GEOPHYSICAL INSTITUTE
UNIVERSITY OF ALASKA

EVALUATION OF ICE PROBLEMS ASSOCIATED WITH HYDROELECTRIC POWER GENERATION IN ALASKA:

Final Report to the State of Alaska
Department of Commerce and Economic Development

Contract 08-73-7-958/08-71-6-114
or Contract AEC81005-3

FINAL REPORT TO THE STATE OF ALASKA

DEPARTMENT OF COMMERCE AND ECONOMIC DEVELOPMENT

Hydroelectric Icing

08-73-7-958/08-71-6-114
or Contract AEC81005-3

EVALUATION OF ICE PROBLEMS ASSOCIATED WITH HYDROELECTRIC POWER GENERATION IN ALASKA: FINAL REPORT TO THE STATE OF ALASKA, DEPARTMENT OF COMMERCE AND ECONOMIC DEVELOPMENT

by

J. P. Gosink

and

T. E. Osterkamp

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SUMMARY

Information regarding ice, its adverse effects upon hydroelectric facilities, and reliable methods to minimize these effects is sparse, located in obscure references or proprietary. As a result, the engineering information and expertise necessary to deal with ice problems is not normally found in U.S. engineering firms. Since there has not been any hydroelectric development in Interior Alaska or along its colder coasts, there is no core of engineering experience to draw upon.

The primary objective of this project has been to acquire, document and develop the necessary engineering information base to be used by hydroelectric power planners, designers and operators to eliminate, avoid or reduce ice problems associated with hydroelectric power production in Alaska's cold winter climate. We proposed to accomplish this objective by compilation of state-of-the-art engineering information, applied research where appropriate and publication of reports summarizing current world-wide engineering practice and research information.

During the first two years of this project, reports were published which include:

1. A survey of manufacturers, available equipment, applicability (head, discharge, KW) and experience with northern climates;
2. A bibliography listing sources of information on small hydropower with critical annotations regarding the usefulness of each;
3. A brief survey of ice problems and mitigating procedures in hydroelectric facilities in Canada, Switzerland, and Scandinavian countries.

This final report completes the limited objectives for this project as set out in the revised work plan May 28, 1982. These objectives, including the complete survey of ice problems and mitigation procedures at hydroelectric

sites in Sweden and British Columbia, and the development and documentation of a water temperature model for downstream thermal predictions, are addressed in appendices 1 through 5 of this report. These appendices represent both compilations of existing international engineering experience and methodology, and original applied research.

The knowledge gained regarding ice problems should be made available to Alaskan hydropower engineers and planners. Correct site selection procedure, knowledge of potential problems and the means to alleviate those problems is of great benefit to Alaska. This information will allow rational management decisions to be made both in the planning and operational stage of hydroelectric development.

Appendix 1

A Survey of Ice Problems at Hydroelectric Facilities:

Report to the State of Alaska
Department of Commerce and Economic Development

by

Greg Penn
T. E. Osterkamp
J. P. Gosink

Geophysical Institute
University of Alaska
Fairbanks, Alaska 99701

There has been some interest in establishing small hydropower plants in northern regions, particularly Alaska. However, cold climates pose some special problems. These problems can be severe, especially for small hydro or run-of-river plants. The problems are often solvable and can be dealt with, but they need to be addressed before beginning construction of a hydropower plant in a very cold climate. A survey of difficulties experienced by existing power plants in northern regions can help identify what problems are likely to occur and how to deal with them. The survey would be useful for planning and for existing facilities.

This is a survey of ice problems that hydropower plants have had or are having. A brief description of a problem and possible solutions is followed by a list of hydropower plants known to have experienced the problem. The intent of the paper is to show that difficulties do exist and to indicate what those difficulties are and their severity and incidence.

Information for the survey was obtained from brief questionnaires sent to hydropower plants and utility companies, letters received from people dealing with hydropower, telephone conversations with power plant personnel, and personal visits to hydropower facilities.

Intake Blocked With Ice

A common problem is the build up of frazil ice on intake trash racks. Frazil ice is produced in the absence of ice cover in turbulent, supercooled water. The small ice crystals are carried downstream where they are drawn into intakes and cling to the trash racks. Build up can be rapid resulting in reduced or no flow to the turbines.

Intakes can also be damaged or blocked by surface ice on a reservoir as the water level drops to or below the intake.

The problem of ice on the trash rcks has been dealt with successfully in many cases, but it still causes difficulties under certain conditions.

Some methods of preventing ice blocking the intake are heating trash racks, back flushing, creating an ice cover to minimize frazil production, lowering the intake water velocity to decrease drawdown and ensuring that intakes are in deep water.

Gold Creek Juneau, Alaska 1.6 MW maximum	The problem is not severe in this case since the plant is usually shut down due to low flow when it is cold.
Dewey Lakes Skagway, Alaska 30-375 kW	Here the water level in the reservoir must be watched to ensure it is deep enough to minimize frazil ice and to keep surface ice above the intakes.
Manitoba Hydro	
Newfoundland and Labrador Hydro	Frazil ice on the trash racks.
Forces Motrices de Mauvois in Switzerland 3 plants 835 million kWh	
Söderfors DalalvenRiver Sweden	Trash racks have been heated to minimize the problem.

Spillimacheen Columbia River British Columbia, Canada 5MW	Trash racks have been heated to minimize the problem.
Western Mica British Columbia, Canada	Air bubblers are used to prevent icing at the intake.
Bennett Dam Peace River British Columbia, Canada	Rapid ice formation in temporary diversion tunnels threatened flooding during construction.

Flooding Caused by Ice

Hanging dams, ice jams, anchor and frazil ice can restrict the flow in the normal river channel causing floods. The floods are sometimes severe and damage property including the power station.

Careful planning is needed so that equipment and structures are above possible flood levels. Blasting with dynamite to break up ice jams has been frequently tried. Ice booms have been used to help establish a stable ice cover. Often, water that normally goes through the turbines must be either stored in the reservoir to float ice jams free or used to float ice masses over a spillway. This can reduce power output significantly. Dikes have been built to prevent property damage from floods.

Manitoba Hydro Winnipeg, Saskatchewan, and Nelson Rivers	Ice damming "has become very critical on several occasions necessitating the mobilization of forces to prevent the topping of coffer dams".
Irve Tolles Real Data, Inc. Manchester, N.H.	A plant under construction would have had water level controls damaged if they had been in place.
Town of Peace River British Columbia, Canada Near the Bennett Dam	Floods in 1973 and 1974. Dikes have prevented the problem since.
Town of Taylor British Columbia, Canada Near the Bennett Dam	A cold snap in 1979 caused increased electrical usage which necessitated greater discharge from the turbines. This affected the ice front upstream of Taylor producing a large ice jam that caused a flood with an 18' rise in 48 hours. Carefully controlling the discharge minimizes this problem.

Icing of Structures from Spray

Falling water at a dam or falls creates spray which wets nearby structures. When the spray freezes, it can damage those structures, often due to the weight of the ice on them. An icy coating can also be hazardous to people who must work in the area.

Usually the ice is manually chipped away when it becomes a problem. Heating structures to melt the ice is also a possibility.

Pidgeon River Plant Vanderbilt, Michigan 11-100 kW	The problem is minor.
Forces Matrices de Mauvoisin Switzerland 3 plants 835 million kWh	
Manitoba Hydro	
Pelican Creek Pelican, Alaska less than 500 kW	A leaky woodstove penstock ices a walkway making its use hazardous and difficult.

Shut Down Due to Low Flow in Winter

The water supply to a power plant usually decreases in the winter in cold climates, often drastically. Decreased output or complete shut down result. Low flow in a pipe increases the danger of freezing in the pipe.

Water storage in a reservoir or piping water in from other drainages can help make up for periods of low flow.

Pelican Creek Pelican, Alaska less than 500 kW	
Gold Creek Juneau Alaska 1.6 MW maximum	
Dewey Lakes Skagway, Alaska 30-375 kW	Low flow increases the danger of pipes freezing. Pipes have split and the plant has been close to shutting down on several occasions. Significant energy is used to heat pipes.

Open Water Downstream

In the winter, when warm water (4°C) is discharged downstream of a power plant, it can flow several hundred kilometers before it cools enough to freeze. This creates a long stretch, or reach, of open water. The upstream edge of the ice cover may be thin or unstable due to fluctuations in discharge.

The frozen river may be a significant roadway for men and animals, and river crossings may be frequent. An open reach can disrupt migratory routes, river crossings, and winter travel on the river in general.

Open water exposed to very cold air produces ice fog which can blanket a large area and create hazardous driving conditions.

An open reach might encourage frazil ice production causing problems for other facilities downstream.

It may be necessary to build bridges to allow river crossings over open reaches or to put up signs warning of thin ice. There are no known effective methods of controlling ice fog. However, the length of the open reach can be decreased with the use of ice booms or by changing the topography of the river bed to decrease water velocity. Controlled discharge can be used to stabilize the upstream edge of the ice cover.

Manitoba Hydro

Columbia River British Columbia, Canada	Ice fog increases due to open water reaches on the Columbia River are expected to be about 5%.

Equipment or Structures Damaged by Ice in Any Way

The hydropower plants listed here are those that responded affirmatively to the statement "Equipment or structures damaged by ice in any way" on a questionnaire. The nature of the damage is unknown to us at this time.

Annex Creek
Alaska
2.8 MW

Pidgeon River Plant
Vanderbilt, Michigan
11-100 kW

The problem is minor.

Forces Motrices de Mauvoisin
Switzerland
3 plants
835 million kWh

Anchor Ice

Anchor ice forms on fixed objects such as the stream bed or manmade structures. It can block intakes or restrict flow in a channel.

An insulating ice cover or heated structures can decrease anchor ice formation. Sometimes it is manually chopped out.

Sheldon-Jackson Junior College Sitka, Alaska 50 kW	Ice in a 2000 foot flume must be manually chopped out.
Bruce P. Sloat Lancaster, N.H. 15 kW	Anchor ice has blocked intake structures.

Reservoir Ice Problems

Changing water levels in a reservoir cause the ice cover to move up and down. This can damage structures, particularly dams. Also, as the water level drops, the center of the ice cover may sag giving the ice a slope that is dangerous for men and animals.

Structures exposed to the ice must be made sturdy enough to withstand its abuse. Warning signs and fences may be needed to keep people and animals away from dangerous ice cover.

Upper Salmon Creek Alaska 2.8 MW	Ice several feet thick rubbing against the upper face of the dam.
Crystal Lake Petersburg, Alaska	Minor damage to the dam. The problem was solved with aluminum facing.

Other Problems with Ice

Annex Creek Alaska 2.8 MW	Icing of transmission line conductors.
Dewey Lakes Skagway, Alaska 30-375 kW	Water seeps under the earth dam creating a glacier on the creek bed below the dam and threatening penstocks that come out of the dam.
Snettisham Juneau, Alaska	Icing on transmission line destroyed the line

APPENDIX 2

RESULTS OF QUESTIONNAIRE STUDY OF 28 BRITISH COLUMBIA HYDROELECTRIC STATIONS

Report to the State of Alaska,
Department of Commerce and Economic Development

compiled by

T. E. Osterkamp
Greg Penn
J. P. Gosink

Geophysical Institute
University of Alaska
Fairbanks, Alaska 99701

BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

BOX 12121
555 WEST HASTINGS STREET,
VANCOUVER, B.C.
V6B 4T6

CABLE ADDRESS "INTERPOW"

TELEX 04-54456

December 14, 1981

File: 1206.10

Mr. T. Osterkamp,
Professor of Physics,
Geophysical Institute,
C.T. Elvey Bldg.,
University of Alaska,
Fairbanks, Alaska, 99701,
U.S.A.

Dear Sir,

This is in reply to your letter dated nil to our Peace Canyon Project, which was referred to me.

Enclosed are a reference map and completed ice questionaires for 28 B.C. Hydro hydroelectric generation stations. All but two of the plants responded and, at those two, ice problems are not usually experienced. The capacity of both unreported plants exceeds 1000KW.

We would appreciate receiving copies of your survey results. We request, if possible, six copies for distribution to our region managers who completed the questionaires.

Yours very truly,

G.M. Salmon

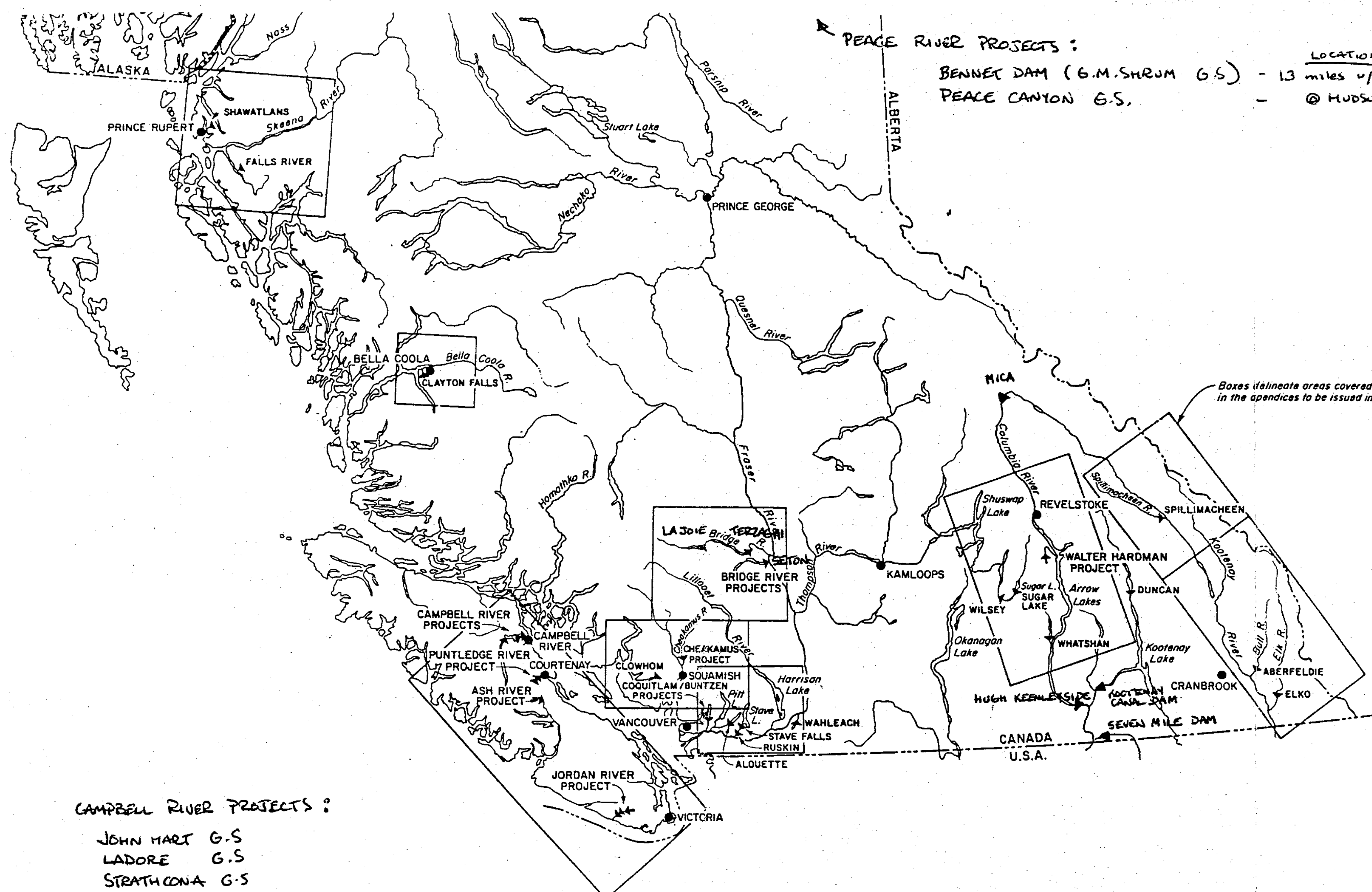
G.M. Salmon
Manager,
Development Department

TPK/rt

Encls.

PEACE RIVER PROJECTS :

		LOCATION
BENNET DAM (G.M. SHRUM G.S)	-	13 miles u/s of PEACE CANYON
PEACE CANYON G.S.	-	@ HUDSON HOPE



CAMPBELL RIVER PROJECTS :

JOHN HART G.S
LADORE G.S
STRATHCONA G.S

BRITISH COLUMBIA

DAM SAFETY PRELIM

MAP OF PROJECT

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Clayton Falls

Put a mark next to the appropriate response.

The capacity of our facility is: 702 kW

0-10 kW___ 11-100 kW___ 101-1000 kW ✓ more than 1000 kW___

Have you had any difficulties with ice? Yes ✓ No___

If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................ ✓
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray.....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify. Run of River Facility

Intake in one end of glow weir.

Frazil Ice Runs plug intakes

& headpond.

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: BUNTZEN

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW ✓ 101-1000 kW___ more than 1000 kW ✓ 76,700 kW

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.________________________________

Thank you for your cooperation.

Buntzen 1 and 2 < 100 MW

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: ALOUETTE G.S.

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW X 8,000 kW

Have you had any difficulties with ice? Yes___ No X
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: G.M. Shrum Generating Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW_XX_ 2,416,000 kW

Have you had any difficulties with ice? Yes_X_ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. .._X_
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way._X_
Other. Please specify.________________________________

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Peace Canyon Generating Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 700,000 kW

Have you had any difficulties with ice? Yes X No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ... X
Icing of structures from spray.................... X
Equipment or structures damaged by ice in any way. X
Other. Please specify.________________________________

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Ruskin G.S.

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW X 105,600 kW

Have you had any difficulties with ice? Yes___ No X
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: STAVE FALLS G.S.

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW_X_ 52,500 kW

Have you had any difficulties with ice? Yes___ No_X_
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ...___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: WAHLEACH G.S.

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW X 60,000 kW

Have you had any difficulties with ice? Yes___ No X
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ...___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: MICA (1,736,000 kW.)

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray................... ✓ (1)
Equipment or structures damaged by ice in any way. ✓ (2)
Other. Please specify.

(1) Heavy ice build up due to operation of discharge facilities (Low Level and Medium Level Outlets).

(2) Gate indication cables broken due to icing of cableway.

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: La Joie Generating Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 22,000 kW

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.

Lake level indicator float has become hung up in ice

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: BRIDGE RIVER GENERATING STATION #1

Put a mark next to the appropriate response.

The capacity of our facility is: BR#1#2
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ = 428,000 kw

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.

Lake level indicator float (Carpenter Reservoir) has become hung up in ice.

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: BRIDGE RIVER GENERATING STATION #2

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ BR#1+2 = 428,000 kw

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify. Lake level indicator float (Carpenter Reservoir has become hung up in ice. NOTE The same device is referred to for Bridge River G.S. #1

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: SETON GENERATING STATION

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 42,000kw

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ...___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Spillimacheen Gen Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW 4,000 Kw

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Aberfeldie Gen Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW 5,000 Kw

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Kootenay Canal Gen. Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 529,200 kW

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice.................___
Flooding caused by ice jams, hanging dams, etc. ...___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.___________________________

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Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Seven Mile Gen Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 607,500 kw

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.___

Thank you for your cooperation.

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PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: ELKO Gen Station

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW 12,000 Kw

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ...___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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____

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Thank you for your cooperation.

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PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: SHUSWAP (5200 kw)

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................ ✓
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray.................... ✓
Equipment or structures damaged by ice in any way.___
Other. Please specify.___

Thank you for your cooperation.

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Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: WHATSHAN GENERATING STATION -- (50,000 kw)

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.___

Thank you for your cooperation.

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Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Walter Hardman Generating station --(8000 kw)

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................ ✓
Flooding caused by ice jams, hanging dams, etc. .. ✓
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.___________________________

Thank you for your cooperation.

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Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: JORDAN RIVER, BC HYDRO.

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 150,000 kW

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way. ✓ HOLLOW CONE VALVE.
Other. Please specify.______________________________

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Thank you for your cooperation.

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PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Ash River

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 25,200 kW

Have you had any difficulties with ice? Yes___ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify. Booms on Elsie Lake broken by lowering lake levels with ice around booms - cured by using short ~~flexible~~ boom sticks allowing boom to follow contours on bottom - also by relocating boom to more gradual contours

Thank you for your cooperation.

short boom sticks

Spray ice on drive worms & gears of Bunger type cone valve - Elsie Lake stream discharge

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Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below. PUNTLEDGE

Name of facility: Puntledge.

