crystalline bonds to fail and the individual crystals to separate into "candles". Eventually the innumerable single crystals composing the ice cover one no longer frozen together and easily collapse (Figure 40).



—Crystallographic axes of snow and ice crystals. If the growth rate along the *a*-axes exceeds that along the *c*-axis, the crystals tend toward a platelike structure. If *c*-axis growth dominates, the crystals assume a columnlike appearance. The mechanisms that cause differences in growth rates are not fully understood; air temperature plays an important role.

Reference: Perla & Martinelli (1976)

3. ICE JAMS

The ice cover breakup on northern rivers is characterized by a weakening of the ice crystal structure by solar radiation, warm air temperatures, and an increasing river discharge initiated by snowmelt and augmented by rainfall. These factors combine to fracture the ice cover. The ice fragments drift downstream until they encounter a barrier such as a solid ice cover, an ice jam, shoals or constrictions. Ice jams are also caused by islands, sharp river bends, bridge piers and abutments.

Two types of ice jams are common during breakup. The simple jam (figure 41) consists of an accumulation of ice fragments floating on the water surface and prevented from continuing downstream by a barrier, usually a stable ice cover. The dry jam (figure 42) is also formed by the accumulation of ice floes at an obstacle, but in this case the jam completely blocks the channel down to the river bottom. The water is forced to flow by percolating through the ice plug, and water levels upstream of the jam rapidly rise. This type of ice jam is responsible for the major flooding commonly associated with breakup. Water generally continues to rise upstream of the ice jam until the flow is either diverted via a side channel, flows overbank, or lifts and destroys the ice jam. The environmental effects of breakup are discussed more thoroughly in Section 7, part 1: Morphology.

D. SUSITNA RIVER ICE COVER DISINTEGRATION

Destruction of a river ice cover progresses from a gradual deterioration of the ice to a dramatic disintegration which is often accompanied by ice jams, flooding, and erosion. The duration of breakup is primarily dependent on the intensity of solar radiation, air temperature, and the amount of rainfall. An ice cover rapidly breaks apart at high flows. Ice debris accumulates at flow constrictions and can become grounded. The final phases of breakup are characterized by long open reaches separated by massive ice jams. A large jam releasing upstream usually carries away the remaining downstream debris, leaving the river channel virtually ice free.

A pre-breakup period occurs as snowmelt begins in the area, usually by early April. Snowmelt begins first at the lower elevations near the Susitna River mouth and slowly works northward up the river. By late April, snow has usually disappeared on the river south of Talkeetna and snowmelt is beginning on the reach above the Chulitna confluence. Tributaries to the lower river have usually broken out in their lower elevations, and open water exists at their confluences with the Susitna River. Increased flows from the tributaries usually erode the Susitna ice cover for considerable distances downstream from their confluence.

As water levels in the river begin to rise and fluctuate with spring snowmelt and precipitation, overflow often occurs onto the ice since the rigid and impermeable ice cover fails to respond quickly enough to these changes. Standing water appears in sags and depressions on the ice cover. This standing water reduces the albedo, or reflectivity, of the ice surface, and open leads quickly appear in these depressions. As the water level rises and erodes the ice cover, ice becomes undercut and collapses into the leads, drifting to their downstream ends and accumulating in small ice jams. In this way, leads become steadily wider and longer. This process is especially noticeable in the reach from Talkeetna to Devil Canyon. In the wide, low-gradient river below Talkeetna, open leads occur less frequently, and extensive overflow of mainstem water onto the ice cover is the first indicator of rising water levels.

The disintegration of an ice cover into individual fragments or floes and the drift of these floes downstream and out of the river is called the breakup drive. The natural spring breakup drive is largely associated with rapid flow increases, due to precipitation and snowmelt, that lift and fracture the ice surface. When the river discharge becomes high enough to break and move the ice sheet, the breakup drive begins. Its intensity is dependent upon meterological conditions during the pre-breakup period. For example, in 1981 a minimal snowpack and light precipitation during spring caused an insufficient increase in the flow to develop strong forces on the ice cover, and the ice tended to slowly disintegrate in place, producing few significant ice jamming events. Conversely, in 1982 a heavy snowpack with cool early spring temperatures prevented the ice cover from deteriorating significantly during the pre-breakup period. The ice remained strong into the later period of normal spring temperatures and rising flows, and the cover broke dramatically, producing several large ice jams.

1. TALKEETNA TO COOK INLET

Solid and continuous ice covers can fragment en masse when the pressure created by the rising water level can no longer be contained. This is especially true on the lower river downstream of Talkeetna. The shattered ice cover, however, may remain in place for several days if the ice downstream remains intact.

Increasing daily duration of exposure to solar radiation begins to have a marked effect in April. Existing leads lengthen as the floating ice cover melts from underneath, and once the snow has melted, solar radiation bearing directly on the ice surface causes the familiar candling process. This gradual melting seems to characterize "breakup" on the lower river (figure 43). The broad flood plain (relative to the area occupied by channels on the lower river) prevents a rapid increase in stage with rising discharges. When ice jams do occur, such as when ice debris from the middle river accumulates against a solid cover on the lower river, water spills over onto the flood plain and bypasses the congested main channel. Although erosion and damage to vegetation have been observed during breakup, these are isolated incidents and are considered insignificant when compared to damage incurred during summer floods.

2. DEVIL CANYON TO TALKEETNA

By the end of April the middle Susitna River is usually laced with long, narrow open leads. Floes that have fragmented from the ice cover accumulate into small ice jams. The configuration of these small ice jams often resembles a U- or V-shaped wedge, the apex of the wedge corresponding to the highest velocities in the flow distribution. The constant pressure exerted by these wedge-shaped ice jams effectively lengthens and widens many open leads, reducing the potential for major ice jams in these areas. The actual breakup of the ice cover occurs when the discharge is high enough to break and move the ice sheet.

Ice jam sites generally have similar channel configurations, consisting of a broad channel with gravel islands or bars, and a narrow, deep thalweg confined along one of the banks. Sharp bends in the river are also good jam sites. The presence of sloughs on a river reach may indicate the locations of frequently recurring ice jams. Many of the sloughs on the Susitna River between Curry and Devil Canyon were carved through terrace plains by some extreme flood. Summer floods, although frequently flowing through sloughs, do not generally result in water levels high enough to overtop the river bank.

During breakup, however, ice jams commonly cause rapid, local stage increases that continue rising until either the jam releases or the sloughs are flooded. While the jam holds, channel capacity is greatly reduced, and flow and large amounts of ice are diverted into side channels and overbank (figure 44). The ice has tremendous erosive force, and can rapidly remove large sections of bank (figures 45 and 46). Old ice scars on tree trunks up to 10 feet above the bank level have been noted along side-channels. It appears that these sloughs are an indicator of frequent ice jams on the adjacent mainstem, influencing the stability and longevity of these jams by relieving the stage increases and subsequent water pressures acting against the ice.

The following channels between Devil Canyon and Talkeetna are regularly influenced by ice-induced flooding during breakup:

Slough 22

Slough 21 from RM 142.2 to RM 141

Slough 11 from RM 136.5 to RM 134.5

Side channels from RM 133.5 to 131.1

Side channels from RM 130.7 to 129.5

Slough 9

Slough 8A and 8

Slough 7

In general, the final destruction of the ice cover is accomplished when a series of ice jams break in succession. The resulting on-rush of water and ice debris clears the channel of any remaining obstructions and ice (figures 47 to 49).

3. SUMMARIZED HISTORICAL BREAKUP CHRONOLOGIES

a. 1981 Breakup Chronology

There was no significant precipitation during early spring to increase runoff in the watershed. Therefore, river discharge did not increase sufficiently to create strong forces on the ice cover and initiate breakup. Instead, the ice began to slowly disintegrate in place with long open leads developing through the length of the river.

Pre-breakup conditions were observed during a reconnaissance trip on April 23. At that time, open leads were growing by ice calving off the lead perimeters. Ice floes accumulated at the downstream end. No floes were observed being carried underneath the ice cover. There was also little evidence of rising water level increasing pressure on the ice cover.

For the next few days changes in the character of ice accumulations and water levels along the river were monitored, especially at Gold Creek. Increased overflow on top of the ice and fracturing of the ice cover indicated that the water level was steadily rising during the first week of May. Open leads continued to grow and connect.

By May 3, the rise in water level and ice movement created ice jams upstream of the Parks Highway Bridge, above Curry at RM 120.5 where the channel bends sharply and begins to constrict, at RM 126.2, at RM 131.3, downstream from the Gold Creek bridge at RM 135.8, above Indian River in the vicinity of RM 139, and upstream at a constriction in the channel at RM 142.3.

On the morning of May 4th, it was observed that most of the previous day's ice jams had released and new jams reformed at several different sites. The jam at RM 142.3 had released sometime overnight, adding more ice and increasing pressure on the ice jam upstream from Indian River. A sharp bedrock outcrop along the left valley wall at RM 139 appeared to be the principal factor holding the ice. The far right channel was acting as an overflow channel, conveying flow around the ice and relieving pressure on the jam. Flow in this channel increased noticeably with the addition of ice from upstream. It also appeared that the center of the ice jam had sagged due to a change in water level. Parallel shear lines could be traced through the ice jam along the boundaries of the main channel on May 4th. This apparent drop in water level may have been related to increased flow spilling into the far right channel or possibly to release of the ice jam below Gold Creek.

Duration and maximum water surface elevations resulting from the jam which keyed at the rock point near RM 135.6 could be read from the streamgage chart at Gold Creek (USGS). On the morning of May 4th remnant ice was stacked up to 6 feet high along both shores upstream and downstream of the bridge. Average thickness of the ice blocks was three feet, but much of it was candled and easily broken apart.

From Gold Creek downstream, the main channel was free of ice accumulations until just below Sherman. Sometime during the night of May 3, the ice jam above Sherman released. Ice from that jam combined with upstream ice packed into the main channel through the reach just below Sherman. The ice jam key was located above a reach of shallow, turbulent flow near RM 129.7, where the channel bed was extremely irregular. In this reach of divided flow, the left channel provided overflow relief, carrying flow around the ice so there was little effect on water levels upstream. This jam held in place until sometime during the night of May 7th, as the channel was clear of ice on the morning of May 8th.

The ice jam downstream of Curry released during the early morning hours of May 4th. The ice sheet that previously existed at Curry broke up and accumulated in the reach at RM 119.2.

Another ice jam keyed near RM 112.7 and extended upstream to the confluence with Lane Creek. On May 4th, there was a noticeable increase in overflow on the upstream ice indicating a rise in water level. Flow had also spilled into the right channel below RM 112.7. The ice jam held until the early morning of May 6th, when the jam released. Ice floes packed into the channel extending from approximately RM 98.5 up to river Mile 101.8. On the morning of May 8th the jam was still in place. Examination of streamgaging charts from Sunshine indicate the jam released sometime later on the 8th or early on the 9th causing the peak recorded on the Sunshine gage chart.

New ice floes adding to the upstream edge of the jam at the confluence and the flood wave associated with release of the jam at Gold Creek on May 7 aggravated conditions at the confluence. Water levels were already high through this reach, with water and ice rising well up into the vegetation on both sides of the floodplain. The accumulating ice floes and rising water level created an unstable situation and the jam released on the morning of May 9.

Ice cover in the lower river had broken up and been washed out several days before the ice moved down from above Talkeetna. First movement of the ice cover on the Deshka River and the lower Susitna River at the confluence was reported on the morning of May 2. Sporadic movement continued throughout the day in this area. By early evening ice movement was also reported downstream at Susitna Station.

For the next few days observers reported continued ice movement in the Susitna, rising water levels, and breakup of the ice cover. On May 3, the Deshka was 95% ice-free, but a jam had developed at the confluence with the Susitna. The Yentna River was also ice-free except for a jam at the confluence with the Susitna River.

By mid-day on May 5, the river at Susitna Station was reported free of ice and the jams at the Deshka/Susitna and Yentna/Susitna confluences had released.

Through the length of the river channel, remnant ice was stranded on shore or packed into side channels with little or no flow. Over the following weeks rising water levels flushed out the rest of the ice or it melted in place.

Overall, breakup during 1981 on the Susitna River was mild. Ice scarring of trees from the release of ice jams was noticed in a few locations, most dramatically in the vicinity of Whiskers Slough (RM 101.5), on the vegetated islands in the channel. However, no major changes in channel configuration or significant scouring of river banks due to ice were observed during the breakup process.

b. 1982 Breakup Chronology

Breakup was more dramatic in 1982 than in previous years, as demonstrated by extensive erosion and by damage to the Alaska Railroad tracks. Air temperatures increased during the second half of April, but nighttime lows still dipped below 0 C. By May 7 minimum daily temperatures averaged 4 C and ice movement began. Jams occurred in most of the areas described for 1981 but with greater consequences, ranging from scarring and denuding of vegetation to flooding and washing away of railroad ties from under the tracks. In several areas below Talkeetna, massive amounts of soil were eroded from cutbanks, jeopardizing at least one residence. In the vicinity of the proposed Watana damsite, breakup effects were not as dramatic, with more ice melting in place and less erosion. The jam just downstream of the mouth of Watana Creek caused total channel blockage and ice accumulations for 1 mile upstream.

The only other significant jamming observed in the upper river took place near the mouth of Jay Creek. This jam backed up ice floes and impounded water for several miles. However, since the channel here is confined, no significant flooding took place.

On April 26, 1982, the river below Talkeetna remained ice-covered, with many areas showing overflow. South of Bell Island, however, the ice had gone out, and the river was open. The Talkeetna River was still frozen, with open leads beginning to extend and connect. Heavy overflows were observed near Chase, indicating some localized runoff. Open leads dominated side channels and sloughs which were influenced by seeping groundwater. With the exception of high-velocity reaches, the ice cover remained stable and continuous from Sherman to Gold Creek. In high-velocity reaches, usually marked by open water leads, ice rafts were breaking away from the ice cover and drifting downstream. From Gold Creek to Indian River, the Susitna had a narrow open channel, probably a direct result of flows from Indian River, which was beginning to breakup. The ice bridges between Devil Canyon damsite and Devil Creek were beginning to show accumulations of ice floes and some jamming activity. No significant water level increases were reported. The areas of overflow previously observed above Devil Creek were showing open water. The quantity and extent of open leads were less upstream of the Fog Creek confluence, with no change in river ice above the Watana damsite.

Between May 10 and May 15 the river showed little change upstream of Devil Creek except for the open leads getting wider and more numerous. The ice cover seemed to be melting in place rather than "breaking up". Ice movement began on many reaches of the Susitna River below Devil Creek. All ice bridges had disappeared except at RM 153, where an accumulation of ice floes had jammed and extended several hundred yards upstream. The river was open from Portage Creek to Gold Creek except for ice jams at RM 142 and RM 139. The ice cover remained stable about one-half mile below the Gold Creek Bridge. Ice had jammed below Sherman at RM 129 and 130, but appeared unstable and reportedly did not last long. The main channel between RM 118 and RM 120 retained its ice cover and appeared stable. Several jams of lesser consequence appeared at RM 115 to 117. At RM 107 (LRX-11), the river remained entirely frozen over. A continuous open lead had formed from Chase upstream to the mouth of Lane Creek. The confluence area was characterized by opening leads on the Susitna, the Chulitna was in final stages of breakup with no ice remaining over the channel. Many ice blocks were stranded on sand bars and bank areas adjacent to the Chulitna.

From May 12-15 a jam occurred at RM 107, flooding the railroad tracks and scouring the east bank. Although jams have occurred in generally the same location in previous years the 1982 breakup caused unusually severe erosion. The section of railroad track adjacent to the Susitna River at RM 108.5 was undermined when impounded water rose about 15 feet. The ice cover at breakup was shorefast and extended far out into the river channel, constricting the flow to a narrow deep channel against the right (west) bank. This cover was very resistant to lifting. Drifting ice blocks were up-ended upon striking this barrier, causing water inpoundment and subsequent increases in stage upstream of the jams. Witnesses claim the impounded water rose high enough to erode the railroad grade and wash away several ties and damage the support structure on a bridge crossing a tributary at RM 110. The jam persisted for three days and backed up ice floes for approximately 1 mile before releasing on May 15. While the jam held, some water flowed over the ice. An extensive area on the right overbank was also flooded. This was by far the most significant damage in recent years according to railroad personnel.

After the final ice drive, a river reconnaissance was made by boat on May 27 to observe the damage caused during breakup. The river reach just below Talkeetna was characterized by significant erosion of river banks on the outside of natural bends. A significant erosion problem exists just downstream of Talkeetna where a cabin situated on a 10-15 foot bank is potentially threatened by future breakup scouring of equal severity as that in 1982. At the confluence, the Susitna left bank at LRX-3 had eroded 3-4 feet, with many mature cottonwood trees now overhanging the river. At RM 99 and 100, ice blocks measuring 20-30 feet diameter had been pushed up onto the banks and sand bars. The upstream ends of vegetated islands had been scoured by ice, some being completely denuded of any vegetation for 100 feet or more inland from the bank. The left river bank had eroded 4-5 feet at RM 102. Areas most notably damaged by ice were characterized by mature (15-20 inch) cottonwoods and birch trees being knocked down and piled up against the upstream ends of islands. The Alaska Railroad had to heavily reinforce the grade by depositing large rip-rap on the river bank from RM 104 to 105 and from RM 108 to 116. The effects of breakup at Slough 9 (RM 129) were particularly evident. The berm at the head of the slough consisted of unconsolidated cobbles and sand, suggesting recent deposition. The ground on the islands was covered by 3-4 inches of freshly deposited silt, and ice blocks were observed within the forest, all evidence of a major flooding event. The jam which caused this flooding was not observed.

In addition to the ice jam at Chase, the Alaska Railroad reported damage to tracks at several locations along the river up to Gold Creek. The most extensively damaged section of railroad track lies between Curry and Chase where recurring ice jams are formed between RM 126.1 and RM 127.5. Additional jamming and damage was reported at Railroad Mile 260 (RM 132) following an ice jam near LRX-37.

Upstream of Gold Greek between RM 141 and 142 is another overflow channel (Slough 21) which receives flood waters during breakup and high summer flows. Extensive damage to the channel and overbank vegetation was reported after the 1982 breakup. Scarring of 30 inch cottonwoods to heights of 5 feet above ground level was estimated. These trees were previously undamaged and are situated well above and away from the normal channel.

c. 1983 Breakup Chronology

The major streams flowing directly into the lower Susitna River were contributing substantial discharges by April 27, 1983. The ice was in varying stages of decay on these tributaries, with Kashwitna River retaining a virtually intact ice cover, and Montana Creek, Sheep Creek, and Willow Creek breaking up rapidly. By April 28, there was an open channel for most of the reach between Talkeetna and the Parks Highway Bridge. Observation during an aerial reconnaissance on April 29 documented a rapidly disintegrating mainstem ice cover from Talkeetna down to the Montana Creek confluence. Further downstream, the mainstem ice cover was extensively flooded but remained intact. Above the Parks Highway Bridge the ice cover had shattered into large ice sheets in several areas. The large size of these fragments prevented the ice from flowing out. At Sunshine, an ice covered reach was flooded by about 0.5 feet of overflow, but remained intact. No ice jams had occurred.

Observers at Susitna Station reported ice beginning to move downstream on May 2, with flowing ice continuing to pass for several days. Deshka River residents observed the first ice moving on May 4, with the steady ice flows ending on May 10. No significant jams were noted. This pattern indicates an upstream progression of ice breakup, which confirmed the aerial observations on the river below Montana Creek.

The largest ice jam observed on the lower river occurred on May 3 near the confluence with Montana Creek at RM 77. Here an extensive accumulation of drifting ice debris had failed to pass around a river bend and jammed. The Montana Creek confluence was flooded but no damage or significant impact by ice or water was noted.

On April 27, 1983, daily observations and data acquisition began upstream of Talkeetna. By this time, the river had opened in some areas by the downstream progression of small ice jams. These minor ice floe accumulations remained on the water surface, often breaking down any intact ice cover obstructing their passage. As described earlier, this process is initiated in open leads which gradually become longer and wider until extensive reaches of the channel are essentially ice free. These small ice jams may be important in preventing the occurrence of larger, grounded ice jams. This was evident in 1983 when large ice jams released, sending tremendous volumes of floating ice downstream. The small jams had provided wide passages for the flowing ice, which may have jammed again if the channel had remained constricted. On April 27, extensive channel enlargements and small ice jams were steadily progressing downstream near the following locations:

Portage Creek, RM 148.8

Jack Long Creek, RM 145.5

Slough 21, RM 142.0

Gold Creek, RM 135.9

Sherman Creek, RM 131

Curry Creek, RM 120

A large jam had also developed near Lane Creek at RM 113.5 and was apparently grounded. Flooded shore ice surrounding the jam indicated that some water had backed up. A noticeable increase in turbidity occurred on this day.

On May 1, the ice jam key at Lane Creek had shifted down to RM 113.3 and was still accumulating ice floes at the upstream end. The source of the floes was limited to fragmenting shore ice. No significant accumulation would occur here until ice jams further upstream released. The ice jam near Slough 21 had increased in size and was raising the water level along the upstream edge. This backwater extended approximately 300 feet upstream. Figure 52 shows a relative stage increase at this measurement site of over 3 feet in 24 hours, illustrating the water profile before and after this ice jam occurred.

By May 2, 1983, several large ice jams had developed. The small ice jam at Gold Creek had broken through the retaining solid ice sheet, forming a continuous open channel from RM 139 near Indian River to a large ice jam at RM 134.5. The small ice jam that had been fragmenting the solid ice at the downstream end of an open lead adjacent to Slough 21 had progressed down to RM 141. A large jam had developed at RM 141.5, leaving an open water area between the two jams. The upstream ice jam was apparently created when a massive ice sheet snapped loose from shore-fast ice and slowly pivoted out into the mainstem flow, maintaining contact with the channel bottom at the downstream left bank corner. The ice sheet was approximately 300 feet in diameter and probably between 3 and 4 feet thick. The upstream end pivoted around until it contacted the right bank of the mainstem. The ice sheet was then in a very stable position, jammed against the steep right bank and grounded in shallow water along a gravel island on the left bank. Several small ice jams upstream had released and were accumulating against this ice sheet, extending the jam for about one-half mile. The water level rose, with an estimated 2,000 cfs flowing around the upstream end of the gravel island at RM 142 into a side channel. The entrance berm to Slough 21 at cross section H9 was also overtopped. Although the estimated discharge at Gold Creek was less than 6,000 cfs based on a staff gage reading, the normal summer flows required to breach this berm exceed 20,000 cfs. The entrance channel at cross section A5 was breached, with about 150 cfs being diverted into the lower portion of Slough 21. Many ice floes also drifted through this narrow access channel and were grounded in the slough as the flow was distributed over a wider area. This illustrates the extreme water level changes caused by ice jams.

By May 4, 1983, stable ice jams had developed and were gradually growing in size at the following locations between Talkeetna and Devil Canyon:

Lane Creek at RM 113.2

Curry at RM 120.5 and RM 119.5

Slough 7 at RM 122

Slough 9 at RM 129

Sherman Creek at RM 131.4

Slough 11 at RM 134.5

Slough 21 at RM 141.8

Downstream from the ice jam at Lane Creek, the ice cover was still intact, although extensively flooded. Between Lane Creek and Curry, the channel was open and ice free with the exception of some remnant shore ice. From Curry upstream to the ice jam adjacent to Slough 7 some portions of the ice cover remained, but were severely decayed and disintegration seemed imminent. An intact ice cover remained from Slough 8 past Slough 9 to the ice jam at Sherman. This ice cover had many open leads and large areas of flooded snow. Between the remaining ice jams at Sherman, Slough 11 and Slough 21, the mainstem was essentially open.

The jam at slough 21 was still receiving ice floes from the disintegrating ice cover above Devil Canyon. As ice floes accumulated against the upstream edge of the jam, the floating layer became increasingly unstable. At some critical pressure within this cover, the shear resistance between floes was exceeded, resulting in a chain reaction of collisions that rapidly caused the entire cover to fail. At this point, several hundred feet of ice cover consolidated simultaneously. These consolidation phases occurred frequently during a 4 hour observation period at Slough 21 on May 4. The frequency was dependent on the volume of incoming ice floes. With each consolidation, a surge wave resulted. During one particular consolidation of the entire half-mile ice jam, a surge wave broke loose all the shorefast ice along the left bank and pushed it onto an adjacent gravel island. These blocks of shore ice were up to 4 feet thick and 30 feet wide. The zone affected was almost 100 feet long, with the event lasting only a few seconds. This process is essentially the same as telescoping during freezeup except that the ice is in massive rigid blocks instead of fine frazil slush, and is thus capable of eroding substantial volumes of material in a very short time. The ease with which these ice blocks were shoved over the river bank indicates the tremendous pressures that build within major ice jams.

During all of the observed consolidations at Slough 21, the large ice sheet forming the key of the jam never appeared to move or shift. The surge waves would occasionally overtop the ice sheet, sending smaller ice fragments rushing over the surface of the sheet. Towards the end of the day, the ice sheet began to deform. Solar radiation, erosion and shear stresses were rapidly deteriorating this massive ice block. Final observations showed it to have buckled in an undulating wave and fractured in places. Observers at the Gold Creek Bridge reported tremendous volumes of ice flowing downstream at 6 p.m. on May 4. Taking into account the travel time, this indicates that the jam had probably released about 1 hour earlier.

The ice released at Slough 21 continued downstream unobstructed until contacting the jam adjacent to Slough 11 at river mile 134.5. The sudden influx of ice displaced the mainstem water and caused a rapid rise in water levels. The stage increased sufficiently to breach berms and flood the side channel below Slough 11 adjacent to mainstem river mile 135. The jam key at this site consisted of shorefast ice constricting the mainstem flow to a narrow channel of no more than 50 feet. Large ice floes, mostly from the original jam at Gold Creek, had lodged tightly in this bottleneck. Pressures appeared to be exerted laterally against the shorefast ice which inherently is resistant to movement due to the high friction coefficient of the contacting river bed substrata.

On May 5, few significant changes were observed in the ice jams despite warm, sunny weather and constantly increasing discharges from the tributaries to the mainstem.

It was at first thought that when the ice broke at Slough 11 on May 6, it would carry away the ice jam at Sherman and start a sequence that could destroy the river ice cover potentially as far downriver as Lane Creek. This was prevented by an event that actually increased the stability of the jam at Sherman so that it held for several more days. When the ice jam released near Slough 11 and the debris approached the jam at Sherman, it created a momentary surge of the water level. This surge broke loose huge sheets of shore ice which slowly spun out into the mainstem. One triangular ice sheet about 100 feet wide wedged tightly between two extended sheets of shore-fast ice. Ice floes continuing to accumulate against the upstream edge of this wedge exerted tremendous pressures on the obstruction. A pressure ridge rising at least 10 feet above the ice formed along the contact surfaces of the wedge. This ridge consisted of angular fragments and ice candles.

The water level continued to rise as the mainstem channel filled with ice, which eventually extended upstream to RM 132.5. The ice jam had lengthened to over 1.5 miles. Flooding quickly occurred on the side channels adjacent to the mainstem, and some ice drifted away from the main channel. The volume of water flowing through the side channel was estimated at approximately 2,000 cfs. As the ice jam consolidated and the water level rose, even more water was diverted through the bypass channels. This volume of diverted flow was critical to the stability and duration of the ice jam. Even though the jam increased in size, any additional hydrostatic pressure was relieved by diverting water into the side channels. The entire sequence of events lasted only about 10 to 15 minutes. The water level rose over 1 foot during this time span. Consolidations occurred periodically for the rest of the day but the jam key was never observed to shift.

Other major ice jams keys on May 6 were located at:

Watana Damsite

Sherman Creek at RM 131.5

Slough 9 at RM 129

Slough 8 near Skull Creek at RM 124.5

Slough 7 at RM 122

Curry at RM 120.5 (Photo 5.12)

Lane Creek at RM 113

A small and unstable ice jam at RM 126 near Slough 8 had consolidated and the resulting surge started a rapid disintegration of the remaining ice cover down to the mouth of Slough 8 near Skull Creek. This same surge appeared to have breached the entrance berm to Slough 8. Slough 9 was flooded by a jam at RM 129 near the upstream channel entrance. The Slough 7 ice jam received some additional floes wh the jam at Slough 8 released. This resulted in a rise in water level and flooding at RM 123.

At 6:30 p.m. on May 6, a moving mass of ice debris that stretched continuously from RM 136 to RM 138, with lesser concentrations extending for many more miles upstream, was observed approaching the Sherman ice jam. However, the consequences of this on the Sherman jam were not immediately observed. The condition of the floes indicated that this ice originated from above Devil Canyon. The well-rounded floes appeared to be no larger than 1 foot in diameter and were presumably shaped by the high number of collisions experienced in the turbulent rapids through Devil Canyon. Reconnaissance of the river above Devil Canyon on May 6 revealed a mainstem entirely clear of an ice cover for many miles. Stranded ice floes and fragments littered the river banks up to the confluence of Fog Creek. In several short reaches from Fog Creek upstream to Watana, the ice cover remained intact. A large jam had developed near the proposed Watana damsite and extended approximately 1 mile.

On May 7, the following ice jams persisted:

Key Location	Length
Watana Damsite, RM 184	1 mile
Sherman, RM 131.5	3.5 miles
Slough 7, RM 122	1 mile
Slough 6A, RM 112.5 (formerly Lane Creek jam)	2 miles

Downstream from the jam at Slough 6A, the river retained an intermittent ice cover that was severely decayed and flooded. Below the Chulitna confluence, the mainstem was ice-free and no ice jams were observed. The reaches between the remaining ice jams were generally wide open. The Curry jam had released overnight and traveled all the way to the Lane Creek jam. Here, the sudden increase in ice mass shoved the entire ice jam downstream about 1 mile where it again encountered a solid but decayed ice cover.

At about 10:30 p.m. on May 8, the ice jam at Sherman released, sending the total 3.5 miles of accumulated ice drifting downstream en masse at approximately 4-5 feet per second. This accumulation of ice easily removed the remaining ice jams at Slough 7 and Slough 6A. The last solid ice cover between Slough 6A at RM 112 and the Susitna/Chulitna confluence at RM 98.5 were also destroyed and replaced by one long, massive ice jam. This jam extended continuously from RM 99.5 to RM 104, and then was interrupted by an open water section up to RM 107. From this point a second ice jam extended upstream to RM 109.5. This blockage was later measured to be over 16 feet thick in some sections, but more commonly was about 13 feet thick.

These ice jams released on the night of May 9. Further observations were conducted on May 10 between RM 109 and RM 110. Along this reach, the final ice release had left accumulations of ice and debris stranded on the river banks, leaving ice floes deep in the forest. When the ice jams released, the ice floes piled up along the margins did not move, probably due to strong frictional forces against the boulder strewn shoreline. This created a fracture line parallel to the flow vector where shear stresses were relieved. The main body of the ice jam flowed downstream, leaving stranded ice deposits with smooth vertical walls at the edge of water. These shear walls at RM 108.5 were 16 feet high. The extreme height of the water surface within the ice jam was demarcated by a difference in color. A dark brown layer represented the area through which water had flowed and deposited sediment in the ice pack. A white layer near the surface was free of sediment and probably was not inundated by flowing water.

