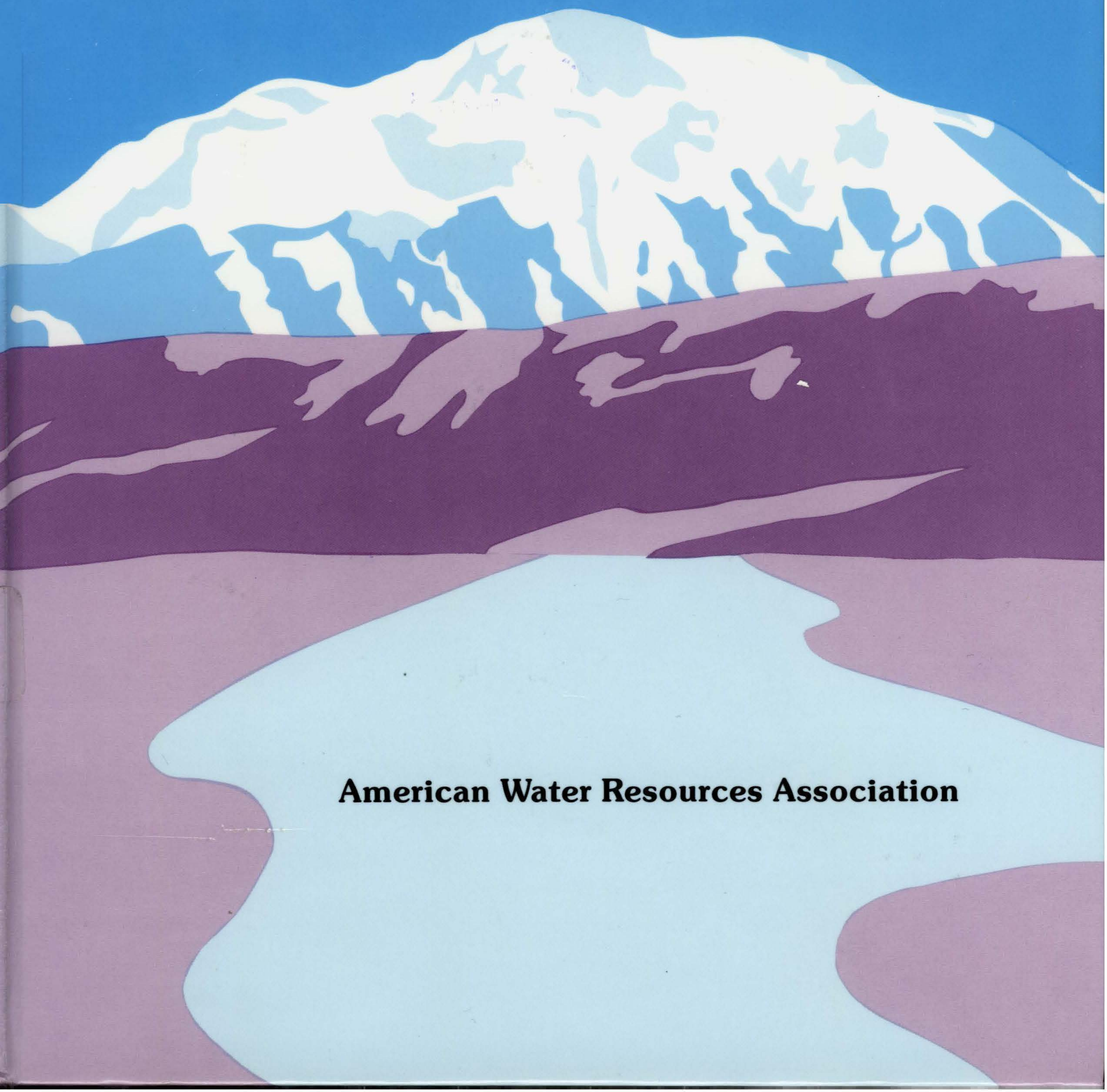
Proceedings: Cold Regions Hydrology



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FREEZEUP PROCESSES ALONG THE SUSITNA RIVER, ALASKA

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ABSTRACT: Operation of the proposed Susitna Hydroelectric Project in southcentral Alaska would significantly alter the flow, thermal, and ice regimes of the river downstream of the projects, potentially causing significant environmental impacts. Consequently, the ice regime of the Susitna River has been monitored since 1980 to document natural ice processes and their environmental effects, and to obtain calibration data for ice modelling of certain segments of the river. This paper describes the different freeze-up characteristics along the river's length which result from the significant variations in climate, morphology, and gradient along the river.
(KEY TERMS: river ice; Alaska; Susitna River.)

INTRODUCTION

The Susitna River basin is located in southcentral Alaska, originating from glaciers on the southern flank of the Alaska Range (Figure 1). The drainage basin covers 19,600 sq. mi. (50,760 sq. km.), and is the sixth largest in Alaska.

The upper basin upstream of the damsites is in the Continental climate zone, with climate characteristics of cold, dry winters and warm, moderately wet summers. The lower basin is in the Transition climate zone (between the Continental and Maritime zones), where temperature is less variable and precipitation is greater than in the Continental zone.