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 27,000 kW

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

Thank you for your cooperation.

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Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Strathcona

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 67,500 kW

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

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PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Ladore

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 54,000 kW

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ...___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.____________________________

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Thank you for your cooperation.

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PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: John Hart

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 120,000 kW

Have you had any difficulties with ice? Yes___ No ✓
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice...............___
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray...................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

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PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Falls River

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW ✓ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 9,600 kW

Have you had any difficulties with ice? Yes ✓ No___
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................ ✓ Frazil Ice Runs
Flooding caused by ice jams, hanging dams, etc. ..___
Icing of structures from spray.................... ✓
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

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Thank you for your cooperation.

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PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

Please complete this questionnaire and return it in the envolope provided.

Write the name and complete mailing address of your facility in the space below.

Name of facility: Shuwatlan

Put a mark next to the appropriate response.

The capacity of our facility is:
0-10 kW___ 11-100 kW___ 101-1000 kW___ more than 1000 kW ✓ 1,320 kW

Have you had any difficulties with ice? Yes___ No X
If not, mail this questionnaire without continuing.

Put a mark next to problems associated with ice and cold climate that have occurred at your facility.

Open water downstream of the facility in winter...___
Intake structures blocked with ice................___
Flooding caused by ice jams, hanging dams, etc. ...___
Icing of structures from spray....................___
Equipment or structures damaged by ice in any way.___
Other. Please specify.______________________________

Thank you for your cooperation.

Geophysical Institute, C.T. Elvey Building, University of Alaska, Fairbanks, Alaska 99701
PHONE: 907-479-7282 TELEX: 35414 GEOPH INST SBK

APPENDIX 3

ICE PROBLEMS AT SWEDISH HYDROELECTRIC POWER PLANTS

by

Lennart Billfalk

an informal translation by the Geophysical Institute

Report to the State of Alaska,
Department of Commerce and Economic Development

ICE PROBLEMS AT SWEDISH HYDROELECTRIC POWER PLANTS

by

Lennart Billfalk

Hydraulics Laboratory
Swedish State Power Board
Alvkarleby, Sweden

ABSTRACT

In the following report, a summary of ice problems in hydropower plants in Swedish rivers is presented. The rivers from Lagan in the south, up to Lule river in the north, are included. The information has been collected by the Hydraulics Laboratory, by sending out questionnaires on two different occasions (1977 and 1978), both to the managers of the power plants, and to private companies.

Mainly, four types of ice problems can be distinguished:

(1) Ice pressure against dams and gates, and freezing-up of gates and blades, in the construction, because of ice build-up,

(2) ice formation on intake gates, blades, or turbines,

(3) ice floe and slush against the intakes, and

(4) ice dams.

As far as gates are concerned, the Power Board, in the beginning of the 40's, decided to have effective heating methods to be drawn up to guarantee the maneuverability. There has been further development in improving the safety of running the movable parts of the structures. In order to avoid ice pressure against the dams and gates, a small opening in the ice cover has been made in front of these constructions. The use of current generators, foot-lights, and, in certain sites, air bubblers has shown that nowadays it should not be any technical impossibility to eliminate ice pressure risks that affect sensitive structures.

As far as ice forming is concerned it seems to be that the heating of intake gates usually results in lessening the problems, but ice forming can start in spite of the installed gate warmers. The effect that has been brought about by heating the iron of the gates is self-

evident, but it seems to be difficult to eliminate entirely the risk of ice formation at certain stations. The only way to surely avoid icing problems is to bring about a fast and lasting freeze-up upstream of the station.

Problems with ice floes and slush affecting the intake and the origin of ice dams are partly connected to how the power stations are regulated. Short term regulating, when there is a great difference between the daytime and nighttime use of water, increases the risk for this type of ice problem (even icing ~~problem~~ becomes greater since the freeze-up has been made more difficult).

In the following report (part 1), the description of ice problems, and the measures to prevent troubles are summed up and commented upon. The report has been based on the information submitted by administrators and power companies. The part 2 of the report is made up of a combination of the letters that were obtained in answer to the questionnaire that was the first one to be sent out in 1977.

Finally it is noted that information about ice problems (information was obtained from the first questionnaire in 1977) was summed up as a contribution to IAHR's ice symposium in Lulea in 1978 [5].

INTRODUCTION

In the year 1937, the general director of the State Power Board gave C. E. Soderbaum an assignment to work systematically at questions that were connected with ice difficulties of hydraulic power plants. In the presence of a threat of a war, there were questions concerning the maneuverability of the gates, and after a study trip during the month of March, Soderbaum and Witalis compiled a report: "Ice problems at hydro power plants(1)". To sum up, it is stated in (1): "There is a need for greater safety against ice difficulties that the power stations have been facing as the technology has been developing. Thus, the gates, where icing can be feared to occur, are fitted with effective warming systems. When it is necessary, there are many different ways to protect buildings against ice pressure. In some waterfalls, the results have been satisfactory, but at this point a further development seems to be desirable. As far as mobile constructions are concerned, methods with fully proven effectiveness have been used, and as such, make it possible to have the gates constantly operating even during winter." Finally it is noted in the report (1) that "Proposal has been submitted that current (generators) and other underwater pumps with piping should be installed at several different power stations. By means of underwater pumps, the water is made to circulate and thereby ice build up is hindered.

In the year 1959, the director of the Hydraulic Laboratory, Stig Angelin, urged the administrators at the hydro sites to compile various experiences that they have gained as far as many kinds of ice problems are concerned. Part of these experiences compiled, because of the request, were presented in an ice meeting held in connection with the

IAHR's 8th Congress in Montreal, 1959 [(2),(3),(4)]. In January 1977, in order to have a general survey of current ice problems in our Swedish hydropower plants, the hydraulic laboratory sent forward a questionnaire partly to the administrators of powerplants and partly via VAST to a number of large power companies. As a result of this questionnaire a lot of good information about ice problems was obtained from certain power stations in sections of some rivers; while information from other regions was scarce or failed to come. In order to complete this inquiry paper a detailed questionnaire was distributed in March 1978 to power companies that administer power stations in Lagar, Kolbacks, Dal River, Ume River, and Lule River. The purpose of this other questionnaire was to get as detailed a description as possible of the ice problems in Swedish power stations in a number of rivers from Lagar to Lule River in the north. Importance is placed this time also on getting information about the design of the power plants and other matters that are important in understanding the causes of the ice problems.

Definition of Ice Terminology

Terminology within the realm of ice is not entirely unambiguous. It also appears to vary within the country. An attempt is made below to briefly describe some phenomena.

Ice build-up (slush, swell)

Frazil ice particles are formed on open stretches of rivers and lakes as the water supercools. There the frazil ice particles grow in size and form small flo~~c~~es and gradually they "fasten" into numerous round ice floes. In rivers, ice covers build up partially from the shores (surface ice) and partially from collections of ice particles which are in their different stages of development. Frazil ice particles, as they evolve, fasten on all kinds of things that come their way. That way anchor ice builds up and blocks the intake of a power plant by freezing the gates.

Ice dams

Ice floes that drift with the current along an open stretch of a river can jam against the surface of the ice edge. They can either be stopped and build up an ice cover of loosely packed ice floes or be sucked under the ice barrier. The maximum flow velocity for the ice floes to build up an ice cover is about 0.6 m/sec. For collection of slush (and thin ice floes) the maximum speed is lower and depends on its thickness and strength. For loosely packed ice floes the maximum flow velocity can be 0.2-0.3 m/sec. If upstream of an ice edge, the stream velocity is so great that ice floes get sucked under the ice cover and get deposited under the ice, the water level rises and the speed of the river flow is reduced. As a result ice can then accumulate against the edge of the ice sheet causing the ice cover to grow upstream.

Ice damming can also start as a result of ice which has run aground. It grows then on stones and shores in such a fashion that damming occurs.

Inquiry 1 (paper 1)

The questionnaire with the requested informtion is given in Appendix 1. This information is concerned in part with ice barriers. In the appendices 2.1-2.7 a survey of our existing Swedish powerplants over 10 MW is shown. A number of stations less than 10 MW are also reported.

Answers to the questionnaire concerning ice problems for each power plant and river are reported in the appendices.

The answers that have come in concerning ice problems and ice barriers are accounted for in a separate report (Ice problems in Swedish hydropowerplants, part 2). The most essential problems concerning existing ice problems are reported, besides what appears in appendices 2.1-2.7 in the section under "comments" in the following report.

Inquiry 2 (paper 2)

In March 1978 a detailed questionnaire was distributed to the owners and administrators of hydropowerplants of Lagan, Kolbäcksan, Dalälven, Indalsälven, Umeälven, and Luleälven. After a certain amount of persuasion, information has been obtained from the aforementioned power plants which are on selected rivers. The respondants did not answer all the questions, which, moreover, were often not too skillfully worded. The unanswered questions are marked with --- in the charts. Any left out answer that applies to questions about ice problems is, nevertheless, interpreted as a problem that does not occur. Certain questions could be misunderstood. Moreover, it appears that people have been less inclined to answer all the questions about power plants if there were no ice problems occurring. A summary of the reported ice problems is compiled in a chart form in the tables 4.1-4.15. Powerplants from six rivers are compiled in the report. In these tables information that is judged to have direct interest for purposes of comparison between different power stations, is also given. The remaining information that was asked for in the questionnaire is not included.

(It can be obtained by request to the Hydropowerplant Laboratory). It ought to be pointed out here that time has not been granted to work with the left out information.

Below are comments about the meanings and thoughts behind the headings on the tables.

Power plants	All power plants upstream from the mouth of the river are considered.
Mean rate of flow and corresponding velocity at the upstream intake.	Information on the mean volume of water transported is obtained from the mean value for a winter day and winter night. The available information comes from hours of different discharge in the nearby power stations without the regulating possibilities. Such information cannot, therefore, be totally accurate. Outward bound stream speed has been calculated from the water mass transported and the width and depth of the power plant. Especially where there are no canals, it can be assumed that the speed of the river can be lower than calculated (max. depth stated).

EVALUATION OF ICE PROBLEMS ASSOCIATED WITH
HYDROELECTRIC POWER GENERATION IN ALASKA:

Final Report to the State of Alaska
Department of Commerce and Economic Development

Contract 08-73-7-958/08-71-6-114
or Contract AEC81005-3

The size of the areas not covered by ice immediately upstream of the stations.	If one supposes that freezing occurs if the speed of the stream falls below 0.6 m/sec., it appears that there is an inconsistency between the calculated speed of the stream and data about ice-free areas. The inconsistency can depend upon the incorrectly calculated speed of the stream or that the data about the size of ice-free surfaces is valid during the freeze-up period.
The heating of gates	It is not clear from the questions in the questionnaire if the warmed part of the total gate area is concentrated in one (or several) intake while gates in front of the remaining intakes lack heating.
Icing	Information about icing occurrence on turbine blades (ledskenor) and gates and whether ice gatewarmers are switched on automatically or manually and at what temperature this occurs. There is information also about production drop as a result of icing.

Ice dams	Presence of ice dams (description of location and cause goes under "other") as well as information about production drop as a result of reduced height of the fall.
Ice floe	Problems with ice floe against the intake. Information about causes, point of time, necessary work, and drop in production.
Other	Added information above all about icing problems and ice dams.

<u>Comments</u>

Besides the six rivers included in the paper 2, a good picture of the state of affairs in many power stations in Göta River, Motala River, Klar River, and Skellefte River is obtained from the paper 2. Below are the comments on the information received about these ten rivers.

<u>Lagan</u>

According to Sydkraft's description, ice problems arise mainly in power plants where upstream is a river bed, inlet canal, or a tunnel. Ice problems almost never start in plants that are directly connected with a reservoir. According to appendix 4.1, however, two out of three power plants which have intakes in a reservoir, indicated in paper 2, icing problems appear. The reason for this probably is that the reservoirs in question are relatively shallow.

Icing is found yearly in six (seven?) out of the eight power plants in spite of the installed gate warmers (exception is Aby power station). It is also stated that problems occur even when the gate warmers were turned on before ice formation started. In three (four) of the power plants with icing problems icing occurs not only on gates but even on turbine blades (ledskenorma).

The gate warmers are turned on already when the water temperature is between 0.3 and 0.5 C. This is unusually early compared with the practices of other stations. If problems with operating the gates occur at +0.3 to 0.5 C, it will not probably be because of icing on the iron of the gates. In such high water temperatures it can be assumed that the ice problems occur when great quantities of slush block the gate openings.

In certain canals strong anchor icing occurs at the bottom (1-1.5 m). When this anchor ice gets loose, it can contain stones (of 10-13 kg) which together with the ice can cause problems to the gates and turbines.

In control dams the ice pressure causes damage on vertical level gates. It should be investigated if laying out generators could help this problem.

Sydkraft has taken different steps to reduce the ice problems. In power stations, where the water upstream is constant, stream flow (velocity) is reduced during the freezing period to increase the rapidity of the ice formation upstream. Even laying out ice booms is used for this purpose.

With variable upstream water levels, the canals must ordinarily have open water surfaces. The great difficulty is to keep the canals ice free at the start. Ice is driven out according to a certain system of starting, stopping, and driving out the ice through the ice outlet many times and using a certain amount of acquired experience of opening ledskenor (blades?, guides?).

Clean up work in the waterways has also brought about as a result à retarding effect on icing in some installations.

In four plants they have installed automatic gate cleaners for general gate cleaning work (such as leaves, litter, ice slush), but the cleaners have even proved to have a good effect against ice formation. It is thought that the gates are given a certain vibration and that the cleaners break the ice film on the upstream side of the gate iron and, therefore, the handling of ice has become considerably easier.

Sydkraft maintains that without taking proper steps, it would be scarcely possible to have power production at all times of ice difficulties. This is especially so since nowadays and there is a lack of personnel to solve difficult ice situations.

Gota River

To a certain degree, ice problems in Göta River are special because of ship traffic which has its demands for passability. On the power plant's side, the people hope to have a fast and as complete a freeze up as possible to avoid icing problems that otherwise appear moderately often, especially at Lilla Edets power plant. The shipping office on their part hopes as a principle to keep the river ice-free for shipping. During recent years the shipping office and the power plant office have found certain solutions that both sides can accept. The objective is to reduce ice production in the river and this can be done by letting a great part of the river form an ice cover. Freeze-up can be facilitated by placing ice booms in strategic places. Further the power plant's side aims at keeping a uniform and low discharge, when conditions for freeze-up occur. This, however, is difficult since power stations in Göta River usually must do short term regulating.

In the river even ice dams are sometimes built up, especially on the stretch of Lilla Edethavet. Ice dams appear, partially because of strong drift ice formation, partially as a result of anchor ice, and during certain years they have given cause to troubling floods.

Motala Stream

Icing has occurred only a few times in Motala and Malfors stations. Icing has never occurred in Nykvarn.

In Malfon and Nykvarn problems with ice floes appear occasionally. Ice floes build up in the intake canals at nighttime if the stations are not operating. Ice floes then break loose with the starting of operation in the morning and travel down to the intake gates. Loss of head appears as a result. The most difficult freeze-up appears during Saturday and Sunday when the stations do not operate from Saturday afternoon until Monday morning.

Klar River

Of Uddelholm's nine power stations in Klar River, there are troublesome ice problems in Munkfors and Forshaga. In Edsforsen, Skoga and Deje there are certain troubles with icing before freeze-up. Icing or ice problems seldom or never occur in the remaining power stations.

In Nunkfors and Deje stations, there are trash racks that work with icing and it seems that they make it possible to keep the operation going on. At Deje, during part of the year, timber is laid down to protect against icing.

Downstream of Höljes power station there are about two ten kilometer stretches of undeveloped (rapids). In spite of that, the water temperature at the station can be about +1°C in February; ice slush and drift ice are built up along the rapids stretch. This ice gets stored up where the water flows slowly and gives rise to damming. Since short term regulating has been started at Höljes, the risk of the problems has increased and things have been closely watched. According to the information from the management, the ice forming is worst in very cold weather and when discharge is low.

Kolbäcksån

Kolbäcksån is included in (Inquiry 2) Paper 2 in order to present detailed information about a small waterway with small power stations. Icing problems are found in five out of the eight stations that are characterized as river power plants or that have intake canals to bring in the water. (Gatewarmers are lacking in all power stations in Kolbäckson.) Reports on icing appear from this waterfall even before the freeze-up, but in Trångfors icing can occur during the whole winter day and night. Trångfors power station has a 400 m long canal that brings in water. It is open the whole winter.

On four out of the five power stations which have icing problems there is ice growth on both gates and ledskeneapparaten (blade apparatus?). Smaller problems with ice floe against intake gates are reported from two stations. The problems occur with greater discharge changes respectively in milder weather.

Dal River

In all thirteen power stations between the confluence of the Väster and Österdal Rivers (Lindbyn included) and the ocean, icing has occurred in the intake gates. Ice growth at both gates and ledskenor (blades?) appears in five stations in a row from Avesta-Lillfors to Lanforsen, at the lower part of the river.

Occasionally in Domnarvet power station icing has occurred on the turbine blades in one of the two Kaplan turbines, this caused an imbalance in the unit and there was some damage as a result. Ice formation in turbine blades (in Kaplan turbines) has also been discovered at the Lanforsen power station.

In Väster River, icing occurs in Eldeforsen each autumn, and only seldom in Hummelforsen. Icing in Hummelforsen happens even though there are gatewarmers. In Österdal River, icing occurs more seldom the further upstream the power stations in the river are.

Ice dams occur regularly downstream of Trängslet and about 6 km upstream of Väsa power station. Flooding caused by these ice dams causes damage to the surrounding settlements. It is to be assumed that in Trängslet the problems are reduced after the installation of air bubblers in the reservoir by which warm bottom water is lifted towards the intake. During the winters 1977 and 1978, ice damming occurred in one of the forks of the river, upstream of Untran power station. Ice damming during these two winters was attributed to the increased water flow of the fork of the river. It happened as a result of diversion of water in connection of building a power station in Soderfors. The ice dams caused the water level to rise above the dam, damaging it. In doing so approximately 75 m^3/sec water flowed on the site of Untran power station and into a drained river basin.

Upstream of Älvkarleby power station, bottom anchor ice can occur in the shallow part of the river which results in the rise of the downstream water level in Lanforsens power station. Problems with the ice floes against the intake gates occur in several power stations mainly downstream of where Väster and Osterdal Rivers flow together.

In order to prevent ice pressure against dams and gates, current generators are used with good results in many stations. In Avesta-Storfors they seem to get good results by using gate cleaning machines, among other things, to remove ice that cannot pass through the ice outlets.

The power companies agree that the most effective measures to prevent icing are to keep low and even discharge of water during the freeze-up period so that an ice cover is formed.

Indals River

Ice build up on intake gates occurs in Svarthälsforsen power station (3-6 days a year). In the Stuguns and Mörsils power stations, ice build up has occurred once since the plant started operating since 1976, and in Hammarsforsen power station once during the last 30 years. In the rest of the power stations there are no problems with ice build up.

Downstream of Bergeforsen the river has ice every year on the shores and bottom, decreasing the area of the river. This causes a 0.7-0.8 m drop in the pressure head at the station.

During February-March 1972, there were serious problems with ice slush (not ice build up) at Svarthälsforsen. Portal cranes with ice scoops were working in three shifts a day and night to remove the slush. Svarthälsforsen company points out that at this time a lot of water was lost as a result of repairs at the Krangede and Gammelänge stations and they speculate that ice problems in Svarthälsforsen appeared because of this spill. No problems, however, appeared at the Hammarforsen power station that lies between Krångede and Gammelange and Svathälforsen. An explanation could be that the water temperature at the outlet from Hammarforsen was lower than normal as a result of cooling in the tailrace in Krangede and Gammelänge. Ice slush build up was lighter than normal on the relatively silty river stretch between Hammarforsen and Svathälsforsen.

The dam in Stadsforsen power station is not considered to withstand from any ice pressure, and therefore, a canal towards the dam is kept open. It is reported that chain saws, ice brakers and scoops of portal cranes and also snowmobiles are used for this work. If no special circumstances prevail in Stadsforsen, an opening along the dam can be maintained with current generators or floodlights which is done in other locations.