On May 10, the only remaining ice in the mainstem was on the upper river above Watana. Here an ice jam about 1.5 miles long had developed near Jay Creek.

Ice floes continued to drift downstream for several weeks after the final ice jam at Chase released. As increasing discharges gradually raised the water level, ice floes that had been left stranded by ice jam surge waves were carried away by the current. On May 21, the massive deposits of ice floes, fragments, slush, and debris were still intact near Whiskers Creek and probably would not be washed away until a high summer flow.

The ice breakup of 1983 occurred over a longer time span than in previous years, according to historical information and local residents. This was primarily due to the lack of precipitation during the critical period when the ice cover had decayed and could have been easily and quickly destroyed by a sudden, area-wide stage increase. During a year with more precipitation in late April, ice jams of greater magnitude may form and cause substantially more flooding and subsequent damage by erosion and ice scouring.

Several important aspects related to ice jams were observed this year and are summarized here:

1. Ice jams generally occur in areas of similar channel configuration, that is, shallow reaches with a narrow confined thalweg channel along one bank.

2. Ice jams commonly occur adjacent to side channels or sloughs.

3. Sloughs act as bypass channels during extreme mainstem stages, often relieving the hydrostatic pressure from ice jams and controlling the water level in the main channel. Ice jam flooding probably formed the majority of the sloughs between Curry and Gold Creek.

4. Ice jams commonly create surge waves during consolidation which heave ice laterally onto the overbank.

5. Large ice sheets can break loose from shore-fast ice and wedge across the mainstem channel, creating extremely stable jams that generally only release when the ice decays.

d. <u>1984 Breakup Chronology</u>

The 1984 lower river breakup was not marked by any unusual or dramatic events. The processes observed in the spring of 1983 were essentially repeated.

As previously described, open water leads developed immediately in some areas where water velocities were high enough to erode the underside of the ice. The following river reaches seem to be particularly susceptible to open lead development, where an ice cover cannot remain stable for any period of time unless cold air temperatures override all other influences:

Below RM 9 (tidal influence)
RM 62 to RM 66
RM 70.5 to RM 74
RM 78 to RM 86
RM 93 to RM 95
RM 96.5 to RM 98.5

The reach from RM 96.5 to RM 98.5 opened within 24 hours after ice cover progression from November 27 to December 8, 1983 to a width of about 100 feet at LRX-3 (RM 98.5). The open water surface area gradually diminished through the winter but was not observed to close in 1984. Reach 5 also opened shortly after the initial cover developed in mid-November 1983. A secondary accumulation progressed upstream though the lead but never achieved a complete closure. The remaining reaches eventually froze over by late January 1984. An ice cover that forms over open leads, by nature is less thick that the initial cover. For this reason these areas are the first to open up again with warmer air temperatures. This is the pattern observed on the lower river over the past three years. By early April 1984 the reaches listed above were again ice free over a portion of the cross section.

The 1983 freezeup initiated with flows at the Sunshine gage of about 13,000 cfs. The leading edge of the ice cover arrived at Talkeetna with the discharge at Sunshine approximately 5,000 cfs. The majority of the ice cover in the downstream reaches of the lower river, formed at higher stages, is subsequently no long floating prior to breakup. Discharge generally begins to increase in late March from the Sunshine base flow of about 3,000 cfs. The corresponding stage increase consequently breaks up the ice cover over the upper reaches of the lower river first, since this ice developed at lower freezeup flows. If the ice is still structurally competent during the discharge increase then large ice sheets break free from the shorefast ice. These remain intact and drift downstream until they contact solid ice or become lodged across the channel. In the latter case a new barrier is created, which may cause ice debris to accumulate into an ice jam. This was observed at RM 79 in 1984. This ice jam remained on the surface and no significant backwater occurred. The ice floes causing the blockage weakened after three days and dislodged. All the accumulated ice debris rushed downstream about 1 mile before contacting a solid ice cover. Here a new ice jam formed, which also remained on the surface with no substantial increase in stage. Historically, ice jams have been documented between RM 77 and RM 96, but rarely do they cause much flooding since the broad flood plain adjacent to the ice choked channel has a large flow capacity.

The lower river is usually ice-free by May 6. At this time the middle river usually has several very large ice jams and the upper river ice may still be intact. When the upper river ice finally disintegrates and moves downstream, it takes out the remaining middle river jams and the ice moves unrestricted through the lower river.

4. ALTERNATE SOURCES OF RIVER ICE INFORMATION

Additional information on the nature and timing of breakup of the ice cover on the Susitna River can be obtained through the National Weather Service River Forecast Center and the Alaska Railroad.

Data from the Alaska Railroad

The table below lists breakup dates on the Susitna River from 1975 to 1980 based on observations by personnel from the Alaska Railroad. It also describes the nature of breakup and identifies specific problem sites.

Year	Dates	Description
1975	May 12-15	Ice out by the 15th. Some minor flooding, no damage to track.
1976	May 5-17	Washouts on the 5th on tracks in the vicinity of Curry from river miles 119.8 to 122. Washouts related to large jam extending from river mile 118.4 to 123 during the same time. Short stretch of track also lost downstream of LRX-30 at river miles 127.0 to 127.2. Heavy flooding of tracks in vicinity of LRX-18 and just upstream. Significant bank scouring and ice pushed up on tracks from LRX-13 (R.M. 110.4) to LRX-18 (R.M. 113.0). Ice out on the 17th.
1977	May 16th	Ice out, some bank scouring, but no significant damage.
1978	May 8-9	Some jams and flooding, minor damage. Ice on tracks at curve approximately river mile 109.6, below LRX-13.
1979	May 8	Gentle breakup, no flooding or damage to tracks.
1980	May 12-13	No flooding, ice and rocks pushed up on tracks at a few spots, no serious damage.

Overall, the Railroad has never had ice problems with the track from Sherman upstream to Gold Creek. The track is farther from the main channel of the Susitna and is higher above the river through that reach. However, flooding and damage to the tracks occur consistently in come reaches below Sherman. The track in the vicinity of LRX-30, where the river channel bends to the west has been damaged often. Rock rip-rap has been dumped to retard active bank erosion during breakup along the far left bank.

Another section that appears vulnerable during breakup is that area below Curry from LRX-23 to below LRX-21. Ice jams of varying magnitude form through this reach nearly every year, causing flooding of the tracks or other damage.

Farther downstream, active bank erosion is threatening the tracks in the vicinity of LRX-20. Rip-rap has been dumped to prevent further erosion.

Rip-rap has also been dumped through the entire reach from LRX-18 to below LRX-13 along the left bank. This reach suffers nearly every year from flooding, ice on the tracks and scouring of the banks.

The sharp bend in the river channel between LRX-09 and LRX-10 has also been the site of ice jams several times in the past. Water flooded the tracks and ice was pushed up on top of the banks, with some scouring occuring.

E. ICE EFFECTS ON THE ENVIRONMENT

River bed and bank material may be displaced directly by moving ice or by flow conditions altered by ice phenomena (Newbury, 1968). The rising ice cover and accompanying shifts of the solid ice fragments during breakup removes vegetation from the banks to a level not attained by high summer flows. The middle river vegetation trim line corresponds to the late winter ice profile rather than the peak annual flood. However, the lower river is not affected severely by breakup, and erosion on this reach is primarily associated with summer floods.

Sloughs and side channels are usually overtopped during the open water season, but severe erosion generally takes place only when flows are accompanied by solid ice fragments during breakup or during extreme floods. Some sloughs may also be overtopped at freezeup. This usually leads to development of snow ice and in some cases short-term deposition of anchor ice.

A rise in groundwater levels corresponding to the staging mainstem flow increases the seepage rate in the sloughs. This results in a storage heat flux to the slough water, causing anchor ice to melt and opening leads open through an existing ice cover.

1. MORPHOLOGY AND VEGETATION

Breakup ice processes historically have been a major environmental force on the Susitna River, affecting channel morphology, vegetation, and aquatic and terrestrial habitats. The impacts vary along the length of the river. Ice processes appear to be a major factor controlling morphology of the river between the Chulitna confluence and Portage Creek. Areas with frequent jams have numerous side channels and sloughs. The size and configuration of existing sloughs appear to be dependent on the frequency of ice jamming in the adjacent mainstem.

Major breakup ice events probably formed sloughs. The size and configuration of existing sloughs is dependent on the frequency of ice jamming in the adjacent mainstem. Ice floes can easily move the bed material, substantially modifying the elevation of entrance berms to the sloughs. In May, 1983, a surge wave overtopped a shallow gravel bar that isolated a side channel near Gold Creek. The surge also created enough lifting force to shift large ice floes. These floes barely floated but were carried into the side channel by the onrush of water, dragging against the bottom for several hundred feet and scouring troughs in the bed material. This same process also enlarges the sloughs. When extreme staging occurs in the mainstem and a large volume of water spills over the berms, then ice floes drift into the side channel. These ice floes scour the banks and move bed material, expanding the slough perimeter. This scouring action by ice can therefore drastically alter the aquatic habitat.

The erosive force of ice affects vegetation along the river. The frequency of major ice jam events is often indicated by the age or condition of vegetation on the upstream end of islands in the mainstem. Islands that are annually subjected to large jams usually show a stand of ice-scarred mature trees ending abruptly at a steep and often undercut bank. A stand of young trees occupying the upstream end of islands probably represents second generation growth after a major ice jam event destroyed the original vegetation. Vegetation is often prevented from re-establishing by ice jams that repeatedly override some islands.

Ice processes have several impacts on aquatic habitat. The sloughs may have snow ice up to 5-6 feet thick. Diversion of flow and ice into the sloughs may cause large changes in channel morphology. Large amounts of silt may be deposited in the system at breakup. The silt deposits move downstream during summer high flows, covering good spawning habitat.

Ice processes do not appear to play as important a role in the morphology of the Susitna River below the Chulitna confluence. This river reach regularly experiences extensive flooding during summer storms. These summer floods seem to have significantly more effect on the riverine environment than do ice processes (R&M Consultants, Inc. 1982a, 1982b). This reach is characterized by a broad, multichannel configuration with distances between vegetated banks often exceeding 1 mile. The thalweg is represented by a relatively deep meandering channel that usually occupies less than 20 percent of the total bank-to-bank width. At low winter flows the thalweg is bordered by an expanse of sand and gravel (R&M Consultants, Inc. 1982b). Although ice cover progression frequently increases the stage about 2-4 feet above normal October water levels, no significant overbank flooding takes place, although some sloughs and the mouths of some tributaries do receive some overflow. The ice cover below Talkeetna is usually confined to the thalweg, and surface profiles rarely approach the vegetation trim line along the banks.

2. SEDIMENT TRANSPORT

The transportation of sediments decreases substantially between freezeup and breakup, primarily because of the elimination of glacial sediment input and the reduction in flows. The glaciers contribute the majority of the suspended sediment by volume to the Susitna. Other factors that significantly influence the sediment regime are turbulence, velocity, and discharge, all of which are greatly reduced during the winter. However, the advent of frazil ice in October provides a variety of processes by which particles, both in suspension and saltation, can be moved. Ice nucleation, suspended sediment filtration, and entrainment of larger particles in anchor ice are some of the processes described in this section. The dramatic nature of breakup often introduces sediment to the flow by re-entraining particles that had settled to the bottom. This ice event is characteristically accompanied by ice scouring and erosion during extreme stages. Ice jam induced flooding commonly flushes sediments from side channels and sloughs. Ice blocks are heaved onto river banks or scraped against unconsolidated depositional sediments, removing soils which may become entrained in the turbulent flow and carried downstream.

Laboratory investigations have determined that ice readily nucleates around supercooled particles. These particles may be in the form of organic detritus, soils, or even water droplets (Osterkamp, 1978). Prior to freezeup, the Susitna River abounds in clay-size sediment particles which may form the nucleus of frazil ice crystals. The first occurrence of frazil is generally also marked by a reduction in turbidity. Visual observations seem to indicate that the decrease in turbidity is proportional to the increase in frazil ice discharge. It is not certain whether this occurs because of the nucleation process or by filtration.

As described in previous sections, frazil ice crystals tend to flocculate into clusters and adhere together as well as to other objects. When frazil floccules agglomerate they form loosely packed slush (Newbury, 1978). Water is able to pass through this slush but suspended sediments are filtered out. Sediment particles are therefore entrained in the accumulating ice pack. Ice shavings from bore holes drilled through the ice often contain silt-size particles of sediment. Early flows of slush ice accumulate on the lower river below Susitna Station and progressively advance upstream. These early slush floes possibly filter high sediment concentrations in October and retain them in suspension all winter.

When frazil ice collects on rocks lying on the channel bottom, it is referred to as anchor ice (Michel, 1971). Anchor ice is usually a temporary feature, commonly forming at night when air temperatures are coldest, and releasing during the day. Like slush ice, anchor ice is porous and often has a dark brown color from high sediment concentrations. These sediment particles were either once suspended and subsequently filtered out of the water, or else were transported by saltation until they adhered on contact with the frazil. When anchor ice breaks loose from the bottom, it generally lacks the structural competence to float any particles larger than gravel. Frazil slush is therefore an effective medium for sediment transport during freezeup, whether the process is nucleation, filtration or entrapment.

An ice cover advancing upstream can cause a local rise in water levels, often flooding previously dry side channels and sloughs. Substantial volumes of slush ice may accompany this flooding. On December 15, 1982, Sloughs 8 and 8A were flooded when the ice pack increased in thickness on the mainstem immediately adjacent to the slough entrance. These sloughs received a disproportionate volume of slush ice relative to water volume since the water breaching the berm constituted only the very top layer of mainstem flow. The majority of slush ice floats near the water surface despite only minimal buoyancy. The flow spilling over the slough berms therefore carried a high concentration of ice. This slush ice and entrained sediment rapidly accumulated into an ice cover that progressed up the entire length of Slough 8A.

Side channels and sloughs that were breached during freezeup and filled with slush ice are not necessarily flooded during breakup. If these sloughs are not inundated then the ice cover begins to deteriorate in place. The entrained sediment consolidates in a layer on the ice surface and effectively reduces the albedo, further increasing the melt rate. What finally remains is a layer of fine silt up to ½-inch thick covering the channel bottom and shoreline.

If berms are breached during breakup, then ice fragments from the main channel may be washed into the slough and become stranded in the shallow reach. These ice floes then simply melt in place, depositing their sediment load in the side channel. This occurred in May 1983 when the "A5" access channel to Slough 21 flooded during a major mainstem ice jam.

Shore-fast ice along the perimeter of an ice jam is usually not floating. When debris accumulating behind a jam consolidates, the resulting surge wave may provide the critical lifting force to suddenly shift the border ice. This occurred near Slough 21 on May 4, 1983. Tons of ice were shoved onto a gravel island, entraining particles up to boulder-size and producing ridges of cobbles, gravels and organics. By this process of laterally shoving substrate material, ice can build up or destroy considerable berms and change the size of gravel bars near ice jam locations. When the lateral pressure exerted by ice is compounded by simultaneous downstream movement such as during an ice jam release, the effects on the river banks can be devastating. Many cubic feet of bank material were scoured away in minutes when massive jams released near Slough 21, Sherman, and Chase in May 1983 (figure 50).

An interesting phenomenon observed during breakup was the effective filtering capability of ice jams and individual ice blocks. Sediment-laden water flows through the many channels and interstices between the fragments in an ice jam. These interstices are usually filled with porous slush which removes suspended sediments from the water. Ice jams can concentrate sediment in this manner and often become very dark in color.

As discussed, Susitna River ice generally consists of alternating layers of rigid, impermeable clear ice and porous, loosely packed, rounded crystals of metamorphosed frazil ice. Water can percolate through the permeable layers, which strain out suspended sediment particles. This sediment becomes concentrated when the ice melts and is either re-entrained into suspension or deposited on the river bank if the ice floes were stranded (figure 51).

3. SLOUGH OVERTOPPING

The sloughs and side channels of the middle and lower Susitna River convey mainstem flow for most of the open water season and generally dewater prior to freezeup. Overtopping occurs when mainstem water levels exceed the threshold elevation at the slough entrances. This typically occurs during floods initiated by snowmelt and augmented by rainfall and glacial melt, and often during freezeup when mainstem water is staged to a higher level before the advancing ice front. Breakup ice jams dramatically increase the water level in a relatively short reach immediately upstream of the obstruction. Water levels can easily exceed those associated with even extreme summer flooding. When this occurs, the river banks can be overtopped as the water seeks an alternate route to bypass the jam.

The sloughs on the middle river are overtopped at different river discharges. The bed material is often composed of large cobbles and gravels which may be transported during the peak annual flood but not by the typical overtopping flow which occurs at the usual mainstem discharges of between 25,000 cfs and 40,000 cfs. This is evident also by the numerous beaver dams and ponds located in some sloughs indicating that flows do not reach extreme velocities. During breakup, the activity of solid ice floes moving bank material has been well documented and little doubt remains that ice can move great volumes of material, even up to the largest boulders (Newbury, 1968). Entrance berms can be built up by ice floes shoved laterally from the main channel, literally bulldozing the substrate in front of them. Conversely these same berms can be removed if ice floes override the channel entrances.

The typical sequence of breakup overtopping occurs as follows. An ice jam develops on the mainstem. This starts as a simple floating jam against a solid ice cover obstruction but evolves into a dry dam when ice accumulations cause a compression of the debris, increasing the thickness and grounding the ice on the channel bottom. The jam now completely blocks the river channel. Water levels rapidly rise, spilling into side channels or flowing overbank. If the flow can be conveyed through side channels, then the mainstem water level stops rising. If the diverted flow is shallow, then ice floes can not leave the ice-choked mainstem before becoming grounded on the channel bed. Subsequent surges due to ice debris compressions may shove the ice blocks laterally, pushing bank material into low mounds or berms.

Compressions also result in increased water levels, also causing more water to flow out of the main channel. If compressions continue, then a water level may be reached that is deep enough to drive the ice floes out of the main channel and into the diversion channel. The solid floes, which may have large dimensions and weigh thousands of pounds, are carried through the side channel, bumping and scraping over the entrance berm, impacting the banks, scouring the bed until finally becoming stranded. Severe modifications of the side channel morphology occur in this manner. Figure 52 shows an extreme example of this process. A massive ice jam on the mainstem caused water to flow into a side channel, which also became blocked and caused flooding of the terrace along the left bank. Ice blocks and water eroded out what is now called Slough 11.

Overtopping may occur at some sloughs during freezeup as well. These events are considerably less dramatic and usually do not affect the channel morphology since solid ice is absent. Mainstem staging causes the water level to rise and eventually seep through the snow cover lying over the entrance berm. During some years this results only in the formation of snow ice. If the water continues to rise, the snow rapidly erodes away and open water flows through the side channel. If overtopping continues, the entire slough may be flooded. Water continues flowing until the mainstem recedes. The side channel flow may be accompanied by slush ice. This, however, has no detrimental influence on the channel since the ice lacks cohesion and usually flows around obstacles. The presence of shallow open water in the slough may result in the formation of anchor ice on the channel bed if air temperatures are cold enough (i.e. less than -10 C). Anchor ice was reported in Slough 8A during the 1982 freezeup when an estimated 140 cfs flowed through that channel.

4. GROUNDWATER

Most sloughs on the middle river have channel bed elevations low enough to intercept the local groundwater table. This water seeps into the channel and prevents any permanent ice development. Groundwater temperatures are generally warm (2-3 C), melting existing ice and causing leads to form in the sloughs. These leads usually remain all winter, often extending beyond the slough mouth and into the main channel ice cover.

Observations and recordings of groundwater levels in wells adjacent to the mainstem indicate that water goes into or out of ground storage depending on mainstem stage. At high stages, when the mainstem water level is higher than the local water table (i.e. during floods), water percolates through the substrate and groundwater levels gradually rise. Conversely, when mainstem stages are low, groundwater seeps from the banks until it reaches a level near the mainstem water level.

Groundwater observation wells located at Slough 9 indicated a rising water table as the main channel ice cover approached in both 1982 and 1983. This coincided with a noticeable increase in the surface area of isolated pools in the slough system. Snow surrounding these pools was inundated and subsequently froze into snow ice. Slough banks began to seep ground water and the flow in the sloughs increased slightly. The increase in groundwater flow rapidly melted through ice covers over the pools and prevented further ice from developing.

The thermal influence of the groundwater is overwhelmed if the slough is overtopped, but since overtopping during freezeup is a relatively short term event, the groundwater provides heat when overtopping ceases. This heat influx continues all winter.

The sloughs effected by groundwater seeps during the winter include:

Slough 21	Slough 8A
Slough 11	Slough 7
Slough 10	Slough 6
Slough 9	Lane Slough
	Whiskers Slough

V. WITH PROJECT STUDIES

A. METHODOLOGY AND SCOPE

Winter with-project studies included simulations of reservoir and river temperatures and ice processes, groundwater, sediment, and channel stability studies. The reservoir and river temperature and ice simulations provided the necessary information on flows, water levels, and temperatures to make the other studies. The sequence of these simulations is given below.

1. Reservoir(s) operation simulations, in which the power and flood releases are determined, on a weekly basis, throughout the year.

2. Reservoir(s) temperature/ice simulations utilize meteorologic and hydrologic data to determine outflow temperatures and winter reservoir ice cover on a daily basis.

3. Instream temperature simulations proceed from the release rate and temperature at the dam(s) and produce temperature profiles in the open-water on a weekly basis.

4. Instream ice simulations begin at the 0 C isotherm determined from the instream temperature model and predict the ice regime downstream.

Additionally, a mail survey of experience in operating hydroelectric projects in cold regions was undertaken. Letters were sent to operators of hydroelectric projects and concerned environmental agencies to ascertain measures employed at the projects to minimize potential problems. Concerns addressed by the survey were:

1. project operation to control ice formation in the river downstream,
2. project operation to control ice cover cracking in the reservoir,
3. effects on terrestrial animals of exposure to ice covered reservoir banks,
4. problems of bank erosion associated with ice in the reservoir and river downstream.

1. RESERVOIR ICE MODELLING

With-project reservoir temperature and ice cover characteristics are simulated with the Dynamic Reservoir Simulation Model (DYRESM), developed by Imberger, Patterson, and others (Imberger and Patterson, 1981). The model has been calibrated by Harza-Ebasco using Eklutna Lake data from 1982-1984 (Harza-Ebasco Susitna Joint Venture, 1984a). Acres used the same model for the License Application studies, with a limited calibration study on Eklutna.

In order to include effects of an ice cover, an ice subroutine developed by Patterson and Hamblin for Canadian lakes has been incorporated in the model.

Ice would begin to form on the reservoir when the surface temperature has cooled to 0 C and daily average air temperatures are below 0 C. At Watana and Devil Canyon this normally occurs in November. Once the river temperature at the upper end of the reservoir has dropped to 0 C, an estimate is made for frazil ice input also. The frazil input is estimated to be 5% of the water flow, and is assumed to be present beginning November 1 and decreasing to 0%

on December 31. Once an ice cover has formed on the reservoir, snow is also allowed to accumulate based on actual precipitation records. The snow acts as insulation, slowing the growth of ice. The ice cover generally grows throughout the winter in accordance with daily air temperature and precipitation data. In the spring, solar radiation begins to melt the cover before air temperatures exceed 0 C. Later, the warm air temperature in combination with the increasing solar radiation tends to melt the cover rapidly, usually in less than 1 month.

2. INSTREAM TEMPERATURE MODELLING

With-project stream temperatures are modeled by SNTEMP, the Stream Network Temperature Simulation Model, developed by the U. S. Fish and Wildlife Service. SNTEMP predicts water temperatures at selected points in a river network. The model uses discharge and temperature output from the reservoir simulation, DYRESM, and routes the flow downstream utilizing meteorologic, hydrologic, and stream geometry data to compute heat flux relationships and water temperature along the river. SNTEMP has been documented by the Arctic Environmental Information and Data Center (AEIDC, 1983).

SNTEMP operates between Watana or Devil Canyon downstream to Sunshine Station at the Parks Highway bridge. Flow and thermal input from tributaries between the dam and Sunshine Station are included. Topographic shading is also an important feature of the Susitna River which is included in the model.

Generally, the SNTEMP output which is utilized by ICECAL is the location of the 0 C river isotherm as a function of time during the winter. From this point, ICECAL computes ice production in the river downstream to the ice front. However, in the spring, the 0 C isotherm as computed by SNTEMP is downstream of the ice front, which indicates meltout is in progress. In this case, the water temperature at the front is interpolated from the SNTEMP results in order to estimate the temperature at the ice front. With this value, the melting of the front and under-ice water temperature decay are computed by ICECAL.

3. INSTREAM ICE MODELLING

Preliminary river ice simulations with the ICESIM model were undertaken by Acres American, Inc. (Acres American, Inc., 1983) in preparation of the FERC License Application. Harza-Ebasco Susitna Joint Venture (1984b) documented the river ice model ICECAL and its calibration to the Middle Susitna River for use in the present study ICECAL was used to generate the river ice simulations presented in this report. The model provides a daily summary of hydraulic, temperature and ice conditions throughout the study reach for the period November through April.

The particular hydraulic and ice operations performed by the ICECAL model include the following:

a. Hydraulic profiles are computed daily for the study reach.

b. The 0 C isotherm is located based on SNTEMP results.

c. Frazil ice production is computed between the 0 C isotherm and the ice front. If the 0 C isotherm is determined to be downstream of the ice front, meltout of the ice front and under ice temperature decay are computed.

d. Shore ice (border ice) growth proceeding from shore is computed in the reach between the 0 C isotherm and the ice front.

e. As frazil ice coalesces into loosely-consolidated slush floes, hydraulic conditions at the ice front are analyzed to determine whether the floes accumulate at the upstream (leading) edge of the ice cover. If not, the ice is swept under the ice cover and deposited on the underside of the ice cover downstream, in accordance with the under-ice velocity profile.

f. Computations are made of the slush and solid ice component thickness of the river ice cover.

g. Meltout of the ice cover is simulated by computing the melting of the cover and retreat of the ice front when warm water, above 0C, reaches the ice front.

Input data utilized by ICECAL include the following:

a. River cross-sectional geometry and bed roughness for the study reach.

b. Weather conditions (daily air temperature and wind velocity) for the study reach.

c. Water inflow hydrograph at upstream boundary of study reach.

d. Daily frazil ice discharges at upstream boundary of study reach, or

e. Location of the 0 C isotherm, or water temperature at the ice front.

Calibration of ICECAL was carried out using observations of natural ice processes during 1982-83 and 1983-84 (R&M Consultants, Inc., 1984a, b).

Computer simulations of natural and with-project ice processes were made for the winters of 1971-72, 1976-77, 1981-82, and 1983-83. The winter of 1971- 72 is considered to be a representative cold winter, whereas, the winter of 1981-82 is average in temperature. The winter of 1982-83 represents a warm winter and 1976-77 represents a very warm winter. Climatic data for these years are summarized on figures 53 and 54. Natural streamflows at Gold Creek for these winters are shown in figure 55.

The basic simulations were run using the Case C release constraint, shown on figure 56. Other simulations have been made using the Case E-VI release constraint, also shown on figure 56. The multi-level intakes at Watana and Devil Canyon were initially operated in an attempt to match the natural flow temperature. Other simulations were made assuming release of warmest water year-round, and additional low power intakes at Watana.

These variations were made to test the sensitivity of release temperatures and ice regime to operating policy and intake design. The simulations are as follows:

a. Basic Runs

Case C Flow Constraints

Inflow-Matching Release Policy

Intake Geometry per License Application

	Year Simulated	Pre-Project	Watana Only 1996	Watana Only 2001	Watana + Devil Canyon 2002	Watana + Devil Canyon 2020	Watana Filling
(Cold)	1971-72	1	5	9.	12.	16.	
(Very Warm)	1976-77	2	6		13.		
(Average)	1981-82	3	7	10.	14.		19. (2nd winter)
(Warm)	1982-83	4	8	11.	15.	17.	18. (1st winter)

b. Attempt to Provide Warmer Releases Throughout the Winter.

(i) Repeat run 5, assuming 4 C releases throughout the winter.

(ii) Repeat run 9, using warmest water available, year-round.

(iii) Repeat run 9, using warmest water available year-round, with additional low intake at El.1800, (approach channel El.1770).

(iv) Repeat run 9, using warmest water available year-round, with additional low intake at El. 1800, (approach channel El. 1500).

(v) Repeat run 9, with additional low intake at El. 1636 (approach channel El. 1470).

c. Effects of Revised Flow Constraints (Case E-VI)

(i) Repeat run 10, with Case E-VI flow constraint.

(ii) Repeat run 14, with Case E-VI flow constraint.

B. SIMULATION RESULTS

1. RESERVOIR ICE

Figures 57 and 58 show typical results of the ice cover simulations on Watana and Devil Canyon reservoirs, respectively, based on DYRESM results.

On Watana, the ice cover begins to form in November and gradually thickens until March or April. The cover begins to melt in April or May and the meltout is generally more rapid than the formation. The ice cover is generally melted sometime in May. In a cold winter, such as 1971-72, the Watana cover is not completely melted until early June.

The timing for the cover on Devil Canyon Reservoir is very similar to Watana Reservoir. However, the cover at Devil Canyon is generally thinner than at Watana. For instance, in a cold winter such as 1971-72, the maximum computed thickness at Watana was about 60 inches, compared to about 48 inches at Devil Canyon. The thinner cover at Devil Canyon is because of the above 0 C releases from Watana into the Devil Canyon reservoir during the winter, compared to the 0 C inflow to Watana reservoir in the winter.

The reservoir cover thicknesses shown on figures 57 and 58 are based on inflow matching" temperature control. That is, the intake port which most closely matches the reservoir inflow temperature is operated. Also, the releases are constrained by Case C. Other operating rule curves have been studied including:

a) Warmest available water year-round,

b) Additional low intakes at Watana, and

c) Case E-VI release constraint.

All of the above operations result in slight differences in the ice thickness, but the timing of formation and meltout are not substantially different.

Figures 59, 60, and 61 show the minimum, mean and maximum Watana Reservoir water levels for operations in 2001, 2002 and 2020. Reservoir levels in 1996 would be similar to 2001. Figures 62 and 63 show the same information for Devil Canyon Reservoir in 2002 and 2020. Watana Reservoir is normally be drawn down between 40 and 90 feet between October and May. Between mid-April and mid-May the water level is fairly stable. Beginning in mid- to late May, the reservoir water surface begins to rise by about 20 to 30 feet a month. During the same periods the Devil Canyon water levels remains relatively constant and is not drawn down.

a. <u>Watana Operation</u>

At Watana, the reservoir would generally freeze over while the water level is near its maximum for the year. Ice would first begin to form in shallow areas and along the edges of the reservoir. This would consist of a very thin sheet. The ice cover would progress toward the reservoir center until it covered the entire surface. It is not uncommon for an overnight cold spell to result in a thin sheet of ice over large portions of the reservoir surface. If solar radiation and winds do not melt or break this sheet up, it is not unlikely that much of the reservoir surface could become ice covered almost simultaneously. Once an ice cover forms, it would thicken to a few inches very rapidly. The thickening rate would be reduced with time because of the insulation effect of the ice and any snow cover. The ice thickness would be relatively uniform over the entire reservoir surface but a little thicker at the edges where the cover first forms. The reservoir ice surface would be relatively smooth. Strong winds may result in delays to ice cover formation by mixing reservoir water and keeping the surface water warm. This wind effect is accounted for in the DYRESM simulations.