The Susitna River travels a distance of about 318 mi (512 km) from its glacial headwaters to Cook Inlet. Just downstream from the headwater glaciers, the river is highly braided. About 18 mi (29 km) downstream from the glaciers, the river develops a split channel configuration which continues for 53 mi (85 km). This initial reach, known as the upper Susitna River, has colder air temperatures than the downstream reaches due to its higher elevation and latitude. However, it also receives a substantial amount of solar radiation during freezeup because of its north-south orientation. The river then flows through a series of steep-walled canyons for about 96 mi (154 km) to the mouth of Devil Canyon. This reach, known as the impoundment zone, contains the Watana and Devil Canyon damsites at river mile (RM) 184.4 and RM 151.6, respectively. The river then emerges from the canyon into the middle Susitna River, which flows through a broad glacial U-shaped valley to the confluence with the Chulitna River (RM 98), about 50 mi (80 km) downstream. The Talkeetna River enters about one mile downstream (RM 97). Steep canyon walls along the impoundment zone and the middle Susitna River tend to shade the turbulent water surface for much of the winter. Average winter flow (November through April) in this reach is 1,600 cfs (45 cms). The river again becomes highly braided at the confluence with the Chulitna River. Average winter flow downstream of the Chulitna and Talkeetna rivers is 4,500 cfs (127 cms). The braided pattern continues for the 98 mi (157 km) downstream to the mouth of the river, with a few intermittent reaches of well-defined single or multiple channels. The Yentna River, the largest tributary to