Breaking up the ice cover together with changes in stage and ice floe movement towards the intake occur in Midskogs, Mörsil, and Svarthälsforsens power stations. Ice floe movements towards the gates occur in some other stations in connection with freeze-up or break up. However, these ice floes do not usually constitute any more serious problems. As an exception, however, considerable difficulties can arise. In Mörsils power station, thaw and strong wind in January 1973 caused a 10-15 cm thick ice on Liten Lake to break up and obstruct all of the 3 km long intake canal. The ice masses were 5-6 m deep in the dam and caused the power production to drop for almost 24 hours.

Ume River

Icing on intake gates occurs at a few years intervals at Storrnorrfors and Bälforsen power stations. In Hällforsen and Betsele, icing has even appeared on ledskenorna (blades?). In Bälforsen, Betsele and Hällforsen power stations, icing caused a total stop of power production in 1971, 1973, and 1975.

At Tuggen power station ice dams appear yearly 5-10 km downstream of the station. The downstream water level at the power station is about 2 m more than the surface in ice-free conditions. During the day, because of water discharge, the speed of the stream in the outflow canal is so high that the canal does not freeze. In cold weather, great masses of ice slush build up along the canal and along the ice-free river stretch downstream, and come to the damming area.

There the speed of the river becomes lower and ice slush gets accumulated under the ice. Karteringar has shown that large sections of the river are obstructed by slush in this manner. As a result of the increased resistance, the water level rises upstream of such an ice dam and the stream velocity decreases and conditions for freeze-up occur. The ice cover that gradually covers a greater part of the canal is made up of slush and ice floes, hence, gets a moderately uneven surface. Ice floe accumulation along the edges indicates that the stream velocity has been very close to the limit of where the ice floes get sucked under the ice cover.

Apart from extensive excavation work in Tuggen outlet canal, the only possibility to reduce the risk of ice damming is to restrict short term regulating during the time when good conditions for freeze-up prevail.

Skellefte River

Information has been only received from Skellfte power plant. Descriptions of ice conditions in Skellfte power station are given by an administrator as follows.

1. Icing in Finnfors, Granfors, Krangfors, and Selfors power stations 1973-11-10 and 1973-11-11.

Because of low water temperature, strong winds, and low air temperature, strong cooling of the river occured without ice formation. We measured water temperatures to an accuracy of one-thousandth of a degree C. Because of freezing there, and the lack of ice cover, the pressure head dropped rapidly at the gates. So, gradually, production had to be reduced very strongly at the power stations. Some turbines had to be stopped because the intake gates froze totally together. In Selfors power station, ledskenorna (blades?) in the turbines froze together so that it became impossible to use the gear shifts. After about 40 hours, the strong winds decreased and freeze-up on the dams of power stations became possible (an ice cover formed). The water temperature started to climb up a few tenths of a degree and so the freeze-up began. After about 44 hours, the power production was resumed to full extent.

Production drop during this period was about 630 MWH. It should be pointed out that the above mentioned problem is very uncommon. No information like that has ever come up before. Therefore, our actions for above mentioned type of problem are limited to trying to keep constant power. The most useful approach is to keep constant water flow during the freeze-up period.

2. Ice dams downstream of Granfors power station during the winters of 1975/76 and 1976/77.

During these winters we have had ice dams above all in downstream Granfors power station. Because of that we got flooding in G1 turbine pits at Granfors on January 7, 1976. The loss of pressure head on this occasion was about 2.7 m (the height of the water head). The immediate procedure was to reduce the water volume going through the station, and to install a warning signal for high downstream water level. (The station is far from our management center in Skelleftea.) Attempts to break away ice dams were performed with certain success, but the problem still remained partially during the winter 75/76 for about a month. The drop in water height (pressure head) varied between 1.7-2.3 meters, and the discharge was about 180-190 m^3/s. We believe the best manner to avoid the aforementioned problems, even here, is to try to keep the discharge constant (and possibly low) during the freeze-up period, that is to say, to keep short term regulating as low as possible.

3. Outflow stretch downstream of Kvistforsen power station.

About 1 km downstream from the central part of Skelleftea city, ice dams often appear. In the winters of 74/75 and 75/76 the dams were particularly big. Damming is caused by ice slush and piled up ice blocks. The cross-section of the river is considerably smaller where the dams start than in the upstream part of the river stretch. In January 1975 in the city center the maximum damming was measured at 0.9 m, and in January 1976 about 1.2 m.

That the ice dams became so big in these years can, among other things, be caused by the unusually high discharge by the power plants during these winters.

During the winter 1975/76, damming was concentrated to quite a short stretch, and that is why it was judged to be possible to break away the ice. On January 8, 1976, an explosive bursting of ice was carried out, and it resulted in an immediate decrease of the damming by 0.8 m and gradually decreased further.

Casualties of damming occur foremost through embankment overflows and water seeping into the community drainage system. These require increased pumping cost and the risks of overflowing wells. Besides, crowding together (narrowed channels?) has caused the water velocity to become so great increased bottom erosion can occur.

Lule River

Apart from certain problems with ice floes against intake gates at Letsi and Akkats power station, and a moderate risk of icing at Boden and Laxede, serious ice problems have appeared only at Vittjäw power station. During the first winter after the present administration took over at Vittjäw power station they were forced to spill all of the water through spillway which is equipped with a so called "ski jump" in order to reduce the velocity of water downstream. This spill together with a couple of stretches of stream open downstream of the station produced a great amount of slush. This slush got accumulated in the rapids and caused damming that reduced the water pressure head (fall height) down to 2 m.

After major dredging work downstream, it appears that the risk of ice damming is considerably smaller than earlier.

Icing at the intake gates has been a yearly recurring problem ever since the present administration took over. As a test, gate warmers were installed on the intake in one or two sets. No reduction of icing or ice build up problems on the warmed intake could be established, however. Therefore, the gatewarmers were disconnected. Neither has the extensive cleaning work performed upstream in order to hasten freeze-up, have substantially reduced the icing problem.

INVENTORY OF ICE PROBLEMS

The nature of problems

- Ice formation on gates, ledskenor,(turbine blades) and so on
- Ice dams, anchor ice (reduced water head, flooding)
- Ice pressure against dams and locks
- Other

The causes of problems and the measures which have been taken

- Descriptions of how often and, if possible, why the special problems occurred
- Which measures have been taken (or should/can be taken), examples
- Reduced water flow (the volume of water) during the freeze-up period
- Laying out of ice booms
- Changing of water ways
- Heaters on gates and other constructions
- Laying out current generators, releasing the warmed water or similar measures
- Other
- What effect have the measures brought about (the degree of difficulty of the problems and frequency before and after the steps had been taken)

Inquiry about ice booms. The purpose of laying out ice booms.

- Accumulate floating ice and thereby initiate the forming of firm ice cover

- Prevent drift-ice from reaching the intake constructions, where the risk of the ice being sucked under or blocking occurs
- Direct ice to ice outlet
- Other

Placing of booms (give reason for the choice of the placing of booms please, enclose a sketch or direction)

- The surface velocity in the selected section is so low that drift ice is gathering toward the boom
- Other

Necessary maintenance

- Recording of booms in summertime
- Exchange of the non-functioning parts

Length of life

- How long have the booms been in use
- If a boom is exchanged; give its life span and the reason to the exchange

Expenses

- The cost of manufacturing
- The cost of placing (laying out) them, including anchoring

River	Stations	Owner/Administrator	Answer to the Inquiry is Indicated by X	Type of Ice Problem
Lagan	4st 10-20 MW 1st 20-50 MW 6st 1-10 MW	Sydkraft "	X	Ice problems at power stations at least sometimes each year (ice dams and ice pressure towards gates)
Mörrumsan	4st 1-10 MW	"	X	The same problems as in the Lagan
Helgean	8st 1-10 MW	"	X	"
Eman	7st 1-10 M		X	"
Nissan	1st 10 MW 5st 1-10 MW	Nissaströms Kraft Co.		
Atran	1st 19 MW 1st 12 MW 6st 1-10 MW	Papyrus Co. "		
Viskan	6st 1-10 MW			
Sävean	4st 1-10 MW			
Göta Alv	Lilla Edet 26 MW	SV	X	Serious ice problems occur every 3 or 4 years. Ice forms on the blades so that they cannot be maneuved and simultaneously intake gates freeze solid.
	Trollhättan 235 MW Vargön 26 MW (Trollhätte kanalverk)	SV SV SV	X	Ice dams, frazil, ice growth on flood gates
Svartan (Ostergötland)	st 1-10 MW			
Motala Ström	Motala 14 MW	SV	X	Lighter icing, once (57/58)
	Malfors 21 MW	SV	X	Icing twice (in the 40's and 57/58) ice floe towards the intake
	Bergsbron 17 MW	Holmens Bruk		
	Nykvarn 2st 1-10 MW	SV	X	Ice floe towards the intake

River	Stations	Owner/Administrator	Answer to the Inquiry is Indicated by X	Type of Ice Problem
Klarälven	Höljes 132 MW	Uddeholms Co.	X	No ice problems at the station. Ice dams downstream.
	Tasan 40 MW	Tasanskraft Co.		
	Skymnäs 16 MW	Uddeholms Co.	X	Never ice problems. Receives warm water from Uvan.
	Krakerum 16 MW	" "	X	Never ice problems. Receives warm water from Uvan.
	Forshult 20 MW	" "	X	Seldom ice problems. Receives warm water from Uvan.
	Skoga 14 MW	" "	X	Minor risk of icing before freezing.
	Munkfors 23 MW	" "	X	Danger every year.
	Dejefors 16 MW	" "	X	Some danger of ice problems each year before freeze-up.
	Edsforsen	" "	X	Minor risk of icing occurs before freeze-up.
	Forshaga	" "	X	Troublesome icing each year (7-8 hours stop).
Svartälven	Karasen 11 MW	Bofors Co.		
	Atorp 10 MW	Gullspangskraft Co.		
	+ about 15 1-10 MW	" "		
Arbogaan	ca 8:1-10 MW			
Kolbäcksan	ca 12:1-10 MW			
Västerdalälven	Lima 13 MW	Stora Kopparberg Co.		
	Hummelfors 10 MW	Korsnäs-Marma		
	Mockfjärd 32 MW	Gränges Kraft	X	Earlier icing on gates each 4-5 years. In 1976 damming was increased upstream, with which the problem will (reduce) decrease hopefully.

River	Stations	Owner/Administrator	Answer to the Inquiry is Indicated by X	Type of Ice Problem
Osterdalälven	Trängslet 335 MW	Stropa Kopparberg Co.	X	Ice damming downstream at about -30°C.
	Asen 26 MW	" " "		
	Väsa 15 MW	" " "		
	Blyberg 15 MW	" " "		
	Spjutmo 35 MW	" " "		
	Grada 24 MW	" " "	X	Icing on gates.
	Förshuvud 18 MW	" " "	X	Icing on gates.
	Lindbyn 11 MW	" " "		
Dalälven (Junction of streams downstream)	Kvarnsveden 50 MW	Stora Kopparberg Co.	X	Icing on gates.
	Bullerforsen 18 MW	" " "	X	Icing on gates (see inquiry) -78.
	Domnarvet 16 MW	" " "	X	Icing on gates.
	Langhag 46 MW	" " "	X	Icing on gates.
	Skedvi 38 MW	" " "	X	Icing on gates.
	Mansbo 11 MW	Alby Klorat Co.		
	Avesta-Storfors 18 MW	Avesta Jernwerks Co.	X	Icing on gates. Small problems.
	Näs <10 MW	SV	X	Icing on gates. Drift ice towards the gates.
	Untra 40 MW	Svarthalsforsen Co.		Icing on gates. Ice dams 76/77 & 77/78
	Lanforsen 38 MW	" "		Icing on gates ledskenor and turbine.
	Alvkarleby 70 MW	SV		Icing on gates and bottoms.
Gavlean	About 5st 1-10 MW			
Ljusnan	Langa 160 MW	Bergvik and Ala Co.	X	Ice dams on undeveloped stretch stream.
	Sveg 33 MW	Gullspangs Kraft Co.		
	Byarforsen 17 MW	" " "		
	Krokströmmen 100 MW	" " "		
	Langströmmen 46 MW	" " "		
	Strorasströmmen 25 MW	Kema Nord Co.		
	Ojeforsen 26 MW			

iver	Stations	Owner/Administrator	Answer to the Inquiry is Indicated by X	Type of Ice Problem
jusnan	Lottefors 13 MW	Korsnäs-Marma		
	Dönje 76 MW	Dönje Kraft Co.		
	Bergvik 18 MW	Bergvik and Ala Co.	X	No problems.
	Höljebro 27 MW	" " " "	X	Serious icing problems about every 5 years in spite of gate heating.
	Ljusne Strömmar 34 MW	" " " "	X	"
	Landafors 13 MW		X	New power station (1976). No problems during the first winter.
	Ljusnefors		X	Started operating in 1976. No experiences.
	Alfta 19 MW + about 4 st 1-10 MW	Voxnanskraft Co.		
jungan	Flasjö 20 MW	Norrlandskraft Co.	X	Minor problems.
	Trangfors 72 MW	" "	X	" "
	Råtan 58 MW	" "	X	" "
	Turinge 17 MW	" "	X	" "
	Järnvägsforsen 105 MW	Skad. Elverk Co.		
	Parteboda 35 MW	" " "		
	Hermansboda 10 MW	Angefallens Kraft Co.		
	Ljunga 56 MW	Kema Nord		
	Torpshammar 120 MW	SV		
	Skallböde 23 MW	Balforsens Kraft Co.		
ıdalsälven	Järpströmmen 118 MW	Svarthalsforsen Co.	X	Small problems. Ice floe settles towards the gates.
	Mörsil 44 MW	Krangede AB	X	Icing once. Ice dams 2 times.
	Sällsjo 152 MW	Norrlandskraft Co.	X	Minor problems.
	Hissmafors 60 MW	Ostersunds komun		
	Kattstrupefors 60 MW	Kattstrupeforsen Co.		
	Olden 120 MW	Balforsens Kraft Co.		
	Stensjöfallet 94 MW	Stensjöns Kraft Co.		
	Kvarnfallet 17 MW	" " "		
	Näsaforsen 12 MW	Ostersund El Co.		
	Midskog 145 MW	SV		
	Närverede 62 MW	SV		

iver	Stations	Owner/Administrator	Answer to the Inquiry is Indicated by X	Type of Ice Problem
ndansälven	Stugen 37 MW	SV		
	Krangede 240 MW	Kragende Co.	X	No problems.
	Gammelänge 72 MW	" "	X	No problems.
	Hammarforsen 73 MW	Balforsen Kraft Co.	X	Ice building at gate guards icing at the intake in 1976.
	Svarthalsforsen 67 MW	Svarthalsforsen Co.	X	Icing problem one week in the autumn.
	Stadsforsen 135 MW	SV		
	Hölleforsen 140 MW	SV		
	Järkvissle 85 MW	SV		
	Sillre 12 MW	SV		
	Bergeforsen 155 MW	SV & Balforsens Kraft Co.		
ngermanälven	Linnvasselv 70 MW	Linnvasselv Kraftlag		
	Blasjön 60 MW	Blasjöns Kraft AB		
	Junsterforsen 40 MW	Holmens Bruk		
	Bagede 13 MW	" "		
	Lövön 36 MW	Graningeverkens Co.		
	Storfinnforsen	Krangede Co.	X	
	Ramsele 157 MW	Krangede Co.	X	
	Edsele 57 MW	Balforsens Kraft Co.	X	Icing on gates yearly. Bottom ice and drift ice towards the intakes.
	Forsse 52 MW	Graningeverkens		
	Hjälta 168 MW	Norrlands Kraft Co.	X	Icing 3-5 times a year (no spill)
	Solleftea 62 MW	" " "	X	Ice dams (0.5-1.0 m) downstream. Ice pressure toward gates. Leakage in guides.
	Dabbsjö 30 MW	Korsselbränna		
	Bergvattnet 21 MW	"		
	Korsselbränna 112 MW	Balforsens Kraft Co.		
	Borgforsen 26 MW	Svanö Co.		
	Bodum 13 MW	" "		
	Fjällsjö 13 MW	Balforsens Kraft Co.		
	Sil 13 MW	" " "		
	Hällby 72 MW	Gulsele Co.		
	Gullsele 62 MW	" "		
	Degerforsen 62 MW	Graningeverkens		
	Edensforsen 63 MW	"		

River	Stations	Owner/Administrator	Answer to the Inquiry is Indicated by X	Type of Ice Problem
	Stornorrfors 410 MW	SV		
Skellefte älv	Rebnis 64 MW	Rebnis Kraft Co.		
	Bastusel 108 MW	Bastusels Kraft Co.		
	Grytfors 32 MW	Grytforsen Co.		
	Gallejaur 115 MW	SV		
	Vargfors 70 MW	SV		
	Rengard 36 MW	Skelleftea Kraftverk	X	
	Batfors 40 MW	" "	X	
	Finnfors 32 MW	" "	X	Severe icing on the gates on one occasion (1973).
Angermanälven	Langbjörn 92 MW	SV		
	Lasele 150 MW	SV		
	Kilforsen 275 MW	SV		
	Nämforsen 110 MW	SV		
	Moforsen 110 MW	Krangede Co.	X	
	Forsmo 155 MW	SV		
	Stalon 110 MW	SV		
Ume Alv	Gejman 65 MW	SV		
	Ajaure 85 MW	SV		
	Gardikfors 60 MW	SV		
	Umluspen 95 MW	SV		
	Stensele 50 MW	SV		
	Grundfors 90 MW	SV		
	Rusfors 45 MW	SV		
	Balforsen 83 MW	Balforsens Kraft Co.	X	Icing on gates and total stop in 1971, 1973 and 1975.
	Betsele 24 MW	" " "	X	"
	Hällforsen 21 MW	" " "	X	"
	Tuggen 105 MW	SV		
	Bjurfors övre 42 MW	Norrlands Kraft Co.	X	Sometimes ice dams downstream.
	Bjurfors lower 78 MW	" " "	X	Minor problems.
	Harrsele 203 MW	" " "	X	Minor problems.
	Pengfors 52 MW	" " "	X	Minor problems.

River	Stations	Owner/Administrator	Answer to the Inquiry is Indicated by X	Type of Ice Problem
Skellefte älv	Granfors 39 MW	Skelleftea Kraftverk	X	Serious icing on the gates on one occasion in 1973. Ice dams downstream 75/76 and 76/77 (max 2.7 m drop in pressure head).
	Krangfors 58 MW	" "	X	Serious icing on the gates in 197
	Selsfors 57 MW	" "	X	Serious icing on the gates in 197 Even the ledskenor froze solid.
	Kvistforsen 140 MW	" "	X	Ice dams downstream station in central Skelleftea.
Lule älv	Seitevare 220 MW	SV		
	Parki 20 MW	SV		
	Akkats 146 MW	SV		In order to sum up, it can be sai that ice problems mainly appear i Laxede, Vittjärv and Boden (icing, ice dams).
	Letsi 450 MW	SV		
	Vietas 320 MW	SV		
	Porjus 295 MW	SV		
	Harspranget 330 MW	SV		
	Ligga 160 MW	SV		
	Messaure 300 MW	SV		
	Porsi 175 MW	SV		
	Laxede 130 MW	SV		
	Vittjärv 32 MW	SV		
	Boden 74 MW	SV		

FOLLOW-UP QUESTIONNAIRE

1. The name of the power station and of the river.
2. (a) The owner of the station.

   (b) The company responsible for the management.
3. The year when the present management took over.
4. The water head m.
5. The volume of water that goes through.

   (a) Max --- m^3/s

   (b) The average water volume on a winter day m^3/s.

   (c) The average water volume on a winter night m^3/s.
6. Turbines

   (a) Type

   (b) How many
7. Give the type of regulating (day and night, week regulating, etc.) and the variations of water level upstream of the power plant.
8. Type of outlet.
9. Are there current generators, air vents or similar structures installed in front of the dams or at the outlet; describe.
10. Type of water intake.

    (a) Open canal

    (b) River power plant (special intake canal missing)

    (c) Intake in connection of reservoir (directly or via a tunnel)
11. The dimensions of the intake canal.