As the water level drops, ice sheets and blocks would be deposited on the banks. These would generally appear as in figure 64 and would conform to the topography of the banks. Local discontinuities in the ice on the banks would occur due to rocks, stumps, changes in slope and other morphological and topographical features on the banks.

Shelving of ice which would result in large discontinuities in the bank ice is not expected. The reservoir water level would begin to draw down in October, prior to freezeup of the reservoir surface. The draw down would be continuous, at a rate of 0. 25 to 0. 5 feet per day. This would preclude the possibility that the ice might freeze into the banks if the water level were stable during freezing and form an ice shelf when the water level draws down further. The thickness of the ice would gradually increase as the water level dropped. Cracks would separate the ice sheets on the banks. The ice would generally be covered with snow.

The ice cover would begin to melt in early April and be completely melted between early May and early June. In general, the melting of the ice cover would coincide with the lowest extent of the reservoir drawdown and reservoir levels during this period would be relatively stable. By the time reservoir water levels begin to rise, the reservoir ice cover would normally be nearly completely melted.

Ice on the reservoir banks would melt from solar and atmospheric radiation as the ice on the reservoir. Heat from water just below the reservoir surface and warm inflows would melt reservoir ice slightly faster than ice which was deposited on the banks. Ice deposited in shaded areas on the banks and along the south shoreline would remain longer. Ice deposited on the northern shore and exposed to direct solar radiation would melt faster than along the southern shore. As the water level rises, ice which remains on the banks would be refloated into the reservoir where it would melt rapidly due to the warm reservoir water.

Ice on the reservoir surface in contact with the underlying soil and along the banks may melt sooner than the ice in the center of the reservoir. This would free the main body of the reservoir ice cover to move with winds. The ice on the reservoir banks near the maximum water level would be thinner than the ice on the banks near the minimum water level, and would thus melt sooner. For this reason, much of the ice on the reservoir banks may,in fact, melt sooner then the reservoir ice cover.

Soon after the reservoir water surface is exposed to direct radiation and winds the upper layers of the water would overturn. The reservoir surface would be at 4 C or higher, and any ice refloated from the banks would be melted rapidly.

During the meltout period, winds would generally be from the north and west and would tend to blow refloated ice blocks and broken ice on the reservoir toward the south and east shores. Some localized accumulation of ice may occur along the banks. However, the continuing rise of the reservoir- during this period should keep most ice afloat.

Some erosion of reservoir shoreline material may be expected to occur in the spring as the mobile reservoir ice cover or floating ice blocks comes in contact with the banks. This is expected to result in localized increases in suspended sediment concentrations near the shorelines, but is not expected to cause slope instability.

Travel across the reservoir by animals may be impeded by the ice on the banks during the winter. However, the experience survey indicates this is not a problem. Travel is more likely to be difficult during the period of initial ice formation when the ice thickness is not sufficient to hold an animal and during the melt out period when the ice is deteriorating. Thus there would be periods in November and May of every year when travel across the reservoir would not be assured. At other times, animals which could swim or walk across the reservoir would not be impeded.

Ice blocks or sheets may be deposited in tributary mouth areas along the reservoir shore. Where the tributary walls are steep, this may shield the ice from direct solar radiation and melting of the ice before it is refloated by the rising water levels, may be delayed. However, it is not believed that this would prevent passage by fish through these areas since normal tributary flows during the melt out would be above freezing, would tend to melt this ice and provide adequate passage conditions.

b. Watana Filling

Watana reservoir would be filled over a three year period as the dam is raised from elevation (El.) 1700 to El. 2205. The winter releases during the two winters of impounding would be the same as natural. That is, the water levels would be held constant in the reservoir. During the first winter of filling the dam crest would be at approximately El. 1950 and the water level would be stable at a level near El. 1880. An ice cover would form on the reservoir in much the same manner as during operation. The thickness would be similar and the melt out would occur at about the same date. During the second winter of filling the dam crest would be at approximately El 2130 and the water level would be stable at a level between El. 2050 and El. 2100. Ice cover formation, thickness and melt out would all be similar to the first winter of filling.

Since there would be no drawdown during the winters of filling there would be no ice blocks on the banks. Passage over the reservoir would not be assured during the initial freeze-up and the melt out periods.

c. Devil Canyon Operation

The Devil Canyon water level would be relatively constant at its maximum level throughout the winter. In dry years, only, there would be period during freezeup, when the water level would be rising from its minimum level to El. 1455. During this period, ice along the reservoir shoreline would be somewhat thinner than ice in the center of the reservoir. This could make travel across the ice cover hazardous. In most years the water level would be at its maximum level by early December. In dry years, the water level would be at its maximum level in January. So, generally, between December and melt out in May, travel across the reservoir would be safe. During initial freezeup and meltout, passage would not be assured. Because the water level would not be drawn down there would be no ice blocks on the banks.

Since the Devil Canyon winter water level would be relatively stable there is a possibility of cover expansion and ice push induced erosion of bank materials and damage to vegetation rooted in the banks (Gatto, 1982). This could lead to some localized increases in suspended sediment concentrations near the eroded areas. The potential for this is probably greater upstream of the canyon, between river mile 162 and the Watana Dam (RM 184).

2. INSTREAM TEMPERATURE SIMULATIONS

a. The 0 C Isotherm Position

The position of the ice cover leading edge, or ice front, is ultimately related to the position of the 0 C isotherm in the river. The position of the 0 C isotherm, for both natural and with-project conditions, has been simulated by the SNTEMP model, utilizing data from various climatic years.

Under natural conditions the 0 C isotherm in the river progresses downriver in early winter. Climatic conditions in early winter normally cause the upper river basin to freeze earliest, and freezing temperatures then progress southward and downriver. With-project, however, warm waters above 0 C would be released from the dams year-round, and the water would slowly cool as it is exposed to below-freezing air temperatures while it moves downriver. Therefore, as air temperatures cool in early winter, the 0 C isotherm in the river would progress upriver.

The position of the 0 C isotherm is dependent upon climatic conditions, flow rate, and reservoir temperature releases. Given a steady flow and temperature release scenario, the 0 C isotherm would progress upstream during the freezeup season at a rate determined by climatic conditions. If the flow rate were decreased or the release temperature decreased, the progression upstream of the 0 C isotherm would be quickened. If the flow rate were increased or the release temperature increased, the 0 C isotherm progression would be slowed.

Generally, with the project in place, the 0 C isotherm would advance upriver during freezeup, and during meltout/breakup it would retreat downriver. However, with-project simulations of the progress of the 0 C isotherm show that the progression rate fluctuates over a relatively wide range from week-to-week, including reversals in direction from advancing upriver to retreating downriver and back again. This fluctuation is caused by short-term air temperature variations in the river basin.

Comparisons of with-project conditions for the same climatic year under one-dam and two-dam scenarios, however, show a greater degree of fluctuation of 0 C isotherm progression for the one-dam scenario than for the two-dam. This can be explained by the fact that there are moderately different flow releases and slightly different release temperatures under each operational scenario. Changes in flow and temperature releases could be used, in fact, to gain some degree of control over the position of the 0 C isotherm and, hence, the ice front. A multi-level intake structure is included in the design of both dams to draw off waters from selected thermal strata for this purpose.

b. Effects on the Ice Cover

SNTEMP assumes an open water scenario and cannot accurately predict the position of the 0 C isotherm in an ice covered reach. Therefore, whenever the 0 C isotherm is downstream of the ice front (i.e.: beneath the ice cover), the ICECAL model supercedes SNTEMP and calculates a new position for the 0 C isotherm. Whenever the 0 C isotherm is again upstream of the ice front, SNTEMP results again take over. Simply stated, it is important to note that whenever the 0 C isotherm is upstream of the ice front, SNTEMP results apply; whenever the ice front is upstream of the 0 C isotherm, ICECAL results apply.

When the 0 C isotherm is upstream of the advancing ice front, cooling air temperatures prevail and the ice front advances upriver. Under these circumstances a reach of open water exists upstream of the ice front with water temperatures at 0 C. In this reach, border ice and anchor ice could form. Simulations predict that a maximum of about 30 miles of border ice could form with a one-dam scenario, while only as much as 10 miles of border ice could form under a two-dam scenario. Anchor ice could form in this reach in a manner similar to that which forms upstream of the ice front under natural conditions.

Whenever the 0 C isotherm is coincident with the ice front, stable air temperatures prevail and the position of the ice front would be stable, neither advancing nor retreating. In this circumstance, all open water upstream of the ice front would be above 0 C, and no significant border ice or anchor ice could form there.

When the 0 C isotherm decays to a position downstream of the ice front, warming air temperatures prevail and the 0 C isotherm lies beneath the ice cover. Under these conditions, water above 0 C underlies the ice front. This causes the ice front to disintegrate and the ice front retreats downriver. In this circumstances, no border ice or anchor ice could form upstream of the ice front.

3. RIVER ICE

a. Freeze-up

(1) Natural Conditions.

Observations of natural conditions in the middle river are available from the winter of 1980-81 through 1983-84 by R&M Consultants (R&M Consultants, Inc., 1982a, 1983a, b). ICECAL model calibrations were made by Harza-Ebasco Susitna Joint Venture (1984a) using the 1982-83 and 1983-84 observations. Additional ICECAL simulations of natural conditions were made for the winters of 1971-72, 1976-77, and 1981-82, for comparison with the with-project runs.

Simulations of natural conditions in the middle river are started when the ice bridges at the Chulitna confluence. This bridge has generally not occurred until the lower river front has reached the confluence area. In cold years with low flows, the middle river progression has begun prior to the lower river being completely covered. For simulation purposes, the 1981-82 and 1982-83 middle reach progression was begun on the observed date, and the 1971-72 and 1976-77 progressions were assumed to begin at the earliest and latest observed bridging dates, respectively.

For natural conditions, the upstream simulation boundary was just upstream of Gold Creek, with ice inflow based on observations for 1981-1982 and 1982- 1983, and ice inflow based on estimates correlated to Talkeetna temperatures for 1971-72 and 1976-77.

(2) With-Project Conditions.

For with-project simulations, lower river ice front progression is assumed to have reached the Yentna River on November 1. This is similar to natural timing, and is expected to be conservative for with-project ice conditions in the middle reach. In fact, the ice bridge near Cook Inlet with-project may form 1 or 2 weeks later than natural because of trapping of the early Upper River frazil by the reservoir(s).

Following the November 1 start of the lower river front, ICECAL computes daily ice generation in the Middle Reach, estimates the ice contribution from the Chulitna and Talkeetna rivers, and estimates the contribution of frazil generated on the lower river. The daily ice volume is accumulated until the estimated volume of ice required to fill the lower river is produced. At this time, the progression is permitted to begin in the middle reach.

The upstream boundary of ICECAL for with-project conditions is the 0 C isotherm location, as determined by the instream temperature model (SNTEMP). ice production is then computed in the reach from the 0 C isotherm downstream to the ice front. At the front, the ice either contributes to the front progression or is drawn down under the ice cover and deposited downstream, depending on hydraulic conditions at the front.

(a) Project Operation. The annual maximum simulated progressions of the ice front in the middle river are summarized in figure 65. The following conclusions can be made:

1. In warm winters, the ice front is not expected to progress past RM 126 (Slough 8A-East head).

2. In a very cold winter, the ice front is expected to progress to the vicinity of Gold Creek, similar to natural progressions.

3. In an average winter, the front is expected to progress to very near Gold Creek with Watana only, and 5-10 miles downstream of Gold Creek with Devil Canyon on line.

The simulated duration of ice cover in the middle reach is summarized figure 66. This summary indicates the following:

1. In the coldest winter, 1971-72, the natural duration is about 6 months. The with-project duration is 4. 5 to 5. 5 months. The duration with Devil Canyon is slightly less than with Watana only. The progression

typically begins 3-4 weeks later than natural, but meltout is generally early to mid-May, similar to natural.

2. In the warmest winter simulated, 1976-77, the natural coverage exists for only 5 months, compared to 3-4 months for with-project conditions. The with-project ice progression starts 2-4 weeks later than natural and meltout is 2-3 weeks earlier.

3. In an average or warm winter, the natural coverage is about 6 months, and the with-project coverage is only about 3 months. With-project progression typically begins in mid-to-late December and melt-out is complete by mid-to-late March.

Maximum stages and ice thicknesses for basic simulations are tabulated in figures 67 and 68. Maximum stages are plotted relative to threshold elevation for sloughs in the middle reach in figures 69 to 72. Maximum ice thicknesses are plotted in figures 73 to 76.

These results indicate the following:

1. In a cold winter such as 1971-72, many sloughs are overtopped in the natural condition as well as with-project. However, with-project, most of the sloughs are overtopped by a larger amount and for longer durations.

2. In a warm or very warm winter such as 1982-83 or 1976-77, there is little or no overtopping naturally, and overtopping is minor, with- project.

3. In the average winter, 1981-82, there is minor overtopping naturally, and moderate overtopping with Watana only.

4. thicknesses, with- project, are generally about the same as natural in the downstream half of the reach and less in the upstream half of the reach. This is particularly true after 2002 since the ice front rarely reaches Gold Creek with Devil Canyon on-line.

Border Ice, (or shore ice, or lateral ice) can be expected along the river banks where the water has cooled to 0 C upstream of the ice front. ICECAL estimates the development of border ice based on the water velocity and air temperature. The greatest rate of border ice development occurs in low velocity zones with cold air temperatures. The development of border ice is important because the water surface covered by border ice is not available for producing frazil ice.

Border ice is simulated based on general experience data, and observations on the Susitna. Figure 65, which shows the maximum progression of ice in the Middle Reach does not indicate the border ice which would exist upstream of the front. Simulations indicate that, with Watana only, border ice would exist, as times, as far as 30 miles upstream of the maximum progression and may cover up to 25% of the water surface in that reach. With Devil Canyon, the border ice is expected to be restricted to a reach of only about 10 miles upstream of the maximum progression, again covering as much as 25% of the surface area.

Anchor ice is generally found in the same general locations as border ice, that is, between the 0 C isotherm and the ice front. Anchor ice is not included in the simulation because little is known about the mechanism of its formation and it is generally not modelled. Natural observations indicate it is quite common in the middle reach, presently, and would also be there with project. It is expected to have a relatively minor effect on with-project water levels upstream of the ice front, which are generally lower than natural levels. Anchor ice generally produces less staging than an ice cover with the same volume of ice, since an ice cover results in a displacement of the water surface as well as an additional roughness surface (shear face). The anchor ice produces a similar displacement but with no additional roughness surface.

(b) Watana Filling. Results of simulations for the first and second winters of filling compared to natural are shown on figure 77. A warm winter was used to simulate the first winter of filling since relatively warm releases would be made through the low level outlet for that condition. For the second winter, colder winter temperatures were used since colder releases would be made from near the reservoir surface with the cone valves. The rates of flow during the winters of filling would be equal to natural flow rates. Thus, these two winters represent a wide range of conditions during reservoir filling.

Figure 77 indicates that middle reach winter stages during filling are similar to or slightly lower than natural stages. Simulated thicknesses are likewise similar to or less than natural conditions.

The ice front during filling is simulated to progress to the vicinity of RM 156-162, which is in the Devil Canyon area. The simulated ice processes during filling upstream of Gold Creek are questionable, however, because observations of natural conditions in this zone have indicated that intermittent closure by border ice is the predominant process, rather than front progression. No significant ice is expected upstream of Devil Canyon during filling under average or warm winter conditions.

Simulated freezeup of the middle reach during filling begins 5-7 weeks later than natural, and meltout is expected in early May, similar to natural conditions.

3. ALTERNATIVE INTAKE DESIGNS AND OPERATING POLICY

The basic simulations discussed above have been made with the "Inflow-matching" release criteria. This generally results in the coldest water available being released in the winter in an attempt to match the 0 C winter inflow temperature. However, there is some interest in warmer releases in the winter in order to reduce the extent of ice coverage and staging with-project. The following studies were made to determine the sensitivity of ice related stages to intake operation for Watana in 1996 and 2001 using hydrologic and meteorologic data for the winter of 1971-72, the coldest winter:

1. A theoretical 4 C release for the entire winter period. This is not a DYRESM result, but assumes that the warmest water in the reservoir can be selected for release throughout the winter.

2. Warmest water available for the present intake design. This generally means using the bottom opening of the multi-level intake throughout the winter.

3. Warmest water available with an additional lower intake at El. 1800. This intake would be 240 ft. below the lowest present intake opening.

4. Warmest water available with an additional lower intake at El. 1636, instead of El. 1800.

Figure 78 is a comparison of the runs in relation to their performances in preventing overtopping of significant sloughs and side channels. Conclusions are as follows:

1. The theoretical 4 C water is not effective for preventing overtopping significantly in the downstream third of the reach between Talkeetna and Gold Creek.

2. In the middle third of the reach, 4 C water would be effective. However, the lowest intake tested, El. 1636, is no more effective than the present design, and 4 C water cannot be withdrawn from the reservoir in this winter.

3. In the upstream third of the reach, 4C water would be very effective. However, only the intake at El. 1636 begins to approach the effectiveness of the 4C water. The present intake design, using warmest water, is a substantial improvement over "inflow-matching." However, an intake at El. 1800 is no more effective than the present intake design.

In summary, an additional low intake at El. 1636 would have some limited benefits in reducing ice related stages. However, the additional cost and other water quality questions related to releases from such depths make the alternative questionable.

4. Case E-VI Flow Constraints.

The bulk of the river ice studies have been made using the Case C flow constraints. However, Case E-VI has now replaced Case C as the recommended flow guidelines. The two release constraints are shown in figure 56. Case E-VI provides a more uniform summer flow.

Additional ICECAL simulations have been made for Watana only in 2001, and Devil Canyon in 2002, with Case E-VI, for comparison with Case C. The comparison of slough stages is shown on figures 79 and 80.

Conclusions are as follows:

1. For 2001, average stage is about the same for both cases. Case E-VI results in one less slough overtopped (Slough 8), but the upstream sloughs (8A, 9 and 9A) are overtopped with a slightly larger head with Case E-VI.

2. For the 2002 comparison, Case E-VI results in slightly higher stages in the downstream reaches and slightly lower stages near Gold Creek. However, most sloughs are not overtopped for either case. Therefore, with Devil Canyon on-line, slough overtopping is not considered important in either case except in a cold winter such as 1971-72.

3. In summary, Case E-VI and Case C produce similar winter ice conditions for the inflow-matching release policy for the years 2001 and 2002, even though the winter release temperatures are slightly colder with E- VI.

b. Breakup

Breakup processes are expected to be different from natural in the Susitna River below the project, especially in the Talkeetna to Devil Canyon reach. Since the maximum upstream extent of the ice cover below the dams would be between RM 124 and RM 142, there would be no continuous ice cover between the damsite and the ice cover and, consequently, no breakup or meltout in that reach. Any border ice attached to the shore would probably slowly melt away in place. Occasional pieces of border ice might break away from shore and float downstream. Ice in the river reach above the project reservoirs would break up normally, but would not drift into this area as it normally does because it would be trapped in the reservoirs.

Ice drifting into the headwaters of the Watana Reservoir may jam against the reservoir ice cover. This could result in elevated water levels in the Susitna River immediately upstream of the reservoir. As the reservoir ice cover melts, the ice from upstream would move further into the reservoir and the elevated water levels would decrease.

At the time of the potential headwater ice jamming, the water level in the reservoir would be at its lowest level and would be between 40 and 120 feet below the normal maximum pool level. Water levels resulting from any ice jam would probably not exceed the normal maximum pool and would therefore not result in any flooding above the normal maximum pool level.

The natural spring breakup drive is usually brought on by rapid flow increases that lift and fracture the ice cover. The proposed project reservoirs would regulate such seasonal flows, yielding a more steady flow regime and resulting in a slow meltout of the ice cover in place, from upstream to downstream.

The warmer than natural water temperatures released from the project would cause the upstream end of the ice cover to begin to decay earlier in the season than natural. Gradual spring meltout with Watana operating alone is predicted to be as much as 4 to 6 weeks earlier than natural, and 7 to 8 weeks earlier than natural with both dams operating. By May, flow levels in the river would be significantly reduced compared to natural as the project begins to store incoming flows from upstream. The result is expected to be that breakup drive processes that now normally occur in the middle river area would be effectively eliminated. Instead, a slow and steady meltout of river ice in this reach would probably occur. Since there would not be an extensive volume of broken ice floating downstream and accumulating against the unbroken ice cover, ice jamming in the middle river would probably not occur or would be substantially reduced in severity. This would eliminate or substantially reduce river staging and flooding normally associated with ice jams, thereby eliminating or greatly reducing the overtopping of berms, flooding of side sloughs and scour of the bank and channel.

Observations of natural conditions indicate that breakup ice jam flooding in the lower river is not as severe as in the Middle Reach. Breakup ice jams have been noted near Montana Creek (RM 77), RM 85. 5 and RM 89 in 1983. However, the wide flood plain with many channels tends to prevent significant staging. With-project, spring flood flows from the Talkeetna, Chulitna and Yentna Rivers would make breakup in the lower river more similar to natural than break-up in the Middle Reach. The earlier meltout, warmer than natural temperatures and reduced flows from the Middle Reach with-project, are expected to cause the lower river meltout or breakup to begin earlier and be milder than natural.

c. Effects of Power Flow Variation on Ice Cover

Natural ice cover formation is generally a very stable process, with minor stage fluctuations in the zone of front progression. In fact, natural flows are generally low and decreasing during the freezeup process which contributes to a well-behaved condition. Natural breakup, however, can be a much more unstable process. Flows are generally increasing in the spring and the ice cover is weakened by solar radiation and warm air. This combination can result in collapse of covers over large reaches, causing- ice jams and flooding.

With hydroelectric power developments on a river, the natural flow and temperature conditions are altered. Power releases in the winter are generally larger than natural and warmer. In addition, hydroelectric generation can respond quickly to system load changes and is well suited to load following or peaking. Flow fluctuations resulting from load following or peaking can result in fracture of an advancing ice cover in early winter, or a retreating cover in spring. Such a fracture of cover can lead to flow surges, ice jamming, and flooding of aquatic, terrestrial, or human habitat.

(1) EXPERIENCE SURVEY.

A mailed survey has been conducted in order to ascertain the effects of winter power operation on river and reservoir ice. Results indicate the following:

1. There are few or no problems within impoundment zones. There are isolated instances of animal casualty, but no specific operation constraints for this.

2. There are a few cases reported in Canada where ice jam flooding of towns has been attributed to upstream hydroelectric power operations.

3. Where operational procedures are in effect, they are generally directed toward protecting human life and property rather than aquatic or terrestrial habitat.

4. Operational restrictions such as those for British Columbia Hydro's Peace River project include the following:

a. During freezeup ice cover progression through sensitive areas on the river, flows are controlled at a high level until the cover develops sufficient strength to withstand flow fluctuations.

b. After freeze-up, the plant can be operated freely without endangering the cover except in the frontal zone.

c. During break-up and melt-out, flows are again maintained at a high level in the sensitive areas to erode the cover as quickly as possible. If tributary break-up appears imminent, B. C. Hydro releases are decreased in order to minimize the effect of the tributary ice surge.

5. In other cases operational constraints are employed to prevent the formation of hanging dams downstream or to reduce water levels upstream after a dam forms. These dams may result in high water levels which can reduce the plant generating capacity, endanger the powerhouse, or result

in flooding of areas adjacent to the river. These types of constraints include:

a. Inducing an early ice cover on the river upstream of known sites of hanging dams, by artificial means such as ice booms or other obstructions. When an ice cover forms, frazil ice production stops and the hanging dams, which result from frazil accumulation, are minimized.

b. Inducing an early ice cover on the river by keeping powerhouse discharges low while the ice cover forms. This may result in more rapid ice cover advance, preventing further frazil production. After the ice cover is formed, powerhouse discharges can be increased.

c. Preventing ice cover formation in sensitive areas by fluctuating discharges, continually breaking up the ice cover and keeping it downstream. This may result in higher water levels further downstream, but lower water levels in sensitive areas.

d. Reducing discharges after a hanging dam forms in order to reduce water levels upstream of the hanging dam.

6. The Canadian Electrical Association and many plant operators indicated that powerhouse operations during the winter to maintain a stable cover would be site specific and require operating experience over a number of years (ACRES, 1980). Climatic conditions, ice characteristics of years (Acres Consulting Services, Ltd. 1980). Climatic conditions, ice

characteristics, channel morphology, and water temperature are all variables which must be considered.

(2) Susitna Operations.

The License Application indicates that with Watana only, the Susitna project would be operated to generate base load electrical energy. In addition, following the construction of Devil Canyon, Watana would load-follow and Devil Canyon would be base-loaded. It is presently proposed to operate Watana before Devil Canyon is built, and later Devil Canyon, as follows (Alaska Power Authority 1985):

1. Allow maximum of ± 10% flow variation from the weekly average flow within a given week.

2. Allow maximum ± 10% flow variation from the current flow within a given hour.

A flow variation of 10% (for instance, 1000 cfs with a base flow of 10,000 cfs) results in an open-water steady-state stage change of only about 0.3 feet. With an ice-cover, the steady-state stage change would be about 0.5 feet. This is considered to be safe from the standpoint of preventing breaking of the cover during freezeup, mid-winter, or breakup conditions. It is not believed that other constraints on winter powerhouse operation would be necessary to keep the ice cover stable.

4. PROJECT EFFECTS ON RIVER CROSS-SECTION CHARACTERISTICS

Project operation in the winter is expected to change the flow cross-section characteristics in the middle reach compared to natural conditions. Parameters such as velocity, cross-section area and wetted bed perimeter would be somewhat different with-project. For example, figures 81 and 82 show the middle reach velocity profile before and after freezeup for the winter of 1981-82, for natural and with-project 1996 conditions. These plots show the following:

1. Before freezeup, velocities are highly variable from section to section, for natural or with-project conditions. Velocities for natural conditions range from about 1.5 to 7 fps. With-project the range is from about 2 to 9 fps. Average velocity is about 3 fps, natural and 4 fps, with-project.

2. After freezeup, velocities range from 1 to 3 fps for natural conditions, and about 2 to 3 fps with project conditions. Average velocity is about 2 fps for natural and 2.5 fps with-project.

3. After freezeup, velocity is controlled by the critical velocity for erosion-deposition of slush beneath the ice cover, for pre-project and with-project conditions. This velocity is about 3 fps and is the practical limit for velocity beneath the cover. This mechanism controls the distribution of ice deposited beneath the cover.

Figures 83 and 84 show conditions at a typical cross-section in the middle reach, LRX 22, RM 119.3, for natural and with-project conditions. These plots show the following:

1. For natural conditions, the under ice water surface after freezeup is almost the same as the open-water stage. Figure 78 shows that at this section, the velocity drops from 3.6 fps to 2.3 fps during the freezeup, corresponding to the flow change from 3000 cfs to 1750 cfs during the freezeup. This also means that, in this case, the velocity decrease just compensates for the friction perimeter increase to produce a similar friction slope before and after freezeup.

2. For natural conditions at this section, there is little change in flow area or bed perimeter as a result of freezeup.

3. For with-project conditions, the under-ice water surface increases during freezeup resulting in a slight increase in exposed bed perimeter. Figure 84 shows that the velocity drops from 5.2 fps to 2.2 fps during freezeup. This is due to the flow reduction from 12,000 cfs to 10,000 cfs and the increase in flow area during freezeup required to balance the effect of additional friction surface with the ice cover.

4. For with-project conditions at this section, the flow area doubles during freezeup and the bed perimeter increases slightly. The under-ice flow velocity after freezeup is almost the same as natural.

Upstream of the with-project ice cover there would be changes from natural conditions as well. Figures 85 and 86 show natural and with-project conditions in 1996 at LRX 33, RM 130.1 for the winter of 1982-83. These plots show the following:

1. The natural condition velocity after freezeup is 1.6 fps and the with-project velocity is 3.3 fps.

2. The flow area after freezeup changes from 1800 square feet for natural conditions to 3000 square feet for with-project conditions.

3. The water surface elevation after freezeup changes from 615.5 feet msl under natural conditions to 613.2 feet msl with-project.

5. EFFECTS ON SLOUGH AND SIDE CHANNEL FLOW

Flows in sloughs and side channels are affected by winter river water levels which can increase infiltration from the mainstem and overtop berms at upstream ends of the channels. Figure 87 is a diagramatic presentation of the sources of slough flow. At a particular slough (or side channel), the general effect of increasing river water levels without overtopping the upstream berm would be to increase the amount of groundwater flow from the mainstem without significantly altering its temperature. At the same location, if the upstream berms were overtopped, both the quantity and temperature of intragravel flow would generally be affected: the quantity of flow could increase significantly, while the temperature would be dominated by that of the diverted mainstem water.

Intragravel flow refers to the flow in the bed material of the habitat area and has two sources (see figure 88):

1. Groundwater flow which has three components (see discussion below under Quantity of Flow).

2. Longitudinal flow in the streambed material caused by surface flow in the habitat area.

In the winter, when a berm at the upstream end of a habitat area is not overtopped, intragravel flow is generally caused by groundwater flow. When the habitat berm is overtopped, the intragravel flow many be dominated by flow induced by surface flows.

Winter water levels and thus slough and side channel flows would be affected differently in areas within and upstream of ice covered reaches of the mainstem. The extent of the ice cover would vary from year to year as shown on figures 65 to 67, depending primarily on climatic conditions. The upstream limit of the ice cover would be located further downstream with Devil Canyon in operation than with Watana operating by itself. In addition, the ice covered reaches would be dynamic and thus areas near the upstream end of the ice cover may experience changing water levels throughout the winter. Figure 67 can be used to determine whether important habitat areas would be affected by overtopping of upstream berms, as well as the mainstem water levels influencing groundwater flow toward each habitat area. This exhibit assumes existing slough berms are not protected from overtopping. The following discussion concentrates on effects on quantity and temperature of slough and side channel flow in areas within and upstream of the ice cover.

a. <u>Quantity of Flow</u>

The rate of flow in sloughs and side channels depends on local runoff, groundwater discharge, and flow resulting from overtopped berms. Under natural conditions, local runoff and overtopping of berms are relatively insignificant from early September until an ice cover forms on the river in

November or December. During this period, the main source of flow in these habitat areas is groundwater which may originate from any of three sources:

1. Shallow localized infiltration from the mainstem,

2. More regional groundwater transport in the downstream direction within alluvial materials comprising the Susitna River Valley, and

3. Transport toward the river from upland glacial till and sedimentary rocks comprising the Susitna River Valley walls.

Between November and May, the middle Susitna River is normally ice covered. Water levels are elevated and overtop some side channels and sloughs. In non-overtopped areas, the higher water levels increase groundwater flow from the mainstem toward the sloughs and side channels.