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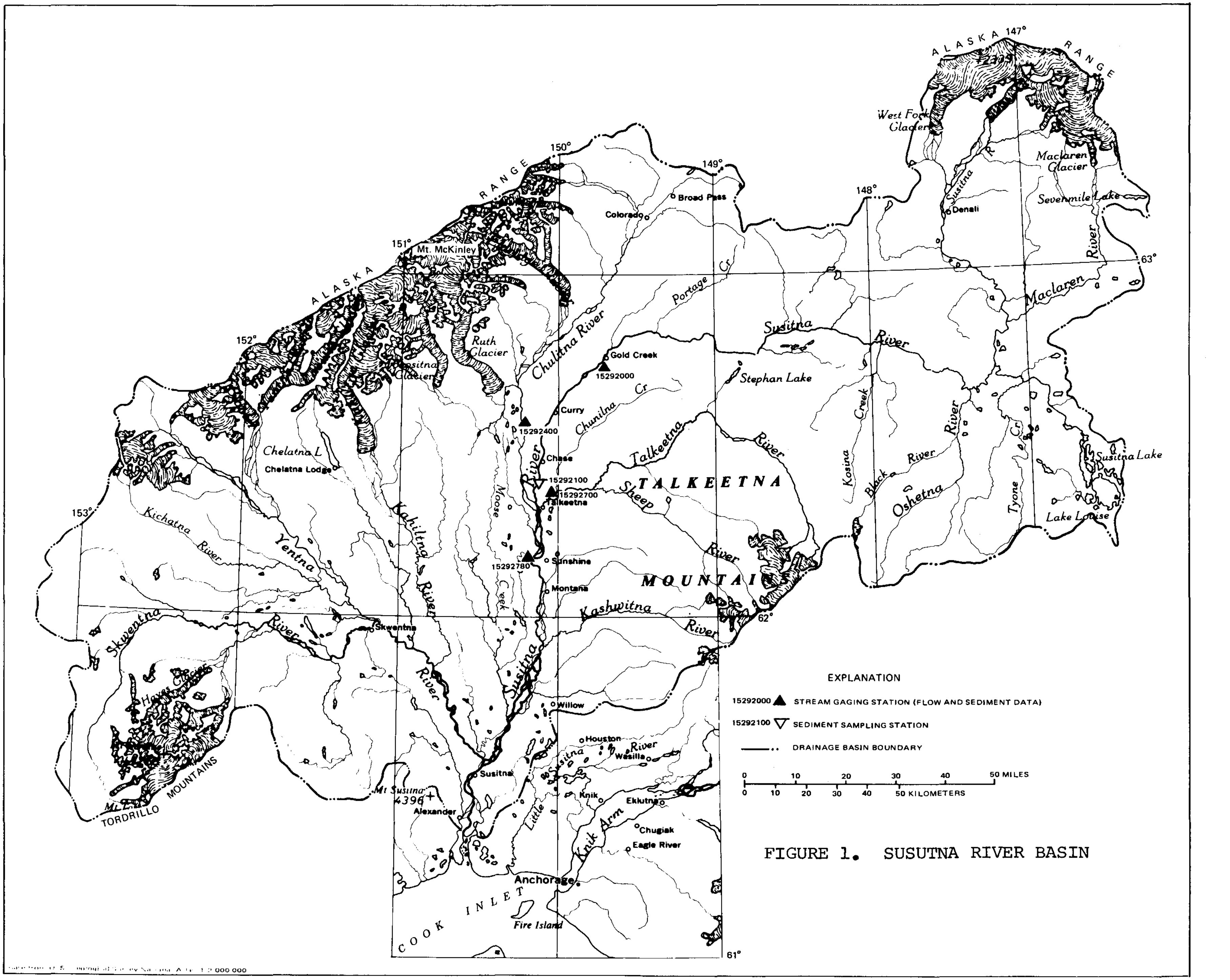

FIGURE 1. SUSUTNA RIVER BASIN

the Susitna River, enters at RM 28.

ICE COVER FORMATION PROCESSES

Progression of an ice cover on the Susitna River begins in late October near the mouth at Cook Inlet. Frazil ice pans from the Yentna River, the middle and lower Susitna Rivers, and the Talkeetna and Chulitna Rivers jam to form a bridge near the mouth. This occurs during a high tide period when the air temperatures are significantly below freezing throughout the basin and frazil ice discharge is high. After the ice bridge forms, the incoming frazil ice accumulates at the upstream or leading edge of the ice cover, or at natural lodgement points such as shallows or islands, and causes the ice cover to progress upstream.

The ice cover advances upstream by different mechanisms, depending on the air temperature, volume of incoming ice, and river hydrodynamics. The mechanisms of upstream progression have been described by Calkins (1983). Additional descriptions of these mechanisms may be found in Pariset et al (1966) and Ashton (1978). The mechanisms are described below, along with observations of processes on the Susitna River.

(1) Progression by juxtaposition of arriving floes with no subsequent thickening, leading to a rapid ice cover development. This occurs at water velocities less than some critical value required to submerge incoming ice floes below the ice cover. On the Susitna River, this has been observed to be approximately 2 ft/sec (0.6 m/sec). Ice cover thickness equals slush floe thickness. On the Susitna River, this is the predominant process of progression upstream to about RM 25. Slush ice floes drifting through this reach have been on the water surface and exposed to cold air temperature long enough to form a solid surface layer, significantly strengthening the floes so that they resist crushing or breaking apart.