    (a) length-m

    (b) breadth-m

    (c) depth

12. The dimensions of the river upstream of the power plant (river power plant).

    (a) breadth-m

    (b) depth-m

13. Water intake

    (a) How many intake openings

    (b) The breadth and height of the intake openings

14. Gates: built in

    (a) Yes

    (b) No

15. Gates leaning out from vertical plane (0° for vertical gates).

16. The dimensions of vertical racks

    (a) diameter--mm

    (b) approximate separation--mm

17. Are there mechanical gate cleaners.

    (a) Yes

    (b) No

18. The heating of gates.

    (a) Lacking

    (b) The fraction of total gate area which is heated (example 2/3)

    (c) The entire gate area is warmed

19. The type of warming the gates have

    (a) Induction

    (b) Circulation of warm water

    (c) Other

20. The power (electric) on the gates

    (a) Total--kw

    (b) Per facing surface

21. Temperature and observing the ice formation. Reading slush term (0 meter) (kvicksilver term) ------------ times a day.

22. ~~One~~ ARE temperatures recorded automatically.

(a) Yes

(b) No

23. If the account of recorded temperatures is missing, how often is the temperature observed when there is a risk of icing. -------- times a day.

24. Is there installed a meter over the gates for measuring the loss of the fall.

(a) yes

(b) no

25. Are cables (chains?), cords etc., used for detecting the beginning of icing.

(a) yes

(b) no

26. At what temperature are the gate warmers switched on. ------ °C

27. Are the gatewarmers switched on manually or automatically.

(a) manually

(b) automatically

28. During winter, the areas which are not covered by ice, directly upstream of the station (including the intake canal), cracks (rifts?)

(a) length ----- m

(b) breadth ---- m

29. Stretches of rapids (streams?) upstream.

(a) distance from the station -------- m

(b) the cracks length ---------------- m

(c) the cracks breadth---------------- m

30. Stretches of rapids (stream?) downstream (incoming) minor rivers upstream of the station.

31. Minor river ------- m^3/s

32. Temperature in relation to the main river.

    (a) same

    (b) colder

    (c) warmer

33. Measures to hasten freeze-up upstream of the station. Laying out ice booms.

    (a) yes

    (b) no

34. Reduction of water flow during the freeze-up.

    (a) yes

    (b) no

35. Is the surface of water constant upstream during freeze-up.

    (a) yes

    (b) no

36. Other

37. Occurrence of icing on gates.

    (a) yes

    (b) no

38. Tracks or turbine blades

    (a) yes

    (b) no

39. Give the time (morning, daytime, evening, night) and the type of weather (temperature, precipitation, the direction of wind and the wind velocity, etc.) when ice forming usually happens. Also inform in what direction the intake canal is (example North-South).

40. How often does the icing occur.

41. Estimate the average production drop per year during the last 10 years ----------- kWh/a year

42. Has icing occurred in spite of that the gate warming was switched on before ice forming started.

    (a) yes

    (b) no

43. Occurrence of ice dams. Where do the ice dams originate (give likely causes).

44. Consequences of ice dams (reduced height of fall, flooding, etc.).

45. How often do ice dams appear.

46. Estimate the average drop in production during the last ten years ------------- kWh/a year

47. Ice floes against intake canals. Interferences in running (extra work input) ----------- man hours/a year

48. When do the ice dams appear.

49. Is there an ice outlet.

50. Does the ice outlet (isutskov) work.

    (a) yes

    (b) no

    (c) partly

51. How is ice removed if the ice outlet does not function.

52. Estimate the average drop in production per year during the last 10 years (because of the decreased waterflow) -------- kWh/a year.

53. Other ice problems (ice pressure against dams, ice on gates and gate folds, etc.).

54. Give the effective methods of fighting against ice.

55. More information (the rest) (for example: details of the form of the station; details which have importance on the occurring ice problems).

EXPLANATION FOR TABLE COLUMNS

1. Type of intake.
2. Average water flow (m^3/s) and corresponding velocity (m/s) upstream of the intake (winter day).
3. Average water flow (m^3/s) and corresponding velocity (m/s) upstream of the intake (winter night).
4. Size of the areas which are not covered by ice and are directly upstream of the station (m^2).
5. The heating of gates. The total warmed gate area, (m^2).
6. The heating of gates. Total power (Kw).
7. (°C) temeperature at which gate warming is switched on (a) automatically or (m) manually.
8. Icing. Tracks (?)
9. Icing. Gates.
10. Icing. Drop in production (MWh/a year).
11. Ice dams.
12. Ice dams. Production drop (MWh/a year).
13. Ice floes against the gates. Reason, point of time.
14. Ice floes against the gates. Work in man hours.
15. Ice floes against the gates. Production drop (MWh/a year).
16. Other.

	Landolm	Karsefors	Skogaby	Knäred	Majenfors G	Majenfors N	Traryd	Åby
1	Intake in reservoir	1450 m canal	475 m canal	1000 m canal	300 m canal	Intake in reservoir	River power plant	Intake in reservoir
2 3	Max Vol. 180	Max Vol. 155	Max Vol. 126	Max vol. 91 Max vel. 0.8	Max vol. 63 Max vel. 0.4	Max vol. 65	60--0.1-0.2 40--0.1	Max Vol.16
4	250 x 100	----------	475 x 12	1000 x 22	300 x 25	25 x 15	16 x 5	vary
5	lacking	total	total	total	total	total	total	lacking
6		----------	----------	200	200	about 200	200	
7		----------	(m)	(m) 0.5	(m) 0.5	(m) 0.5	(m) 0.3	
8	Yes(?)	Yes	Yes	No	Yes	No	No	No
9	----------	Yes	Yes	Yes	Yes	Yes	No	Yes
10	----------	----------	----------	----------	----------	----------	0	----------
11	----------	----------	No	----------	No	No	No	Yes
12	----------	----------	----------	----------	----------	----------	----------	----------
13	----------	----------	----------	----------	----------	----------	----------	----------
14	----------	----------	----------	900	100	100	----------	0
15	----------	----------	----------	----------	----------	----------	----------	----------
16		Icing has happened in spite of gate warming.	Icing has occurred in spite of the warming of the gates.	Icing about 2 times a year (has occurred in spite of the warming of the gates).	Icing about 2 times a year (has occurred in spite of the warming of the gates).	Icing about 2 times a year (has occurred in spite of the warming of the gates).		Icing 2-3 times a year

	Vä[illegible]kva[illegible]	No[illegible]va[illegible]	S[illegible]fo[illegible]	E[illegible]sfa[illegible]	[illegible]je-stationen	[illegible]ngf[illegible]	[illegible]ätr[illegible]	[illegible]rah[illegible]r
1	River power station	250 m canal	River power plant	River power plant	32 m canal	400 m canal	River power plant	River power plant
2	17--0.1-0.2	17--0.4	17--0.1-0.2	32--0.4	2--<0.1	16	17--0.2	17--0.1-0.2
3	17--0.1-0.2	17--0.4	17--0.1-0.2	32--0.4	2--<0.1	16	17--0.2	17--0.1-0.2
4	100 x 50	1000 x 50	40 x 30	Up to the power station (about 400 m)	-------	400 m long	100 x 30	150 x 150
5	lacking	lacking	lacking	lacking	lacking	----------	lacking	lacking
6						----------		
7						----------		
8	Yes	No	No	Yes	No	----------	Yes	No
9	Yes	Yes	No	Yes	No	----------	Yes	No
10	--------	----------	---------	500		----------	----------	
11	No	No	No	At gates	----------	----------	No	No
12				-----------	----------	----------		
13	--------	----------	---------	Mild winter	----------	----------	----------	----------
14	--------	----------	---------	50	----------	----------	----------	----------
15	--------	----------	---------	-----------	----------	----------	----------	----------
16	Icing occurs often before freeze-up.	Icing occurs often before freeze-up.		Icing when weather changes, northerly wind and -10°C or colder.		Icing occurs day and night when the ~~north~~ wind blows from the north ~~east~~ or northeast (4 times during Jan., Feb., and March 1978).	Often icing before freeze-up evening and night.	

250 m canal	300 m canal	1000 m canal	Canal	150 m canal
325--0.8 100--0.3	300--0.4 200--0.3	300--0.8 200--0.5	Max Vol.180	83--0.3 83--0.3
250 x 30	2000 x 100	1500 x 80 the canal can freeze-up totally.	500 x 100	850 x 110 m
1/2	2/5	1/2	lacking	lacking
700	400	1500 KVA		
(a)0.04	(m) 0.01	(a) 0.005		
No	Yes	Yes	Yes	Yes
Yes	Yes	Yes	Yes	Yes
--------	---------	Little	700	2
Yes (anchor ice)	Yes	Yes	Yes	No
--------	---------	----------	---------	---------
Ice cover breaks up because of storm or variations of water level	During freeze-up.	Appears	---------	When there is a change in water use in Storforse
50	50	----------	---------	50
		----------	---------	1
Ice forming against dams and gates. Icing on gates as a rule each winter before freeze-up in SW-wind and at colder temp. than -2°C (canal SN). Great problems if ice cover breaks up and get into the intake canal).	Icing about 1 week a year in the evenings and at times in negative temperatures and north-westerly wind (canal EW).	Total of 200-300 hours of extra work a year because of icing problems in the evenings and at nighttime in NW wind (canal in NW direction).	Icing 0-8 times a year when there is a westerly wind and -8°C (or colder).	Icing on the afternoons and nights about 2 times a year in the westerly wind (the canal is in E-W direction) and when it is colder than -10°C.

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	93 m canal	100 m canal	River power plant	River power plant	River power plant	River power plant	River power plant
2	210--0.4	125--1.0	300--0.2	300--0.2	210--0.2	210--0.1-0.2	210--0.1-0.2
3	210--0.4	125--1.0	240--0.1	240--0.1-0.2	210--0.2	210--0.1-0.2	210--0.1-0.2
4	400 x 100 m^2 from 70 m up-stream of the station	150 x 25-50	Minimum 20 x 20-30	Minimum 20 x 20-30	100 x 50	150 x 70	0 x 0
5	lacking	lacking	lacking	lacking	lacking	lacking	lacking
6							
7							
8	No	No	No	No	No	No	No
9	Yes	Yes	Yes	Yes	Yes	Yes	Yes
10	10	2	--------	---------	0	---------	0
11	No	--------	No	No	No	---------	No
12	---------	--------	--------	---------	0	---------	----------
13	When there are changes in water level.	In spring, in fast changes in water volume that goes through.	--------	---------	--------	---------	----------
14	100		--------	0	0	---------	----------
15	12		--------	0	0	0	----------
16	Ice in gates and gate guards. Icing about once a year.	Icing once a year.	Strong icing 2 times in 30 years under north-erly wind (canal is NW/SE).	Strong icing 2 times in 30 years under north-erly wind (canal is NW/SE).	Icing 2 times in 10 years at 10°C or colder as well as in wind and precipitation.	Icing once in every 7 years at -10°C or colder as well as in wind and precipitation.	Icing once in 3 years.

Lindbyn	Mockfjärd	Eldforsen	Hummelforsen	Forshuvud	Lima
River power plant	River power plant	250 m canal	River power plant	River power plant	River power plant
60--<0.1 60--<0.1	60--<0.1 60--<0.1	25--0.2 25--0.2	25--<0.1 25--<0.1	210--0.1-0.2 210--0.1-0.2	20--<0.1 20--<0.1
0 x 0	0 x 0	-----------	-----------	400 x 40	0 x 0
lacking	lacking	lacking	total	lacking	lacking
			150 KVA		
			(m)		
No	No	No	No	No	No
Yes	No	Yes	Yes	Yes	No
About 100	---------	12	-----------	-----------	--------
---------	---------	-----------		No	No
---------	---------	-----------	-----------	0	0
---------	At the time of ice-breakup.	At the time of ice-breakup.	-----------	-----------	--------
---------	---------	-----------	0	0	0
---------	---------	-----------	-----------	0	0
The last time icing occurred 1975.	No icing after a rise in the height of the dam since a stretch of rapids about 1 km upstream of the station "disappeared"	Icing each autumn. At the time of icing, the station is stopped overnight so that (freezing can start) freeze-up can happen.	Icing extremely seldom but it has happened in spite of the fact that the gate warmers have been installed.	Icing about once in every 3 years at -10°C and colder temperatures as well as in wind (gale) and snowfall. Ice on gates and gate guards.	

	Grada	Spjutmo	Blyberg	Väsa	Asen	Trängslct
1	River power plant	River power plant	River power plant	River power plant	Intake in reservoir	Intake in reservoir
2	160--0.2	80--<0.1	80--<0.1	80--<0.1	80	150
3	160--0.2	50--<0.1	50--<0.1	50--<0.1	50	0
4	--------	0 x 0	0 x 0	0 x 0	0 x 0	5 m long
5	lacking	lacking	lacking	lacking	lacking	lacking
6						
7						
8	No	No	No	No	No	No
9	Yes	No	No	Yes	No	No
10	15	0	0	6	0	0
11	No	No	No	6 km upstream	No	---------
12	0	0	0	0	----------	0
13	---------	----------	-----------	No	----------	---------
14	0	0	0	0	0	0
15	---------	----------	-----------	-----------	----------	0
16	Icing each 3rd year.			Icing once in every 5 years (can occur at any time day or night).		Prior to the installation of air outlet very deep in the reservoir (air outlet lifts up the warm bottom water to the intake) ice dams appeared downstream of the power station at very low temperatures (-30°C) they can still appear.

	Bergeforsen	Sillre	Järkvissle	Hölleforsen	Stadsforsen	Svarthalsforsen	Hammarforsen
1	River power plant	Intake in reservoir (300 m long canal)	River power plant	Intake in reservoir	Intake in reservoir	River power plant	River power plant
2	450-500--0.5	Max volume 8	250	450	425	Max volume 525	Max volume 460
3	120--0.1-0.2	Max vel. 0.2	100	350	250	Max vel. 0.2	Max vel. 0.3
4	0 x 0	---------	----------	0 x 0	0 x 0	-----------	85 x 15
5	lacking	lacking	lacking	lacking	-----------	lacking	lacking
6					-----------		
7					-----------		
8	No	---------	----------	No	No	No	No
9	No	---------	----------	No	No	Yes	No
10		---------	----------		-----------	0	
11	Yes	---------	----------	----------	No	-----------	No
12	500	---------	----------	----------		0	------------
13	Sometimes in spring.	---------	At freeze-up --at breakup	----------	-----------	In the atmospheric disturbances in the system.	------------
14		---------		----------		-----------	0
15		---------		----------		0	0
16	Ice dams downstream reduce the height of fall by about 0.7-0.8 m.			Ice in gate guards and on sills.	In order to eliminate ice pressure against dam, a lead is kept open next to the dam.	Icing in the mornings 3-6 days a year.	Icing on the intake gates in January 1976. Previously icing has not occurred for about 30 years.

	Gammelänge	Krangede	Stugun	Näverede	Midskog	Mörsil	Järpströmmen	Olden
1	River power plant	River power plant (intake in reservoir)	Intake in reservoir (a river power plant)	Intake in reservoir	Intake in reservoir (river power plant)	Intake in reservoir via 100 m long canal	River power plant	Intake in reservoir
2	400--0.1	400--0.1	Max vol. 600	Max vol. 600	Max vol. 600	150--0.2	180--0.2	Max vol. 34
3	360--0.1	360--0.1	Max vel. 0.2	Max vel. 0.1	Max vel. 0.1	60--0.1	160--0.2	
4	--------	--------	40 x 0-2	40 x 0-2	50 x 2	50 x 25	1000-1500 x 80-300	10 x 6
5	lacking	lacking	--------	---------	lacking	lacking	---------	lacking
6			--------	---------				
7			--------	---------				
8	No	No	--------	No	No	No	No	No
9	No	No	--------	No	No	Yes	No	No
10			--------	---------		---------		
11	No	No	--------	---------	----------	Yes (seldom)	No	No
12	0	0	--------	---------	----------			
13	--------	----------	In connection of break-up.	In connection of break-up.	Late break-up and in connection of switching off.	When discharge is increased.	Very seldom	
14	0	0				---------		
15	0	0				---------		
16		The size of the reservoir (deep) makes the water temperature at the intake stay above +0.04°C.	Icing once since ~~1956~~ ~~since~~ the production started. in 1956			Icing only once ~~1949~~ since the production started. in 1949		

	Storrnorrfors	Pengfors	Harrsele	Bjurfors nedre (lower)	Bjurfors övre (upper)	Tuggen	Hällforsen
1	2500 m canal	Intake in reservoir	Intake in reservoir	Intake in reservoir	Intake in reservoir	Intake in reservoir	Intake in reservoir
2	210--0.5	284--0.1	284--<0.1	284--<0.1	284--0.1	330--<0.1	Max volume 300
3	120--0.3	86--<0.1	86	86	86	165	Max vel. 0.1
4	0 x 0	--------	---------	---------	--------	0 x 0	-----------
5	lacking	lacking	lacking	lacking	lacking	lacking	lacking
6							
7							
8	No	No	No	No	No	No	Yes
9	Yes	No	No	No	No	No	Yes
10	-------						10
11	-------	--------	---------	---------	--------	Each year downstream.	------------
12	-------	--------	---------	---------	--------	3000	------------
13	Before freezing on canal.	--------	---------	---------	--------	--------	------------
14	10	--------	---------	---------	--------	--------	------------
15		--------	---------	---------	--------	--------	------------
16	Icing once every 3-5 years (cold, no precipitation, calm, canal ice free).		Icing has occurred once 20 years ago.			High velocity in the drainage canal causes strong ice production and thereby ice dams downstream (up till 2 m each year).	Icing 5 times since ~~1964~~, ~~since~~ the plant started operation. IN 1964

	Betsele	Balforsen	Rusfors	Grundfors	Stensele	Umtuspen
1	Intake in reservoir	Intake in reservoir	Intake in reservoir	Intake in reservoir	Intake in reservoir	Intake in reservoir via 300 m long canal
2	Max vol. 300	Max vol. 300	160--<0.1	220--<0.1	220--<0.1	250--0-0.2
3	Max vel. 0.1	Max vel.<0.1	100	120	---------	110--<0.1
4	----------	----------	0 x 0	0 x 0	0 x 0	40 x 40
5	lacking	lacking	lacking	lacking	lacking	lacking
6						
7						
8	Yes	No	No	No	No	No
9	Yes	No	No	No	No	No
10	12	----------	------------			
11	----------	----------	no (see notes)	----------	No	No
12	----------	----------	------------	----------	----------	
13	----------	----------	------------	----------	Sometimes in spring.	Sometimes in spring.
14	----------	----------	------------	----------		
15	----------	----------	------------	----------		
16	Icing 4 times ~~since 1965~~, since the plant started operation. In 1965	Icing 3 times ~~since 1958~~, since the plant started operation. In 1958	Swell (surge?) has been caused by leaking gates. Anchor ice has occurred 3-4 km downstream of the station with accompanying loss of water heat?	Sometimes swell forming in leaking gates.		

	Gardikfors	Ajaure	Gejman
1	Intake in reservoir	Intake in reservoir	Intake in reservoir
2	150--<0.1	------------------	23--<0.1
3	150--<0.1	------------------	23--<0.1
4	5 x 15	------------------	------------------
5	lacking	lacking	lacking
6			
7			
8	No	No	No
9	No	No	No
10			
11	No	No	No
12	-------------		
13		------------------	------------------
14		------------------	------------------
15		------------------	------------------
16	Swell (surge) of ice because of leaking gates.	Swell (surge) of ice because of leaking gates.	

	Boden	Vittjärv	Laxede	Porsi
1	Intake in reservoir	River powerplant	River powerplant	Intake in reservoir
2	450--0.1-0.2	450	450--0.3	450--<0.1
3	450--0.1-0.2	450	450--0.3	350--<0.1
4	0 x 0	---------------	0 x 0	0 x 0
5	lacking	lacking	lacking	lacking
6				
7				
8	No	No	No	No
9	Yes	Yes	Yes	No
10	21	---------------	1	
11	No	Yes	----------------	No
12	--------------	---------------		
13	--------------	Ice floe can be sucked under towards the gates.	Do not exist	----------------
14	--------------	---------------	0	0
15	--------------	---------------		----------------
16	Icing 2 times since 1971 when the plant started operations	Risks of considerable ice damming downstream after extensive dredging. Considerable icing problems on intake gates come up each year before freeze-up period.	Icing 1 time since the plant started operating in 1962. (Evening strong snowfall and -10°C). Ice damming has stopped after building of Vittjärv power station.	