With-project mainstem flows would be higher than natural between September and April. Formation of ice cover in the middle Susitna River would be delayed relative to natural conditions by approximately two to six weeks, until sometime in December. The maximum extent of ice-affected water levels would be reduced relative to natural conditions. Water levels would be increased within of the ice-covered areas, and decreased upstream of ice-covered areas.

(1). Period Immediately Prior to Ice Cover Formation.

Under with-project conditions, mainstem water levels would be higher than natural between September and November when an ice cover normally occurs. When Watana is operating alone, flows in this period would vary between 6,000 cfs and 13,000 cfs and would average approximately 9,000 cfs. This is about 6,000 cfs above average natural flows for the period. When Devil Canyon first comes on line, flows would be in a much narrower range and would average approximately 7,000 cfs. As system energy demands increase, flows would also increase to near Watana-only levels. Resulting water levels would be about two feet above natural levels, and would be similar to minimum with project water levels for the summer period (May through August). The groundwater flow resulting from shallow infiltration from the mainstem would thus be increased about natural conditions and would be similar to that component for the previous summer of operation. The component of groundwater discharge to sloughs resulting from regional downstream transport within alluvial valley materials would be largely unchanged from natural conditions or the previous summer period because the downstream gradients would remain about the same. Elevated groundwater levels resulting from elevated mainstem stage, with ice cover, could result in somewhat larger areas of upwelling, thus increasing slough discharge somewhat. The component of groundwater discharge originating from upland areas would be unchanged from natural conditions. However, this component normally declines throughout the winter as recharge to these aquifers is reduced. Consequently during this period, groundwater flow in side channels and sloughs would be higher than under natural conditions, and similar to, although perhaps slightly smaller than, groundwater flows corresponding to minimum mainstem flows during the previous summer.

(2). Within Ice-Covered Areas.

An ice cover would form on the middle Susitna River during December and January. With-project discharges during this period are approximately 9,000 cfs above natural conditions and water levels within the ice-covered areas are generally a few feet higher than natural. For this reason, the groundwater component due to local mainstem infiltration would be increased above that under natural conditions and would also be increased above that during the with-project summer open water period. The other two components of groundwater flow would be largely unchanged from natural conditions, although the component due to regional down-valley groundwater flow may increase slightly if the area open to upwelling increases because of generally elevated groundwater levels in the valley. Groundwater discharge from upland areas would be the same as under natural conditions, and thus lower during this period than during the summer open-water period.

There would be an increased frequency of berm overtopping in these areas relative to natural conditions if they are not protected, and the total flow in the sloughs and side channels would increase considerably from natural flows where this occurs.

(3). Upstream of the Ice-Covered Area.

The ice-covered reach of the middle Susitna River would extend upstream to between river mile 125 and river mile 142, depending on climatic conditions and whether or not Devil Canyon is operating. Upstream of the ice front, open water conditions would prevail. Winter time discharges would normally result in river water levels which are less than or equal to natural ice-affected water levels in this reach. The differences are generally on the order of zero to two feet. The maximum allowable winter discharge for Case E-VI is 16,000 cfs, which is not sufficient to overtop berms at the upstream ends of any of the sloughs upstream of the ice front. Some side channels, however, could still be affected by mainstem flows. The groundwater component due to shallow mainstem infiltration would be lower than natural in this area.

However, winter discharges are higher than minimum with-project summer discharges so that the mainstem-affected component of groundwater flow would be higher in the winter than the minimum summer component. Other components of groundwater flow would be largely unaffected. Therefore, upstream of the ice-covered area, side channel and slough groundwater flows would be higher than minimum with-project summer groundwater flows but lower than natural winter groundwater flows.

6. Water Temperature

Surface water temperatures in sloughs and side channels are affected by the temperature of upwelling groundwater, climatic conditions, the temperature of mainstem water if the berm is overtopped, and the temperature of local surface runoff. In the winter, runoff can be neglected. Intragravel temperatures are primarily influenced by the temperatures of the components of groundwater flow. In habitat areas, intragravel temperatures appear to remain more stable than river temperatures.

The degree to which intragravel temperatures at a habitat site change in relation to changes in mainstem temperature appears to be a function of

1. the distance between the site and the mainstem, which affects the travel time for groundwater from the mainstem:

2. overtopping of berms by cold mainstem water, which may depress intragravel temperatures; and

3. the relative contributions of the three components of groundwater flow.

Measurements of intragravel temperatures by the Alaska Department of Fish and Game (ADF&G 1983) at a site near the mouth of Slough 8A showed that, following the progression of an ice front past the slough, the intragravel temperature dropped to near 0 C within approximately a mouth. The ice cover raised mainstem water levels near the slough by 3.4 feet (R&M Consultants, Inc., 1984b) and caused overtopping of the upstream berm. ADF&G hypothesized that the cold surface water depressed intragravel temperatures. It may also be possible that intragravel temperatures were responding to mainstem temperature transmitted with groundwater flow. Intragravel temperatures at this site seem to reflect mainstem temperature influence more than at another site upstream in Slough 8A. Intragravel temperatures at the upper site are constant near 3 C all winter. The differences in the temperatures at the two sites may be related to the fact that the downstream site is within 1,000 feet of the river while the upstream site is approximately 4,000 feet from the river. Observations on intragravel temperatures and mainstem staging for the winter of 1983-84 were similar to 1982-83, although overtopping of the berm was not reported (ADF&G 1985, R&M Consultants, Inc., 1984a).

Measurements by ADF&G (1983) at a site in Slough 9 indicate that slough surface water temperatures drop to near 0 C during the winter, while suggesting that intragravel temperatures remain fairly constant at about 3 C. However, this latter inference cannot be confirmed because of the lack of intragravel temperature data for the period from mid-November 1982 through mid-March 1983. Intragravel temperatures recorded in 1983-84 (ADF&G 1985) were constant at about 3.5 C throughout the winter while surface water temperatures varied to as low as 0.5 C. As a result of overtopping during ice breakup in May of 1983, intragravel temperatures fell rapidly although only minimally (less than 0.5 C) in response to a rapid 5 C decline in surface water temperature. This suggests a response of intragravel temperatures to overtopping flows of very cold water, but still a dominance by warmer upwelling water.

At slough 11, both surface water and intragravel temperatures remained approximately constant at about 3.5 C from September 1982 through April 1983. However, it was discovered on April 29, 1983, that the surface water probe was covered with about one inch of silt (ADF&G 1983). When the probe was uncovered, the recorded temperature quickly rose by 1 C to the inferred true surface water temperature. Thus it is unclear whether the recorded surface water temperature reflects a predominance by warm upwelling water, or whether it is in effect a measurement of intragravel rather than surface water temperature. Intragravel temperatures measured in 1983-84 (ADF&G 1985) show similar values to those measured in 1982-83. Surface water temperatures are more sensitive to climate conditions, are less varied than at Slough 9 and generally between 1 C and 2 C between November and February.

At Slough 21, intragravel temperatures near the mouth of the slough remained fairly constant at about 3.5 C during the winter of 1982-83, while surface water temperatures were somewhat colder, fluctuating between 0 C and 2 C (ADF&G 1983). At a site further upstream in the slough, both the surface water and intragravel temperatures varied in apparent direct correlation with each other, with the surface water temperatures about 1.5 C-2 C colder than the intragravel temperatures. During overtopping events in September (warm water) and May (cold water), both the surface water and intragravel temperatures showed approximately equivalent responses of several degrees. This suggests that surface water temperatures in the upper portions of the slough may be dominated by upwelling groundwater, except during overtopping of the upstream berm, when diverted mainstem water would dominate. Intragravel temperatures measured in 1983-84 (ADF&G 1985) showed similar trends, although overtopping was not reported.

Intragravel temperatures measured in side channels (ADF&G 1985) show the same characteristics as in sloughs. The measured temperatures are much more stable than mainstem and side channel surface temperatures, but show more variability over the year and more short term fluctuations than slough intragravel temperatures. This may be explained by their closer proximity to the mainstem. Side channels may be subject to more frequent overtopping than sloughs.

In general, it appears that the intragravel temperature in many habitat sloughs and side channels would be dominated by warm groundwater flows during the winter, except for periods of overtopping of upstream berms as a result of ice staging or ice breakup if the berms were not protected from overtopping. the temperature of groundwater flow in slough areas appears to remain fairly stable, at a temperature approximately equal to that of the mean annual mainstem water temperature (Alaska Power Authority 1984). Side channel intragravel temperatures show about 1 C to 2 C variability about the mean annual river temperature. The mean annual mainstem temperature is not expected to change significantly with-project, and the temperature of that component of groundwater flow which is directly related to mainstem flows should not be changed.

For those slough areas and side channels which appear to be more directly influenced by mainstem temperature variations, such as near the mouth Slough 8A and near the upstream end of Slough 21, the increased winter flows relative to natural conditions and increased mainstem water levels as a result of ice formation could produce colder than natural upwelling groundwater and thus colder intragravel temperatures. However, the intragravel temperatures in these sites are often found to be near 0 C especially at Slough 8A, for natural conditions.

6. ICE EFFECTS ON SEDIMENT TRANSPORT AND CHANNEL STABILITY

Ice processes affect sediment transport and channel stability in the following manners:

1. The formation of an ice cover on a river may double the flow wetted perimeter, reduce the flow velocity and reduce the tractive force of the flow. This will reduce the sediment transport capacity of the flow. (Sayre and Song 1979)

2. Elevated water levels associated with ice cover formation and breakup jamming may result in overtopping of sloughs and side channels along the perimeter of the main channel. Flow velocities associated with these events may remove material in the slough streambed. Velocities associated with breakup jamming and overtopping may be sufficient to erode large amounts of material and change the character of the slough. A breakup ice jam in 1976 resulted in changing Slough 11 from an upland slough to a side slough. (LaBelle 1984)

3. High flow velocities associated with surges resulting from the failure of an ice jam may result in the scour of river banks and may remove vegetation and streambed material. (Gerard 1983, R&M Consultants, Inc. 1984b)

4. Anchor ice may attach to a streambed and when refloated by rising temperatures and solar radiation, may carry some fine sediments from the streambed with it. (R&M Consultants, Inc. 1984b)

5. The flow of water through a porous slush ice cover may result in the filtering of some fine material carried by the water. (R&M Consultants, Inc. 1984b)

6. The melting of ice deposited on riverbanks, floodplain areas, or sloughs may result in the deposition of sediments carried in the ice on the underlying material. (R&M Consultants, Inc. 1984b)

The discussion of effects of project operation is organized by habitat type.

a. Mainstem Habitat

(1). Suspended Sediment Concentration.

With-project suspended sediment concentrations in the mainstem of the middle river would be increased over natural winter concentrations, which are near zero mg/l. Fine materials influent to the reservoir are expected to remain in suspension and be discharged throughout the year. It has been estimated that the suspended sediment concentration in the powerhouse flows would be between 0 and 100 mgl (Peratrovich, Nottingham, and Drage 1982) with an average of about 60 mgl. This concentration would remain relatively stable between the dams and the upstream end of the ice cover. There would be a reduction in the amount of frazil and anchor ice occurring in the middle reach due to the warmer releases from the dams. Some sediment may be picked up by the frazil and anchor ice. However, any reduction in suspended sediment concentration caused by frazil and anchor ice may be compensated by sand particles picked up from the river bed as a result of higher winter flows (Harza-Ebasco Susitna Joint Venture 1984c).

Downstream of the ice cover, some sediment may be trapped by the frazil ice. The ice cover would reduce the capacity of the river to pick up additional sand particles. Suspended sediment concentrations are expected to remain relatively constant at levels similar to levels upstream of the ice cover.

In the reach downstream of the confluence with the Chulitna and Talkeetna Rivers, the suspended sediment concentration is also expected to be controlled by the concentration upstream of the confluence. Flow from the Chulitna and Talkeetna Rivers would dilute the suspended sediment concentration slightly. Winter discharges in this reach would be higher with project than natural conditions. This would cause additional sediment to be picked up. However, some sediment may also be trapped by the ice. Suspended sediment concentrations would be similar to the middle river.

(2). Channel Stability.

Winter flows throughout the middle and lower rivers would be higher than natural. However, they would not be high enough to affect the stability of the streambed. The water levels downstream of the ice front would be higher than under natural conditions but the velocities would be similar to natural conditions. Streambed substrate would be stable during this period, although some sand may be picked up by the increased flows. This would not alter the channel geometry.

Breakup ice jams in the middle river would be reduced in frequency or eliminated due to project operation. Stream flows would be regulated by the project and spring floods, which normally lift and fracture the ice cover, would not occur. Warmer than natural releases from the reservoir would melt the ice cover from the upstream end. Meltout would occur up to 8 weeks earlier than natural breakup. Therefore, the main channel streambed and banks would not be subject to scour resulting from ice jams.

Some sediment suspended in the flow may be trapped in the porous frazil ice cover. The presence of layers of sediment in frazil ice covers has been observed in the Tanana River. The mechanism for this is not known. The concentration of sediment in the ice appears to be highest at the bottom of the ice cover (Chacho 1985).

Since the amount of material suspended in the flow may increase with project, the amount of sediment trapped in the ice may also increase. During the spring meltout, the water level would reduce gradually as the ice cover melts. The ice cover would melt primarily from the bottom due to the warm water in the river. Air temperatures would not be high enough to cause significant surficial melting of the ice. Most sediment trapped in the ice would be near the bottom of the ice and should be transported downstream as it is freed from the melting ice, rather than deposited on the river banks and underlying material. There would not be breakup ice jams which normally transport ice blocks onto overbank areas.

Because of the higher than natural water levels within the ice covered area, there would be some stream-deposited ice in unprotected sloughs, side channels and on the banks. Under natural conditions, this does not occur, except at breakup. However, some border ice commonly breaks up and is deposited on banks.

In shallow areas the ice would not be exposed to much flow. The potential for accumulation of sediment in this ice would be lower than in the main channel. During the melt out of the main channel ice cover, the ice in these areas would not be as exposed to warm water as the mainstem ice and may remain in place after the main channel ice is melted out. Deposition of sediment from the melting of this ice is not expected to be significant and may be less than has been noted to be deposited on streambanks from ice remaining after breakup ice jams.

In other areas along the stream margin the ice may be exposed to more flow throughout the winter. Potential sediment accumulation in this ice would be higher than in shallow areas, but less than in the mainstem. These areas would be exposed to melting from warm water in the same manner as the main channel. Sediments accumulated in the ice would be washed downstream as the ice melts and the sediment is exposed to flows. The ice would melt out in the same manner and time as the ice in the main channel. Deposition of sediments on underlying material might not exceed levels resulting from ice deposited during spring breakup.

b. Side Channels

(1). Suspended Sediment Concentration.

With-project winter flows and water levels would be sufficient to prevent most middle reach side channels from being dewatered. Downstream of the ice front, elevated water levels would keep side channels watered. Suspended sediment concentrations would be similar to the main channel with-project conditions in these areas. Upstream of the ice front, water levels would not be affected by ice. Side channels which would not be dewatered at flows of

12,000 cfs to 13,000 cfs would have suspended sediment concentrations similar to conditions in the main channel. Dewatered side channels would be free of the main channel influence and would have clear upwelling flows.

Anchor ice may form in watered side channels prior to the formation of an ice cover. Warm groundwater upwelling would inhibit this in some areas. This anchor ice may attache to and, when floated, transport some fine sediment out of the side channel. However, this is not expected to be significant.

(2). Channel Stability.

Within the ice covered area, high winter water levels would result in greater depths of flow in side channels than under natural conditions. Velocities, however, would not exceed approximately 2 feet per second. Additionally, the presence of an ice cover would effectively reduce the tractive force in the side channel. Substrate materials are expected to remain stable; however, materials such as sands and silts may be flushed from the substrate. The meltout of the ice cover would eliminate breakup ice jams as a source of scour in th side channels in the spring. Thus their streambeds would be more stable at that time also. Substrate materials in side channels upstream of the ice covered area would remain stable.

Since ice jams would be less frequent or eliminated there would be less frequent stranding of ice which may contain sediment that would deposit in the area. Some ice from the ice cover may remain on the side channel banks, and could result in deposition of sediment.

c. Side Sloughs

(1). Suspended Sediment Concentration.

With-project winter flows and water levels would be sufficient to overtop unprotected berms at the head of sloughs within the ice covered reaches (figure 67). Suspended sediment concentrations in these sloughs would have the characteristics of main channel flow. Upstream of the ice front water levels would not be sufficient to overtop berms. Water in these areas would be clear, resulting from groundwater flow.

An ice cover may form in some side sloughs prior to ice caused staging in the mainstem. Warm groundwater flow would inhibit this in some areas of these slough. This ice may transport some fine sediments downstream when it is broken up and floated downstream, but this is not expected to be significant. Ice which may form in sloughs not late overtopped may cause some increase in suspended sediment concentration when broken up and floated, but this also would occur under natural conditions.

Shorefast ice would also form in sloughs not subject to overtopping. This also occurs under natural conditions. In general, sloughs which are not overtopped by elevated water levels would not have any change from natural conditions with respect to suspended sediment concentrations.

(2). Channel Stability.

Flow depths in side sloughs within ice covered reaches would be greater than under natural conditions. However, the velocities would not exceed approximately 2 feet per second and the ice cover would reduce the tractive force of the flow. Sediment transport should be limited to fine materials. Side slough substrate would be stable under with project conditions. Substrate in side sloughs which are not overtopped would remain stable.

As with side channels, the melt-out of the ice cover would eliminate breakup ice jams as a source of scour in side sloughs. This would improve the stability of their substrate material. Since ice jams would be less frequent or eliminated, there would be less frequent stranding of ice which may contain sediment that would deposit in the area. In overtopped sloughs, some ice from the ice cover may remain stranded on banks. This could result in some deposition along the banks.

In non-overtopped sloughs, shore ice that forms would melt out in much the same manner as for natural conditions. This ice would remain for longer periods than main channel ice since it is not subjected to warm water from the main channel. Warming air temperatures, increased solar radiation and warm groundwater upwelling would melt the shore ice.

d. Upland Sloughs

Project effects on winter time suspended sediment and channel stability in upland sloughs would be similar to side sloughs. Fewer upland sloughs would be affected by overtopping than side sloughs.

e. Tributary Mouths

(1). Suspended Sediment Concentrations.

Suspended sediment concentration in the tributary mouth habitat areas would be affected in the same manner as the main channel habitat areas.

(2). Channel Stability.

Channel stability in tributary mouth habitat areas would be affected in the same manner as main channel habitat areas. The manner of ice deterioration would eliminate the potential for main channel ice to remain in tributary mouth areas and potentially block fish passage in these areas.

Tributary mouth habitat areas are subject to deposition of sediments brought down from the tributaries (Harza-Ebasco Susitna Joint Venture 1984d). This deposited material would normally be removed periodically by high summer flows. It can be speculated, although it hasn't been observed, that failure of breakup ice jams may cause surges which could also carry this deposited material downstream. With project, the manner of ice cover deterioration would preclude the removal of deposited sediments in these areas. Thus, aggradation affecting access may be encouraged by with project ice conditions. However, normal summer flows in the mainstem and tributary would cause downcutting of aggraded sediments and removal of sediments at most tributary mouths.

f. Tributaries

With project ice conditions would not affect sediment concentrations or channel stability in tributaries.

VI. ENVIRONMENTAL EFFECTS

A. OVERVIEW OF ICE-RELATED ISSUES

This section describes the environmental effects of ice processes on major resources of the Susitna River specific to the upper, middle and lower river zones referenced by proposed location of hydroelectric facilities. Natural ice processes would perceivably undergo dramatic changes due primarily to different flow and temperature regimes anticipated during the construction and operational phase of the project. This transformation raises issues and problems central to the welfare of fish, animal and habitat resources, and the people dependent upon them for recreational, commercial and subsistence purposes.

Natural ice processes have a dynamic effect on the physical characteristics of a subarctic river system by constantly altering channels and surrounding flood plain. Ice and related flooding phenomena have negative and positive effects on a riverine environment. Fish and animals are most notably effected by the destruction, creation and alteration of habitats. Human dependence on fish and animal life is incontrovertibly linked to habitat stability and availability.

1. SOURCES OF ISSUES

Because altered ice processes apparently evoke less public controversy, virtually all ice-related environmental issues originated with investigative agencies and consultants during the environmental analysis phase of the Susitna River study. Based on previous environmental assessments, the Alaska Power Authority and Alaska Department of Fish and Game identified the majority of issues associated with altered ice processes. LGC Alaska Resource

Associates, Inc. and E. Woody Trihey and Associates identified pertinent issues and problems in conjunction with ongoing environmental studies respective to their contract responsibilities. Except for commentary from a local citizen (letter dated March 3, 1984 from Leon B. Dick) ice-related issues from the private sector have been remarkably nil. Issues and problems can be categorized as those pertaining to fish and aquatic habitat, riparian vegetation, wildlife and terrestrial habitat, and public use activities.

a. Fish and Aquatic Habitat

Fish related issues focus on the effect of ice processes on incubation and fry production. More perplexing is the effect of altered ice processes on habitat. This aspect is considerably more complex since aquatic habitats could be destroyed, created or altered during different freezeup and breakup scenarios as a result of project construction and operations. Major issues relate to changes in channel morphology and substrate composition resulting from project-related ice and flooding processes.

b. Riparian Vegetation

Changes in riverine morphology obviously affect the shore line and adjacent substrate and subsequently the successional stage of vegetation. Plant composition and growth patterns would also be influenced by sediment deposition and different ambient temperature caused by higher water temperature and rate of heat transfer.

c. Wildlife and Terrestrial Habitat

The most significant issues concern the relationship of different ice conditions to the mobility and survival of large mammals. The number of potential ice-related mishaps that normally occur as animals move and forage in bottom land habitats may change as a result of more varied and less stable ice associated with higher winter flows and warmer temperatures. Of equal concern is the effect of ice and flooding forces on food and cover components of riverine habitats, especially those of low relief. During construction and operational phase, feeding niches subjected to flooding and overtopping would be significantly altered.

d. Public Use

The question of ice stability and presence of open water and its effect on winter human travel and access is addressed in this section. Untenable conditions prevail as a result of warmer water temperatures, open water stretches and weaker ice formations.

B. Mechanisms of Effects

The physical effects on river ice processes that would ensue from the construction and operation of the Susitna River Hydro- electric Project are detailed in Chapter V. The altered physical processes that are expected to have important effects on the biological and human use environments are briefly summarized here in order to help orient the reader to the discussions that follow.

1. IMPOUNDMENT ZONE

In this zone, where only the river occurs under natural conditions, Watana reservoir would first occupy the area from approximately RM 184 to 239 when full, a distance of about 55 miles. It would vary in width along its length from 500 feet to 22,000 feet (4.2 miles), not including runup into tributary mouths.

Later, Devil Canyon reservoir would occupy the area between about RM 152 to 184 when full, a distance of about 32 miles. Devil Canyon reservoir would vary in width along its length from about 500 feet to 3,800 feet, not including runup into tributary mouths.

While Watana reservoir is on line alone, the river would extend continuously below the dam . Once Devil Canyon reservoir comes on line, there would be no river reach between the two reservoirs when Devil Canyon reservoir is full; Devil Canyon reservoir would back up all the way to Watana Dam. Little drawdown of Devil Canyon reservoir would occur during the winter season, so there would never be much river reach between the two reservoirs in winter (although, in the summer, drawdown is sufficient to produce about 6 miles of river reach between the reservoirs). Below Devil Canyon dam, there would be a river reach in Devil Canyon of about 3 miles to the end of the zone at the canyon's mouth.

a. <u>Watana filling</u>

During filling, winter water levels in Watana reservoir would be held constant. During the first winter of filling, the water level would be stable at an elevation of 1880 feet, while during th second winter of filling it would remain at about an elevation of 2100 ft. Ice cover formation, thickness, and meltout would be similar in character to those of normal reservoir operations (see below), except that no drawdown would occur, preventing the formation of draped ice ramps along th reservoir shores.

Below the reservoir, no significant ice would occur in the river upstream of Devil Canyon under average or warm climatic conditions.

b. <u>Watana only on line</u>

(1). <u>Freezeup</u>.

Watana reservoir would generally begin to freeze over sometime during mid November. Initially, very thin border ice would form along the shores of the reservoir, and then progress toward the center. At maximum ice cover development,the ice thickness on the reservoir would average about 3 to 5 feet. The ice cover would be relatively smooth.

Drawdown of the reservoir during the winter would average about 90 feet, and would cause the ice near shore to fracture and become draped along the banks of the reservoir, creating an ice ramp surrounding the entire impoundment. The steepness and width of the ramp would vary depending upon local topography. Narrow cracks would appear at topographic breaks in the ice ramp. Where the ice cover comes in contact with the shore some bank erosion might occur, resulting in localized increases in suspended sediments near shore.

Below Watana reservoir for the 36 miles to the end of the zone, river water temperatures would remain above freezing and the river would not freeze over all winter. Open water would prevail throughout the river in this zone.

(2). Meltout/breakup.

In the spring, meltout on the Watana reservoir would occur generally from early May to early June, depending on the climate. The ice would begin melting along the shores first. The melting ice cover would then fracture into numerous large and small pans of ice. These pans would float around the reservoir until they melted away, probably being concentrated from time to time along the south and west shores due to winds. Draped ice above the water level would melt away more slowly. Some of it would be refloated and quickly melted away as the water level rises to store summer flows.

Ice drifting from the upper river into the headwaters of Watana reservoir might jam against the ice cover there. This could cause river staging to occur just upstream of the reservoir until its ice cover begins to melt and retreat. However, since the reservoir would then be at its minimum level due to drawdown, no flooding would probably occur outside the reservoir limits.

Where the draped ice ramp caused by drawdown overlies tributary mouths entering the reservoir, the ice would probably become grounded and block the stream mouths. However, these tributaries begin flowing early in the spring, often sometime in March, and the their warm flows would probably melt or erode out the draped ice in the stream mouth long before the reservoir itself began to melt out in April or May.

c. Watana and Devil Canyon on line

(1). Freezeup

Watana reservoir would freeze over in a similar fashion and timing to the Watana-only scenario, again starting with very thin border ice along shore and then freezing toward the center. Ice thickness would again average about 3 feet at maximum ice cover development. During the winter, drawdown on Watana reservoir would average about 40 feet, fracturing the ice cover and causing draping of ice along shore. However, because the drawdown in this case would be less, the severity of draping and ice ramp formation would be somewhat reduced, compared to the Watana-only scenario.

Devil Canyon reservoir would begin freezeup during November. During early freezeup, border ice would probably form along the shoreline before freezing toward the center. During dry years, when water levels may be rising during freezeup, ice near shore may be somewhat thinner than in the center. Ice thickness at the maximum development of the ice cover would average about 2-1/2 to 4 feet. Since no significant drawdown of the reservoir during the winter would occur, no nearshore ice fracturing and draping would occur.

Downstream from Devil Canyon reservoir, a river reach of about 3 miles of open water would occur to the end of the zone. This reach would all be within the confines of Devil Canyon. It is unlikely that any significant amount of border ice would form with the relatively warm water temperatures released from the dam within the turbulent canyon.

(2). Meltout/breakup.

In the spring, Watana reservoir would melt out in a similar fashion and timing to the Watana-only scenario. Devil Canyon reservoir would slowly melt out throughout May. There would be little rise in water level and therefore little fracturing of the ice cover until it had decayed and thinned considerably by melting, at which time winds might fracture the remaining cover and drive the debris to downwind shores.

2. MIDDLE RIVER ZONE

a. Freezeup

When Watana reservoir is filling, freezeup of the middle river would be delayed compared to natural conditions. Delay during the first year of filling would amount to about 7 weeks, while during the second year of filling it would be delayed about 5 weeks. The maximum upstream position of the ice front is predicted to be between RM 156 and RM 162. Ice thicknesses should be about one foot thinner than natural. Maximum river stages are expected to be 0 to 5 feet lower than normal during the first year of filling, and 0 to 3 feet lower than normal during the second year of filling.

When the project comes on line, freezeup in the middle river is predicted to be delayed due to higher winter flows, warmer water temperatures, and reduced frazil ice input into the middle river compared to natural conditions. The advancing ice front would be delayed in reaching the Susitna/Chulitna confluence and freezeup in the middle river would be delayed by 17 to 44 days with Watana dam alone on line, and by 27 to 47 days with Devil Canyon dam also on line.

Ice cover duration normally lasts 5 to 6 months under natural conditions. Duration with-project would range from 3 to 5.5 months, depending on climate.

With only Watana dam on line, the advancing ice front is predicted to reach only to somewhere between RM 124 and 142, while with Devil Canyon dam also on line, the ice front would reach somewhere between RM 123 and 137, depending on the climate and the operational scenario. No ice cover would mantle the river upstream from there; open water with temperatures above 0 C would prevail all winter. The position of the ice front would probably fluctuate significantly throughout the winter, as weather conditions changed.

When the ice front is downstream from the 0 C isotherm, border ice would form between the ice front and the 0 C isotherm, covering approximately 25 percent of the water surface. Anchor ice would also form at times in this reach, but would have little effect on water levels.

Upstream from the ice front no freezeup staging would occur; therefore no sloughs would be overtopped or flooded in that area. Downstream from the ice front freezeup staging would occur, and the higher winter flows would produce overtopping and flooding in more sloughs, more frequently, and for longer durations, than under natural conditions. With Watana dam alone, freezeup staging is expected to be 2 to 7 feet higher than under natural conditions. When Devil Canyon comes on line, freezeup staging is predicted to be 1 to 6 feet higher than natural. The higher stage levels may be sufficient to flood some vegetated islands as well as sloughs.

Upstream from the ice front, mainstem water temperatures would depend on the weather and the project operating scenario. Just below the dams, water temperatures would range from 0.4 C to 5.6 C from early November to late April. From there, temperatures would decline downstream until reaching the 0 C isotherm. With Watana dam operating alone, ice thicknesses below the ice front are expected to be similar to natural conditions. With Devil Canyon dam on line, ice thicknesses are expected to be 1 to 2 feet less than under natural conditions.

The altered flow regime would probably cause a change in the lengths of open leads throughout the winter. As under natural conditions, anchor ice which had formed in the river before the passage of the ice front would sometimes be exposed in these open leads.

b. Meltout/breakup

In the spring, the river ice is predicted to slowly melt away in place 4 to 6 weeks earlier than natural breakup with Watana alone, and 7 to 8 weeks earlier than natural with Devil Canyon also on line. Any border ice would slowly melt away in place. There would probably be little or no breakup drive, with its associated ice jamming. Therefore, there would be no overtopping and flooding of sloughs during this period, and no associated ice scouring and flow erosion in the sloughs.

3. LOWER RIVER

a. Freezeup

The ice cover is expected to begin forming in the lower part of the lower river early in November, about the same as under natural conditions. However, the increased flows and reduced frazil ice production from the middle river are predicted to delay the movement upstream of the ice cover such that it reaches the Susitna/Chulitna river confluence 17 to 44 days later than natural with Watana dam alone on line, and 27 to 47 days later than natural with Devil Canyon dam also on line.