(2) Hydraulic thickening, in which slush floes arriving at the leading edge thicken to a greater value than the original ice floe thickness. The ice thickness is sufficient to transmit hydraulic forces to the banks. The ratio of ice cover thickness to flow depth is usually less than 0.33. A related process also described by Calkins (1983) and often observed on the Susitna River is mechanical thickening or shoving of an ice cover already in place. This apparently occurs due to an instability within the ice cover relative to water velocity and increased upstream water levels which increase the pressure on the ice cover. A portion of the ice cover that has progressed by juxtaposition or hydraulic thickening may suddenly fail and move downstream, thickening as the surface area decreases. The ice cover thickness created by hydraulic processes is not sufficient to withstand the forces acting on it during its progression. The ice cover thus breaks and moves downstream, being mechanically thickened until it can withstand the forces imposed on it. The momentum of the moving ice mass may cause the ice thicknesses to be greater than the hydraulic stability requirement. The ratio of ice cover thickness to flow depth usually exceeds 0.33. Shoving usually causes a downstream progression, sometimes moving the leading edge downstream as far as 1 mile (1.61 km). This process usually occurs where water velocities exceed 4 ft/sec. (1.2 m/sec.). Hydraulic thickening and shoving are the primary processes of ice cover advance from RM 25 upstream to near RM 130. Compressions may occur repeatedly, creating higher upstream water levels and lower velocities, until progression can resume.

(3) Arriving slush 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. They may be deposited some distance downstream.

The process of undercover deposition is difficult to document, but most likely occurs on the Susitna River. Juxtaposition and hydraulic thickening seem to be the dominant progression processes on the Susitna River, with undercover deposition and shoving the primary thickening processes.

Two other processes are also common, but do not significantly affect ice cover progression in the reach between the river mouth and Gold Creek (RM 137). These are anchor ice and border ice formation.

Anchor ice formation is common in shallows throughout and downstream of a turbulent reach. Anchor ice is particularly prevalent upstream from RM 120, where the river may not develop an ice cover until late December. Anchor ice dams up to 2 feet thick have been documented between RM 130 and RM 149.

Border ice forms along the banks of the river as a result of (a) freezing of water in shallow areas, (b) accumulation of frazil pans in eddies and on obstructions such as bars or tree limbs, or (c) shearing of moving frazil pans on the river banks or on the border ice shelves. Border ice does not generally close the river downstream of RM 137, but may result in raising of water levels and obstructions to the downstream passage of frazil ice pans. This may lead to intermittent bridging of the river, resulting in the ice cover progressing upstream of the bridge prior to the downstream ice cover completely forming.

Border and anchor ice processes are more dominant in the reach upstream of Gold Creek (RM 137), due to the high velocities and to the fact that the ice cover normally does not progress upstream to this reach.

SEQUENCE OF ICE COVER PROGRESSION LOWER SUSITNA RIVER

Frazil ice usually first appears by October in the upper Susitna River. This ice drifts downriver, often accumulating into loosely bonded slush ice floes, until it either melts or exits from the lower Susitna River into Cook Inlet. The initiation of ice cover progression usually occurs in late October. An ice bridge forms near the mouth of the Susitna River during a period of high tide and high slush ice discharge. Initial ice bridges have been observed at RM 1.9, RM 5, and RM 9.

During the freeze-up period, the Yentna River (RM 26) often contributes from 50 to 60 percent of the total estimated ice volume below the Yentna-Susitna confluence (R&M Consultants, 1985a,b). Upstream of the Yentna River, about 80 percent of the ice is contributed by the middle Susitna River, with the Chulitna and Talkeetna Rivers contributing only about 20 percent (R&M Consultants, 1985a,b).

The ice cover progression the lower Susitna River occurs primarily by juxtaposition to about RM 25 and by hydraulic thickening upstream to about RM 130. Intermittent bridging may occur at natural lodgements points, such as shallows and islands. When this happens, the ice cover may progress upstream before the river downstream is fully ice covered. Depending on weather conditions, the ice cover will reach Talkeetna between early November and early December.