	Letsi	Akkats	Randi	Parki	Seitevare	Messaure
1	Intake in reservoir via 100 m long canal.	Intake in reservoir(?)	2100 m canal 480 m tunnel	Intake in reservoir(?) (tunnel & canal).	Intake in reservoir via 210 m long canal	Intake in reservoir via 75 m long canal.
2	330--1.2	330--<0.1	330--1.1	150	110--<0.1	350
3	90--0.3	0	0	150	50	195
4	5 x 30	5 x 20	2000 x 20 (in midwinter the canal freezes up).	20 x 20	0 x 0	15 x 20
5	lacking	lacking	lacking (being constructed)	lacking	lacking	lacking
6						
7						
8	No	No	No	No	No	No
9	No	No	No	No	No	No
10	------------	-------------				
11	No	No	No	No	No	No
12						
13	At the break-up	-------------		Does not exist.	Does not exist.	Does not exist.
14	2	2	-----------			
15	------------	-------------	-----------			
16		In 1974-02-25 the station lost out because ice floes stopped the intake.	Icing in 1976 since the plant started operating.	?		

	Ligga	Harspranget	Porjus	Vietas
1	Intake in reservoir	Intake in reservoir	Intake in reservoir	Intake in reservoir (tunnels)
2	380	350--<0.1	380	350
3	175	205--<0.1	240	0
4	30 x 40	40 x 30	30 x 40	50 x 50 at two tunnel intakes
5	lacking	lacking	lacking	lacking
6				
7				
8	No	No	No	
9	No	No	No	
10				
11	No	No	No	
12				
13	Does not exist.	Does not exist.	Does not exist.	
14				
15				
16				

APPENDIX 4

LENGTH OF THE OPEN-WATER REACH BELOW A DAM OR RESERVOIR:

Report to the State of Alaska,
Department of Commerce Economic Development

by

J. P. Gosink

Geophysical Institute
University of Alaska
Fairbanks, Alaska 99701

May 7, 1984

ABSTRACT

The prediction of the open water length downstream from a dam is an essential safety concern for hydroelectric development in Alaska. This information provides the position of the ice front and determines the stability of that ice front during changes in atmospheric conditions and/or changes in discharge from the dam. During very cold weather (T_{air} < -25°C) the open water reach will be the site of severe ice fog, causing icing on structures, visibility problems, and adversely affecting nearby residents. In addition, the open water reach may eliminate a traditional winter crossing route for man and animals.

In this report we examine different approaches for the prediction of the open water length; they are compared for simplicity, for generality and for accuracy. Formulae for direct application of certain of the models are given in tabular and/or graphical format. Several simple-to-use analytic formulae are given for steady-state and transient boundary conditions. The impact of various complications, including lateral temperature gradients, effects of side streams, water clarity and braided channels, which characterize realistic conditions in Alaskan rivers but which unfortunately are not included in the simpler formulae, are discussed and methods are suggested for the quantitative analyses of these problems. Finally, a finite difference computer program of the transient river temperature distribution for the single channel, constant discharge case is given.

INTRODUCTION

Hydroelectric development in Alaska is proceeding at an accelerating pace. The recently completed hydroelectric projects at Solomon Gulch, Green Lake and Tyee Lake will provide 48.5 megawatts to cities in southeastern Alaska. Other projects either under construction or recommended for construction, including the Susitna site, can provide some 1800 megawatts to the state.

The creation of new reservoirs or the deepening of existing lakes and reservoirs can drastically alter the thermal regime in the lake basin and in the downstream river. Water released from the dam will be warmer in the winter and colder in the summer than under pre-construction conditions. In Arctic and sub-arctic regions the temperature of the outfall water during winter is a critical parameter controlling the length of the open water reach downstream from the dam and the position of the leading ice edge. There is a great deal of concern regarding the length of the open water reach since the released water vapor will cause icing on nearby structures and equipment, and will produce thick ice fog during periods of extremely cold temperatures. In addition traditional winter crossing routes for man and animals would be eliminated by the open water reach.

Several different methods have been used to determine the length of the open water reach. In general these methods could be classified as either statistical or semi-empirical. The first class uses data acquired for many years at a particular site to establish a curve or set of limits for the length of the open water reach as a function of meteorological and discharge parameters. Two examples of this procedure are the analyses of Goryunov and Perzhinskiy (1967) and of Gotlib and Gorina (1974). Only one of the examples of the statistical method shows actual comparisons of the predictions with measured open water lengths. The statistical method is useful only at sites where there exists a long data base for analysis. In addition, the predictions are no longer valid when the hydrology of the reservoir basin and river system are appreciably altered, as for example, by deepening of the reservoir.

The other class of semi-empirical methods for finding the open water length is analytical in the sense that some attempt is made to model the basic physics of the problem. These models vary in the assumptions made, but in general, they utilize a semi-empirical heat balance for the open water reach. A major shortcoming of all the models considered in this report is that none takes the dynamics of the ice cover into consideration; that is, all of the models are primarily thermodynamic. This approach is suitable as long as the ambient conditions (discharge and meteorology) are relatively stable, so that changes in the ice conditions occur relatively slowly. These models are not applicable for example, during a sudden thaw or with a sudden drastic change in discharge.

For stable winter conditions, the analytic models yield reasonably accurate predictions of open water length. Both steady state and transient models are available, and the steady state assumption allows a particularly simple closed form solution to be written for the open water length. In the present report we introduce a closed form solution to the transient problem which is exact whenever the air temperature and/or short wave radiation can be expressed as a sum of sinusoidal terms of arbitrary frequencies - a fairly common case. All closed form solutions are based on the assumption of uniform river hydrology, i.e., constant width, depth, velocity, discharge and specifically, no braided channels or stream inflow. If variations in these parameters are to be included, a finite difference or finite element solution of the governing equations is necessary. An example of this type of finite difference model is given by Ashton (1979). His model allows arbitrary variations in air temperature, and changes in river width and depth and may be modified to improve the surface heat transfer expression or to include the thermal effects of inflowing streams.

The purpose of this report is to summarize and assess models for the prediction of the open water length downstream from a dam in arctic and sub-arctic conditions. We include two statistical models to demonstrate their use and the required data. The primary emphasis is on analytical models which are of general applicability. We explain the derivation of the governing equations and differences in the surface heat transfer expression. Using comparisons with data from sub-arctic rivers, we demonstrate that the Dingman and Assur (1969) version of the "Russian winter equation" for linearized heat exchange provides the best estimate of surface flux. The simple closed form solutions of the heat balance equations are presented for both steady state conditions and for sinusoidally varying air temperatures. These closed form solutions are useful estimates of the open water length when there are no side streams entering the river, and little variation in river width and depth. Finally, for more general applications, we present a finite difference model based on the Ashton (1979) model, which may easily be extended to include heat flux from side streams and heat exchange by the Dingman, Weeks and Yen (1967) formulae. Other complications including water clarity and transverse mixing are discussed quantitatively, and recommendations are made for Alaskan applications.

Classification of Models to Determine the Open Lead Area Downstream of a Power Station

There are two distinct types of models which predict the open lead area downstream of a power station. The first is the totally statistical technique suggested by Goryunov and Perzhinskiy (1967) and by Gotlib and Gorina (1974). All the remaining models discussed in this paper may be classified as semi-empirical models. The models to be discussed are listed for reference in Table 1.

Statistical Techniques

1) Gotlib and Gorina (1974)

Gotlib and Gorina present a graph (Figure 1) which represents the length of the open lead downstream from the Bratsk hydroelectric plant under cold winter conditions (air temp.: Dec. and Jan., - 29°C). D is outflow discharge in m^3/sec, and L is open water length in km. These curves represent the minimum length of the lead; a maximum length of 30-48 km is suggested for warm-winter conditions. Each curve is associated with a specific water outflow temperature at the dam ranging from 1.0°C to 3.0°C with increments of 0.2°C. Apparently winter discharge temperatures at the Bratsk hydroelectric site always vary between 1.0°C and 3.0°C.

From Figure 1, it is evident that the length of the open lead varies directly with reservoir discharge and with the temperature of the outflow water (T_w). No details are given by Gotlib and Gorina (1974) regarding their analysis; furthermore, no comparison with data is given. Although the length of the open water reach increases with the magnitude of the warm discharge and with the temperature of the discharge, neither increase

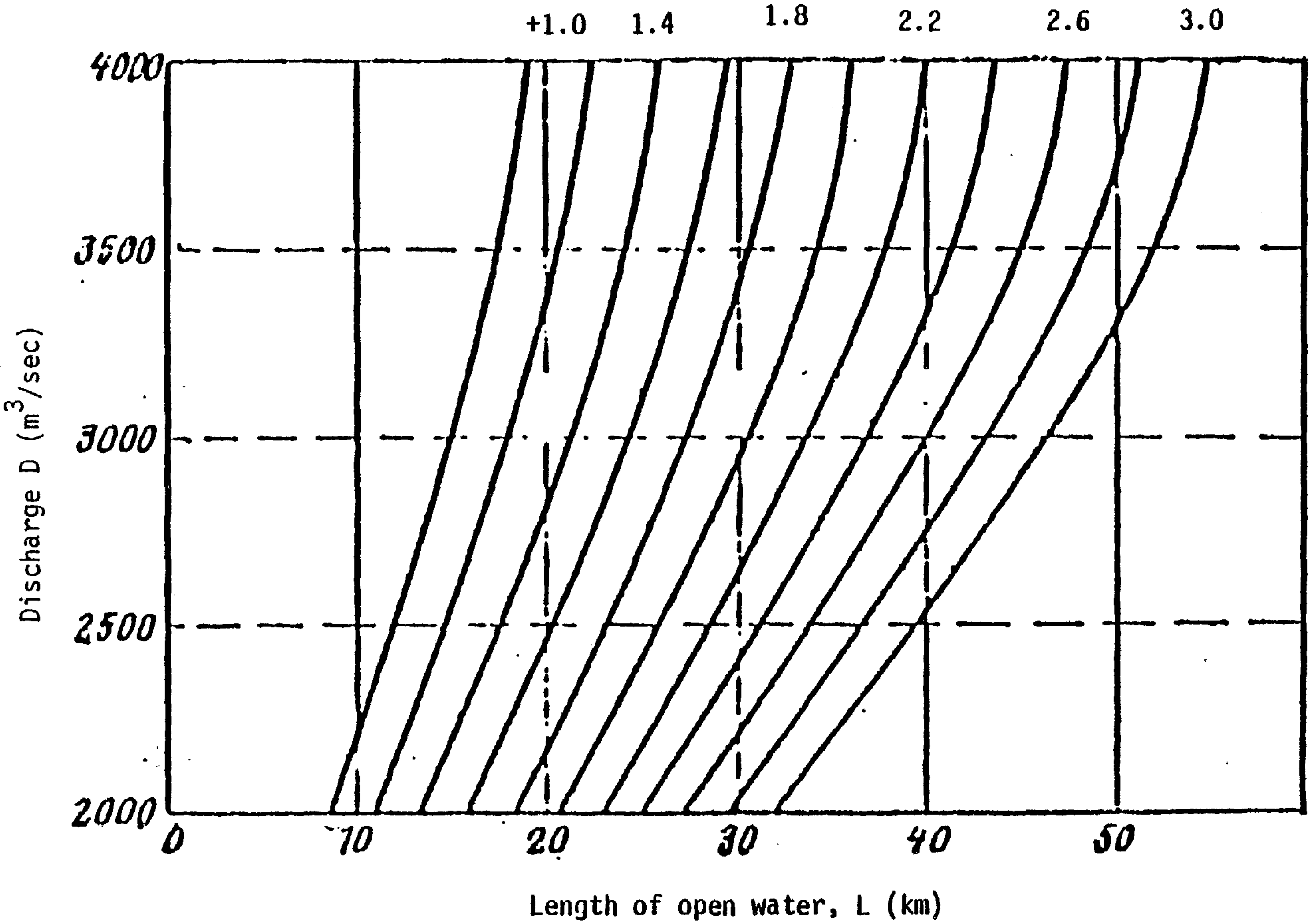


Figure 1. (from Gotlib and Gorina, 1974) Open water length downstream from the Bratsk hydroelectric plant vs. discharge from the dam. The curves represent lines of constant outfall temperature ranging from 1.0°C to 3.0°C in increments of 0.2°C.

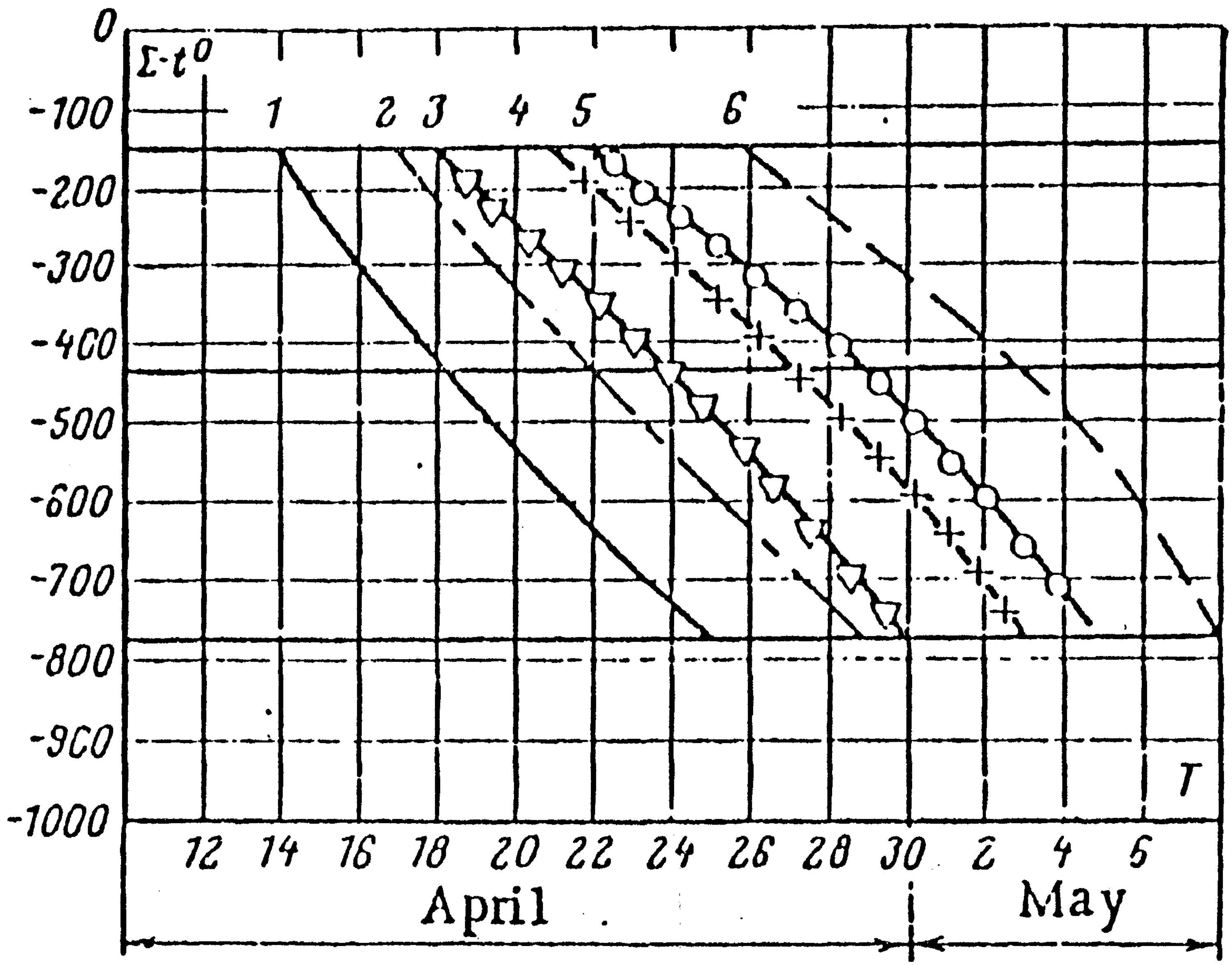


Figure 2. (from Gotlib and Gorina, 1974) Date of the onset of break-up downstream from the Bratsk hydroelectric plant vs. sum of the daily air temperatures during March and April. The curves 1 through 6 represent the following conditions: 1) discharge = 3500 m^3/sec and downstream ice thickness before break-up = 0.6 m; 2) 3000 m^3/sec and 0.6 m; 3) 3500 m^3/sec and 0.8 m; 4) 3000 m^3/sec and 0.8 m; 5) 3500 m^3/sec and 1.0 m; 6) 3000 m^3/sec and 1.0 m.

is linear. This implies that extrapolation beyond the range of the curves is impossible, since the systematic variation of the open water length with these parameters is not provided, nor is any indication of open water length for varying winter air temperatures.

Gotlib and Gorina (1974) also provide graphical information concerning the date of the initiation of ice edge recession (i.e., date of onset of break up) as a function of positive degree days, reservoir discharge, and existing ice thickness (see Figure 2). Parameters for the six curves, discharge and initial ice thickness, are given in the caption. Figure 2 demonstrates that for constant ice thickness, break-up of the ice edge begins 3-4 days earlier when the discharge D = 3500 m^3/sec than when D = 3000 m^3/sec. Furthermore, for constant discharge, say D = 3500 m^3/sec, ice edge recession is delayed 4 days for every 0.2 meter of ambient ice thickness above 0.6 meter.

2) Goryunov and Perzhinskiy

Goryunov and Perzhinskiy (1967) present an empirical curve (see Figure 3) to represent the relation between the length of the open water lead, L, and the sum of the negative degree days. The formula suggested by Goryunov and Perzhinskiy (1967) is:

$$L \text{ (in km)} = 5.5 \cdot 10^6 \, (\Sigma\text{-}T_{air})^{-2} \qquad (1)$$

This formula is applicable to the Lower Volga downstream of the Volgograd Reservoir. Discharge rates and meteorological conditions are not given; thus direct comparison with analytic techniques cannot be made. The data points represent the open lead length for a particular winter as a function of total negative degrees. It is not clear whether this length is a minimum or a winter average. It would be interesting to see whether discharge rates from the Volgograd Reservoir varied during

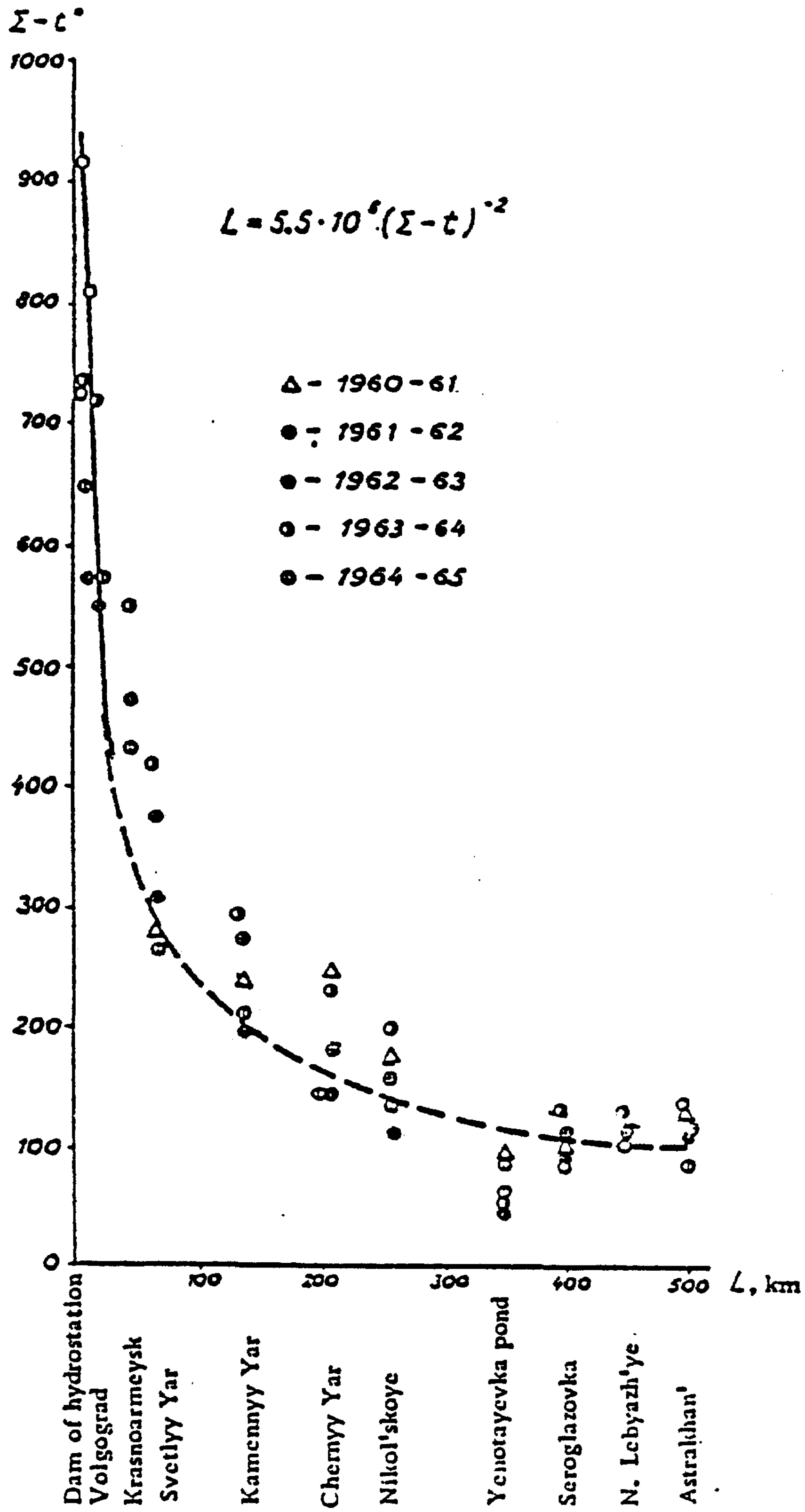


Figure 3. (from Goryunov and Perzhinskiy, 1967) Open water length downstream of the Volgograd Reservoir in km vs. sum of negative degree days. Note that ice covers Yenotayevka Pond with less than 100 degree days.