Due to the increased flows from the middle Susitna River throughout the winter, it is speculated that there would be somewhat more ice in the lower river than under natural conditions. This, however, has not been quantified.

b. Meltout/breakup

The lower river is expected to melt out sooner than it does naturally because of the earlier meltout of the middle river and the resulting earlier influx of warm water into the lower river. The middle river is predicted to melt out earlier than in natural conditions by 4 to 6 weeks with Watana alone, and 7 to 8 weeks with Devil Canyon also on line. Therefore, the lower river could be expected to melt out at similar times. The meltout should be gentle compared to natural conditions because there would be no breakup drive of ice into the lower river from the middle river. The ice is expected to slowly melt away in place, with no ice jamming and its associated scour and flooding.

C. EFFECTS ON FISHERIES

1. INTRODUCTION

This section describes the potential effects of changes in Susitna River ice processes on fish habitats, resulting from various project operational scenarios. The Susitna River and its tributaries provide habitat for at least 19 species of fish (table 11); seven are anadromous and 12 are year-round residents. (Figure 89 shows the distribution of these species by study area). The Susitna River basin provides reproductive and rearing habitat for millions of salmon (recorded escapements vary from over 500,000 to more than 5 million, table 12). More than 99% spawn in its tributary systems. Available information indicates that the mainstem Susitna River may provide essential rearing habitat for two salmon species--chum and chinook. Like salmon, resident species such as rainbow trout and Arctic grayling mostly use the mainstem for migration. Some resident species also depend on the mainstem for overwintering habitats; others like burbot, whitefish, and longnose sucker reside year-round in the mainstem.

This analysis examines the likely with-project ice effects of Watana Dam alone and of Watana and Devil Canyon dams together on fish habitat in three stretches of the Susitna River. These are known as impoundment zone, middle river zone, and lower river (figure 89). The results of 21 ICECAL simulations are examined (table 13), four of which are natural (i.e. without project) and 15 of which are with-project and two are filling scenarios. These simulations were run under various meteorologic and hydrologic conditions. Thirteen of the with-project ICECAL simulations used Case C flow regimes while two used Case E VI Flows.

Table 11. Common and Scientific Names of Fish Species Recorded in the Susitna River Basin.

Arctic lamprey	Lampetra japonica (Martens)
Eulachon (hooligan)	Thaleichthys pacificus (Richardson)
Arctic grayling	Thymallus arcticus (Pallas)
Bering cisco	Coregonus laurettae Bean
Round whitefish	Prosopium cylindraceum (Pallas)
Humpback whitefish	Coregonus pidschian (Gmelin)
Rainbow trout	Salmo gairdneri Richardson
Lake trout	Salvelinus namaycush (Walbaum)
Dolly Varden	Salvelinus malma (Walbaum)
Pink (humpback) salmon	Oncorhynchus gorbuscha (Walbaum)
Sockeye (red) salmon	Oncorhynchus nerka (Walbaum)
Chinook (king) salmon	Oncorhynchus tshawytscha (Walbaum)
Coho (silver) salmon	Oncorhynchus kisutch (Walbaum)
Chum (dog) salmon	Oncorhynchus keta (Walbaum)
Northern pike	Esox lucius Linnaeus
Longnose sucker	Catostomus catostomus (Forster)
Threespine stickleback	Gasterosteus aculeatus Linnaeus
Burbot	Lota lota (Linnaeus)
Slimy sculpin	Cottus cognatus Richardson

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Table 12. Susitna River Salmon Escapement Estimates, 1981-1984

Year	Chinook	Sockeye[1]	Pink	Chum	Coho	Total[2]
1981	-	272,500	85,600	282,700	36,800	677,600
1982	-	265,200	890,500	458,200	79,800	1,693,700
1983	-	176,200	101,300	276,800	24,100	578,400
1984	250,000	605,800	3,629,900	812,700	190,100	5,488,500

[1] Second run sockeye only.

[2] Total 1984 drainage escapement estimate. Escapement counts for 1981 through 1983 do not include chinooks or any escapements into tributaries downstream of RM 77, with the exception of those into the Yentna River.

Source: ADF&G 1983a; Barrett, Thompson & Wick 1984 and 1985.

TABLE 13
SIMULATED SUSITNA MIDDLE RIVER ICE FRONT PROGRESSION[1]
AND
WINTER OVERTOPPING OF SLOUGHS

Scenario	Start of Freezeup	Meltout	Maximum Upstream Extent of Ice Front	Slough Overtopping					Open Water Downstream of Devil Canyon (RM 152)
	Date	Date	River Mile	8 (RM 113.7)	8A (RM 125.1)	9 (RM 128.3)	11 (RM 135.3)	21 (RM 141.1)	Miles[B]
Natural[2]									
1971-72	Nov 05		152[A]						0
1976-77	Dec 08		152						0
1981-82	Nov 18	May 10-15	152						0
1982-83	Nov 05	May 10	152		C				0
Watana Only									
1996 Case C									
1971-72	Nov 28	May 15	140	D	D		D		12
1976-77	Dec 26	Apr 18	126		D	D			26
1981-82	Dec 28	Apr 03	137	D	D		D		15
1982-83	Dec 12	Mar 20	126	D					26
2001 Case C									
1971-72	Nov 28	May 15	142	D	D		D		10
1981-82	Dec 30	Apr 03	134	D	D	D			18
1982-83	Dec 19	Mar 16	124	D					28
2001 Case E-VI									
1981-82	Dec 28	Mar 23	134		D	D			18
Watana and Devil Canyon									
2002 Case C									
1971-72	Dec 02	May 03	137	D	D				15
1976-77	Jan 08	Apr 14	124						28
1981-82	Dec 30	Mar 12	124						28
1982-83	Dec 22	Mar 20	123						29
2002 Case E-VI									
1981-82[3]									
2020 Case C									
1971-72	Dec 03	Apr 15	133	D	D				19
1982-83	Dec 14	Mar 12	127						25
Watana Filling									
1982-83 (YR1)	Dec 23	May 02	156						0
1981-82 (YR2)	Dec 23	May 30	162						0

Legend:
- A - Ice cover for natural conditions extends upstream of River Mile 137 to Devil Canyon (RM 152) by means of lateral ice bridging.
- B - Number of miles of open water from the ice front upstream to Devil Canyon at River Mile 152. Some open leads can be found in the ice cover.
- C - Observed natural overtopping.
- D - Slough is overtopped with project, but not under simulated natural conditions.

Notes:
1. ICECAL Model Simulations
2. Weather Conditions: 1971-72, cold winter; 1976-77, very warm winter; 1981-82, average winter; 1982-83, warm winter.
3. Results unavailable to date.

Source: Harza/Ebasco Susitna Joint Venture, 1985.

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Table 14. SUSITNA HYDROELECTRIC PROJECT
ICE ISSUES LIST FOR FISH.

	ISSUE	SOURCE[1]	IMPOUNDMENT ZONE	MIDDLE RIVER ZONE	LOWER RIVER REACH
1.	The effects of altered ice processes on salmon and resident fish habitats and populations downstream of the dams, including fish access and changes due to staging.	APA		X	X
2.	Impacts on egg incubation, rearing and rearing cover, especially disruption of incubation or emergence timing from lower water temperatures and dewatering. Attention to middle river sloughs and side channels are of primary importance.	ADF&G/Su Hydro		X	
3.	The effect of ice staging on upwelling in slough and mainstem habitats.	EWT		X	X
4.	The level of ice cover. Could it effect primary productivity and rate of food production? Would it increase available overwinter habitat?	EWT		X	X
5.	Importance of altered breakup on the formation of ice jams and corresponding flushing of slough habitats.	EWT		X	
6.	Ice process effects on staging overtopping.	AEIDC		X	X
7.	Changes in anchor ice formation.	AEIDC		X	

Table 14 (cont'd). SUSITNA HYDROELECTRIC PROJECT
ICE ISSUES LIST FOR FISH.

	ISSUE	SOURCE[1]	IMPOUNDMENT ZONE	MIDDLE RIVER ZONE	LOWER RIVER REACH
8.	Effect of ice shelf formation in the reservoir drawdown zone.	AEIDC	X		
9.	Increased amount of ice in the inundation area near tributary mouths impeding fish passage.	AEIDC	X		

[1] Source: APA - Alaska Power Authority Issues List March 6, 1984.

ADF&G/Su Hydro - Alaska Department of Fish & Game/Su Hydro Aquatic Studies memorandum to AEIDC October 5, 1984.

EWT - E. Woody Trihey & Associates memorandum to AEIDC October 2, 1984.

AEIDC - Arctic Environmental Information and Data Center plus information from literature reviews of hydroelectric projects in northern environments.

This analysis addresses nine ice-related issues of concern, which were identified by the Susitna Hydroelectric Study Group (table 14). The majority focus on middle river incubation and rearing habitats, which for the most part, are limited to sloughs and side channels. Concerns here rest principally with the potential for increased frequency of overtopping of slough berms by ice-induced staging and with the potential for changes in the thermal regime of upwelling waters on natal habitats. Expressed concerns directed at the lower river are fewer in number. The project staff feels that this reach has less significant salmon spawning and rearing habitats and ICECAL modlers believe that with-project ice processes would change less dramatically here than in the middle river. Impoundment zone ice-related concerns focus on the potential for blockage of tributary stream mouths by ice and on the influence of ice on the littoral environment.

2. METHODOLOGY

To conduct this analysis, AEIDC first reviewed the literature on high latitude water bodies (both regulated and unregulated) for information describing various ice condition effects on fish habitats. Relevant information was then synthesized to provide an overview of the type and scope of potential ice-related with-project effects which could occur in the Susitna River basin. Next, pertinent Susitna River-specific biological and physical information was assembled. These two steps provided the basis for the ice effects analysis, which was performed by comparing knowledge of fish overwinter life history stages to ICECAL simulations.

This analysis was constrained by a number of factors. Chief among these was that ICECAL was designed primarily to address river ice physical processes *per se* (rates of formation, timing of freezeup, etc), rather than the effects of icing on the environment. Being one dimensional, ICECAL simply lacks the power to describe site-specific ice processes in areas possessing multiple habitat types (e.g. side sloughs, mainstem, etc). Second, extant Susitna River basin data on fish distribution, abundance, and habitat uses focus on salmon and are temporally and spatially limited. Third, knowledge of the effects of various winter conditions on fish mortality is particularly scant. The fourth problem relates to the fact that issues were identified for evaluation primarily by a approach. Representatives of E. W. Trihey & Associates, Harza-Ebasco Susitna Joint Venture, the Alaska Department of Fish and Game, R&M Consultants, Inc. and AEIDC met on September 9, 1984 in AEIDC's offices to plan the ice assessment approach. It was agreed that participants would nominate ice related issues of concern to be addressed in the report by October 1, 1984. Subsequently, E. W. Trihey & Associates, Alaska Department of Fish and Game, and AEIDC responded. Offered issues of concern are listed in Table 14. Since no similar project exists in Alaska and time was of the essence, the project team relied on icing information from other Northern areas to nominate issues. Because of this, issues raised are not necessarily wholly pertinent to the basin nor are they necessarily all encompassing.

3. IMPOUNDMENT ZONE EFFECTS ANALYSIS

a. Fish Resource

The principal source of information on fish distribution, abundance, habitat use, and life histories in the impoundment zone is ADF&G 1983b. The natural environment between Devil Canyon and the upstream end of the proposed Watana Reservoir provides habitats for nine fish species (ADF&G 1983b); eight are year-round residents and one (chinook salmon) is anadromous. Within Devil

Canyon, Cheechako Creek (RM 152.5) and Chinook Creek (RM 156.8) mark the upstream limit of salmon in the mainstem Susitna River. Devil Canyon's constricted river channel apparently creates a velocity barrier to upstream migrants. In total, fewer than 100 salmon utilize these two tributary habitats for reproductive purposes (Barrett, Thompson & Wick 1985).

Arctic grayling are the most widely distributed and abundant species utilizing habitats above the canyon. The total 1982 Arctic grayling population in the impoundment zone was estimated to be over 16,000 (ADF&G 1983b). Mainstem impoundment areas above the canyon provide essential overwintering habitat for Arctic grayling, which move into its tributaries to spawn following breakup in late May or early June (ADF&G 1983b). Arctic grayling migrate out of natal tributaries in September as water levels begin to drop. They overwinter in mainstem environments which become less turbid following freezeup (ADF&G 1983b).

Except for documentation of their presence, little is known of the life histories or relative abundance of other species resident in the impoundment zone. Based on limited capture data, it seems that both burbot and longnose sucker are relatively abundant in the proposed impoundment areas (ADF&G 1983b). Elsewhere in the Susitna River, burbot spawn under the ice from January to February over gravel near tributary stream mouths (such as the Deshka River) (R. Sundet, pers. comm.). During the rest of the year, they apparently distribute themselves throughout the deeper portions of aquatic environments. Susitna River longnose sucker are spring spawners which move from overwinter habitats in the mainstem to tributary natal areas from late May to early June (ADF&G 1983b). Small numbers of round and humpback whitefish have been captured (at two locations) within the impoundment areas, but there are no estimates of their relative abundances. If they behave similarly to lower river reach and middle river whitefish, they overwinter in mainstem environments. Although available information is scant, it appears that this species spawns in early October in clearwater tributary streams.

Although not present in mainstem impoundment areas, some lake trout and rainbow trout might gain access to them as a result of the project. Sally Lake, which supports a lake trout population of undetermined size, would be inundated by the Watana Reservoir (ADF&G 1984b). Lake trout generally spawn from August through December and require stable lake shore gravel substrates for reproduction. High Lake (located immediately north of Devil Canyon) is a tributary system to Devil Creek which has a resident population of rainbow trout. Nothing is known of the lake's trout population size. Should the project be completed, we believe that some rainbows might outmigrate down Devil Creek to the Devil Canyon Reservoir. Elsewhere in the basin, rainbow trout typically overwinter in lakes and mainstem habitats, returning in the spring following breakup to spawn in tributary streams. Most rainbow trout spawn in clearwater streams, which are paved with relatively small cobbles and have relatively moderate velocities (ADF&G 1983c).

b. The With-Project Environment

The following is a synopsis of selected aspects of the with-project environment that are relevant to this ice effects analysis. (A detailed description of with-project ice processes is found in Chapter IV.) The Watana Reservoir would inundate roughly 55 linear miles of the mainstem Susitna River and about 30 miles of tributary stream environments, converting them to a lentic system. The Watana Reservoir would generally begin to freeze sometime in mid-November, with probable maximum ice thicknesses ranging from 3 to 5 ft. Winter reservoir drawdown would cause nearshore ice to fracture and drape over exposed banks. While on line alone, the Watana dam reservoir's winter drawdown would average about 90 ft. With both dams drawdown would average about 40 ft. In mid-winter, grounded ice would probably form barricades at tributary mouths. Based on observations of natural ice processes within the upper basin, project team members generally believe that tributary flows would downcut grounded ice before reservoir ice meltout. This would generally occur between May and early June.

The Devil Canyon Reservoir would inundate a maximum of 32 linear miles of mainstem Susitna River environments. Freezeup times would be similar to those of the Watana Reservoir, but probable maximum ice thickness would not exceed four ft. Yearly winter reservoir drawdown would be slight if it occurred at all. Consequently, less ice draping would occur than in the Watana Reservoir. A few miles of open water may occur in the upper part of Devil Canyon Reservoir due to the warm water released from the Watana Reservoir.

c. Anticipated With-Project Effects

(1). Watana Reservoir.

Ice processes attendant to winter reservoir drawdown would affect reservoir salmonid spawning and rearing habitat quality. The littoral zone environment would experience periodic dehydration, substrate freezing, ice gouging, and erosion. Lake drawdown, coupled with ice draping, would preclude evolution of a stable littoral zone conducive to lake trout (from Sally Lake) reproductive and rearing success. Lake trout reaching the impoundment would likely live a normal life span. The effects on other salmonids would be less severe, because they spawn in tributary stream habitats. Thus, only their rearing life stages would be affected. Impoundment rearing habitats for Arctic grayling and whitefish would probably be less than ideal. Lake drawdown, ice draping, ice gouging, erosion and associated effects would likely reduce cover and food availability, because together they would preclude establishment of riparian vegetation and limit invertebrate productivity.

The effects of Watana Reservoir operation on burbot are more difficult to predict, because they have more generalized habitat requirements. They often inhabit deep, cold, and turbid environments. Although burbot can utilize lake shore gravels for spawning, most spawn in tributary stream environments. These would be unaffected with-project. Thus, the impoundment probably would not exert discernable negative effects on them. The impoundments littoral zone would not afford them viable reproductive habitat because of its unstable nature (see above).

Ice blockage of tributary stream mouths should be a problem for fish only in extremely cold years, when spring ice meltout is retarded. If climatic conditions match long term averages, the tributary mouths should be ice free before late May when Arctic grayling and longnose sucker migrate to instream spawning habitats. If spring meltout does not occur until after early June, both grayling and longnose sucker could experience reproductive failure that year. From a fish population biology standpoint, loss of a single-year class is not particularly troubling unless the population is being simultaneously stressed by other factors such as epidemics or sport fishing. In Alaska, it is common for some local fish populations to have certain year classes predominate while others are absent or nearly so.

Once the Devil Canyon Dam was on-line, the Watana Reservoir operations schedule could exert somewhat less influence on fish habitats because the expected drawdown would be less. However, this point is moot, since its predicted drawdown still exceeds 40 ft. For reasons discussed above, a drawdown of this magnitude would severely limit littoral zone productivity.

(2). Devil Canyon Reservoir.

Because of its smaller scale, winter drawdown of the Devil Canyon Reservoir would be less influential on impoundment littoral zone habitats than that predicted for the Watana Reservoir. Ice draping would be minimal (if it occurred at all) and ice gouging negligible given the bedrock substrate and lack of ice fracturing from extensive drawdown (Chapter V). Perhaps, importantly, impoundment area geomorphology and geology are such that they naturally constrain the amount of potential lentic spawning habitat available. The canyon's steep side walls and bedrock substrate severely limits potential use by spawning fish. For this reason it is unlikely that this reservoir would be a productive environment for fish.

Arctic grayling, burbot, longnose sucker, and (possibly) rainbow trout could gain access to the Devil Canyon Reservoir and become residents. None depend on lentic littoral zones for reproductive purposes. Arctic grayling, burbot, and longnose sucker naturally occur within the area to be impounded. Rainbow trout might gain access through outmigration from High Lake. Lake trout are not resident within the Devil Canyon impoundment area. They would have to gain access from the Watana Reservoir either by passing through the turbines, over the spillway, or through the gate valves.

With-project ice blockage of tributary stream mouths should not be a problem in this reservoir. The two main tributaries capable of providing reproductive habitats for the subject species [Fog Creek (RM 177) and Tsusena Creek (RM 181)] are located in the upper end of the reservoir where little, if any, ice accumulation is expected to occur (G. Gemperline, pers. comm.). Normal spring tributary meltout in this area would then easily wash out any remaining ice allowing timely access to spawning and rearing habitats for all reservoir residents.

4. MIDDLE RIVER ZONE FISH RESOURCE EFFECTS ANALYSIS

a. Fish Resource

A complete summary of available information on middle river fish resources is available in a report by Woodward Clyde Consultants and Entrix 1985. Sixteen fish species are known to inhabit middle river zone waters (figure 89). All are ultimately dependent on mainstem environments for some aspects of their life histories. Five of the fish species present (all salmon) are anadromous.

Salmon utilize mainstem river environments for migration, rearing, overwintering, and to a lesser extent spawning (Woodward Clyde Consultants & Entrix 1985). An indication of the importance of middle river mainstem habitats as a travel corridor to returning salmon adults is found in escapement counts made at the ADF&G fish wheel stations at Curry and Talkeetna (table 15). Population estimates (based on Talkeetna station data) for 1984 indicate that approximately 6% of all coho, 12% of all chum, 2% of all sockeye, 10% of all chinooks, and 5% of all pink salmon spawning in the entire Susitna drainage basin travel through the mainstem middle river to reach their natal grounds (table 5). Adult migration timing varies by species, but in general the peak inmigration time above Talkeetna is from late June through the end of September (table 16).

At least eighteen tributary streams in the middle river provide salmon spawning habitats (table 17). Viewed as a whole, most salmon spawn in tributary streams (which would be unaffected by the project). Based on escapement counts for 1984, 34 middle river sloughs collectively provided habitat for approximately 5.5% of all salmon migrating above Talkeetna station (Barrett, Thompson & Wick 1985). Coho and chinook in this river reach apparently spawn only in tributary stream environments, pink salmon primarily in tributary streams (with a small number utilizing slough habitats) chum salmon in both tributary and slough environments, and sockeye spawn almost exclusively in sloughs (Barrett, Thompson & Wick 1985). Despite their relative importance to both chum and sockeye salmon in the middle river, slough spawning habitats are not central to the maintenance of the total Susitna River stocks of either species. Only about 2% of all chum and less than 0.5% of all sockeye spawning in the drainage in 1984 utilized these sloughs for this purpose.

TABLE 15. SUSITNA RIVER SALMON ESCAPEMENT FOR THE MIDDLE SUSITNA RIVER, 1981-84.[1]

Sampling Location	River Mile	Chinook[2]			Pink				Chum				Sockeye				Coho			
		1982	1983	1984	1981	1982	1983	1984	1981	1982	1983	1984	1981	1982	1983	1984	1981	1982	1983	1984
Talkeetna Station	103	10,900	14,500	24,591	2,300	73,000	9,500	177,881	20,800	49,100	50,400	98,236	4,800	3,100	4,700	13,050	3,300	5,100	2,400	11,847
Percent of Total Susitna Escapement				9.8	2.7	8.2	9.3	4.9	7.4	10.7	18.2	12.0	1.8	1.2	2.4	2.2	8.9	6.4	9.9	6.2
Curry Station	120	11,300	10,000	17,351	1,000	58,800	5,500	116,858	13,100	29,400	21,100	49,278	2,800	1,300	1,900	3,593	1,100	2,400	800	2,162
Percent of[3] Total Susitna Escapement				6.9	1.1	6.6	5.4	3.2	4.6	6.4	7.6	6.1	1.0	0.5	1.1	0.6	3.0	3.0	3.3	1.1

[1] Escapement numbers were derived from tag/recapture population estimates.

[2] Total basin escapement data for chinook are only available for 1984.

[3] Escapement numbers for 1981-83 do not include any counts into tributaries downstream of RM77, with the exception of the Yentna River.

Source: ADF&G 1983a; Barrett, Thompson and Wick 1984, 1985.

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Table 16. Susitna River Salmon Phenology.

	HABITAT	DATE RANGE	DATE PEAK
CHINOOK (KING) SALMON			
Adult Inmigration	Cook Inlet - Talkeetna	May 25 - Aug 18	Jun 18 - Jun 30
	Talkeetna - D.C.	Jun 07 - Aug 20	Jun 24 - Jul 04
	Middle River Tributaries	Jul 01 - Aug 06	
Juvenile Migration	Middle River	May 18 - Oct 03[1&3]	
Spawning	Middle River Tributaries	Jul 01 - Aug 26	Jul 20 - Jul 27
	Lower River Tributaries	Jul 07 - Aug 20	Jul 20 - Jul 27
COHO (SILVER) SALMON			
Adult Inmigration	Cook Inlet - Talkeetna	Jul 07 - Sep 28	Jul 27 - Aug 20
	Talkeetna - D.C.	Jul 18 - Sep 19	Aug 12 - Aug 26
	Middle River Tributaries	Aug 08 - Sep 27	
Juvenile Migration	Middle River	May 18 - Oct 12[1&3]	May 28 - Aug 21
Spawning	Middle River Tributaries	Sep 01 - Oct 08	Sep 05 - Sep 24
	Lower River Tributaries	Aug 08 - Oct 01	
CHUM (DOG) SALMON			
Adult Inmigration	Cook Inlet - Talkeetna	Jun 24 - Sep 28	Jul 27 - Aug 02
	Talkeetna - D.C.	Jul 10 - Sep 15	Aug 01 - Aug 17
	Middle River Tributaries	Jul 27 - Sep 06	
	Middle River Sloughs	Aug 06 - Sep 05	
Juvenile Migration	Middle River	May 18[3] - Aug 20	May 28 - Jul 17

Table 16 (cont'd). Susitna River Salmon Phenology.

	HABITAT	DATE: RANGE	DATE: PEAK
Spawning	Middle River Tributaries	Jul 27 - Oct 01	Aug 05 - Sep 10
	Middle River Sloughs	Aug 05 - Oct 11	Aug 20 - Sep 25
	Middle River Mainstem	Sep 02 - Sep 19	
	Lower River Tributaries	Jul 27 - Sep 09	Aug 06 - Aug 14
SOCKEYE (RED) SALMON[2]			
Adult Inmigration	Cook Inlet - Talkeetna	Jul 04 - Aug 08	Jul 18 - Jul 27
	Talkeetna - D.C.	Jul 16 - Sep 18	Jul 31 - Aug 05
Juvenile Migration	Middle River	May 18 - Oct 11[1&3]	Jun 22 - Jul 17
Spawning	Middle River Sloughs	Aug 05 - Oct 11	Aug 25 - Sep 25
PINK (HUMPBACK) SALMON			
Adult Inmigration	Cook Inlet - Talkeetna	Jun 28 - Sep 10	Jul 26 - Aug 03
	Talkeetna - D.C.	Jul 10 - Aug 30	Aug 01 - Aug 08
	Middle River Tributaries	Jul 27 - Aug 23	
	Middle River Sloughs	Aug 04 - Aug 17	
Juvenile Migration	Middle River	May 18[3] - Jul 24	May 29 - Jun 08
Spawning	Middle River Tributaries	Jul 27 - Aug 30	Aug 10 - Aug 25
	Middle River Sloughs	Aug 04 - Aug 30	Aug 15 - Aug 30
	Lower River Tributaries	Jul 27 - Sep 09	Aug 06 - Aug 09

1 All migration includes migration to and between habitat, not just outmigration.
2 Second run sockeye only.
3 No data available for pre-ice movement; earlier date of range refers to initiation of outmigrant trap operation.

Source: Barrett, Thompson and Wick 1984, 1985; Schmidt et al. 1984; ADF&G 1983a,c.

TABLE 17
Peak Salmon Survey Counts Above Talkeetna for Susitna River Tributary Streams

STREAM	SURVEY DISTANCE	Coho						Chinook								
		1974	1976	1981	1982	1983	1984	1975	1976	1977	1978	1979	1981	1982	1983	1984
Whiskers Creek (RM 101.4)	0.25	27		70	176	115	301	22	8						3	67
Chase Creek (RM 106.9)	0.25	40		80	36	12	239							15		3
Slash Creek (RM 111.2)	0.75				6	2	5									
Gash Creek (RM 111.6)	1.0			141	74	19	234									
Lane Creek (RM 113.6)	0.5			3	5	2	24						40	47	12	23
Lower McKenzie (RM 116.2)	1.5			56	133	18	24									
McKenzie Creek (RM 116.7)	0.25															
Little Portage (RM 117.7)	0.25				8											
Fifth of July (RM 123.7)	0.25													3		17
Skull Creek (RM 124.7)	0.25															
Sherman Creek (RM 130.8)	0.25													3		
Fourth of July (RM 131.0)	0.25	26	17	1	4	3	8	1	14					56	6	92
Gold Creek (RM 136.7)	0.25				1									21	23	23
Indian River (RM 138.6)	15.0	64	30	85	101	53	465	10	537	393	114	285	422	1,053	1,193	1,456
Jack Long (RM 144.5)	0.25				1	1	6							2	6	7
Portage Creek (RM 148.9)	15.0	150	100	22	88	15	128	29	702	374	140	140	659	1,253	3,140	5,446
Cheechako Creek (RM 152.5)	3.0													16	25	29
Chinook Creek (RM 156.8)	2.0													4	8	15
TOTAL		307	147	458	633	240	1,434	62	1,261	767	254	425	1,121	2,473	4,416	7,178

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TABLE 17 (cont'd)
Peak Salmon Survey Counts Above Talkeetna for Susitna River Tributary Streams

STREAM	SURVEY DISTANCE	Chum								Sockeye							
		1974	1975	1976	1977	1981	1982	1983	1984	1974	1975	1976	1977	1981	1982	1983	1984
Whiskers Creek (RM 101.4)	0.25					1											
Chase Creek (RM 106.9)	0.25					1			1								
Slash Creek (RM 111.2)	0.75																
Gash Creek (RM 111.6)	1.0																
Lane Creek (RM 113.6)	0.5		3		2	76	11		31								
Lower McKenzie (RM 116.2)	1.5					14		1	23					1			
McKenzie Creek (RM 116.7)	0.25										46						
Little Portage (RM 117.7)	0.25						31		18								
Fifth of July (RM 123.7)	0.25							6	2								
Skull Creek (RM 124.7)	0.25					10	1		4								
Sherman Creek (RM 130.8)	0.25					9			6								
Fourth of July (RM 131.0)	0.25	594		78	11	90	191	148	193		1						
Gold Creek (RM 136.7)	0.25																
Indian River (RM 138.6)	15.0	531	70	134	776	40	1,346	811	2,247		1	2	1			1	1
Jack Long (RM 144.5)	0.25						3	2	4								
Portage Creek (RM 148.9)	15.0	276		300			153	526	1,285								12
Cheechako Creek (RM 152.5)	3.0																
Chinook Creek (RM 156.8)	2.0																
TOTAL		1,401	73	512	789	241	1,736	1,494	3,814		48	2	1	1		1	13

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TABLE 17 (cont'd)
Peak Salmon Survey Counts Above Talkeetna for Susitna River Tributary Streams

STREAM	SURVEY DISTANCE	Pink							
		1974	1975	1976	1977	1981	1982	1983	1984
Whiskers Creek (RM 101.4)	0.25			75		1	138		293
Chase Creek (RM 106.9)	0.25			50		38	107	6	438
Slash Creek (RM 111.2)	0.75								3
Gash Creek (RM 111.6)	1.0								6
Lane Creek (RM 113.6)	0.5	82	106		1,103	291	640	28	1,184
Maggot Creek (RM 115.6)	0.25								107
Lower McKenzie (RM 116.2)	1.5						23	17	565
McKenzie Creek (RM 116.7)	0.25						17		11
Little Portage (RM 117.7)	0.25						140	7	162
Deadhorse Creek (RM 120.8)	0.25								337
Fifth of July (RM 123.7)	0.25					2	113	9	411
Skull Creek (RM 124.7)	0.25					8	12	1	121
Sherman Creek (RM 130.8)	0.25					6	24		48
Fourth of July (RM 131.0)	0.25	159	148	4,000	612	29	702	78	1,842
Gold Creek (RM 136.7)	0.25			32			11	7	62
Indian River (RM 138.6)	15.0	577	321	5,000	1,611	2	738	886	9,066
Jack Long (RM 144.5)	0.25					1		5	14
Portage Creek (RM 148.9)	15.0	218		3,000			169	285	2,707
Cheechako Creek (RM 152.5)	3.0						21		
Chinook Creek (RM 156.8)	2.0								
TOTAL		1,036	575	12,157	3,326	378	2,855	1,329	17,417

Source: Barrett 1974; Barrett, Thompson and Wick 1984, 1985; Riis 1977; ADF&G 1976, 1978, 1981, 1983a.