As the ice cover progresses upstream, the water level increases (stages) due to the increased resistance of flow and the displacement of the ice. Water levels generally increase about 2 to 4 feet (0.6 to 1.2 m) in the lower Susitna River due to ice, although increases of up to 8 feet (2.4 m) have been observed at the mouth of Montana Creek (R&M Consultants, 1985ab). The increased water levels due to ice are illustrated for a number of sites on the lower Susitna River in Figure 2.

The increased water levels often result in the overtopping of previously dewatered or isolated side channel entrances. The increased water flow caused by overtopping may wash out the snow cover and fracture existing ice. Slush ice from the mainstem will generally not flow into the side channel unless the overtopping depth at the overtopped upstream berm exceeds about one foot (0.3 m). If slush ice flows into the side channel, an ice cover forms rapidly in a manner similar to that described for the mainstem. Otherwise, the ice cover forms by border ice growth, which may take several weeks.

Many of the side channels dewater prior to freezeup. Others have separate water sources from tributaries or groundwater seeps. However, the groundwater seepage is greatly reduced from summer levels due to the lower flow and water level in the mainstem. During ice cover progression, the increase in mainstem water levels raises the groundwater levels in the river alluvium. Consequently, even if the entrance to a side channel is not overtopped, the increased groundwater levels may result in seepage flow in the