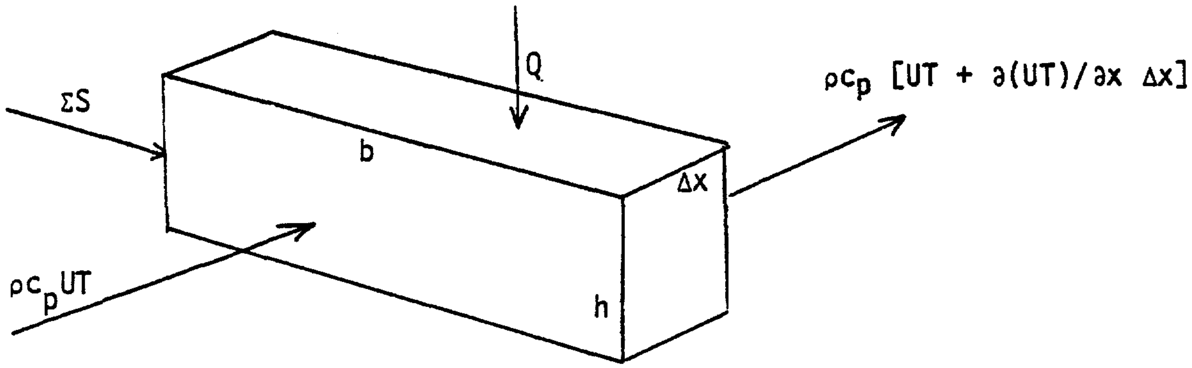
the years of observation, since the analytical models discussed in the following sections all predict a linear increase of open water length with discharge. The data from the Lower Volga suggest that the least variability in open water length occurs during the warmer periods (smaller degree days). Furthermore, local hydrologic effects would appear to play a major role in establishing ice coverage at Yenotayevka pond; although never stated explicitly, it is reasonable to assume that the pond is a wide river reach with slow water velocities.

Finally, it should be noted that the general appearance of the L vs. $-T_{air}$ curve found by statistical methods by the Russian investigators is similar to the theoretical curve predicted by the semi-empirical models. The latter models suggest a relationship of the form $L \propto \ln [1+T_w/-T_{air}]$ for steady-state conditions, and this logarithmic function approaches $L \propto 1/-T_{air}$ when $T_w \ll -T_{air}$.

Statistical models can provide useful guidelines at existing sites where a good data base already exists. They have no predictive value at the site for any major alterations in the reservoir-river system or for weather extremes. They are not useful as predictive tools for the planning of new projects or expansions. These statistical models yield the following qualitative information on open water length: open water length decreases with negative degree days and with decreasing dam water outflow temperature, and increases with reservoir discharge. With respect to the timing of ice cover break-up, the statistical models suggest accelerated break-up with increased discharge and thinner initial ice thickness.

Analytical Techniques

Another approach to finding the open water length involves analysis of the basic physics or thermodynamics of the flow. Consider the thermal balance on a slab of fluid:



Rate of change of heat in the slab	=	Heat convected in	-	Heat convected out	+	Heat flux through top	+	Other heat sources

(1) $\rho c_p\, \partial(hb\Delta xT)/\partial t = \rho c_p hbUT \quad -\rho c_p(hbUT + \partial(hbUT)/\partial x\, \Delta x) \quad + \quad Q\, b\Delta x + \Sigma\, S$

or

(2) $\rho c_p\, [\partial(hbT)/\partial t + \partial(UhbT)/\partial x] = Qb + \Sigma S'$

where ρ is water density, c_p is specific heat, h is river depth, b is river width, T is water temperature, t is time, U is average streamwise velocity, x is streamwise distance, Q is net surface heat exchange [W/m^2], and Σ S' represents the sum of other heat sources including side stream inflow and longitudinal heat diffusion.

Initially we will consider only rivers with constant discharge (Uhb = D = constant), constant width, depth and velocity, and zero stream inflow. Then the governing equation simplifies to:

(3) $\rho c_p h[\partial T/\partial t + U\, \partial T/\partial x] = Q$

All of the analytical models use a simplified form of equation (1), usually equation (3). Q, the surface heat transfer expression, is determined from semi-empirical models for radiative, turbulent, latent and bottom heat exchange; the formulae for Q vary substantially between the different models, and the complexity of the formulae for Q determines whether or not a closed form solution is available for T(x,t). The expressions for Q take three forms: Q is a function of atmospheric parameters only, Q is linearly proportional to the air and water temperature difference, and Q is a complex function of water temperature and atmospheric parameters. Details of the second and third types of expression will be given in subsequent sections. In the following section we discuss models for open water length based on all three types of expressions for Q. We have listed the models in the order of increasing mathematical complexity, i.e., increasing complexity of the functional form of Q. In a subsequent section predictions of the models and field data will be compared to assess their realiability; finally guidelines will be offered for the selection of an appropriate model for a given application.

Asvall (1972)

Asvall (1972) greatly simplifies equation (1) by assuming steady state conditions, constant discharge, river depth and width, and a surface heat transfer expression for Q which depends only on atmospheric conditions. Asvall suggests using the net surface heat loss expression for Q from Devik (1964); this is given in equation 35 of this report and will be discussed subsequently. Since Q is assumed to be a constant (a known function of air temperature and wind velocity), equation (1) may be integrated directly to become,

(4) $\rho c_p U h T_0 / |Q| = L$

where L is the open water length and T_0 is the outflow temperature at the dam. Another way of determining this simple formula for L is by equating the net heat into the river at the dam (= $\rho c_p U h b T_0$) and the net heat lost over the open water area (=QLb). However equation 4 fails to take into consideration the fact that the surface exchange Q is a function of water temperature, time and river location.

In order to incorporate in a simple way the variation of Q with water temperature, various linearized expressions have been determined for the surface heat exchange. A particularly useful linearization formula expresses Q as a linear function of water temperature,

(5) $Q = A + BT$

When an expression of the form of equation (5) is assumed for Q, simple steady state solutions of equation (1) exist, and yield more reliable estimates of the open water length. Consequently, there is no real advantage in using constant values of Q, and a real physical advantage in including water temperature dependency in the formulation of Q.

Dingman and Assur (1969)

Dingman and Assur (1969) introduce a simple steady state analysis for open water length. The major simplification comes from the linearization of the surface heat transfer expression Q, given previously in equation (5) and written in a more general form below as,

(6) $Q = -Q_0 - K(T - T_{air})$

The linear coefficients, Q_o and K, were obtained by analysis of the empirical expressions of Dingman et al. (1967) for net long wave sensible and latent heat flux; net measured short wave radiation should be added to the expression. The coefficients are given as functions of wind velocity and cloud cover in Table 2. With this linearization, the steady state heat balance from equation (3) becomes

$$(7) \quad \rho c_p hU \, dT/dx = -Q_o - K(T - T_{air})$$

and this equation has the closed form solution,

$$(8) \quad T = T_o - [Q_o/K + T_o - T_{air}][1-\exp(-Kx/\rho c_p Uh)]$$

where $T_o = T(x=o)$ is the average well-mixed temperature at the outfall. The temperature of the water decreases exponentially with distance from the outfall, and approaches a theoretical equilibrium temperature ($T_e = T_{air} - Q_o/K$) at $x = \infty$. In actuality the temperature decreases to 0°C at the leading edge of the ice; beyond this distance the expression for surface heat exchange is no longer valid, the water temperature remains 0°C, and heat loss through the ice cover implies ice growth. The position of the zero isotherm, L, can be found by setting T = 0°C in equation (8):

$$(9) \quad L = (\rho c_p Uh/K) \ln [1 + KT_o/(Q_o - K\, T_{air})]$$

Note that the coefficients for atmospheric heat transfer, Q_o and K, are simple functions of wind velocity and air temperature; clearly equation (9) is a very easy-to-use formula for open water length. However, the assumptions required for this derivation should be kept in mind. These include: 1) uniform and constant river discharge, width and depth, 2) constant air tempratures and wind velocity, 3) no inflowing streams,

4) no heat flux from or to the river bottom, 5) applicability of the linearized surface heat transfer expressions. Where these assumptions are violated, an appropriate strategy might be the use of equation (9) as a first estimate of the open water depth, with subsequent analysis of the effects of other parameters. Quantitative discussion of some of these parameters follows in a subsequent section.

Paily, Magagno and Kennedy (1974)

Paily et al. (1974) solve the following version of equation (2),

$$(10) \quad \partial T/\partial t + U\, \partial T/\partial x = Q/\rho c_p h + E\, \partial^2 T/\partial x^2$$

with a linearized heat exchange expression for Q similar to the expression used by Dingman and Assur (1969), but involving different values of the linearization coefficients K and Q_o. In Paily et al. (1974) the coefficients are given in tabular form rather than as functions of wind speed and cloud cover; the coefficients are presented in Table 3 of the present report. The additional term, $E\partial^2 T/\partial x^2$, represents streamwise diffusion of heat. Obviously diffusion is a much less effective mechanism for heat transport in a river than is convection. Nevertheless it is included in this model for completeness and to demonstrate the relative effect of longitudinal diffusion of heat. For steady state cases, Paily et al. (1974) give a closed form solution of equation (10);

$$(11) \quad T = T_o - [(Q_o/K) + T_o - T_{air}][1-\exp\{(Ux/2E)(1-\sqrt{1+4KE/\rho c_p hU^2})\}]$$

This solution was devised earlier by Daily and Harleman (1966). It is important to note that in the limit as E approaches zero, the argument of the exponential term goes to $-Kx/\rho c_p Uh$, exactly as predicted by the Dingman-Assur (1969) model (see equation 8); this can be seen either by

Table 3. Values of Q_0 and K from Paily et al. (1974)

Air temperature, in degrees Celsius (1)	Wind velocity in miles per hour (meters per second) (2)	Relative humidity, as a percentage (3)	Base heat exchange rate, Q_0 in Watts per square meter (4)	Heat exchange coefficient, K in Watts per square meter per degree Celsius (5)
-1.0	11.0 (4.95)	70.0	16.25	31.40
-3.0	11.0 (4.95)	70.0	65.35	32.50
-5.0	1170.0 (4.95)	70.0	114.67	33.58
-10.0	11.0 (4.95)	70.0	239.39	36.22
-15.0	11.0 (4.95)	70.0	366.96	38.77
-18.0	11.0 (4.95)	70.0	445.27	40.28
-5.0	0.0 (0.0)	70.0	23.04	16.67
-5.0	3.7 (1.65)	70.0	53.59	23.30
-5.0	7.4 (3.30)	70.0	84.13	27.94
-5.0	11.0 (4.95)	70.0	114.67	33.58
-5.0	14.7 (6.60)	70.0	145.22	39.21
-5.0	18.4 (8.25)	70.0	175.76	44.85
-5.0	11.0 (4.95)	10.0	171.79	34.25
-5.0	11.0 (4.95)	30.0	152.75	34.02
-5.0	11.0 (4.95)	50.0	133.71	69.80
-5.0	11.0 (4.95)	70.0	114.67	33.58
-5.0	11.0 (4.95)	90.0	95.64	33.35
-5.0	11.0 (4.95)	100.0	86.12	33.24

[a]Values valid for range of water temperature between 0°C and 5°C; values of other meteorological variables are: barometric pressure = 996.0 mb; cloud height = 3,275 ft (1,000 m); cloud cover = .6; and visibility = 1.87 miles (3 km).

applying L'Hopital's rule or by expanding the square root with the binomial expansion. The latter procedure yields the following series for the argument,

$$(12)\quad (Ux/2E)\ \{-2(KE/\rho c_p hU^2) + 2\ (KE/\rho c_p hU^2)^2 - 4(KE/\rho c_p hU^2)^3 + \ldots\ \}$$

This series shows that the diffusion term lessens the longitudinal temperature decrease, producing a slightly longer open water length. The tempering effect of the diffusion term can also be seen directly from equation (10) when it is noticed that the second derivative term is positive definite in these problems.

A closed form expression for the open water length can be written as follows,

$$(13)\quad L = (\rho c_p Uh/K)(1/2 + \sqrt{1/4 + KE/\rho c_p hU^2})\ln[1 + KT_o/(Q_o - K\ T_{air})]$$

Here the effect of the diffusion term on the open water length is immediately apparent. Clearly when $E << 4\rho c_p hU^2/K$ there is very little increase in open water length. Numerical estimates of this increment for typical Alaskan conditions will be given in a subsequent section. Note that if E is small, then differences between values of L calculated by the Paily et al. (1974) formulae and the Dingman and Assur (1969) formulae will depend primarily upon the linearization coefficients, K and Q_o, in the respective formulae.

Paily et al. (1974) also provide a closed form solution for the transient case of equation (10) for linearized surface heat exchange and particular initial boundary conditions. However the specific initial and boundary conditions assumed by these authors are not appropriate for the temperature regime for water released from a dam. Paily et al. (1974)

are interested in the temperature regime in a flowing river with a heat source at $x = o$ in which the entire river including upstream ($x < o$) is subject to atmospheric heat transfer. That is to say, the water arriving at $x = o$ from upstream is changing temperature due to atmospheric forcing. The application of the Paily et al. (1974) model is to temperature prediction in a river with a thermal effluent injected at $x = o$. Therefore they assume that the boundary temprature $T(x = o, t)$ is not constant, but instead, equals the sum of the inflow temperature T_0 plus the transient river response to uniform atmospheric heat transfer. This boundary condition is not appropriate for the water released from a dam. Water released from the dam is at a constant temperature since this water comes from depth below the ice cover, and reservoir water under the ice cover has very little if any diurnal temperature variation. During breakup or during intense wind mixing, or when alternative outlets from the dam are used, the released water temperature will vary, but the released water temperature cannot be predicted from a simple river temperature model. It is essential that a reliable reservoir temperature model be used to define the outflow temperature. In the present analysis we consider the outflow temperature as given either through measurements or by prediction from a reservoir model.

Other analytic solutions

An interesting and useful analytic solution can be found for the problem of the transient response of the river to periodically varying meteorological conditions. The meteorological condition may represent diurnal variation in air temperature and/or short wave radiation, or alternately, seasonal climatic variation. The formal statement of the problem consists of the governing equation (equation 3) with the atmospheric heat transfer expression as follows,

(14) $Q = - Q_o - K(T-T_{air}) + \tilde{Q} \sin \omega t$

with the initial conditions,

(15) $T(x,o) = T_o - [(Q_o/K) + T_o - T_{air}][1-\exp(-Kx/\rho c_p Uh)]$

Note that this initial condition has the expected behavior at x = o, i.e., $T(x = o, t) = T_o$, the constant outflow temperature. Furthermore, the initial condition is actually the steady state temperature for the case when $\tilde{Q} = 0$. The solution then defines the transient river response to sinusoidal atmospheric forcing. The analytic solution to this problem is,

(16) $$T = T_o - [(Q_o/K) + T_o - T_{air}][1-\exp(-kx/Uh)] + \Delta T \{\sin(\omega t-\beta) - \exp(-kx/Uh) \sin (\omega t-\omega x/U-\beta)\}$$

where $k = K/\rho c_p$

$\Delta T = \tilde{Q}/\rho c_p \sqrt{k^2+\omega^2 h^2}$

and $\beta = \sin^{-1} [\omega h/\sqrt{k^2+\omega^2 h^2}]$

The form of the solution highlights the role played by the periodic air boundary conditions. If $\tilde{Q} \equiv 0$, or a constant air temperature is assumed, the solution reduces to the steady-state case. When $\tilde{Q} \neq 0$, the periodic nature of the temperature distribution in the river becomes evident. The river temperature lags the air temperature by the phase angle β. This phase lag is directly proportional to river depth and inversely proportional to the surface heat loss coefficient, matching the intuitive expectation for river temperature adjustment to air temperature variation. That is, shallow rivers ($h \rightarrow 0$) cool faster than deeper rivers with the same discharge, and rapid heat transfer ($k >> 0$), which occurs for example with high winds, is characterized by rapid temperature adjustment. An estimate of the typical diurnal adjustment time lag for winter conditions may be found by assuming reasonable values for K, ω and h: $\omega = 2\pi/(24 \cdot 3600)$ s^{-1}, h = 3 m, and $k = 7 \cdot 10^{-6}$ m/sec. This value of k corresponds to a coefficient of T_{air} in the Dingman-Assur formula (Table 2) equal to 30 W/m^2. These parameters suggest a daily time lag between air and water of about 5.8 hours during winter conditions. A similar estimate can be made for a seasonal time lag when an annual period is assumed for the air temperature; this estimate suggests a time lag of about 5 days.

A still more general transient solution may be found for the case where the atmospheric heat transfer can be represented by a sum of periodically varying terms of arbitrary frequency and magnitude. This boundary condition may represent the combination of diurnal and seasonal variation in air temperature, and in short wave radiation or other parameters, or it may represent a complex transient surface heat flux determined from measured values by harmonic analysis. For this general case the heat transfer expression is,

$$(17) \quad Q = -Q_o - K\,(T - T_{air}) + \sum_{i=1}^{N} \tilde{Q}_i \sin(\omega_i t + \Theta_i)$$

and the initial conditions are given by equation (15). The analytic solution is,

$$(18) \quad T = T_o - [(Q_o/K) + T_o - T_{air}][1 - \exp(-kx/Uh)]$$
$$+ \sum_{i=1}^{N} \Delta T_i \{\sin(\omega_i t + \Theta_i - \beta_i) - \exp(-kx/Uh)\sin(\omega_i t + \Theta_i - \omega_i x/U - \beta_i)\}$$

where $\Delta T_i = \tilde{Q}_i/\rho c_p \sqrt{k^2 + \omega_i^2 h^2}$

and $\beta_i = \sin^{-1}[\omega_i h/\sqrt{k^2 + \omega_i^2 h^2}]$

Each phase β_i can be calculated independently, and each phase lag is directly related to the period of the respective heat flux fluctuation. The amplitude of the periodic temperature waves in the river, ΔT_i is inversely proportional to the forcing frequency; i.e., short period fluctuations in air temperature are hardly felt in the river and longer period fluctuations are strongly impressed upon river temperature. In all cases, the amplitude of periodic temperature waves in the river is inversely related to river depth, and if river depth is very small, that amplitude approaches the amplitude of air temperature variation $(\tilde{Q}_i/K)$.

Finally, a slightly more general transient solution may be found for the case where the atmospheric heat transfer varies in a known way as a polynomial function of river distance. This boundary condition may represent a spatially varying air temprature because of lapse rate, weather pattern, or systematic change in radiative heating. For this general case the heat transfer expression is,

$$(19) \quad Q = -Q_o - K(T - T_{air}) + \sum_{i=1}^{N} \tilde{Q}_i \sin(\omega_i t+\theta_i) + \sum_{i=1}^{M} q_i x^i$$

where q_i represent the known longitudinal variation, and the initial conditions are given by equation (15). The analytic solution is given by equation (18) plus a linear summation from the longitudinal variation:

$$(20) \quad T = T_o - [(Q_o/K) + T_o - T_{air}][1-\exp(-kx/Uh)]$$

$$+ \sum_{i=1}^{N} \Delta T_i \{\sin(\omega_i t+\theta_i-\beta_i)-\exp(-kx/Uh)\sin(\omega_i t+\theta_i-\omega_i x/U-\beta_i)\}$$

$$+ \sum_{i=1}^{M} q_i x^{i+1}/(i+1)\rho c_p Uh$$

This solution is the most general closed form expression for the temperature regime downstream from a dam when the surface heat transfer has been linearized. Allowable functional forms for the surface heat transfer (equation 19) can be quite general including differing periodicity of air temperature and radiation, as well as combinations of diurnal, seasonal and episodic events and arbitrary persistent longitudinal variation.