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Spawning habitat quality apparently varies greatly between sloughs as, in the last four years, the majority of chum salmon spawners counted were in 10 of the 34 (table 18 & 19). Three of the 10 most used sloughs have added significance in that they also provided over 90% of all sockeye spawning habitat in the middle river (table 18).

Relatively few salmon spawn in mainstem non-slough habitats, of those which do chum salmon predominate. Generally, spawning habitats within the mainstem proper are small areally and widely distributed. In 1984, ADF&G made a concerted effort to identify mainstem middle river spawning habitats; they identified 36 spawning sites. Numbers of spawning fish counted at each of these sites varied from one to 131 with an average of 35 (Barrett, Thompson, & Wick 1985).

Four of the five salmon species use middle river waters for rearing purposes (Dugan et al. 1984). At this time insufficient information exists to characterize the relative importance of individual mainstem rearing habitats. From May to September juvenile chinook rear in tributary and side channel environments, coho mostly rear in tributary and upland sloughs, and sockeye are evenly distributed between upland and side sloughs. From May to July rearing chum juveniles are distributed throughout side slough and tributary stream environments (Dugan et al. 1984).

Of the five salmon species present, only two have been captured in winter in the middle river (ADF&G 1983c). Preliminary studies indicate that significant numbers (perhaps 25% to 50%) of chinook and coho juveniles reared in this zone overwinter in side slough and tributary stream environments (ADF&G 1985a). Perhaps significantly, preliminary evidence indicates that few juvenile salmon utilize the mainstem proper for overwintering purposes (ADF&G

TABLE 18

Peak Slough Escapement Counts Above Talkeetna

		CHUM								SOCKEYE								PINK					
SLOUGH NO.	RIVER MILE	1974	1975	1976	1977	1981	1982	1983	1984	1974	1975	1976	1977	1981	1982	1983	1984	1976	1977	1981	1982	1983	1984
1	99.6					6			12								10						
?	100.4					27		49	129								7						2
3B	101.4		50					3	56		15			7		5	20			1			28
3A	101.9								17					1			11						56
Talkeetna St.	103.0																						
4	105.2										*												
5	107.2						2	1									1						4
b	108.2	1																					
bA	112.3					11	2							1							35		
7	113.2																						
R	113.7					302			65								2			25			1
Bushrod	117.8								90														10
Curry St.	120.0																						
8D	121.8						23		49														
8C	121.9						48	4	121						2								1
8B	122.2					1	80	104	400				2		5		1						68
Moose	123.5					167	23	68	76						8	22	8				8		25
A'	124.6					140		77	111														24
A	124.7					34		2	2											2			
8A	125.1				51	620	336	37	917				70	177	68	66	128				28		134
b	126.3						58	7	108						8	2	9				32		
9	128.3	511	181		36	260	300	169	350	8			6	10	5	2	6				12		1
9B	129.2					90	5		73					81	1		7						
9A	133.3					182	118	105	303					2	1	1							
10	133.8				2		2	1	36							1							
11	135.3	33		66	116	411	459	238	1,586	79	84	78	214	893	456	248	564	1			131		121
12	135.4																						
13	135.7		1			4		4	13														
14	135.9	2							1														
15	137.2		1			1	1		100			1					1				132	1	500
16	137.3	2	12		4	3			15										13				
17	138.9	24				38	21	90	66					6		6	16						1
18	139.1								11														
19	139.7	4				3		3	45	3		32	8	23		5	11				1	1	
20	140.0	107		2	28	14	30	63	280		20			2							64	7	85
21	141.1	668	250	30	304	274	736	319	2,354	13	75	23		38	53	197	122				64		8
21A	145.5								10														
22	144.5					8		114	151								2						
TOTAL		1,352	495	98	541	2,596	2,244	1,458	7,547	103	194	134	300	1,241	607	555	926	1	13	28	507	9	1,069

Source: Barrett 1974; Barrett, Thompson and Wick 1984, 1985; Riis, 1977; ADF&G 1976, 1978, 1981, 1983a.

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TABLE 19

Chum Salmon Escapement
for the Ten Most Productive Sloughs
Above RM 98.6, 1981-83.

Slough	River Mile	1981	1982	1983	3-Year Average	Percent of Total Escapement
8	113.7	695	0	0	232	5.6
8B	122.2	0	99	261	120	2.9
Moose	123.5	222	59	86	122	2.9
A'	124.6	200	0	155	118	2.8
8A	125.1	480	1,062	112	551	13.2
9	128.3	368	603	430	467	11.2
9A	133.8	140	86	231	152	3.6
11	135.3	1,119	1,078	674	957	23.0
17	138.9	135	23	166	108	2.6
21	141.1	657	1,737	481	958	23.0

Source: Barrett, Thompson and Wick 1984.

1985a). This helps somewhat to demonstrate the significance of sloughs to these species.

Of the 11 resident middle river fish species (figure 89), capture data indicate that only rainbow trout, Arctic grayling, burbot, round whitefish, longnose sucker, and slimy sculpin are common (ADF&G 1983c). Dolly Varden, humpback whitefish, threespine stickleback, and Arctic lamprey also occur, but all appear to be more abundant in the lower river (Sundet and Wenger 1984). Lake trout are found only in surrounding area lakes, none of which would be influenced by the project.

Little is known of either the numbers or the life histories (especially during the winter) of any fish species residing year-round in the middle river. Given the naturally reduced winter flow regimes of tributary streams in winter, it is probable that the majority of these resident fish (with the exception of lake trout) overwinter somewhere in the mainstem. It is generally believed, however, that most resident fish overwinter further down stream in the lower river (ADF&G 1983c).

Of the most common resident species, three (burbot, longnose sucker, and slimy sculpin) occur year-round in the mainstem. Rainbow trout, Arctic grayling, and round whitefish spend most of the open water season in tributary environments which provide spawning and rearing habitat. Aspects of the winter life histories of these species (with the exception of slimy sculpin) pertaining to this analysis have been discussed previously. Too little is known of Susitna River slimy sculpins to adequately describe their habitat needs. However, it is known with some certainty that they are distributed year-round throughout lentic and lotic environments within the basin, and that no large-scale movements or migrations have been noted. Spawning probably occurs around mid-June (ADF&G 1983c).

b. The With-Project Environment

The with-project Middle River Zone ice environment would differ dramatically from natural conditions. Formation timing of a contiguous river ice cover would be delayed, there would be an extensive reach of ice-free water below Devil Canyon, river flows would be four to five times more voluminous, and ice meltout would be earlier. These changes would occur as a consequence of dam interception of mainstem frazil ice input, increased winter flows due to the reservoir's operating schedule(s), and warmer than normal instream winter temperatures (the reservoirs would function as heat sinks).

Middle river freezeup is predicted to be delayed between 17 to 44 days with Watana Dam and 27 to 47 days with both dams in place. Depending on the year and with only Watana Dam on-line, the ice front is predicted to range somewhere between RM 124 and 142 and ice thickness below the front would be similar to natural. With both dams operating, the ice front is expected to range between RM 123 to 137 and ice thickness is expected to be less than for natural conditions. It would likely be dynamic, changing location significantly throughout the winter in response to changes in weather conditions and with-project flows. Upstream of the ice front, no ice cover would mantle the river; open water with temperatures above 0 C would prevail throughout the winter. Between the 0 C isotherm and the upstream edge of the ice front, a zone of anchor ice formation would occur; no anchor ice would form upstream of this zone.

Portions of the river near the ice front would be subject to freezeup staging, a phenomena which occurs as flowing water encounters the rough bottom surface of the ice mantle. When this happens, water velocity slows and the water stage rises (Chapter IV). Staging generally lasts one to two weeks under natural conditions and could last a month or more with-project.

Regardless of the final reservoir operation regime adopted, winter flow volumes would increase significantly with-project. Consequently, the aquatic instream environment would be substantially greater in extent, i.e. the wetted area would be increased. Because no ice staging would occur in the open water reaches immediately below Devil Canyon, no winter flooding is anticipated in this area. However, localized flooding would occur within ice-mantled river reaches, since higher than natural flows would be coupled with ice-induced staging. Higher flow volumes might also increase the length of open leads in ice-mantled areas downstream of the ice front.

From early November to late April with-project water temperature is predicted to range between 0.4 C to 5.6 C at the dam outlet (AEIDC 1984). Water temperatures are expected to decline relatively uniformly downstream, reaching the 0 C isotherm near the ice front.

The with-project springtime environment would differ from natural conditions chiefly in breakup phenology. Predicted higher than normal stream flows and instream temperatures would cause a gradual in-place melting of the ice mantle; there would be no breakup drive. Ice meltout is expected to occur four to six weeks earlier than natural with the Watana Dam and seven to eight weeks earlier with both dams operating.

c. Anticipated With-Project Effects

Seven of the nine ice-related issues of concern identified for the proposed project relate to the middle river (table 14). Most are interrelated. Chief among these are concerns with slough incubation and rearing habitat quality. One deals with the potential introduction of near freezing water to slough incubation and rearing environments through ice-induced overtopping. Other issues concern the potential of with-project flows altering the character of upwelling waters and the lack of with-project ice cover upstream of the ice front. Potential effects in the ice-free reach include increased primary production (as more light penetrates the ice-free water surface) and increased overwinter habitat (as a result of higher than normal with-project winter flows). Of lesser concern, are issues pertaining to the with-project end of the natural cycle of breakup-induced flooding of slough habitats, and the amount of with-project anchor ice. Natural breakup-induced floods are thought necessary by some project team members to flush fines from spawning grounds. When anchor ice breaks up, melts, or otherwise disperses, it dislodges considerable amounts of substrate which can be life threatening to developing embryos.

Overtopping of slough berms occurs naturally during freezeup as a result of ice-induced staging and during breakup as a consequence of ice dam formation. It is believed to influence overwinter embryo mortality in the middle river (ADF&G 1983d). Overtopping from freezeup-induced staging is the most troublesome to salmon, because it would introduce colder than ambient mainstem waters to developing embryos, for relatively long periods of times.

During the period of incubation, survival of developing embryos naturally varies greatly and is dependent on several factors. The principal natural phenomena inducing embryo mortality are freezing of the spawning habitat, redd desiccation from dropping water levels, changes in the thermal and chemical characteristics of groundwater, and silting of redds (Buklis and Barton 1984, Canada Department of Fisheries & Oceans 1984). Dewatering and freezing of salmon redds have been identified as the principal factor inducing chum salmon embryo mortality in the middle Susitna River (ADF&G 1985b). Natural mortality is generally high during incubation; reported survival rates from North America and Asia range between 1.5% to 30% (Buklis and Barton 1984; McNeil 1980).

Temperature ranges that cause increased mortality to embryos are much narrower than those for adults (Alabaster and Lloyd 1982). Generally, the lower and upper temperature limits for successful initial incubation of Pacific salmon eggs fall between 4.5 and 14.5 C (Reiser and Bjornn 1979). Salmon embryos are most vulnerable to temperature stress in their early development stages, before closure of the blastopore. This occurs at about 140 accumulated Celsius temperature units (Combs 1965; Bams 1967). (A temperature unit is one degree above freezing experienced by developing fish embryos per day). Merrell (1962) suggested that pink salmon embryo survival in Sashin Creek, southeastern Alaska, may be related to water temperature during spawning. Embryos exposed to cooler spawning environmental temperatures have been shown to experience greater incubation mortality than those which began incubation at warmer temperatures (McNeil 1969). Bailey and Evans (1971) reported an increase in pink salmon mortality when initial incubation water temperatures were held below 2 C during the initial incubation period. Laboratory experiments with developing Susitna chum and sockeye salmon embryos resulted in increased mortality and alevin abnormality when average temperatures were maintained at a level less than 3.4 C (Wangaard and Burger 1983). However, these increases were relatively slight. Following the period of initial sensitivity to low temperatures, i.e., after the blastopore has closed (approximately 30 days at 4.5 C), embryos and alevins can survive temperatures near 0 C (McNeil and Bailey 1975), but their development is slowed. During the incubation period, mean intragravel water temperatures in the primary middle river spawning sloughs range from 2.0 to 4.3 C (ADF&G 1983d). Since peak chum salmon spawning in sloughs occurs between late August and September (table 16), it follows that blastopore closure occurs by October.

Slough 8A was naturally overtopped in late November 1982 by cold mainstem water (near 0 C), providing some insight into potential effects of with-project overtopping events. Slough 8A intragravel water temperature was depressed during this event. Subsequently, embryo development and emergence was delayed, and large numbers of dead embryos were seen (ADF&G 1983d). This suggests that increased mortality may have occurred.

The significance of with-project overtopping to developing salmon varies between sloughs, being more problematic in those downstream of the predicted ice front. As noted above, the predicted ice front location with the Watana Reservoir occurs between RM 124 to 142 (table 13). When it is at RM 124 (the farthest downstream ice front location predicted with the Watana Reservoir), none of the sloughs upstream of this point would be overtopped (table 13). Of the five most productive chum salmon sloughs in the middle river, only slough 8 is located downstream of RM 124 and would be overtopped. An average of 232 chum salmon spawned in slough 8 between 1981 and 1983 (table 19). This represents approximately 5.6% of the total chum salmon escapement to middle river sloughs for those three years (table 19). At the other extreme, when the predicted ice front is RM 142, three of the top five chum salmon producing sloughs (8, 8A and 11) would be overtopped (table 13). From 1981 to 1983, these three sloughs supported an aggregate average of 1,740 spawning chum salmon, approximately 42% of those spawning in middle river sloughs (table 19).

Predicted river freezeup dates with the Watana Reservoir range from November 28 to December 30 (Harza-Ebasco Susitna Joint Venture 1984). Ice formation in all simulations is assumed to begin at the Chulitna River confluence and progresses upstream from there. Of the eight ICECAL simulations run, six predict overtopping of sloughs 8 and 8A, three predict overtopping of sloughs 9 and 11, and none predict overtopping of slough 21 (table 13). The expected rate of ice front progression upstream from the Chulitna River confluence varies annually due to climatic influence and temperature of the outflow. With the Watana Reservoir, ice front advance is predicted to take between one to six weeks (Harza-Ebasco Susitna Joint Venture 1984). Given the predicted start of river freezeup (late November) and the predicted rate of ice front advance, the earliest an overtopping event could occur is early December, which is generally post-blastopore closure. Most model runs indicate that freezeup start dates would be later, occurring in mid to late December (table 13). Therefore, the majority of predicted overtopping events from ice staging could not occur before late December and perhaps not until sometime in January.

Based on ICECAL simulations of river freezeup timing, subsequent ice front advance, and what is known of the relationship of temperature to chum salmon embryo development, with-project ice-induced overtopping events could lead to widespread embryo mortality in affected sloughs. While the likelihood of any direct embryo mortality from thermal stress diminishes after October following blastopore closure, some ICECAL simulations predict that staging overtopping events could last until spring meltout. Indirect mortality could be significant given that cold temperatures of this severity (near 0 C) and duration should delay embryo development and fry emergence to such an extent that they would be unable to complete their life cycle.

The environmental consequences of ice-staging overtopping events appear to be less with both dams on-line. This is because initial freezeup dates are predicted to be later, meltout dates are expected earlier, and ice thickness would be less (see Chapter V). Further, the predicted duration of overtopping events is shorter, and they would occur later in winter.

According to the two-dam ICECAL simulations, only sloughs 8 and 8A would be overtopped due to ice staging (table 13). Together, these two sloughs accounted for about 19% of all chum salmon spawning in middle river sloughs from 1981 to 1983 (table 19). Importantly, only the "cold winter" simulations, which represent environmental extremes, predicted overtopping. Preliminary evidence indicates that (at least in sloughs proximal to the mainstem, e.g. 8, 9, and 11) intragravel water temperature is somewhat influenced by mainstem water temperature (Beaver 1984). If true, it would serve to further cool overtopped slough environments.

Overtopping of slough berms by colder mainstem waters could also affect overwintering fish as water temperature affects fish metabolism, growth, food capture, swimming, and disease resistance. Juvenile salmonids can tolerate a wider range of water temperatures than embryos and can survive short exposures to temperatures which could ultimately be lethal. They can live for long periods at relatively low temperatures at which time they abstain from feeding, are less active, and spend more time resting in secluded habitats (Alabaster and Lloyd 1982; Chapman and Bjornn 1969). For example, in Carnation Creek, British Columbia, fish stopped feeding and moved into deeper water or closer to objects providing cover at temperatures below 7 C (Bustard and Narver 1975). Similarly, in Grant Creek near Seward, Alaska, juvenile salmonids were inactive at water temperatures between 1.0 to 4.5 C and inhabited cover afforded by streambed cobbles (AEIDC 1982). Regardless of whether one or two dams are on-line, some slough overwintering fish would be exposed to colder overflow waters. As mentioned above, the chief difference between the one and two-dam options in this regard lies in the frequency and duration of overtopping events.

Overwintering salmonids exposed to cold overflow waters (near 0 C) could respond in one of two ways, given that a critical thermal minimum has not been demonstrated in them short of actual freezing (AEIDC 1984). They conceivably might simply seek cover within the slough, becoming relatively inactive until temperatures once again rise following the end of the overtopping event. Alternately, they might elect to leave since they are mobile. However, given that overflow water temperature would be identical to mainstem temperature, it is arguable whether they would do so. If they did emigrate, their survival would ultimately depend on their finding suitable replacement habitat which appears limited in this reach.

Overtopping of slough berms from breakup-driven ice jams is not a with-project issue, given ICECAL predictions. According to model simulations, river ice would melt in place rather than breakup. Thus, no ice jams are predicted to form at this time and no flooding of slough environments would occur.

The next concern to be discussed is the effect of with-project ice-staging on upwelling water in middle river spawning sloughs (table 14. Maximum winter river stages upstream of the with-project ice front are predicted to be lower than corresponding natural conditions, because there would be no freezeup staging (Harza-Ebasco Susitna Joint Venture 1984). Hence, there is concern that this lower stage could reduce the amount of slough upwelling. This should be of minimal concern since with-project winter flows upstream of the ice front with either dam scenario are predicted to be similar to those occurring naturally in September. As upwelling is presently sufficient for incubation purposes during natural September flows, one could assume that with-project upwelling would also be sufficient. Downstream of the ice-front, with-project river stages with both dams on-line are predicted to be higher than natural. Consequently, concern over project effects on upwelling rates in this zone are apparently moot.

The third issue raised deals with the potential effects of the with-project open water zone below Devil Canyon on fish habitat quality (table 14. Regardless of whether one or two dams are built, an ice-free zone of open water would occur each winter below Devil Canyon. With Watana Reservoir, this (predicted by ICECAL) would stretch between 10 to 28 miles; with both dams operational the zone would stretch between 15 to 29 miles (table 13). Conceivably, primary productivity could be enhanced in this area because there would be less snow and ice cover. Taken by itself, ice removal would allow more light to penetrate the water column, stimulating primary production. However, the question is complicated by the fact that released reservoir waters would be turbid, whereas natural winter flows are relatively clear (Acres American 1983). An ongoing study seeks to answer the productivity question. Estimates of released water turbidities are currently being reforecasted. At present, there is no reliable information to use to describe the probable influences of the with-project open water area on winter productivity.

Another aspect of the open water reach lies in its potential to become overwintering habitat. Present juvenile salmon overwintering areas are characterized by the presence of ice cover and upwelling warmer than ambient water (Mike Stratton pers comm). Little is known about resident species overwintering habitats, but generally it seems that upwelling is not as critical a component for them. Resident species are thought to overwinter in deeper mainstem pools and at tributary mouths (ADF&G 1983c).

The open water reach could conceivably provide some overwinter habitat for juvenile salmon, since released reservoir waters (0.5 to 5.6 C) would be within the normal range of upwelling temperatures (0.8 to 4.2 C) and cover could be afforded by the turbid conditions. Since it is presently impossible to accurately predict turbidities, it is premature to speculate on the effectiveness of this type of cover. The open water area should provide more overwinter habitat for resident species than now exists, chiefly because of the combined effects of higher with-project flows (which could create favored deep pool environments) and the relatively warmer temperatures.

The open water area could also provide additional salmon spawning and incubation habitat. Chum salmon have been observed spawning in other mainstem areas influenced by upwelling groundwater (ADF&G 1985b). Although undocumented, it is possible that upwelled mainstem water temperatures at these sites are similar to those seen in sloughs. Given that released water temperatures are predicted to be in the range of upwelled slough water temperatures, and given the proclivity of chum salmon for spawning in mainstem environments, it is conceivable that the middle river could function as reproductive habitat provided that suitable substrate exists there. A more detailed analysis of water temperature effects on incubation is found in AEIDC 1984.

Another expressed ice-related concern in the middle river pertains to the natural flushing of fines from slough spawning habitats by breakup-induced flooding (table 14). Regardless of whether one or two dams are built, ICECAL simulations predict that breakup events would no longer occur; the river ice mantle would gradually melt in place. The issue rests in some visual estimates made of the appearance of slough spawning substrates following breakup. For example, an ADF&G biologist (Drew Crawford pers. comm) reported that following a breakup flood, slough 8A substrates appeared cleaner.

Unfortunately, no sediment samples have been taken before and after breakup floods, so the issue remains founded on subjective appraisal of environmental conditions. While it is conceivable that breakup flooding is important for the maintenance of slough spawning substrates (at least in some locations), it is equally possible that hydraulic upwelling pressure (coupled with the actions of redd building adults) is sufficient for this purpose. Given the lack of information on the amount and size of intragravel fines before and after floods, no defensible conclusions can be drawn.

The last question analyzed is that of the effect of with-project anchor ice on fish and their habitats (table 14). Mechanisms of anchor ice formation are poorly understood, but is is known to occur most often in supercooled reaches over gravel substrates (Michel 1971; Mason 1958). Anchor ice is relatively common in the middle river, but none has been found to date in either mainstem or slough salmon incubation areas. Presumably, this is due to the influence of warm upwelling at these sites.

Little is known of the influence of anchor ice on Susitna River fish habitats. Benson (1955) studied the effect of anchor ice on trout stream ecology in Michigan. There, anchor ice was not found to affect trout eggs buried in the gravel. However, trout fry were apparently vulnerable to mortality if they were emerging at the same time that anchor ice formed. In California, Needham and Jones (1959) noticed that when anchor ice was dispersing and breaking up, it dislodged substrates and considerable numbers of invertebrates were carried away. In the middle river, anchor ice can carry gravel substrates away in a similar manner (R&M Consultants Inc. 1984). However, no invertebrate sampling was done at these times, so its influence in this regard is unknown.

ICECAL does not simulate anchor ice formation; therefore, no with-project predictions of its rates or timing of formation, distribution, or thicknesses have been made. Project team ice modelers believe that there would be less anchor ice with-project in the middle river. Upstream of the 0 C isotherm in the open water lead below Devil Canyon, no anchor ice formation is likely due to the influence of the warmer than natural released water. This could be seen as a potentially stabilizing effect on instream invertebrate habitats there. Anchor ice would form with-project between the upstream edge of the ice-front and the 0 C isotherm in a manner similar to that seen naturally. However, its annual aggregate areal extent could increase over natural conditions, given the predicted dynamic nature of the ice front. More anchor ice would form with the Watana Reservoir than with both dams on-line because of the greater variability of anticipated flow releases. It is probable that no anchor ice could form in areas influenced by relatively warm upwelled water. Thus, with-project anchor ice should not influence salmon reproductive habitats. Given the imprecise nature of current knowledge of anchor ice formation processes and its influence on other fish habitat components, it is impossible to speculate further on how changes in the present ice regime would affect other species.

5. LOWER RIVER EFFECTS ANALYSIS

a. Fish Resource

Nineteen species of fish are known to inhabit lower river waters (figure 89). All are dependent to some extent on mainstem environments to fulfill aspects of their life histories. Seven of these species are anadromous; they include five species of Pacific salmon and eulachon and Bering cisco. Available information on fish species presence, distribution, habitats, and behavior in the lower river is not as complete as in the middle river. Based on extant data, it seems that fish use of lower river environments largely parallels that described for the middle river and impoundment zone, with a few major exceptions.

At least 17 tributary streams and six sloughs provide salmon reproductive habitats in this reach. To date, no chinook, sockeye or pink salmon have been observed spawning in project-affected lower river mainstem waters; all apparently use tributary streams exclusively for this purpose (Barrett, Thompson & Wick 1985). Small numbers of chum and coho salmon have been seen spawning in 13 separate mainstem sites and six side sloughs; most members of these two species also spawn in tributary environments. ADF&G estimates that, in aggregate, the number of chum salmon spawning within mainstem environments there represents roughly 0.3% of 1984 escapement to the basin. The estimated number of spawning coho in the mainstem represents roughly 0.2% of the 1984 escapement (Barrett, Thompson & Wick 1985). Chum salmon were the principal users of side slough spawning environments, being present in five of the six sloughs used. Their estimated numbers represent roughly 0.1% of the total 1984 escapement. Only six coho were seen spawning in sloughs in 1984; all were in one of the six sloughs (Barrett, Thompson & Wick 1985). This indicates that, unlike the middle river, lower river sloughs are less important for spawning purposes.

Less is known of salmon rearing and overwintering habitats in lower river mainstem environments than in the middle river. Given their respective life history requirements and the natural hydrologic conditions occurring in winter, it is possible that some chinook, coho, and sockeye salmon overwinter in the mainstem and that some chum, chinook, and coho rear there. A few coho and chinook have been captured during winter in mainstem environments (ADF&G 1983c).

Several million eulachon spawn in late May to early June in the lower 50 miles of the mainstem Susitna River. Most of these fish spawn below RM 29 in main channel habitats near cut banks over loose sand and gravel substrates (Barrett, Thompson & Wick 1984). Bering cisco return to the Susitna River in late August and spawning takes place in September through October. In 1981 and 1982, spawning activity peaked the second week of October. Bering cisco are known to spawn only in main channel environments; the majority of spawning apparently takes place between RM 75 and RM 85 (Barrett, Thompson & Wick).

Little is known about resident fish life histories in the lower river. A forthcoming ADF&G report (due to be released in late April), reportedly will contain a synopsis of available information on resident species. The 12 resident fish species found in the lower river, with the exception of lake trout and northern pike, are generally believed to be common (Sundet & Wenger 1984; ADF&G 1983c).

Rainbow trout, Arctic grayling, and Dolly Varden probably spend most of the open-water season in tributaries, using the mainstem principally for migration and overwintering (ADF&G 1983c). Burbot, whitefish, longnose sucker, sculpin, stickleback, and Arctic lamprey are found in both the mainstem and tributaries during the open-water season. All of these species are believed to overwinter in the mainstem, but only rainbow trout, burbot, and slimy sculpin were captured there during 1982 winter sampling (ADF&G 1983c).

Based on ongoing radio-telemetry studies, it appears that favored mainstem overwinter habitats for adult rainbow trout and burbot differ principally by depth and location. Tagged rainbows are most frequently relocated in mainstem side channels near tributaries in waters generally less than five feet (Rich Sundet, pers. comm.). They are often found close to open leads. Tagged burbot are most frequently located in winter in pools greater than six feet deep along river bends (Rich Sundet, pers. comm.). Both species seem to favor low velocity environments. Only one Arctic grayling has been successfully radio-tagged; it was frequently relocated in close association with rainbow trout (Rich Sundet, pers. comm.). No other resident species have been radio tagged. It may be that other resident salmonids with habits like rainbow trout also frequent relatively shallow low velocity environments in winter; the same type of relationship may exist between burbot and other bottom feeders such as longnose sucker.

THE WITH-PROJECT ENVIRONMENT

ICECAL simulations have not been run for the lower river, and the following discussion is based wholly on subjective input provided by the Project Team. Ice would probably begin forming with-project in early November about the same time it does naturally. Increased with-project flows could delay upstream movement of the ice front. This delay is thought likely to be similar to that modeled for the middle river (i.e. 17 to 44 days with Watana Reservoir and 27 to 47 days with both dams on-line). Increased winter flows might produce somewhat more ice than now occurs; however, this is uncertain.

Lower river ice meltout could be advanced over natural conditions due to the expected earlier than normal meltout of the middle river. Meltout timing (if the above is true) would be closely coincidental to that predicted for the middle river. Since ice is expected to melt gradually, there would be no breakup event as such.

b. Anticipated With-Project Effects

Four of the nine ice-related issues of concern identified in the middle river could also pertain to lower river aquatic resources (table 14). Three issues (Nos. 1, 3, and 6) relate to staging and one (No. 4) to the amount of ice cover. As indicated above, no ice modeling has been done for the lower river; thus, conclusions presented here are tentative.

With regard to staging, freezeup is thought likely to occur later than normal with either one or two dams operating. The view held by project team ice modelers is that freezeup staging would not lead to overtopping of slough berms in the lower river. Consequently, there would be no with-project ice effects on slough incubating salmon embryos. It is important to reiterate, however, that no ice modeling has yet been done for this reach.

Should the prediction of no overtopping of slough berms prove false, the consequence to the salmon resource as a whole would be minimal. Lower river slough reproductive habitats are severely limited areally and are utilized by only a small number of chum salmon. Consequently, their collective contribution to maintenance of Susitna River salmon stocks is very low.

As in the middle river, the question of ice-related effects on upwelling pertains to salmon reproductive habitat quality. In essence, the question rests with two points: the rate of upstream migration of the ice front and the assumption that mainstem upwelling has a controlling influence on embryo survival. Salmon spawning naturally occurs in the mainstem at a time when river flow is decreasing. Successful mainstem reproduction is partly dependent on freezeup staging, which raises the water level and assures that upwelling is not diminished. This concern is more acute near the Chulitna River confluence than further downstream for two reasons; it would take longer for the ice front to arrive and more fish spawn in this area.

With the project, ice front advance would be slower than natural, but flows would be greater than those now occurring. These two factors seem to offset each other. If so, effects to incubating embryos would be minimal, because flows should be sufficient to maintain upwelling. However, it is important to point out that to date there is no direct evidence that mainstem upwelling in the lower river exerts a controlling influence on incubation environments there.

The last lower river ice-related issue raised pertains to the question of how the with-project ice cover would affect primary productivity and the amount of overwinter fish habitat (table 14). Project ice modelers believe that regardless of whether one or two dams is built, there would be more ice in the lower river with-project than naturally. However, the exact morphology of the ice cover is unknown. Provided that extensive lead systems did not develop, instream primary production with-project should be reduced in rough proportion to the increase in ice cover seen. If an extensive system of open water leads does develop, then the converse would be true. It is possible that winter habitat availability could increase with-project, given the combined effects of ice-induced staging and greater flows. However, overwinter habitat is comprised of more components than just water volume. Numerous other variables, such as bed morphology, water depth, water velocity, temperature, and cover are at play. So, the belief that overwinter habitat might increase with-project is provisional and pending on acquisition of information describing how all habitat variables would be affected. Regardless, there would be no decrease in the amount of current overwinter habitat available for fish.