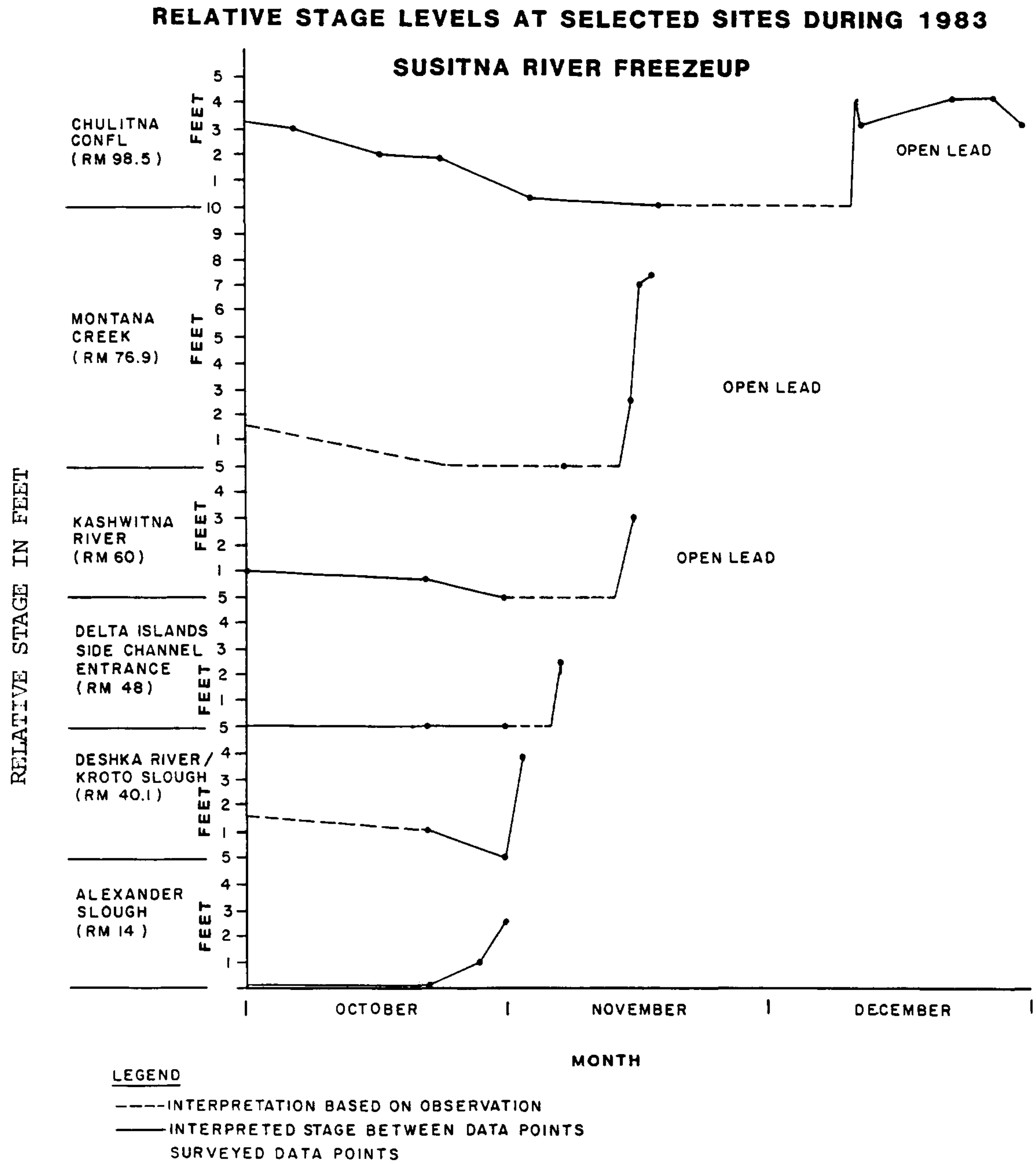

FIGURE 2. RELATIVE STAGE LEVELS AT SELECTED SITES DURING 1983 SUSITNA RIVER FREEZEUP

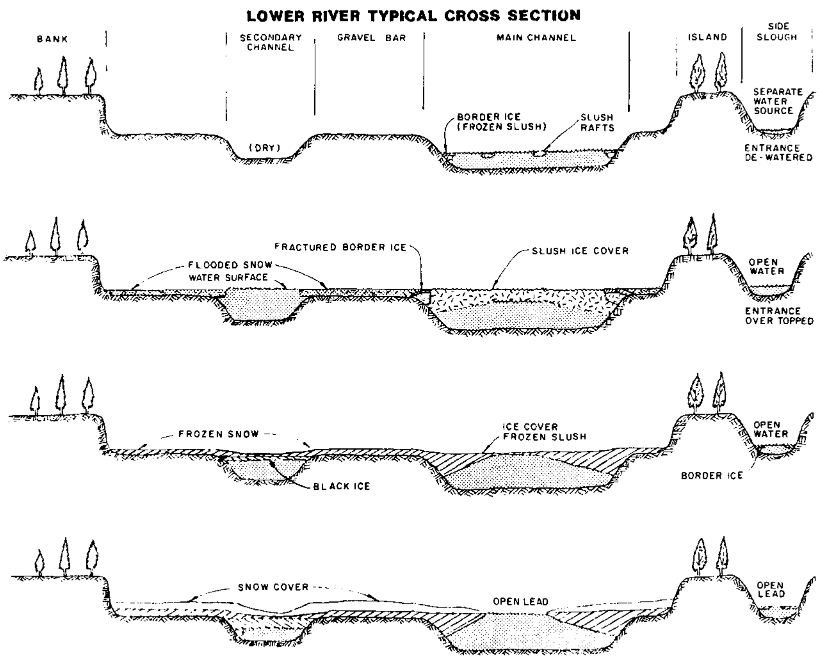

FIGURE 3. TYPICAL ICE COVER DEVELOPMENT, LOWER SUSITNA RIVER.

channel.

Major tributaries of the Susitna River (such as the Yentna, Deshka, Talkeetna, and Chulitna rivers) form an ice cover by surface accumulations of frazil slush ice after their mouths are blocked by the ice cover on the Susitna River. Smaller tributaries generally develop an ice cover by border ice and anchor ice accumulations. These minor tributaries are generally too shallow and turbulent to form a stable ice cover.

Following freezeup on the mainstem, the ice cover sags due to a gradual decrease in discharge, ice cover erosion, and bank storage. Open leads may persist in the mainstem and side channels due either to high velocity or to the thermal effects of warm groundwater.