None of the transient analytic solutions for temperature (equations 16, 18 or 20) can be directly inverted to determine open water length since the equations are transcendental. However the temperature regime can be easily calculated as a function of x and t, and, for a particular time, the open water length determined directly.

It is important to remember the limitations of all the analytic models. First, none of the analytic thermal models include latent heat exchange with an ice cover and are therefore only useful for river temperatures above or equal to 0°C. They can be directly applied only in uniform river stretches, i.e., with no variation in river width, depth and velocity and no inflowing streams. The allowable heat transfer functions, although reasonably general, are based on linearized analysis of higher order surface heat transfer expressions, and the appropriateness of the linearizations must be considered. In the following section we shall consider semi-empirical formulae for surface heat expressions, and discuss some assumptions involved in the linearization of these formulae. Measurements of open water length in typical Alaskan conditions will be compared with predictions from the different linearization expressions.

Heat Transfer Expressions

Dingman, Weeks and Yen (1967) provide a very extensive analysis of the mechanisms of heat transfer to a flowing stream. These authors consider the following eight heat transfer terms:

(21) $Q = Q_R + Q_B + Q_E + Q_H + Q_S + Q_G + Q_{GW} + Q_F$

where Q_R short wave radiative flux

Q_B net long wave exchange with the atmosphere

Q_E evaporative heat exchange

Q_H sensible or turbulent heat flux

Q_S heat lost by influx of snow

Q_G heat added by geothermal transfer

Q_{GW} heat added by ground water

Q_F heat added by friction from stream bottom

The expressions for each of these terms are given in Table 2. Dingman et al. (1967) were particularly interested in the selection of appropriate expressions for Q_E and Q_H in arctic and sub-arctic conditions. They compared the formulae of Kohler (1954) and of Rimsha and Donchenko (1957) to cold region data and determined that the "Russian winter equation" as given by Rimsha and Donchenko (1957) was the more accurate of the two formulae. We have included both the Kohler (1954) and the Rimsha and Donchenko (1957) formulae for Q_E and Q_H in Table 2 for comparison.

More recent formulae for water-atmospheric heat transfer have been given by the Tennessee Valley Authority (1972), Hicks (1972), Pond et al. (1974), and Holmgren and Weller (1968); however, the first three of these were devised primarily for temperate regions, and all four were devised for deep water. McFadden (1974) presented a comprehensive comparison of heat transfer formula with measurements for arctic conditions; the reader is referred to that report for details of the comparisons. In this report we shall not attempt to compare in detail the formulae for heat transfer mechanisms given by each author. Instead we shall make recommendations for both the full empirical formulae and for the linearized versions of these formulae based on our calculations and those of Dingman et al. (1967) and of McFadden (1974). In all these discussions the units of heat flux, Q, are W/m^2.

Q_R: Short wave radiation

Short wave radiation is always positive and represents a relatively small component of the heat budget of Alaskan rivers in winter. McFadden (1974) cites several references which report the daily flux of short wave radiation near 65° latitude to be less than 5 W/m^2 in December. Wendler (1980) gives the average measured short wave radiative flux as less than 5 W/m^2 during November, December and January. This contrasts with lower latitudes where the short wave radiation is often the dominant mode of heat transfer to a water surface (e.g., see Fischer et al. 1979). Because of the reliability and simplicity of short wave radiometer systems, it is recommended that short wave radiation be measured directly at the site, and the measured values used in the calculations for open water length. In the linearization formulae, Q_R can be added directly to the heat flux terms.

If short wave radiation measurements are not available, then the following estimation procedure modified from Dingman et al. (1967) is recommended:

(21) $Q_R = 0.892\ Q_{RI} + 1.397 \cdot 10^{-4}\ Q_{RI}^2$ $[W/m^2]$

and

$$Q_{RI} = Q_{CL} \, (0.96 - 0.61C) \qquad [W/m^2]$$

where C is cloud cover in tenths (e.g., complete cloud cover implies C = 1.0) alnd Q_{CL} is incoming short wave radiation for a cloudless sky. Q_{CL} may be found for various latitudes as functions of season in tablular and graphical form (see TVA, 1972 and Bolsenga, 1964).

A distinctive feature of the short wave radiation flux is the fact that it is not completely absorbed at the water surface; it penetrates to some depth depending upon the water clarity and turbidity. The short wave flux available at a depth y is usually assumed to follow Bouger's Law for absorption:

$$(22) \quad Q_R \, (y) = Q_R \, (y{=}o) \, \exp \, (-\eta y)$$

where η is an extinction coefficient ranging from about 0.2 m^{-1} for very clear water to 4.0 m^{-1} for turbid water. This implies that in a very clear shallow stream with depth equal to 1 meter, only 20% of the short wave radiation is absorbed by the water column, and the remaining 80% penetrates into the river bottom. At night some of this stored heat flux is released into the water column, implying an increase in geothermal heat flux Q_G which lags the short wave flux. In sediment laden streams η may be even larger than 4.0 m^{-1}, and therefore virtually all short wave radiation is absorbed in the topmost meter of the water column. In order to reliably model the bottom flux it would be necessary to couple the river temperature model to a ground thermal model. However, due to the fact that Q_R in late fall is only a minor component in the thermal budgets for high latitude rivers, it is uaually possible to ignore heat absorption in the river bottom. In any case the main effect of bottom heat absorption on river temperatures would be a lag in the diurnal temperature maximum of the river or a slower decrease in river temperature in the evening. Quantitatively Q_R will represent less than 5% of the overall river heat budget from late fall through early spring; therefore the lagged release of heat from bottom sediments may equal 4% of the river heat budget in clear streams. In this report we will not propose a mathematical model which couples predictions of the ground thermal regime to predictions of water temperatures. For rivers deeper than 2 meters and in sediment laden streams, we recommend assuming that Q_R is entirely absorbed by the river, unless it is critical at the particular site to determine the diurnal variation in water temperature. For clear shallower streams we recommend that an experimental study be undertaken to determine the diurnal lag in river temperature due to gradual release of stored radiative heat in the river bottom.

Q_B: Net long wave radiation exchange with the atmosphere

Net long wave exchange with the atmosphere consists of the outgoing long wave radiation emitted from the water surface Q_W plus the net incoming radiation from the atmosphere Q_A:

$$(23) \quad Q_B = -Q_W + Q_A$$

The net long wave exchange may be measured directly at the site. If these measurements are not available, then the long wave exchange may be estimated by semi-empirical formulae relating Q_B to water and air temperatures. The radiation from the water surface is modeled by the Stefan formula,

$$(24) \quad Q_W = \varepsilon_W \sigma (T + 273)^4$$

where ε_W is the emissivity of water (=0.97), σ is the Stefan-Boltzman constant ($5.67 \cdot 10^{-8}$ W/m^{2}K^4) and T is the surface water temperature in °C. This formula is widely accepted in the literature and is recommended here.

There has been some speculation that at the time of ice formation a thin supercooled layer of water may exist on the river surface. While this assumption may be valid in quiescent ponds, it has been shown to be unfounded in turbulent rivers (Osterkamp et al., 1983). For rivers with mean velocity greater than about 0.6 m/sec the surface water temperature may be assumed to be equal to the mean river temperature.

Usually the atmospheric radiation can be modeled by a Stefan formula

(25) $Q_A = f(e,C,H,\alpha)\ \sigma\ (T_{air} + 273)^4$

where f is a function of air vapor pressure (e), cloud cover (C), cloud height (H), absorptivity of the water surface (α) and T_{air} is the air temperature in °C at a specific height, usually 10 meters. McFadden (1974) has discussed various expressions for f in some detail, and proposed a complex formula especially for cooling ponds which includes an additional dependency on the cooling pond shape factor. McFadden (1974) also compared long wave radiation data at a site with ice fog with the predictions of long wave radiation determined by the formulas of Brunt (1944), Ångstrom (1920), Elsasser (1942) and Andersen (1952), and used a correlation technique to modify these formula and thereby improve the agreement with the data. We recommend McFadden's (1974) modified version of the Andersen (1952) formula. The Anderson equation (1952), both in the original format and in the modified version, exhibited the minimum standard error of all those investigated. The Andersen equation (1952) was also adopted in the Dingman, Weeks and Yen (1967) river thermal model. The modified version of the Andersen equation is:

(26) $$Q_A = [.814 + .11C \exp(-.19H) + e_a (.0054 - .000594\ C \exp(-.197H))]\ \sigma\ (T_{air} + 273)^4$$

where H is cloud height in km and e_a is vapor pressure of the air in mb.

Q_E: Evaporative heat flux, Q_H: Turbulent heat flux

Semi-empirical formulae for turbulent heat flux are usually written in the form,

$$(27) \quad Q_H = (A + Bw)(T - T_{air})$$

where w is wind speed, and A and B are empirically determined parameters. There is an extensive core of literature related to the determination of A and B (e.g., Friehe and Schmitts, 1976; Kohler, 1954; Rimsha and Donchenko, 1957; TVA, 1972; Hicks, 1972; Kays, 1966). The form of the equation models the intensification of convective or turbulent heat transfer by strong winds and increased temperature difference between the air and water. In addition, the parameter A assures upward heat transfer from a water surface which is warmer than the air even when the wind velocity is small. This situation frequently occurs in interior Alaska where air temperatures 30° below water temperatures may exist with no wind. Under these conditions the air is buoyantly unstable, and strong vertical motion in the form of thermal plumes or buoyant convective cells may develop, facilitating surface heat transfer.

Evaporative heat loss Q_E occurs when there is a net upward transport of vapor from the water surface; the heat loss is the product of the specific heat of the vapor and the evaporation rate. There is extensive literature on evaporative heat loss (e.g., Hicks, 1972 and 1975; TVA, 1972; Friehe and Schmitt, 1976; Anderson, 1954; Pasquill, 1949; Rimsha and Donchenko, 1957; Devik, 1964). It is usually assumed to be linearly proportional to the air-water specific humidity difference and is modeled by equations of the form,

$$(28) \quad Q_E = (C + Dw)\ (e - e_{air})$$

where w is wind speed, C and D are empirically determined parameters, e is the saturated vapor pressure of air at the temperature of the water, and e_{air} is the vapor pressure of the air at a specific height, usually 10 meters. It should be noticed that the transfer of water vapor or any gas across the water surface is a complex problem and the subject of intense recent research (e.g., see Brutsaert and Jirka, 1984).

Dingman et al. (1967) and McFadden (1974) reviewed several models for Q_H and Q_E, and compared the predictions of these models with data from arctic conditions. Both concluded that the Rimsha-Donchenko (1957) formulae for Q_H and Q_E more accurately predicted turbulent and evaporative heat exchange in arctic conditions than did other models under consideration. The Rimsha-Donchenko formulae are given here:

(29) $$Q_H = [3.87 + 0.17\,(T - T_{air}) + 1.89\,w\,]\,(T - T_{air})$$

(30) $$Q_E = [6.04 + 0.264\,(T - T_{air}) + 2.94\,w\,]\,(e - e_{air})$$

where Q_H and Q_E are in W/m^2, w is wind speed in m/sec, T is water temperature, e is saturated vapor pressure at T, T_{air} is air temperature at 2 meters, and e_{air} is vapor pressure at 2 meters.

<u>Q_S, Q_G, Q_{GW} and Q_F</u>

For the four types of heat transfer, Q_S, Q_E, Q_{GW} and Q_F we follow the recommendations of Dingman et al. (1967).

Latent heat exchange from snow Q_S is proportional to the snow accumulation rate $\dot{A}$:

(31) $$Q_S = c\dot{A}\,[\lambda + C_i\,(T - T_{air})]$$

where $\dot{A}$ is given in g/cm day, λ is the latent heat of fusion of ice in cal/g, C_i is the heat capacity of ice in cal/g °C, and c is a dimension conversion constant c = 0.484 [$W/m^2 \div cal/cm^2$ day]. If snow accumulation rate is not available, then $\dot{A}$ may be estimated as a function of visibility by an expression of the form (Mellor, 1964):

$$\dot{A} = 7.85\ v^{-2.375} \tag{32}$$

where v is visibility in km. For consistency the river discharge should be increased by $\dot{A}$ times the river width, although the net change in discharge would be very small.

Q_G is the geothermal heat flux below the river plus heat released from bottom sediments and must be determined from local data. The geothermal flux is expected to be small except possibly in areas of high geothermal flux (Osterkamp, Kawasaki and Gosink, 1983). As discussed earlier some of the daily short wave radiation Q_R may penetrate through the river and be absorbed into the river bottom. This stored heat may then be released later in the day, thus delaying the diurnal river temperature decrease. Accurate knowledge of this effect can only be established by analysis which couples temperature distribution in the river with temperature distribution in the bottom sediments. The effect will not be significant (< 4% of total heat flux) for rivers deeper than 1 meter with extinction coefficient greater than about 0.2 m^{-1}. If it is essential to determine the diurnal temperature regime in a very shallow and clear stream, then a more complex coupled analysis of river and sediment temperature is necessary.

As a general rule, where there are no indications of high geothermal heat flux, where the river is deeper than about 2 m, and where the short wave extinction coefficient is greater than 0.2 m^{-1}, the total geothermal flux Q_G may be considered negligible.

Q_{GW} is the heat added by flow of ground water and smaller streams into the river. In order to model this heat flux, information is needed on both the ground water recharge or stream discharge and the temperature of the inflowing water. Note that Q_{GW} affects both the right hand and left hand sides of equation (3), by changing the heat input and the river discharge respectively. If stream inflow and temperature measurements are known, these may be incorporated into the model by relatively small changes in the finite difference form of equation (3).

Q_F is the heat added to the river due to friction of the water flowing over the river bottom. It is generally assumed that the decrease in potential energy in the river as it flows downhill is compensated for by the frictional drag at the bottom; subsequently, the drag creates turbulent eddies which, through the turbulent energy cascade, ultimately cause viscous heating. The major problem with this assumption is the neglect of the wall (river bottom) temperature, since if the river bottom is colder than the bulk river temperature, frictional heating will be directed downward into the sediment (Schlichting, 1968). Therefore, the model for frictional heating suggested here and in Dingman et al. (1967) or Starosolszky (1970) should be considered an upper limit to heat flux by frictional heating of the river.

The relation between bottom shear stress and the change in potential energy of a volume of water is given by standard hydraulic theory (Henderson, 1966). The shear stress at the river bottom is,

(33) $\tau_w = \rho_w ghS$ [kg/m-sec^2]

where ρ_w is water density in kg/m^3, g is the gravitational constant in m/sec^2, h is river depth in m, and S is the slope of the water surface. Then the heat flux generated by this stress is (Ince and Ashe, 1964),

(34) $Q_F = U \tau_W = \rho_W g U h S$

For steep rivers both U and S may be high, suggesting that frictional heating may be a significant fraction of the total heat transfer Q. For example, for h = 3m, U = 2m/sec and $S = 10^{-3}$, $Q_F \simeq 60$ W/m^2, and for water at 0°C, the long wave radiative flux $Q_W = 305$ W/m^2. Even if it is assumed that half the frictional heating is directed upward into the water, Q_F represents at least 10% of the long wave radiation and therefore should be included in the total budget. It should be noted that Dingman et al. (1967) suggest that Q_F is insignificant while Starosolszky (1970) recommends that Q_F be included in the heat budget. Q_F is relatively easy to estimate for a given river reach, and its magnitude may be included in the governing equation (equation 3) as an additive constant, posing no real complication to the solution of the governing equation. We suggest including Q_F when the river slope is greater than about 10^{-4}.

Linearization formulae

The long wave radiation from the water surface (equation 24) and the turbulent heat flux (equation 29) depend nonlinearly upon water temperature; due to this fact an analytic solution of equation 3 is generally not available. However, it is possible to solve equation 3 when all heat fluxes are expressed as linear combinations of water temperature and other parameters, as demonstrated by the solutions given in equations 4, 8, 11, 16, 18 and 20. Therefore, several authors have determined linearized forms of several terms in the heat budget, specifically Q_B, Q_H and Q_E. It is assumed that since the remaining heat flux terms, Q_R, Q_S, Q_G, Q_{GW} and Q_F are not dependent upon water temperature, their cumulative effect is equivalent to an additive constant in Q, i.e., they are simply added to the linearization constant Q_o in equation 6:

$$(6) \quad Q = Q_R + Q_S + Q_G + Q_{GW} + Q_F - Q_o - K\,(T - T_{air})$$

Using regression techniques, Dingman and Assur (1969) determined the following expressions for Q_o and K:

$$(35) \quad Q_o = \begin{cases} 50.93 + 11.21\,w & \text{(clear sky)} \\ -35.28 + 4.40\,w & \text{(cloudy sky)} \end{cases} \qquad K = \begin{cases} 16.99 + 2.05\,w & \text{(clear sky)} \\ 17.97 + 2.22\,w & \text{(cloudy sky)} \end{cases}$$

where w is wind speed in m/sec (the height of the anemometer was not given), and the units of Q_o are W/m^2 and of K, W/m^2-°C. These expressions are linearizations of the Dingman et al. (1967) heat flux formulae for long wave radiation, and turbulent and latent heat flux (see equations 24, 26, 29 and 30).

Other linearization expressions include formulae derived specifically for a reach of the St. Lawrence River by Pruden et al. (1954):

$$Q_B + Q_H + Q_E = -\,88.91 - 7.5\,T_{air} - 20.87\,(T - T_{air})$$

and the formulae given by Asvall (1972) and adapted from Devik (1964):

$$(36) \quad Q_o = \begin{cases} 136.05 + 2.09\,w & C = 0.0 \\ 77.38 + 2.09\,w & C = 0.5 \\ 23.00 + 2.09\,w & C = 1.0 \end{cases} \qquad K' = \begin{cases} 12.59 + 1.63\,w & C = 0.0 \\ 9.44 + 2.41\,w & C = 0.5 \\ 10.92 + 2.05\,w & C = 1.0 \end{cases}$$

where C is cloud cover and K' multiplies $- T_{air}$ (°C) instead of $T - T_{air}$ (°C) as in equation (6).

Paily et al. (1974) also determined empirical fits to the Dingman et al. (1967) formulae for Q_B, Q_H and Q_E by a least squares polynomial approximation technique. Values of Q_0 and K determined by Paily et al. (1974) are given in tabular form in Table 3. These coefficients differ from the set given by Dingman and Assur (1969) and there are two reasons for the differences: 1) values of Q_0 and K from equations (35) are not dependent on air temperature while the Paily et al. (1974) coefficients are, and 2) the Paily et al. (1974) coefficients were selected as best fits over the range of air temperatures $-18°C < T_{air} < 0°C$, while the coefficients in equation (35) were selected as best fits over the range of air temperatures $-50°C < T_{air} < 0°C$. This latter effect becomes critical for application to Alaskan rivers. Although the Paily et al. (1974) expressions for Q_0 and K are reliable within their range of applicability, they deviate from the complex Dingman et al. (1967) formulae when air temperatures are substantially below -18°C.

Since only discrete values of Q_0 and K are given in the Paily et al. (1974) report, we have determined the following interpolation formulae which agree with their tabular values with a maximum deviation of 1.7% and an average deviation less than 0.5%.

$$(37)\quad K = 14.795 + 3.45\,w - 1.11 \cdot 10^{-2}\,q + .540|T_{air}| - 1.12 \cdot 10^{-3}|T_{air}|^2$$

$$Q_0 = -32.796 + 18.513\,w - .952q + (24.290-K)|T_{air}| + 4.016 \cdot 10^{-2}|T_{air}|^2 + 2.696 \cdot 10^{-5}|T_{air}|^4$$

where w is wind speed in m/sec, q is humidity in % (100. is saturated), and T_{air} is air temperature in °C. Note that K must be calculated first, since it is used in the evaluation of Q_0.