6. SUMMARY

In conclusion, winter drawdown of the Watana Reservoir would be a destabilizing influence on its littoral zone, making it unproductive for salmonids. Some species would be more affected than others. In all likelihood, winter drawdown would preclude successful fall reproduction by lake trout; if spawning took place at all, eggs would desiccate or freeze. Ice draping, gouging, and associated erosion would probably limit invertebrate productivity and cover availability, which in turn would diminish rearing habitat quality for Arctic grayling and whitefish. Burbot and longnose sucker should not be negatively influenced by ice-related processes. Both are bottom dwellers which do not depend on stable littoral zones for any of their life requirements. In some extremely cold years, ice blockage of tributary stream mouths could delay Arctic grayling and longnose sucker natal migrations. At such times, it is likely that reproductive failure could occur. This is not considered a major problem, since loss of a single year class is not overly threatening to relatively long-lived and fecund organisms like fish, and given that the necessary cold climatic conditions seldom happen consecutively.

The environment of the Devil Canyon impoundment would be much more stable, given its winter drawdown schedule. However, the canyon's geomorphology and substrate geology limit establishment of a productive littoral zone. Fish reproductive habitats near the mouths of Fog and Tsusena creeks may not be influenced by with-project icing events. Both are located in the upper end of the reservoir where little ice accumulation is expected.

The chief with-project middle river ice concern lies in potential altering of slough incubation habitat quality. Ice staging downstream of the ice front would cause overtopping of slough berms by colder than ambient mainstem water. This would have consequence to natal habitats.

ICECAL simulations predict that all with-project ice-induced overtopping events would occur after embryonic blastopore closure. Thus, there is little likelihood that direct mortality of embryos would ensue. However, indirect mortality would be significant given the predicted duration of most overtopping events ($\geq$ one month). This would delay embryonic development to such a degree that it is unlikely that any could complete their life cycles. Overtopping waters could also affect overwintering juvenile fish. Effects would be more severe the longer cold exposure lasted. Overtopping events would be more frequent and severe with the Watana Reservoir alone than with both dams on-line.

Concern has been raised that the absence of with-project ice staging in the area upstream of the ice front would alter slough upwelling rates. This does not seem likely as with-project winter flows are forecast to be between 8,000 and 12,000 cfs. This is similar to flows occurring naturally in September. Since September upwelling rates are apparently sufficient to maintain salmon natal habitat quality, it seems likely that with-project winter flows should also be adequate. The with-project 10 to 29 mile long open water zone in winter below Devil Canyon could enhance primary productivity in the mainstem. Theoretically, more light would be able to penetrate the open water column thereby stimulating photosynthesis. However, winter flows would be somewhat turbid confounding the issue.

A more likely effect of this open water zone could be the creation of additional overwinter habitat due to the combined influence of higher flows and warmer than natural water temperatures. Higher flow volumes could create deep pool overwinter habitats for resident species. Since released reservoir waters are predicted to be about the same temperature as that of upwelled slough groundwater, this area might also provide some salmon overwinter and spawning habitat. The with-project flow regime would eliminate breakup-induced flooding of slough habitats. Although unsubstantiated, this process may be necessary for maintenance of slough natal habitats (through flushing of fines from interstitial gravel spaces). Given present knowledge, it is impossible to predict the long term consequences of elimination of breakup-induced flooding on these habitats. Anchor ice has been shown to be a destabilizing influence on invertebrate and fish embryo habitats by dislodging substrates during melting or breakup. No anchor ice is expected to form with-project in the open water lead upstream of the 0 C isotherm; however, it would form between the ice front and the 0 C isotherm in a manner analogous to that seen naturally. Cessation of anchor ice formation in the open water zone could stabilize incubation habitats.

Less physical and biological information exists on the lower river than on the other two zones. No temperature or ice modeling has been attempted for this reach, making evaluation of with-project effects completely subjective. The general belief held by project ice modelers is that ice-induced staging would not lead to overtopping of lower river sloughs. With-project winter icing probably would not negatively influence upwelling rates, given that the effects of the predicted slower than normal ice front advance and the higher than natural flows would likely offset each other. Higher with-project winter flows coupled with ice-induced staging could increase the amount of overwinter fish habitat (since wetted area would be increased); however, this is uncertain given the present level of knowledge. Overwinter habitat is comprised of more than just water volume. Regardless, it seems likely that no existing overwinter habitats would be lost with-project.

E. EFFECTS OF ICE ON RIPARIAN VEGETATION

1. GENERAL

a. Impoundment Zone

The early successional area in the potential impoundment zone is usually a band approximately 15 feet or less wide under lain by a cobbly or sandy substrate. It is dominated by a variety of forbs, graminoids (grass and grass-like species), and shrubs, including low willows and tall alders. Vegetation advancement is inhibited by ice and, to a lesser extent, summer floods.

Existing effects of ice on vegetation in the proposed impoundment zone include ice scars on trees, bending and scraping of low and tall shrubs, local sediment deposition from melting ice blocks, and silt deposition in the waters backed up behind ice jams. These events occur primarily during spring breakup. No ice effects on vegetation during freezeup have been reported along any reach of the river. As ice jams form, water levels may rise rapidly upstream from the jam and inundate vegetation for a short period of time, probably less than 5 days. This inundation probably has little effect on plant species or vegetation succession because of its relatively short duration. However, sediment may be deposited at that time or as the ice melts in place.

Ice blocks in a jam may be pushed laterally against and over the bank where they may scar, break, and scrape woody species such as alder (Alnus spp.) and several species of willow (most commonly Salix alaxensis). Herbaceous species such as sedges (Carex spp.), fireweed (Epilobium latifolium), hedysarum (Hedysarum alpinum), and horsetail (Equisetum variegatum) may also be scoured, but undamaged graminoids (grass or grass-like plants) have been observed under ice blocks piled several feet high near Clarence Creek (Helm and Mayer 1985).

Ice has the greatest effect when the jam breaks, releasing huge quantities of ice and water moving very rapidly downstream. The ice blocks may scrape against trees, removing bark and living cambium, and possibly some outer layers of wood. Cambium is a thin layer of living tissue between the bark and wood, and is essential for wood production. When the cambium is removed by scraping, wood cannot form in that area in following years, resulting in a scar. Most scarring does not have any important lasting effects on an individual plant's growth or vegetation succession. Freshly scarred white spruce trees (Picea glauca) were observed in spring 1982 downstream from Goose Creek. Some shrubs, usually willows and some alders, have been bent at about 45 degrees by blocks of ice pushing laterally along the shore.

b. middle river

Vegetation succession sequences along the Middle and Lower reaches are similar to each other except for the more important role of ice in the Middle River. Since the channel is still incised in the middle river, early successional sites occur in a relatively narrow band compared with similar areas on the lower river. Early successional vegetation usually consists of horsetail (Equisetum variegatum), balsam poplar (Populus balsamifera), and feltleaf willow (Salix alaxensis), alone or in various combinations. Willow and poplar between 0.4 and 2.0 meter tall and larger stems that can be bent over are important as moose browse. Dryas (Dryas drummondii) occurs on more cobbly areas, while occasional forbs and graminoids are found in some areas. Approximately 10 to 20 years after stabilization, alder (Alnus tenuifolia) becomes dominant (McKendrick et al. 1982). Balsam poplar then overtops it after another 25 years. These alder and immature balsam poplar stages are considered intermediate and have few shrubs of either the species or size classes needed for browsing.

When poplars are 70 to 100 years old, the overstory becomes patchy and rose (Rosa acicularis) and highbush cranberry (Viburnum edule) dominate the shrub understory. Both of these shrub species are browsed. Mature paper birch (Betula papyrifera) - white spruce (Picea glauca) forests occur approximately 200 years after stabilization. These sites also have patchy canopies and rose and highbush cranberry in the understory. More details have been reported in McKendrick et al. (1982) and will be reported in Helm (1985). (Ages and time spans may be changed as data are analyzed for Helm (1985).)

Natural effects of ice on vegetation in the middle river also include ice scars on trees, bending and scraping of low and tall shrubs, local sediment deposition from melting ice blocks, and silt deposition during staging behind ice jams. Old scars have been found on balsam poplar (Populus balsamifera) approximately 7 feet above the ground near the mouth of Whiskers Creek (R&M Consultants, Inc. 1981, Helm 1985). These individuals were probably 30 feet or more from the present water line under normal summer flows. Freshly scarred trees have also been found along a cutbank near the confluence of the Susitna and Chulitna Rivers (R&M Consultants, Inc. 1982).

Woody species, especially low willows and tall alder shrubs may also be bent or even have stems partly broken, but are capable of growing new shoots from the existing stem or rootstock (McKendrick et al. 1982). The degree of bending varies from slight (less than 10 degrees) to major (approximately 90 degrees). Most bent alder are flattened against the ground while most bent willow are only bent at approximately a 45 degree angle. Stems are usually partly broken only in intermediate stages of vegetation succession, such as 15 to 20-year old alder, where the stems have become more rigid, but may still bend. Some cracked stems can still grow new shoots if enough cambium remains. Younger plants in earlier successional sites are usually only bent, and stems are rarely broken. Older, more rigid trunks, especially of balsam poplar, may be broken near the base and carried away by floods. This appears to happen to individuals near the edge of the vegetation type which get in the way, but not to the whole stand, although this would be possible in a large flood. Moberly and Cameron 1929, in Gerard, (no date) reported an ice jam flood that knocked down trees 3 feet in diameter near Fort McMurray on the Athabasca River in 1875.

This bending and resprouting process does not normally change the successional stage of vegetation in terms of type of vegetation, but it does change the age structure. Where 20-year old alder stems once occurred, one-year old sprouts would occur the next year. This scraping may increase the shoot production of willows to create more browse. If a particular portion of an island is subjected to ice scour repeatedly (say, every 20 years for alder) then vegetation succession would not advance beyond this stage, and individual stems would not grow more than 20 years above ground on the average. Rootstocks, however, could be 50 or more years old. A longer period of time without a jam because of weather may allow vegetation succession to advance beyond that stage.

Large ice blocks containing unsorted sediment may become grounded and stay in one place until they melt. The sediment load is then deposited where the ice melts (R&M Consultants, Inc. 1984), possibly forming a hummocky microtopography which could affect moisture availability for plants. Individuals growing between mounds would have more moisture and more litter deposited in those depressions. This could slow evaporation in the summer time and increase soil nutrient status if the material decomposes sufficiently. However, decomposition in northern latitudes is frequently slow. Individuals growing on top the mounds would be subjected to a drier moisture regime, but would probably experience warmer temperatures. The unsorted nature of the sediment deposited by ice creates a diverse substrate for plant growth.

Silt may also be deposited when water backs up behind ice jams and the water velocities slow (R&M Consultants, Inc. 1984). On some rivers, such as the Yukon River with a broad floodplain, layers of silt 1/2 to 2 inches thick may be deposited over large areas (Eardley 1938). Local deposition could not occur this high any other way on some bars and inside meander bends because summer floods did not reach this high (Eardley 1938). Because of the relatively incised channel on the middle Susitna River, deposition would not cover as large an area.

Studies of aerial photographs from 1949 to 1980 from Talkeetna to Devil Canyon have indicated that the size and shape of islands have changed little over this time period although they have become more vegetated (LaBelle 1984). Hence, the borders of young vegetation (less than 15 years) around most of these islands must be regrowth after some riparian event either prevented succession from advancing or denuded a site to set vegetation succession backward to an earlier stage, and do not represent colonization of newly deposited substrate (R&M Consultants, Inc. 1982, Helm 1985). Ice is believed to keep the younger vegetation (5 to 25 years old) from advancing while summer flows are believed to control where new vegetation becomes established on bare surfaces. Bare surfaces probably result from ice scour where soil has been eroded or shoved by ice blocks (R&M Consultants, Inc. 1982). However, these surfaces may be colonized between ice events which would not occur every year. These scouring events are relatively localized, but occur repeatedly in the same places although not every year (R&M Consultants, Inc. 1984).

The line between young vegetation, dominated by graminoids, that has not been allowed to advance, and the riparian woodland is sometimes considered the trimline (Gill 1973). This is probably controlled by ice on the Mackenzie (Gill 1973) and Susitna Rivers (Shoch, pers. comm.). Rapidly developing woody species may be able to colonize the area between years when ice jams occur.

A classic example of ice effects on vegetation occurs near the mouth of Whiskers Creek near LRX-7. The downstream end of the island contains an immature (approximately 50 to 70 years old) balsam poplar stand with some alder in the understory (Helm 1985, subject to revision pending further analysis). Old ice scars occur approximately 7 feet high on balsam poplar. Just upstream is a younger site. Although we do not have information on those ages, stems appear to be 20 - 30 year old alder. These do not appear to have been affected by ice recently (last 10 or 15 years) although many alder stems have been bent and then resprouted. On one side of the island, willows have been beaten down (approximately 45 degree angle), but do not appear to have had any damage other than bending and minor scraping. At the upstream end of the island, the surface was almost bare except for a few young willow stems that had survived the scraping (Helm

1985). Visual evidence of ice shoving soil and of silt being deposited from melting ice blocks was present.

Many of these islands have gradually sloping banks above water during normal summer flows. In some areas, however, particularly along the main bank, cutbanks are lined with mature vegetation. These areas may be eroded by ice shoving against them (R&M Consultants 1982). Mature balsam poplars were observed overhanging the left bank near LRX-3 after a large ice jam flood (R&M Consultants, Inc. 1982). Tree roots have been observed sliced by ice along a cutbank (Shoch, pers. comm.). Summer floods may also contribute to this erosion started by ice. In this case, however, the soil, as well as the vegetation, is removed.

c. lower river

Ice effects on the lower river are less dramatic because of the width of the river and its braided morphology; however, ice jams have been reported near Montana Creek in 1983 (R&M Consultants, Inc. 1984). Occasionally minor jams may occur, but because there are so many other places for the water to flow, no major effects have been observed. Vegetation succession is similar to the middle river except that more extensive areas are usually available for colonization.

2. EEFFECTS OF ALTERED RIVER ICE

a. Impoundment Zone

The majority of areas that are now directly affected by the river, as well as many mature forests, in the proposed impoundment zone would be inundated by the project. Relatively mature forests and shrublands would border a band of relatively unvegetated area around the impoundment. Water levels would increase through the summer, but would be drawn down for power production during the winter. Hence, the summer water levels would probably determine where vegetation grows. Except for annuals and species that can withstand prolonged flooding, the area between the winter ice and summer high water levels would probably be unvegetated. Some of the area near the highest fill level could be vegetated by species that tolerate wet rooting zones. Some established species could be affected by higher water tables, but this area is expected to be narrow. Species that prefer well-drained soils generally occur on steeper slopes; hence, an extensive area of existing vegetation would not be affected. Nilsson (1981) reports that since ice along lake reservoirs in Sweden melts in place along the shore, substrate is exposed for colonization for a few weeks before the reservoir fills again. If the reservoir does not fill up each year, then more time is available for colonization. The Susitna reservoirs are expected to fill to maximum level each year so this should not occur. Ice effects should be minor, at most, with the project.

Bears use the potential impoundment zone in the spring (Miller and McAllister 1982), when they are believed to be foraging for hedysarum roots and possibly horsetail. Hedysarum generally grows in sandy or gravelly areas and could be found in forests or treeless sites above the impoundment. It has not been established what horsetail species bears eat. One species, Equisetum variegatum, is usually found in floodplain sites, while E. silvaticum and E. arvense are found in wooded areas. Hence, it is not clear if there would be an impact on bears. Similarly, many plant species eaten by moose along the floodplain are found at higher elevations.

b. Middle River

Areas of the middle river will not have continuous ice cover above RM 124 to 142 (Harza-Ebasco Susitna Joint Venture 1984). Existing vegetation in these sites is expected to advance successionally without setbacks attributable to the river except where areas are being eroded away by channel movement, which is relatively minor because of the incised channel. Areas that are currently unvegetated may become vegetated because of the lower summer flows if the substrate has sufficient fines (sand-sized particles and finer) to support plant growth and if sufficient moisture is available. With enough time (possibly 5 years or decades, depending on the environment), enough fines may be deposited to support plant growth. Much of the newly exposed substrate probably would consist of cobbles.

Areas of the middle river that would have ice cover would not be subject to the destructive breakup floods that currently occur because the ice would melt in place (LaBelle 1984a). However, because of the winter flooding of areas that could be colonized in the summer, winter inundation and formation of ice may retard vegetation development. Species that currently grow along the river are adapted to summer flooding, sometimes for long periods of time, as well as overflow flooding and refreezing in the winter. Most of the natural winter flooding is short-lived and probably does not seal the ground. Gas exchange may still occur among the roots, soil air, and the above-ground atmosphere. Winter flooding as a result of the project would remain all winter and would freeze in place (downstream from the icefront), possibly inhibiting gas exchange between soil and atmosphere. Plant roots respire in winter although at a slower rate than in warmer temperatures of summer. Winter ice-sealing is harsher than summer flooding because summer flooding is usually of shorter duration and involves moving water, which allows better gas exchange (Kozlowski 1984).

This sealing of the ground by ice is devastating to some forage crops, such as alfalfa and grasses grown for hay (Smith 1981). This is a more severe treatment than the riparian plants currently receive, but they would probably tolerate it, although growth may be hampered. Some areas with established vegetation (LRX 3, 7, and 17) may become covered with winter ice under certain conditions (Harza-Ebasco Susitna Joint Venture 1984), but presumably these plants would be able to survive. Established vegetation would be expected to tolerate this treatment better than new individuals.

The factors which influence vegetation establishment most are probably precipitation and water tables during the short period in May and June when viable willow and balsam poplar seeds are dispersed. Seeds of these early successional species are short-lived (2-6 weeks), are dispersed in late May and June, and require moisture for early growth (Schreiner 1974, Zasada et al. 1983). Even under natural conditions, new areas may not be immediately colonized depending on moisture (Helm 1985). Colonization of new areas with the project in place might be slowed from normal rates, but as a result of flows in May and June rather than the ice effects (Helm 1985). The earlier meltout (4 to 6 weeks with Watana only and 7 to 8 weeks with both Watana and Devil Canyon) and reduced water levels by May (Harza-Ebasco Susitna Joint Venture 1984) could make it difficult for vegetation to become established from seed unless sufficient precipitation occurs at this time.

Mosaics of vegetation types and their resultant edge effect which are considered important for wildlife would be lost without ice effects, which control much of the vegetation dynamics in the middle river. However, some of the mature paper birch - white spruce sites may have patches of trees alternating with shrubby areas where old trees have fallen and left a gap in the canopy. Shrubs become more abundant and larger in these openings. Once vegetation becomes established, it is expected to advance unhindered by river effects. Artificial means of mitigation, such as logging, could be used to setback vegetation succession if that is considered desirable (Helm 1985).

Early sites would probably advance to alder sites in 10 to 20 years, while alder stands would have advanced to immature balsam poplar stands in 20 years. Another 30 years would be required for maturation of the stand. It may take 5 years for a new site to colonize under the new flow regimes unless favorable rainfall occurs during May and June. More details will be found in Helm (1985) when it is completed.

c. Lower River

Ice effects on the lower river would probably be similar in nature to those of the middle river, but would be less because the project would have less effect on the lower reaches of the river. Other rivers, such as the Chulitna, Talkeetna, and Yentna, reduce the effects of the middle Susitna below Talkeetna. Areas that currently have ice jams, such as near Montana Creek, would be less affected by ice as a result of the project. The lower summer water levels would control vegetation establishment. Colonization and vegetation succession would be similar to the middle river.

E. Effects on Wildlife

1. GENERAL

A large and diverse group of wildlife species uses the Susitna project area year-round or seasonally (Alaska Power Authority 1983, LGL 1985). Moose, caribou, Dall sheep, black bear, brown bear, wolf, red fox, beaver, muskrat, and some members of the weasel family -- river otter, marten, mink, short-tailed and least weasel -- are all locally abundant there. Lynx and wolverine are present in low densities, ranging widely through large territories, and evidence of coyotes is limited (Gardner and Ballard 1982, Whitman and Ballard 1984, Gipson et al. 1982, 1984). Many bird species have been documented in the Susitna Basin, including 15 species of raptors (eagles, hawks, falcons, harriers, and owls), up to 60 species of waterbirds (swans, geese, ducks, gulls, and shorebirds), and many more species of terrestrial birds (songbirds, ravens, woodpeckers, grouse, and ptarmigan) (Kessel et al. 1982a,b). However, only a few of these bird species are permanent residents in the project area. Most use the region primarily as summer breeding habitat, migrating in the fall to temperate or tropical latitudes up to thousands of miles distant from the Susitna Basin, and returning to northern latitudes in the spring. The comparatively few bird species that remain as winter residents include spruce grouse, ptarmigan, ravens, magpies, gray jays, chickadees, and several other species (Herter 1985).

The following discussions, based on the results of studies sponsored since 1980 by the Alaska Power Authority, emphasize those mammal and bird species most likely to be affected, either beneficially or adversely, by altered ice conditions associated with the Susitna Project.

a. Impoundment Zone

Moose (Alces alces) occur throughout the impoundment zone and surrounding region at all times of the year, but are present in the Watana impoundment area in greater numbers than in the Devil Canyon impoundment area. For example, an estimate of 193 to 278 moose was made from an aerial census of the Watana impoundment area on March 28, 1983; a similar census on March 31, 1983 of the Devil Canyon impoundment area out to ¼ mile beyond its maximum fill level estimated only 14 moose (Ballard et al. 1984a). Studies of radio-collared moose have shown that some animals consistently confine their movements to relatively small home ranges in and near the impoundment zone, with considerable overlap between summer and winter range areas, whereas others travel far from the impoundment zone, spending only a portion of the year there (Ballard et al. 1984a).

The impoundment zone may be especially important to moose during the winter (November through April), because the canyon of the Susitna River offers lower elevations where forage may be more accessible due to shallower snow than on surrounding higher lands. Availability of winter forage is an important limiting factor to moose. Accumulating snow covers browse vegetation and, if deep enough, restricts the ability of moose to reach their food either by digging or by moving to areas of shallower snow. Studies of radio-collared moose have shown that use of lower elevations (1,800-3,000 feet) within the impoundment zone increases during late winter and early spring, when snow is deepest. Many moose remain at these lower elevations during the summer, but move to higher elevations in October and remain there until accumulating snow may again influence their return to lower elevations (Ballard et al. 1984a).

Studies of radio-collared moose have also revealed that moose cross the Susitna River at all times of the year; 79 crossings were documented from 1980 through 1982 (figure 90), and a March 1981 survey counted 14 sets of moose tracks crossing the river between Watana and Kosina creeks (Ballard et al. 1982, 1983a).

Caribou (Rangifer tarandus) in the vicinity of the impoundment zone belong to the Nelchina herd, which currently contains about 24,000 animals (Pitcher 1985) (figure 91). This is the herd most accessible to the majority of sport hunters in Alaska, because of its proximity to roads and to human population centers. Size, calving areas, migratory movements, and other herd characteristics have been documented annually since 1948 (see Skoog 1968, Hemming 1971, and Pitcher 1983, 1985). The known range of the Nelchina herd is generally bounded as follows: to the west by the Chulitna River and Parks Highway, to the north by the Alaska Range, to the east and southeast by the Mentasta and Wrangell mountains, and to the south by the Glenn Highway (figure 92) (LGL 1985). The range of the Nelchina herd thus includes the entire impoundment zone and its surrounding area.

Caribou of the Nelchina herd migrate across the Susitna River several times each year. The Watana impoundment area includes the reach of the river where most crossings occur, between Deadman and Jay creeks, and it is likely that members of the Nelchina herd would continue to cross the Watana reservoir annually in the future. As recently as 1982, approximately 50% of the female segment of the Nelchina herd migrated through the upper reaches of the Watana impoundment area enroute to spring calving grounds (Pitcher 1983). The Watana impoundment area would probably serve as a crossing route in future years for large numbers of migrating caribou (Pitcher 1984).

Dall sheep (Ovis dalli) occur at high elevations (above about 3,000 feet) in the Watana Creek Hills, Mount Watana-Grebe Mountain, and Portage-Tsusena creek areas, each of which supports an identifiable sheep population (figure 93) (Ballard et al. 1982, Tankersley 1984). However, in early summer (mid-May through mid-July) sheep of the Watana Creek Hills population descend overland 5 miles or more to use a mineral lick complex along Jay Creek, just inside the Watana impoundment high-pool margin (2,185 feet) (figure 94) (Tobey 1981, Ballard et al. 1982, Tankersley 1983, 1984). A minimum of 46 sheep used the lick area in 1983, about 31 percent of the observed Watana Creek Hills population in 1983 (Tankersley 1984).

Because all of the major lick sites (including the intensively used Bluff and East Ridge; see figure 94) are on the banks of Jay Creek canyon above 2,185 feet, they would not be flooded by the Watana reservoir. However, most sheep arrive at the lick complex from the northwest, and sheep have been observed crossing the creek to reach lick sites on the southeast side (Tankersley 1984). The observed crossing point (just downstream from the Bluff and East Ridge) would be inundated at the maximum reservoir fill level in late summer, but would be exposed when sheep cross during May and June (figure 94).

Brown bear (Ursus arctos) and black bear (Ursus americanus) are both abundant within the impoundment zone and would be affected in important ways by the Watana and Devil Canyon reservoirs (LGL 1985). However, because these species hibernate, effects related directly to ice would be limited to the early spring, when bears emerge from dens while the Susitna River is still frozen. Because bears are powerful swimmers and climbers, they would not be affected greatly by reservoir conditions.

Wolves (Canis lupus) range widely throughout the impoundment zone, with heaviest concentrations usually in areas that support their major prey, moose and caribou (Ballard et al. 1984b). Wolves commonly occur in social units called "packs" which maintain exclusive territories. Ballard et al. (1983b) found pack territories occupying all available habitat around the impoundment zone and along the upper river. Areas inside the impoundment zone were occupied by at least six packs. For nine intensively studied packs, territory size averaged 452 square miles (range 124-803 square miles). Although observations concerning wolf numbers in the Susitna Basin have been recorded since the 1950's, comparison of those estimates is difficult because of different methods used and different areas included in the estimates (Van Ballenberghe 1975). Pack sizes of the wolves studied by Ballard et al. (1983b, 1984b) ranged from about 2 to 6 individuals per pack and fluctuated seasonally. In contrast to wolves, evidence of coyotes (Canis latrans) in the impoundment zone is limited, and trappers in the area report catching few (Gipson et al. 1984).

Smaller furbearers are also abundant in and around the impoundment zone. Red fox (Vulpes fulva) frequent the rolling uplands and foothills (between about 825 and 1,900 feet) of the middle Susitna Basin (Gipson et al. 1982, Hobgood 1984). Fox abundance generally increases with distance upstream from Devil Canyon to the mouth of the Tyone River. Hobgood (1984) found summer home ranges of adult red fox to average about 14 square miles, with one fox family per 32 to 48 square miles. Trappers commonly catch foxes along Susitna River tributaries throughout the impoundment zone (Gipson et al. 1984).

River otter (Lutra canadensis) and mink (Mustela vison) are abundant along the Susitna mainstem throughout the impoundment zone and along most tributaries up to 2,000 feet in elevation (Gipson et al. 1982). Marten

(Martes americana) are locally abundant but restricted to mature spruce and spruce-birch forest below 1,700 feet. Gipson et al. (1982) found that marten occur along the Susitna mainstem in highest densities between Devil Creek and Vee Canyon; Buskirk (1983) noted that individual marten in the area tend to use the higher elevations of their home ranges in the spring and lower elevations in the autumn. Short-tailed and least weasels (Mustela erminea and M. rixosa, respectively) are locally abundant throughout the impoundment zone (Gipson et al. 1982, 1984).

Beaver (Castor canadensis) and muskrat (Ondatra zibethica) are present in the slow-flowing sections of most of the larger tributaries of the Susitna River and in lakes and ponds associated with those tributaries. However, these two species appear to be absent from the Susitna mainstem in the impoundment zone; the current is probably too swift to support them (Gipson et al. 1982, 1984).

Most birds, because of their great mobility and seasonal use of the impoundment zone, would not be affected appreciably by changes in ice conditions resulting from the Susitna Project. However, the bald eagle (Haliaeetus leucocephalus) is generally restricted in central Alaska to river valleys, including the Susitna, where large, mature white spruce and balsam poplar provide suitable nest trees along banks and on islands (LGL 1985). Ice conditions affecting active or potential nest trees would influence the distribution of this species in and around the impoundment zone. In June 1984, three bald eagle nests, two currently active and one inactive, were present in the impoundment zone (Roseneau 1984). Two waterbird species, the American dipper (Cinclus mexicanus) and occasionally the common merganser (Mergus merganser), remain as far north as the impoundment zone during the winter if open water is present (Kessel 1982a,b). The extent and locations of open water and available food resources would determine with-project winter distributions of these species.

b. Middle River Zone

Moose use the middle river throughout the year but are present in greatest numbers during the winter (late October through late April) (Modafferi 1982). Census data from the four winters of 1981-82 through 1984-85 indicate that movements of moose onto the floodplain tend to correspond with the timing of snowfall, and that numbers of moose on the floodplain relate closely to snow accumulation. During the moderate winters of early 1982, 1983, and 1984, census results showed highs of 36, 84, and 88 moose present in the middle river (Modafferi 1984). In contrast, a winter census high of 132 moose -- 50 percent greater than any previous census of the middle river -- was recorded in January 1985 (Modafferi 1985 pers. comm.) during the heaviest snow accumulation in ten years (SCS 1985). Moose cross the river at all times of the year and freely walk on stable river ice. In May and June, some females calve in riparian habitats along banks and on islands, then move with their calves to south- and southeast-facing slopes away from the floodplain during the rest of the summer and fall (Modafferi 1982). Males also move away from the river to higher elevations during spring and summer, returning with winter to the floodplain.

Black bear populations are substantial in the middle river zone and lower river and this species relies heavily on riparian habitats throughout its active period from approximately early May through early October (Miller and McAllister 1982; Miller 1983, 1984).

Wolves are probably not abundant throughout the middle river. Although Ballard et al. (1983b) found most available habitat in the upstream portion (near Devil Canyon) to be occupied by wolves, Modafferi (1984 pers. comm.) has observed little evidence of wolves in the majority of the middle river, despite high numbers of wintering moose. Coyotes are apparently common between Portage Creek and Talkeetna (Gipson et al. 1984), but population size, distribution, and habitat use have not been documented. Red fox occur along the floodplain but are more abundant at higher elevations away from the river.

Beaver and muskrat occur throughout the middle river. October 1984 surveys conducted by Woolington et al. (1984) documented at least 45 active beaver colonies preparing to overwinter. Fourteen colonies were found in sloughs, 14 in upland sloughs, 13 in the mainstem, and four in side channels. Evidence of muskrats was infrequently observed, but they probably occur in side channels, sloughs, and upland sloughs. River otter, mink, marten, short-tailed weasel, and least weasel are known to be present throughout the middle river, but distribution and abundance have not been documented for these species.

Only a few bird species are directly dependent on riparian habitat in the middle river for nesting and feeding. These include the semipalmated plover (Charadrius semipalmatus), spotted sandpiper (Actitus macularia), harlequin duck (Histrionicus histrionicus), and common merganser. With the potential exception of bald eagle nest trees, terrestrial birds and their habitat would not be appreciably affected by altered ice conditions within the floodplain.