Typical ice cover development on the lower Susitna River is illustrated in Figure 3. The days numbered on the left indicate the approximate passage of time since the leading edge of the progressing ice cover advanced upstream past each cross-section. These cross-sections are only schematics and do not represent the actual river. The lower river is much wider than shown here, with widths exceeding 6,000 feet (1,829 m), so that the depth-to-width ratio is not representative. The schematic illustrates many of the processes of ice cover development documented on the Susitna River.

Day 1 shows slush ice rafts drifting downstream in the mainstem. The discharge has dropped low enough to dewater secondary channels and side sloughs. The drifting slush ice rafts have accumulated in low-velocity flow margins or eddies and subsequently frozen to form border ice. Little additional border ice growth occurs until water velocities decrease further. Open water exists in side sloughs, since this water is generally warm, flowing from seeps or springs. The ice front progresses to the area on Day 2, resulting in a rapid increase in water level, flooding of the surrounding gravel bars, and overtopping of the side slough. The secondary channel is inundated and now conveys water that bypasses the ice-choked mainstem. Snow on the floodplain is saturated, eventually freezing into snow ice. The ice accumulation and compressions in the mainstem have fractured the existing border ice, which was either shoved laterally or incorporated into the cover. By Day 10, the slush ice cover has probably frozen solid, black ice has grown under the new ice, and the side channel is beginning to freeze over by border ice growth. Within about one month after the ice cover has formed over the mainstem, few additional changes will occur for the remainder of the winter. Open channel leads will typically erode through the ice cover. Depressions over the secondary channels are typical. The side channels are essentially ice-covered, but may retain an open lead.

SEQUENCE OF ICE COVER PROGRESSION MIDDLE SUSITNA RIVER

When an ice bridge forms at the Chulitna confluence (RM 98.6), ice cover progression continues upstream to the vicinity of RM 137. Depending on flow rate, ice concentrations, climatic conditions, and channel morphology, this bridge may form either when ice cover progression on the lower Susitna River reaches the confluence, or else independently of the lower river progression at a point just upstream of the Susitna-Chulitna confluence. Flow in the middle Susitna River during this period is typically about 2,000 - 3,000 cfs (610 - 914 m). In very cold years, one or more secondary bridges may form upstream of this bridge, resulting in secondary progressions of the ice cover.

Ice cover shoving, sagging, open lead development and secondary ice cover progression predominate through the reach from the Chulitna confluence to about RM 137. The ice cover progresses by juxtaposition and hydraulic thickening until encountering a critical velocity, which causes leading edge instability and failure of the ice cover. The subsequent consolidation results in ice cover stabilization due to a shortening of the ice cover, substantial thickening as the ice is compressed, a stage increase, and lateral expansion (telescoping). As the stage increases, the entire ice cover lifts, and pressures are then relieved by lateral expansion of the ice across the river channel. This process of lateral telescoping can continue until the ice cover has expanded bank to bank or else has encountered some other obstruction (such as gravel islands) on which the ice becomes stranded.

Ice cover sag, collapse, and open lead development usually occur within days after a slush ice cover stabilizes. A steady decrease in streamflow gradually lowers the ice surface along the entire river. Prior to breakup, much of the ice rests on the channel bottom.

The typical ice cover development on the middle Susitna River is shown on Figure 4. The sequence is essentially the same as on the lower Susitna River, with the primary difference being the higher degree of staging and compression of the ice cover. The slush ice cover is shoved laterally, often to the top of the bank and vegetation line. Some ice may be eroded in high velocity areas, and redeposited where velocities are lower. As the ice is redistributed into a more hydraulically efficient cross-section, the water level recedes, causing the cover to sag, often conforming to the configuration of the channel bottom. Open channel leads are typical through this reach, but often freeze over by early March. The progression rate decreases as the ice front moves upriver, due to the increasing river gradient and the decreasing amounts of ice flowing downstream as the upper river freezes over.

The reach from RM 137 to Devil Canyon (RM 150) gradually freezes over, with complete coverage occurring much later than further downstream. The reach has a steep gradient, high velocities, and a single channel in winter. The most significant freezeup characteristics include extensive anchor ice, wide border ice layers, ice dams and snow ice.

Anchor ice dams have been observed at several locations which are constricted by border ice. The dams and constrictions create a backwater area by restricting the streamflow, subsequently causing extensive overflow onto border ice. The overflow bypasses the ice dam and re-enters the channel further downstream. Within the backwater area, slush ice accumulates in a thin layer from bank to bank and eventually freezes.

The processes of ice cover progression described for the reach downstream of RM 137 generally do not occur in

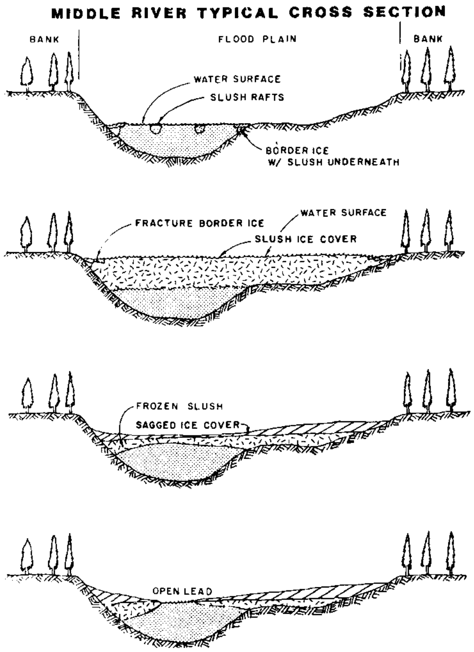

FIGURE 4. TYPICAL ICE COVER DEVELOPMENT MIDDLE SUSITNA RIVER.

this reach. There are only minimal water level increases due to anchor ice growth on the channel bottom. Sloughs and side channels are generally not breached. Open leads exist in the main channel, primarily in high-velocity areas between ice bridges.

Ice processes in Devil Canyon (RM 150 to RM 151.5) create the thickest ice along the Susitna River, with observed thicknesses of up to 23 feet (7 m) (R&M Consultants, 1981). Large volumes of slush ice enter the canyon, generated by upstream rapids or by heavy snowfall. Additional frazil ice forms in the extreme turbulence within the canyon. The slush ice repeatedly jams in a plunge pool near RM 150 and an ice cover progresses upstream, eventually staging more than 25 feet (7.6 m) above the open water level. However, 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 with each staging repetition. The ice cover forms and erodes several times during the winter (R&M Consultants, 1984).

Upstream of Devil Canyon, the Susitna River generally has a steep single channel with banks rising gradually from the water surface to the vegetation trim line. Low discharges through the winter result in generally shallow water. Numerous boulders exist along the channel margin, providing anchors for slush ice that drifts along the banks. Shore ice develops rapidly into the channel until water velocities exceed about 1-2 ft/sec (0.3 - 0.6 m/sec). As streamflow decreases, there is a gradual filling of the narrow open channel into a continuous ice cover.

Anchor ice thicknesses exceed 2 feet (0.6 m) in some areas, raising the water level accordingly. The rising water either fractures the border ice or overflows on top. When overflow occurs, snow on the shore ice is flooded and eventually freezes, significantly thickening the border ice.

CONCLUDING REMARKS

The paper discusses the various types of ice formation processes documented along the length of the Susitna River, a major Alaskan river being considered for hydroelectric development. Operation of the proposed Susitna Hydroelectric Project would significantly alter the flow, thermal, and ice regimes of the river downstream of the project. The studies have been conducted to document the natural physical processes on the Susitna River, both to determine their environmental effects and to provide calibration for ice modelling of with-project conditions. Since ice processes play a major role in the natural regime of northern rivers, knowledge of the effects of water resource development on the ice regime is necessary before any assessment of the environmental impacts of the project can be made.

ACKNOWLEDGMENTS

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