2. EFFECTS OF ALTERATION OF RIVER ICE

a. Impoundment Zone

(1) Watana Dam On Line Alone.

(a) Non-uniform ice formation during freeze-up. In November, ice would form along shorelines while the reservoir center remains open. Moose or caribou venturing to the outer edge of the border ice may fall through and be unable to regain a solid footing. Because only a few animals are likely to only occasionally die in this way each year, the effect would not be important.

(b) Ice deposition along reservoir margin during winter drawdown. As winter reservoir drawdown proceeds, shorefast ice would fracture and become draped along the banks; on steeper slopes, ice-shelving may occur (Hanscom and Osterkamp 1980, Alaska Power Authority 1983). Cracks would form as the ice drapes and settles over irregular shoreline topography. Cracking would also occur between shorefast ice and the receding reservoir surface. These effects may impede or injure moose and caribou.

The potential for ice-related hazards would be greater with Watana dam alone, as compared to the Watana and Devil Canyon facilities together. The deeper drawdown (about 90-foot) with Watana alone would expose more of the lower, steeper portions of the Susitna River canyon, as well as a greater overall depth of shoreline. Exposure of steeper slopes would produce higher gradients of shorefast ice and tend to facilitate ice-shelving.

Moose crossing ice-draped reservoir slopes may be injured by slipping. However, the sloping surfaces would not necessarily be smooth; overflow onto the frozen impoundment would partially melt and freeze snow to the surface ice (Nilsson 1981a,b), creating a coarse texture and reducing the subsequent hazard to moving animals. Moose may be injured also by stepping into snow-covered cracks. Most injured moose would probably starve from an inability to move and forage efficiently in deep snow, or succumb to wolf predation. Although individual moose would occasionally die from ice-related injuries of this nature, the resulting level of mortality is not likely to be important.

In contrast, ice deposition in the drawdown zone would create a potentially important hazard to caribou. Segments of the Nelchina herd would cross the Watana impoundment southward in group migrations from late April to mid-May, enroute to their calving grounds. These crossings would occur when the ice-covered drawdown zone is exposed to its maximum extent and, at the same time, unstable breakup conditions exist (Pitcher 1984, LGL 1985). In Norway and Sweden, groups of reindeer have been killed when attempting to negotiate similar ice conditions (Klein 1971, Villmo 1975). Along steep banks, caribou unable to gain purchase on ice-covered slopes may be forced to swim sufficiently to deplete energy reserves, which are at their lowest ebb in late winter. At this time, pregnant females are in their poorest condition of the year (Skoog 1968). An extended or unusually difficult migration prior to calving could result in higher-than-normal adult mortality rates and decreased viability of newborn calves, thereby affecting herd productivity (Pitcher 1984).

If a large proportion of the Nelchina herd attempts to cross the Watana impoundment during breakup, a substantial mortality could result from ice hazards in the water and along the reservoir banks. It is not feasible to predict with accuracy the behavioral responses of caribou encountering spring ice hazards in the impoundment, nor to gauge the probable extent of mortality if caribou are trapped in the water or injured on ice-covered slopes. Ice-related effects would be important only if they produced mortalities consistently from year to year, or a single event large enough to suppress population levels to a point at which annual calf recruitment would not offset losses to predation and other causes. Given the known resourcefulness of migrating caribou, the probability of such major mortalities is considered to be low, but sufficient to warrant routine annual monitoring of herd movements during breakup (LGL 1985).

Dall sheep use of the Jay Creek mineral lick area may be affected slightly by shorefast ice. The drawdown zone would include the Jay Creek streambed immediately below the heavily-used Bluff and East Ridge lick sites. Sheep attempting to cross Jay Creek at this location may encounter some residual ice during May but would probably not be deterred from crossing.

If ice-related hazards occur, wolves may benefit from a greater availability of weakened, injured, or dead moose and caribou, their major prey in the Susitna Basin (Ballard et al. 1984b). Smaller carnivores (e.g., coyote, red fox, wolverine, marten) that feed on wolf-killed or winter-killed moose and caribou might also benefit; the extent of any benefit to these species would depend on the distribution and number of injured or killed animals. If mortalities occur over a sufficient area of the impoundment margin to include many different carnivore territories or home ranges, and occur consistently from year to year, the beneficial effect of this enhanced winter food availability on carnivore populations could be important. However, as explained above, moose and caribou mortalities of this magnitude are unlikely.

(c) Deterioration of reservoir ice cover in spring. The slow deterioration of the melting reservoir ice cover would present a barrier to movements across the Watana impoundment from early May through early June. The unstable ice conditions would be hazardous to moose and caribou throughout this period. As meltout progresses, there would be an increasing probability that moose or caribou will fall through the ice cover and be unable to regain solid footing. Swimming animals would encounter numerous ice floes, produced as the melting reservoir surface fractures. These may impede crossings and, where prevailing winds cause pile-ups, delay or prevent animals from leaving the impoundment.

In the spring, some female moose cross the Watana impoundment area in either direction and calve on the opposite side. The majority of females probably do not cross the river prior to calving, as vegetative cover used for calving exists on both sides, and crossings appear to be infrequent. Parturition generally occurs in the middle Susitna Basin from May 15 though June 15, peaking between May 25 and June 2 (Ballard et al. 1982). Individual moose attempting to cross the Watana reservoir during this period would encounter unstable ice conditions. However, suitable calving habitat would remain on both sides of the Watana impoundment after filling, and the existing pattern of calving would probably continue. Therefore, although moose may be lost while attempting spring crossings on unstable ice, this loss is not likely to be important because relatively few individuals would be affected.

Migrating caribou normally encounter hazardous breakup conditions during spring crossings of rivers and lakes, and the melting reservoir ice cover would probably not have an important adverse effect on the Nelchina herd. As discussed above, caribou are more likely to be affected by ice-related hazards as they reach the drawdown zone.

(d) Accumulation of windblown snow along impoundment shoreline. Prevailing northeast winds would tend to sweep snow from the frozen reservoir surface, producing drifts along the southwest shore. Because of winter drawdown, it is likely that much of the windblown snow accumulation would be confined to the immediate reservoir area. However, snow would also accumulate in the vegetation growing above the edge of the high-water level (Nilsson 1981a,b). The magnitude of effects of snow drifting on vegetation and wildlife would depend on such factors as prevailing wind direction, fetch, wind velocities, cumulative snow depth, presence or absence of crusted layers in the snow profile, proportion of reservoir surface snow melted and/or frozen by overflow, slope of exposed impoundment shorelines, local variations in shoreline topography, and vegetation types on the windward reservoir margin.

Snow accumulation on the reservoir surface would not occur until after the surface freezes during November. Direct observations of snow accumulation along the downwind shorelines of lakes in the middle Susitna Basin (e.g., the Fog Lakes) indicate that snow tends to be removed from exposed areas and redeposited in downwind drifts behind trees or topographic irregularities (Steigers 1985 pers. comm.). However, snow drifting is a dynamic phenomenon, and drifts would tend to shift or be removed by changes in wind speed or direction. Although snow accumulations would occur along downwind shorelines of the Watana impoundment, especially in wider areas of the reservoir where fetch is increased (e.g., opposite Watana Creek, where the impoundment will be 4.2 miles wide), snow drifting along shorelines would be partially offset by shifting winds, sublimation of snow, and water overflow onto the reservoir ice cover, which would not melt and freeze it in place (Nilsson 1981a,b).

The effects of windblown snow accumulation on wildlife are not expected to be important. Only moose and their primary winter predators, wolves, would potentially be affected. Snow drifting along the reservoir shoreline is not expected to cover sufficient browse to produce a population-level food shortage. Although deep snow may hinder the mobility and browsing efficiency of moose, increasing their vulnerability to wolf predation, these effects are more likely to be important during a severe winter with deep snowfall, rather than as a result of local snow drifting. Snow accumulation would fill cracks and cover irregular ice formations along windward shorelines, reducing the hazard potential for moose and caribou; these effects have been observed at the Williston Lake reservoir in northern British Columbia (Thomas 1982 pers. comm.).

(e) Increased extent of open water during winter. The approximately 36 miles of open water between Watana dam and the mouth of Devil Canyon, coupled with much higher winter flows than under pre-project conditions, would inhibit river crossings by moose in this reach. However, since winter moose crossings are infrequent in the Devil Canyon impoundment area (Ballard et al. 1984a), the effect of open water would not be important. The extensive reach of open water would provide locally production foraging habitat for mink and river otter. Augmented winter flows would increase water depth and backwater volume at tributary mouths, providing increased overwintering habitat for stream-dwelling fish that would congregate in high densities at these locations (Alaska Power Authority 1983). Access to this improved winter food supply may have an important beneficial effect on mink and river otter populations.

Open water availability in late fall and early spring, when other waterbodies are frozen, would attract and potentially benefit migrant waterbirds by affording safe resting areas. Although fish and invertebrate prey bases are expected to be generally low in the impoundment zone (Alaska Power Authority 1983), fish overwintering areas near tributary mouths would provide food appropriate for some migrants, as well as for overwintering mergansers and bald eagles. The number of individual birds affected would probably be too small to be important.

(2) Watana and Devil Canyon Dams on Line.

With both the Watana and Devil Canyon dams in operation, ice-related effects on wildlife would be similar to those discussed above for the Watana dam alone. Because of its narrower width and steeper sides, the Devil Canyon impoundment area currently provides much less habitat value for overwintering wildlife than the Watana impoundment area (Alaska Power Authority 1983). Although many of the ice-related effects described above for the Watana impoundment would also occur in the Devil Canyon impoundment, they would be minimal in comparison. Caribou do not presently, and have not historically, crossed the Devil Canyon impoundment area in large numbers during seasonal migrations (Hemming 1971; Pitcher 1983, 1984), and few winter crossings by moose have been recorded (Ballard et al. 1984a). With both dams operating, drawdown in the Watana impoundment would be reduced from about 90 feet to about 40 feet, minimizing the exposure of lower, steeper canyon sides and correspondingly reducing hazards associated with ice-covered slopes in the drawdown zone. This would have a beneficial effect on moose and caribou in comparison with the Watana dam alone. Devil Canyon reservoir would experience little drawdown in winter. In terms of ice-related conditions only, the Watana and Devil Canyon dams together would produce fewer adverse effects on wildlife than the Watana dam alone, because the benefit of the reduced Watana drawdown zone would offset most ice-related adverse effects of the Devil Canyon impoundment.

b. Middle River

(1) Watana Dam.

(a) Longer open-water period and larger open-water areas resulting from higher temperatures of regulated flows. With Watana only, freezeup in the middle river would be delayed 17 to 42 days and the ice would melt 28 to 48 days earlier than under pre-project conditions. Moreover, the ice front would reach only to the Curry-Gold Creek vicinity (RM 124 to 142), with its final location depending on ambient temperature and the temperature and volume of released flows. This will produce an open-water reach up to 60 miles long downstream from the Watana dam. Under pre-project winter conditions, moose frequently cross the frozen middle river and use it extensively as a corridor for upstream and downstream travel, avoiding the deeper snow on surrounding land (Modafferi 1983). A prolonged open-water period would restrict these movements in the early winter and early spring. Persistent thin ice and open leads may cause increased mortality; even under pre-project conditions, moose attempting to cross the river sometimes fall through the ice and are killed (Modafferi 1983, Schock 1985 pers. comm.). Browse vegetation on islands rendered inaccessible by open water would not be available to wintering moose, and in a few cases, female moose would be restricted in the early spring from reaching islands where they might otherwise have calved. None of these potentially adverse conditions is expected to affect a sufficiently large number of moose to be considered important, and wintering success of moose populations using the middle river would not appreciably change as a direct result of regulated flows.

The lack of ice cover between Watana dam and the ice front, along with open leads downstream from the ice front, would provide foraging habitat for aquatic furbearers (river otter, mink, beaver, muskrat). As noted above, mink and river otter would have increased access to overwintering fish. The extent to which beaver and muskrat would benefit from delayed freezeup and open leads during the winter is not clear. Beaver cache surveys in October 1984 indicated that there were no active colonies upstream of RM 140; therefore open water above the projected maximum ice front would not affect beaver unless the area is colonized in the future. Sixteen colonies, including an estimated 80 beaver, were identified between the projected maximum and minimum ice front locations (i.e., between RM 140 and 124). Colonies in this reach and farther downstream would be affected by delayed freezeup and open leads. These conditions may benefit beaver by extending the fall cache construction period, increasing the probability of overwinter survival. However, where open water allows beaver to reach the shore, border ice and deep snow would probably prevent them from foraging on land, and beaver that do forage on land during the winter would be highly vulnerable to wolf and coyote predation. In late winter or spring, 2-year-old beaver disperse from the parent colony (Leege 1968). Early spring melting of the ice cover, along with the absence of dynamic pre-project breakup conditions, may facilitate the dispersal of young beaver and extend the active season for adults.

Prolonged open water in the middle river may increase available overwintering habitat for the common merganser, American dipper, and bald eagle. Mergansers and dippers would probably not benefit in sufficient numbers for this effect to be considered important. However, the availability of relatively ice-free side channels and sloughs may increase access of bald eagles to living fish and to salmon carrion. Because bald eagles tend to congregate near winter food sources, there is a potential for numerous individuals to benefit. However, because the project area is near the edge of bald eagle range (Alaska Power Authority 1983), population density is relatively low, and the increased winter feeding habitat may not attract a sufficient number of eagles to produce an important effect. Moreover, high turbidity may offset the value of open-water areas as eagle feeding habitats.

(b) Higher staging resulting from increased winter flows. Higher staging would probably cover (with flowing water or ice) early-successional willow and balsam poplar otherwise available to moose as winter browse, and open water coupled with higher staging may prevent moose from reaching islands where browse is available. Although access to browse plants would thus be reduced along the active floodplain, these riparian shrubs are relatively tolerant to flooding and would not be permanently affected. However, the higher staging, increased flows, and daily variations in flow would cause overflow of water onto the existing ice cover, forming a progressively thicker ice sheet (aufeis) that would spread to higher islands and terraces supporting mature shrubs and trees (Nilsson 1981b). The effect of yearly winter flooding and ice cover on mature floodplain vegetation cannot be predicted with certainty, and the probable locations and cumulative areal coverage of aufeis are not known. It is likely, however, that the annual spring development of trees, shrubs, and herbaceous plants overlapped with thick ice layers would be measurably delayed (Nilsson 1981b). The interrelated effects of higher winter flows and staging on moose mobility, winter browse availability, and spring plant development are considered important to the long-term productivity of moose populations wintering in the middle river.

Ice cover that persists into the late spring on banks and terraces will locally cover or delay the development of herbaceous floodplain vegetation foraged by black bears during the immediate post-denning period (Miller and

McAllister 1982). However, the reduction in available forage will probably not be extensive enough to produce population-level effects on this species.

Higer winter staging would have more important effects on furbearers. As described above, overtopping of floodplain islands, sloughs, and low terraces would flood habitat and in places form a lasting ice cover, removing hunting areas otherwise available to wolves, wolverine, mink, marten, and weasels. Beaver, however, would be the furbearer most severely affected by higher winter staging, because of the potential for flooding of lodges in the mainstem, side channels, and sloughs. Because summer and fall river stages would govern the siting and construction of beaver lodges and caches, higher winter staging would flood many of these sites, and the beaver in the colonies would be lost to drowning, starvation, and predation (Hakala 1952, Boyce 1974). Lodges within or nearest to the mainstem would be most susceptible to this effect, but side channels and sloughs would also be exposed to higher staging, and even upland sloughs may receive increased water from upwelling. October 1984 food cache surveys in the middle river identified 45 beaver colonies preparing to overwinter between Devil Canyon and Talkeetna. Of these, 13 were in mainstem habitat, four in side channels, 14 in sloughs, and 14 in upland sloughs (Woolington et al. 1984). Based on these results, with an estimated five beaver per colony, the long-term capacity of the middle river to support about 155 beaver in mainstem, side-channel, and slough habitats could be permanently lost, with as many as 70 additional beaver potentially affected by higher water levels in upland sloughs. This would be an important adverse effect.

Persistent spring ice cover on floodplain islands and terraces would reduce available foraging and nesting habitats for shorebirds (e.g., semipalmated plover, spotted sandpiper), gulls (e.g., herring and mew gulls), arctic terns, and potentially other species. However, few extensive areas of early-successional riparian habitats selectively used by these species are present in the middle river (Kessel et al. 1982a), and the effect on birds is therefore not expected to be important.

(c) Early in situ melting of ice during spring breakup Warmer temperatures and reduced volumes of released flows in the spring would cause river ice to melt in place several weeks earlier than under pre-project conditions, avoiding the dynamic spring breakup drive that normally characterizes the Susitna and other northern rivers. This change would reduce the probability of moose injuries or mortality resulting from floating ice and debris (Modafferi 1983), but the small number of moose likely to benefit in this way would not appreciably affect population levels. A more important effect of changed breakup characteristics would result from habitat alteration. Ice-scouring associated with normal dynamic breakup would be greatly reduced in the middle river zone under with-project conditions. As riparian vegetation encroaches into river channels towards the mean summer high-water line, the availability of early-successional browse would increase during approximately the first ten years of project operation. However, the spring ice-scouring that normally helps to maintain early-successional stages in the riparian zone would be largely absent. Over time, the quality of riparian habitat for wintering moose would decline as the early successional stages encouraged by reduced summer flows mature and grow out of reach. Because it is likely to occur throughout the middle river, this reduction in moose winter habitat quality would become important during the life of the project.

Reduced spring flows during the meltout period would allow stranded ice cover to remain in sloughs and on overtopped islands and terraces. Because this ice would not be in contact with active river flows, it would tend to melt slowly and persist into the late spring in sheltered places. If this persistent ice cover is extensive in area, the resulting habitat reduction and delay in spring plant development may be important to furbearers and birds.

(2) Watana and Devil Canyon Dams on Line.

With both dams in operation, ice-related effects on habitat and wildlife would be qualitatively similar to those described for the Watana dam alone. The annual open-water period would be slightly longer, as warmer released flows would delay freezeup and advance the spring melting of river ice. In addition, the ice front would extend only to between RM 123 and 133, maintaining an open-water reach up to about 30 miles long downstream from the Devil Canyon dam. Staging levels at freeze-up and short-term fluctuations in released flows would decrease slightly. These conditions would moderate, but not substantially reduce, the ice-related adverse effects discussed above.

c. Lower River

(1) Watana Dam on Line Alone.

(a) Longer open-water period and larger open-water areas resulting from higher temperatures of regulated flows. With the Watana dam alone, ice would begin forming in the lower river at about the same time as under pre-project conditions (November), but the ice front would not reach the Susitna/Chulitna confluence until 17 to 44 days later than under pre-project conditions. Delay in the formation of a stable ice cover would correspondingly delay the period during which moose can safely cross the lower river zone. Under pre-project conditions, moose freely cross this reach during annual migrations to winter range, and extensively use the frozen lower river zone as a movement corridor (Modafferi 1982, 1984). Increased numbers and areas of open leads, coupled with delayed freeze/up, may impede migratory movements, reduce access to browse vegetation, and contribute to direct mortality from falling through thin ice. However, variations in the timing of freezeup and extent of open water exist under pre-project conditions, and moderate project-related increases in these factors are not expected to produce important adverse effects on moose. Because of the major contributions of flows from the Chulitna and Talkeetna rivers, along with lesser tributaries, ice-related effects on vegetation would not differ appreciably from pre-project conditions.

An increase in the annual ice-free period may benefit mink and river otter by prolonging the availability of aquatic hunting habitat. This effect would also allow beaver to remain active and store food later into the fall or winter, as cache construction continues until freezeup. In upstream reaches of the lower river zone where these effects are greatest, they may be important to furbearer populations.

Ice-related effects in the lower river will not differ sufficently from pre-project conditions to influence bird populations in important ways.

(2) Watana and Devil Canyon Dams on Line.

(a) Longer open-water period and larger open-water areas resulting from higher temperatures of regulated flows. With both dams in operation, ice formation would be delayed slightly longer into the early winter, and spring melting would occur earlier. Effects on moose and furbearers would be similar to those described for the Watana dam alone.

F. EFFECTS ON PUBLIC USE

This section describes preproject ice conditions relative to public use of the Susitna floodplain. The effect of altered ice processes on winter-oriented public use activities are then discussed based on commentary from local residents and casual observations incidental to regular investigative field work.

1. NATURAL ICE CYCLE CHRONOLOGY

Frazil ice appears in the upper river by late September and by late October, frazil slush accumulates into an ice cover that begins to form near Cook Inlet and extends upriver toward Talkeetna. Later in November the ice cover progresses into the middle river. Ice cover progression above Gold Creek is at a reduced rate due to a steeper gradient and less frazil ice generation. The reach from Gold Creek to Devil Canyon takes longer to freeze and differs further by this area's subjection to shore ice development and anchor ice daming. The upper river develops wide shore ice by forming successive layers of frazil and snow slush which causes the channel to narrow and eventually freeze into continuous ice cover with the entrapment of flowing slush. Open leads develop over turbulent water and may close as a result of fine slush accumulating against the downriver edge of the lead. Many open leads persist at intermittent locations along the river throughout the winter.

Increased solar radiation early in April signals the pre-breakup period. This process begins in the lower river and gradually extends upriver. Snow disappears along the river south of Talkeetna by late April. With an increase in snow melt discharge, the ice begins to lift and fracture as leads widen and small jams form downriver of leads. Breakup accelerates with increased discharge and more ice jamming. The ice cover continues to fragment, deteriorate and flow until the river in ice free usually in early May.

2. PUBLIC USE PERSPECTIVE

Major public use activities may be categorized as outdoor recreation, commercial, and subsistence oriented functions. Major recreational activities during winter include dog mushing, ice fishing, snow mobiling, small game hunting and cross country skiing. Commercial activities are generally limited to trapping fur animals and operating recreational lodging facilities. Subsistence oriented activities refer to gathering plant and animal material for personal consumptive purposes. Prevalent activities in this category include tree cutting for fire wood, house logs and saw timber as well as fishing and hunting for sustenance.

3. PRESENT USER GROUP ACTIVITY

The level of public use varies by river zone and its relationship to population density. The river area between Devil Canyon and Watana Creek receives little if any public use during the winter period. There are no permanent or seasonal residents in this zone. The lack of public use is attributed to the area's inaccessibility, rugged topographic features and, perhaps, unusable ice substrate due to the river's gradient and treacherous shoreline. These conditions would not preclude occasional aircraft landings in select places since relatively straight and even stretches of river surface occur between Devil Canyon and Watana. Ice shelving provides a sufficient platform to land and temporarily moor aircraft, however, such events were not evidenced during this study. Aircraft operators are deterred from using this river zone during winter because of the area's remoteness and unsafe landing conditions.

Moderate public use occurs in the middle river. About 12 trappers reside and travel between the Chulitna confluence and Gold Creek area during winter. With some exception, these people wisely avoid using and crossing river ice because of unsafe conditions. The ice surface continually changes with new leads forming and freezing over in which case drifting snow may conceal an unsafe ice surface. In the area between Talkeetna and the Chulitna confluence only two river crossings (noted in separate years) were noted and at considerable risk. Within a few days of each observation, river ice snowmachine tracks gave way. Two trappers from the Chase area operate along either side of the river by crossing at a point where a freezeup ice jam forms a suitable thickness for safe crossings. Non-resident use appears to be non-existent in the middle river.

The proximity to railbelt settlements and homesteaders, as well as the increased accessibility afforded by the Parks Highway, account for greater public use of the lower river zone. People in the Talkeetna, Sunshine, Montana, Caswell, Kashwitna and Willow areas use the river corridor for recreational, commercial and subsistence purposes. The preponderance of use occurs along the east side of the river that has highway access. Evidence of snowmachining is commonly observed along the river's edge and on frozen side channels. Variable ice conditions and accident potential deters the casual traveler from attempting to cross the river. River crossings do occur during the period of mid-winter ice coverage and appear more prevalent in those portions of the river between the Caswell area and the Deshka River confluence, and confluences of Alexander Creek and the Yentna River. Public use activities of major importance include trapping, ice fishing, dog mushing, snowmachining and gathering firewood. Several commercial lodge owners accommodate a few recreationists from Anchorage and outlying urban areas. Nonresident use of the lower river zone appears to be negligible.

4. EFFECTS OF ALTERED ICE PROCESSES ON PUBLIC USE

The effect of altered ice processes on public use would vary by river zone and level of human activity known to occur within each zone. In the impoundment zone, the Watana reservoir would begin to freeze over around mid-November with the formation of border ice. Solid ice would be expected later in December and gradually increase in thickness to an estimated 4 feet as freezing temperatures persisted. Reservoir drawdown would cause near-shore ice to fracture and drape, thus creating an ice ramp. Water temperatures below the reservoir would remain above freezing and moving water would prevail throughout this portion of the zone. A similar scenario is expected to occur in the Devil Canyon reservoir except that ice fracture and drape along the periphery would be minimal or none because of a greatly reduced drawdown. Downriver from Devil Canyon, an open water reach would extend for several miles. Since public use of this zone has been minimal during winter these physical changes would have no appreciable effect on human activities. Future public use may be slightly enhanced since solid ice cover in the reservoir areas may provide suitable landing places for ski-equipped aircraft during the mid-winter period. Draping and the formation of an ice ramp after reservoir drawdown may deter or impede foot access to shoreline areas, should aircraft landings be attempted.

Freezeup of the middle river would be delayed because of altered flow, warmer water temperatures and reduce inflow of frazil ice. Under these conditions, the firmness of river ice would be untenable during mid-winter from the vicinity of Curry upriver to about Gold Creek. The altered flow regime would probably change the size and duration of open leads occurring downriver from the ice edge. Flooding and overtopping would occur in the downriver portion of the middle river freezeup. The limited public use this area currently receives would probably be significantly reduced. Mechanized and foot travel on an unstable ice substrate, expecially in the zone of instability between Curry and Gold Creek, would be extremely hazardous. The reach between the Chulitna confluence and Curry probably would not be adversely effected except that the duration of solid ice cover would be confined to a shorter period during January and February when leads and overflow reaches form enough solid ice cover to permit safe travel. The few individuals from the Talkeetna and Chase areas who trap fur animals on the opposite side of the river would probably continue to operate at essentially the same level of effort and risk.

Ice formation in the lower river is expected to be near natural conditions. Above Talkeetna, however, ice cover in the upriver portion is not expected to be solid enough for surface transportation until later in the winter, probably 17 to 47 days later than normal. Because of increased water flow from the middle river zone, more ice may form in the lower zone than under natural conditions. Public use activities are expected to occur at a near-normal level except that the outset of winter time activity could be delayed by a month or so to produce safe ice cover. However, surface transportation in the river corridor under natural conditions does not occur until users feel confident that safe operating conditions exist. The size and number of open leads may increase as a result of more water flow in the lower river and could disrupt human activities to an undetermined degree.

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VIII. GLOSSARY OF TERMS AND DEFINITIONS*

Agglomerate	- An ice floe formed by the bonding or freezing together of various forms of ice.
Anchor Ice	- Submerged ice attached or anchored to the bottom, irrespective of the nature of its formation.
Anchor Ice Dam	- An accumulation of anchor ice which acts as a dam and raises the water level.
Beginning of Breakup (Date)	- Date of definite breaking or movement of ice due to melting, currents or rise of water level.
Beginning of Freezeup (Date)	- Date on which frazil ice, forming stable winter ice cover, is first observed on the water surface.
Black Ice	- Transparent ice formed in rivers and lakes.
Border Ice	- An ice sheet in the form of a long border attached to the shore and growing laterally out over the channel; same as shore ice, or lateral ice.
Breakup	- Disintegration of ice cover.

Breakup Date BS/sn	- The date on which a body of water is first observed to be entirely clear of ice and remains clear thereafter.
Candle Ice	- Rotten columnar-grained ice.
Channel Lead	- Elongated opening in the ice cover caused by a water current or thermal erosion by warm groundwater seeps.
Degree-Day	- A measure of the departure of the mean daily temperature from a given standard, usually 0 C. For example, a day with an average temperature of -5 C represents 5 freezing degree-days. Cumulative degree-days are simply the sum of any number of degree-days. For example, the cumulative freezing degree-days of a week with mean daily temperature of -5 C, 0 C, +5 C, -2 C, -5 C, -8 C, and -5 C are 25 freezing degree-days.
Dry Crack	- Crack visible at the surface but which does not extend through the ice cover, and therefore remains dry.
Floc	- A cluster of frazil particles.

Flooded Ice - Ice which has been flooded by melt water or river water and is heavily loaded by water and wet snow.

Fracture - Any break or rupture formed in an ice cover or floe due to deformation.

Frazil - Fine spicules, plates or discoids of ice suspended in water. In rivers and lakes it is formed in supercooled, turbulent waters.

Frazil Slush - An agglomerate of loosely packed frazil which floats or accumulates under the ice cover.

Freezeup Date - The date on which the water body was first observed to be completely frozen over.

Freezeup Period - Period of initial formation of an ice cover.

Frozen Frazil Slush - Accumulation of slush that has completely frozen solid.

Grounded Ice - Ice which has run aground.

Hinge Crack - Crack caused by significant changes in water level.

Hummocked Ice - Ice piled haphazardly, one piece over another to form an uneven surface.

Ice Bridge - A continuous ice cover of limited size extending from shore to shore like a bridge.

Ice Cover - A significant expanse of ice of any form on the surface of a body of water.

Ice Floe - Free floating piece of ice.

Ice Free - No floating ice present.

Ice Jam - A stationary accumulation of fragmented ice or frazil.

Ice Ledge - Narrow fringe of ice that remains along the shores of a river after breakup.

Ice Push - Compression of an ice cover, particularly at the front of a moving section of ice cover.

Ice Run - Flow of ice in a river. An ice run may be light or heavy, and may consist of frazil, anchor, slush or sheet ice.

Ice Sheet - A smooth, continuous ice cover.

Ice Shove	-	On-shore ice push caused by a compression in an unconsolidated ice cover that transmits internal forces laterally towards the banks.
In situ Breakup	-	Melting in place.
Lateral Ice	-	See Border Ice.
Lead	-	Long, narrow opening in the ice.
Pressure Ridge	-	A line or wall of broken ice forced up by pressure.
Shear Crack	-	Crack formed by movement parallel to the surface of the crack.
Shearing	-	Motion of an ice cover due to horizontal shear stresses.
Shore Ice	-	See Border Ice.
Shore Lead	-	A water opening along the shore.
Shore Depression	-	Depression in the ice cover along the shore often caused by a change in water level.

Snow Ice	-	Ice that forms when snow slush freezes on an ice cover. It appears white due to the presence of air bubbles.
Snow Slush	-	Snow which is saturated with water on ice surfaces, or as a viscous mass floating in water after a heavy snowfall.
Stranded Ice	-	Ice that has been floating and has been deposited on the shore by a lowering of the water level.
Unconsolidated (Ice Cover)	-	Loose mass of floating ice.

* Source: U.S. Army Corps of Engineers, 1982