The linearized heat transfer from equations 35, 36 or 37 represents QS the sum of long wave radiative exchange plus evaporative and turbulent heat flux, as given by the approximate expression:

$$QS = Q_W - Q_A + Q_H + Q_E \cong Q_o + K\ (T_W - T_{air})$$

Both left and right hand sides are functions of T_W the water temperature. The agreement between the different linearization formulae and the "exact" formulae may be tested for an appropriate range of river temperature and atmospheric conditions. We shall plot both sides of the expression for the range of values, $1.0 < T_W < 4.0$, with the terms Q_W, Q_A, Q_H and Q_E calculated from equations 24, 26, 29 and 30 respectively and Q_o and K from equations 35, 36 and 37. In Figure 4, we assume zero wind velocity and clear sky or zero relative humidity. The "exact" values of QS (as given by equations 24, 26, 29 and 30) are shown for air temperatures $T_{air} = \{0, -10, -20, -30, -40\}$ by the vertical braces. (Note that in some cases the vertical braces have been shifted slightly left or right for clarity). Since the Devik (1964) formula (equation 36) is not a function of water temperature, only a single value of QS may be plotted at each air temperature. The Dingman and Assur (1969) expressions or equation 35 yield the range of QS denoted on Figure 4 by the solid bar; and the Paily et al. (1974) expressions or equation 37 yield the range of QS denoted by the open bar. There is a clear tendency for equation 37 to diverge from the exact solution, becoming less accurate as the air temperature decreases below -20°C. Equation 36 (from Devik (1964)) also diverges from the exact solution with decreasing air temperature. The Dingman and Assur (1969) expression or equation 35 provides the best overall estimate of the exact solution.

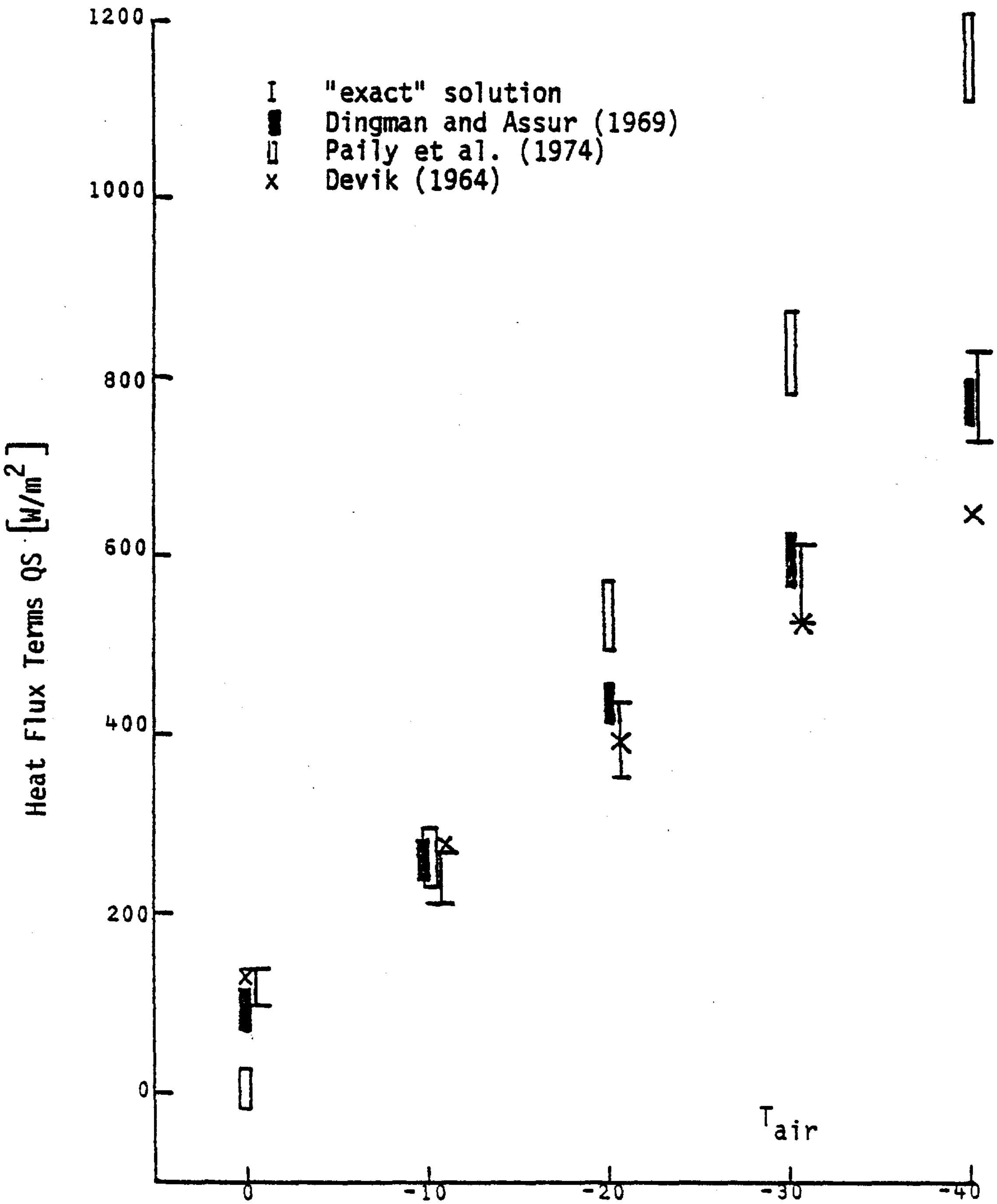


Figure 4. Comparison of complete heat flux equations with linearized approximations for zero wind velocity.

In Figure 5, we assume a wind velocity of 10 m/sec and clear sky or zero relative humidity. Again the Dingman and Assur (1969) expression or equation 35 provides the best overall agreement with the exact solution, keeping pace with the intense heat transfer associated with high wind-low air temperature. The Devik (1964) expression consistently underestimates the heat transfer rate, and the Paily et al. (1974) expression diverges from the exact solution beyond about -15°C. The Dingman and Assur (1969) expressions or equation 35 are significantly more accurate than the others at low air temperatures.

Comparison with Data: Example 1

Studies of ice-free reaches downstream from a warm discharge seldom contain complete meteorological and hydrological conditions. For example, Carlson et al. (1978) do not report air temperature, wind velocity, cloud cover or radiation data. However, this information is sometimes available from local weather records. The information should be acquired from weather stations as close as possible to the study site to minimize errors in the determination of heat loss and whenever possible, at the study site. Carlson et al. (1978) specify that the data were recorded at the MUS Power Plant in Fairbanks during December 1971. Thus, referring to Fairbanks meteorological reports for this period, it is possible to calculate heat loss with the different linearization models, and then to compare calculated and measured open water areas. In particular we wish to compare the linearization formula of Dingman and Assur (1969) (equation 35), Asvall (1972) (equation 36), and Paily et al. (1972) (equation 37) and the analytic solutions for river temperature as given by equations 4, 9 and 13.

For the month of December 1971, discharge rates for the Chena River and the MUS Power Plant are approximately 800 ft^3/sec and 25 ft^3/sec respectively.

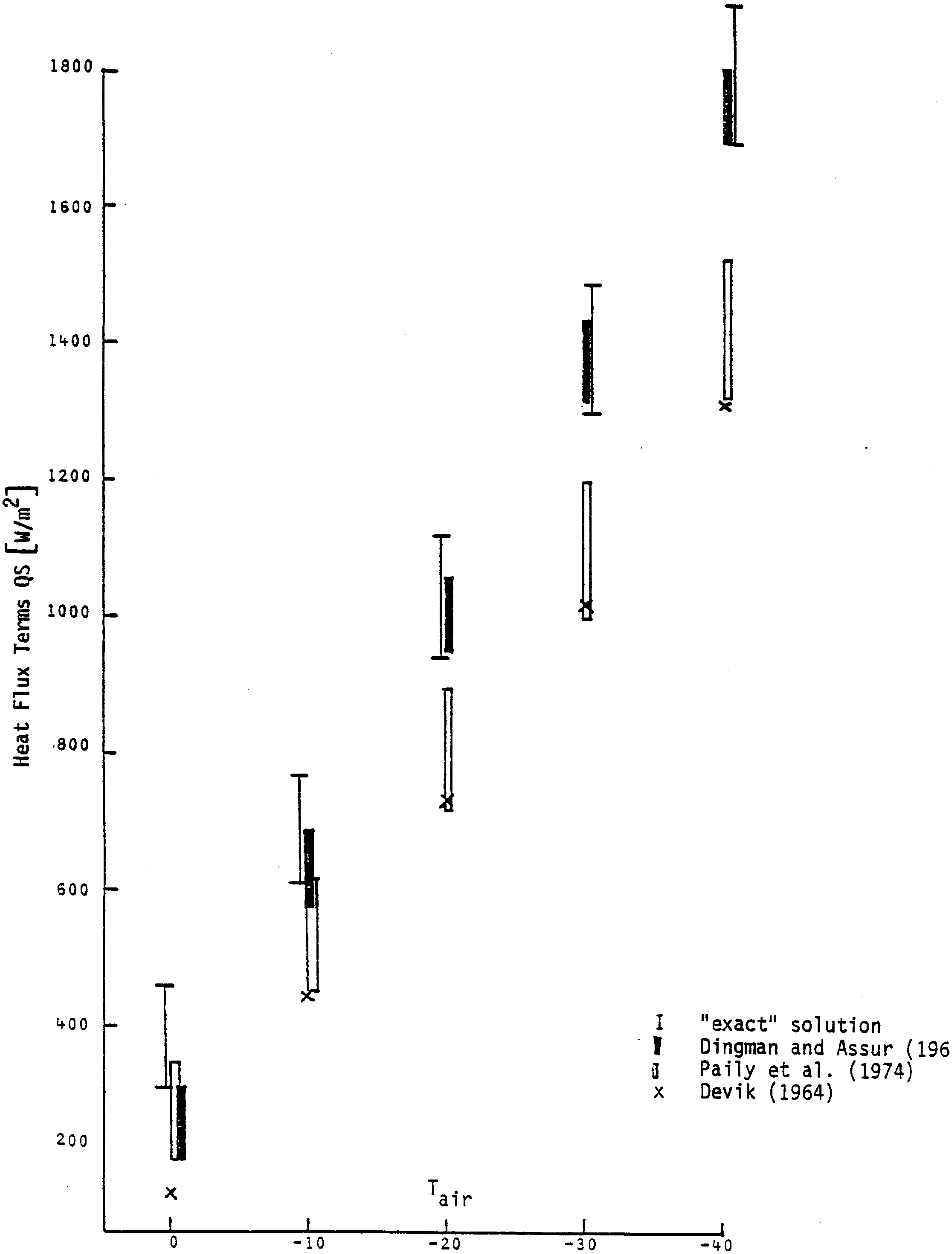


Figure 5. Comparison of complete heat flux equations with linearized approximations for wind velocity = 10 m/s.

If complete mixing near the discharge is assumed, the effective temperature rise becomes:

$$T_o = 10° \ (25/800) = 0.31°C$$

when the effluent temperature is 10°C.

The MUS Power Plant uses two different types of discharge. The first and more conventional mode of discharge is the subsurface diffuser. When this technique is employed, there is considerable turbulent mixing near the diffuser. Consequently, mixing may be assumed to be complete, and the one-dimensional assumption implicit in the models is appropriate. Measurements of the open water length in the Chena when the subsurface diffuser was in use in December 1971 indicated an ice-free area of 15 acres (Carlson et al., 1978).

Measurements of the open water length were also made when the second type of discharge, the surface dispersion field, was in use. In this mode, the effluent enters the stream at the surface through a series of pipes with little turbulent mixing. Hence, the dispersion field operates as a surface spreading scheme. Heat transfer is rapid, since heat loss is proportional to the temperature differences between the water and the air. As expected, the surface dispersion scheme produces smaller ice-free area; in December 1971; average areas of 8 acres were measured. The surface dispersion field is characterized by strong vertical and lateral temprature gradients. The existence of steep temperature gradients invalidates the assumptions implicit in the one-dimensional models, indicating that comparisons of prediction schemes with existing data are appropriate for only the subsurface diffuser.

Fairbanks weather data for the month of December 1971 was compiled by the Environmental Data Service, National Oceanic and Atmospheric Administration.

Average temperature for the month was -21°C; wind speed, 3.7 mph = 1.65 m/sec; cloud cover, 0.7. Air temperature was about normal for December, and cloud cover, heavier than normal. We have used the above values of the mean air temperature, wind speed, and cloud cover in each of the linearization formulae (equations 35, 36 and 37) and have determined the parameters Q_o and K listed in Table 4. For equations 35 and 36, interpolation between cloud covers of 5 and 10 was required. Equation 37 contains no functional dependence on cloud cover but is dependent upon humidity, which, for this test case was assumed to be 10%. There is a surprising lack of agreement of the calculated values of Q_o and K between the different models, particularly between the Dingman and Assur (1969) and the Paily et al. (1974) formulae which both represent linearizations of the Dingman et al. (1967) formulae. However it is encouraging to note that the open water areas predicted by these two expressions are in good agreement and bracket the measured open water length of 15 acres. The Paily formula is somewhat sensitive to the selection of humidity, and when a humidity of 90% is assumed, the predicted open water area is 16.6 acres or identical with the Dingman and Assur (1969) prediciton. We have determined the open water area for the Paily (1974) model using E = 4.51 m^2/sec which is the value recommended by Paily et al. (1974) and E = 0 to test the sensitivity of the longitudinal diffusion term; as expected the difference is negligible. It should be noted that 4.51 m^2/sec is about twice the value of the longitudinal dispersion coefficient calculated by using the Fischer et al. (1978) expression for dispersion coefficient. As previously suggested, longitudinal diffusion of heat becomes important only for slow rivers, in particular for conditions in which the ratio $KE/\rho c_p U^2 h$ is about 0.1 or greater (see equation 13). For this example when E = 4.51, the ratio is $2 \cdot 10^{-5}$. Whenever the ratio

Table 4. Calculations for Example 1
(measured open water area = 15 acres)

Model	Equations for length	Equations for Q_o, K	Q (W/m^2) equation 6	Q_o (W/m^2)	K (W/m^2 °C)	E (m^2/sec)	Area 10^4 m^2	Area Acres
Asvall (1972)	4	36	-348.22	59.08	13.77	-	8.71	21.51
Dingman and Weeks (1969)	9	35	-447.46 + 21.25 T	1.214	21.25	-	6.73	16.62
Paily et al. (1974)	13	37	-521.27 + 31.22 T	-134.35	31.22	4.51	5.76	14.24
Paily et al. (1974)	13	37	-521.27 + 31.22 T	-134.35	31.22	0	5.76	14.24

$KE/\rho c_p U^2 h$ is less than 0.1, we recommend the simpler Dingman and Assur (1969) formula for open water length (equation 9) over the Paily et al. (1974) formula (equation 13).

Comparison with Data: Example 2

Data from W.A.C. Bennett Dam on the Peace River in British Columbia can also be used to compare the accuracy of the various models. Measurements of open water length downstream from the dam are available for the winters of 73/74, 74/75, 75/76, 76/77 and 77/78 (British Columbia Hydro and Power Authority, personal communication), with the length varying between 60 and 203 miles during these years. However, it is difficult to apply the theoretical models for open water length directly to the Peace River data for several reasons related to the assumptions implicit in the models: 1) the models (equations 4, 9 and 13) are all steady state cases, implying both steady discharge and meteological parameters; 2) the Peace River meanders in the region of interest and a typical river width is difficult to determine; 3) the closest meteorological data come from Fort St. John about 15 miles downstream from the dam, and meteorological data from this location often disagree substantially with data from the next downstream source, Peace River some 60 miles from the dam.

Nevertheless it is useful to determine rough estimates of the open water length for the five winters by using "mean" meteorological and hydraulic parameters at the site. Discharge and average outflow temperature are known (British Columbia Hydro and Power Authority, personal communication). We assume a constant river width of 200 meters. A mean air temperature is probably the most subjective choice since it is not clear whether the period of averaging should include the entire winter or a specific period proceeding the time of the minimum open water length. We have chosen a degree day method to determine the mean air temperature. Using the measured air temperatures from Fort St. John assembled by British Columbia Hydro we divide the maximum accumulated degree days by the number of degree days; these "mean" air temperatures are listed in column 4 of Table 5. The minimum measured open water length and the measured average winter discharge (Nov-Feb) were provided by British Columbia Hydro. We have determined mean winter wind velocity and cloud cover from the Meteorological Data for Canada. Humidity was not available, but we have assumed a constant 10% throughout the winter which may be slightly high considering the cold air temperatures at the site. Using this combination of averaged meteorological and hydrological data, we determined Q_0 and K according to equations 35, 36, and 37 and applied the heat loss coefficients to the appropriate models of open water length, i.e., we used equations 36 and 4 to determine open water length according to Asvall (1972); equations 35 and 9 according to Dingman and Assur (1969); and equations 37 and 13 according to Paily et al. (1974) with E set equal to 0.0. These calculated open water lengths appear in columns 8, 9 and 10 of Table 5. Clearly the Asvall (1972) formulae consistently overpredicts open water length. The Dingman and Assur (1969) and the Paily et al. (1974) formulae are in substantial agreement, as should be expected considering that both heat loss formulae are linearizations of the earlier Dingman et al. (1967) equations. It appears that equation 35 is in better agreement with the data than equation 37, with the former yielding an average deviation from measured open water length of 13 miles and the latter, an average deviation of 15 miles. However, considering the assumptions employed in determining an "average" air temperature, wind speed, discharge etc., the difference is not significant. It is worth noting that the Asvall (1972) formulae overpredicts open water length both in this example and in the earlier example, and that equations 35 and 37 predict the same trend in open water length as is found in the measured open water length.

TABLE 5 - Example 2; Peace River

Year	Measured Open Water Length (miles)	Measured Discharge (m^3/sec)	Mean Air Temperature (°C)	Mean Wind Velocity (m/sec)	Cloud Cover	Humidity (%)	Calculated Open Length (miles) with Heat Loss Expression From Eq. 35 Dingman & Assur	36 Asvall	37 Paily
73/74	60	1201.3	-14.7	4.01	.70	10	72.7	90.6	72.0
74/75	103	1581.5	-9.7	5.22	.62	10	120.3	142.9	123.5
75/76	98	1213.4	-10.1	4.91	.70	10	94.0	112.9	94.5
76/77	203	1572.3	-5.0	5.71	.63	10	190.9	214.8	185.2
77/78	102	1725.2	-12.4	3.9	.62	10	120.5	146.5	120.8

Based on the two examples for the Chena River and the Peace River, we recommend either the Dingman and Assur (1969) heat loss expressions (equation 35) or the Paily et al. (1974) expression (equation 37) when a simplified version of surface heat transfer is to be used and when the air temperature is warmer than -19°C. Since the Paily et al. (1974) formulae have not been tested below about -21°C, and since they were derived explicitly for temperatures greater than -19°C, we suggest using equation 35 exclusively whenever air temperatures below -19°C are possible.

Finite difference methods

In the foregoing sections of this report, we have primarily examined steady state and analytic models for the temperature regime in a river. These are important tools for environmental assessment for known meteorological forcing. That is, for design purposes when only the large scale hydrologic conditions and climatic variability are known, the analytic models provide useful estimates of the expected open water length. However for operational purposes on a day to day basis, a finite difference on finite element model is needed to simulate the site specific variations in river hydrology, and variations in discharge and meteorology.

General finite difference models for arbitrary surface heat loss have been given by Dingman, Weeks and Yen (1967), by Ashton (1979), and more complicated models for coupled hydrodynamic and thermodynamic analysis have been given by Chaudry et al. (1983) and Bowles et al. (1977). The first model is for steady state conditions and therefore, except for allowing the non-linear surface heat transfer expressions (see equations 26 and 29), offers no real advantage over the analytic models when reliable linearization formulae are used (e.g., equations 35 and 37). The coupled hydrologic thermal models of Chaudry et al. (1983) and Bowles et al. (1977) represent a very sophisticated approach to the analysis of river temperature. However, at this time we do not recommend this level of modeling for application to Alaskan rivers due to the scarcity of the necessary hydrological data. It should be noted that in order to simulate continually varying discharge it is necessary to use the coupled hydrologic thermal models; for gradually changing discharge the thermal models described in this report should give reasonable estimates of the water length. Furthermore, if a coupled hydrologic thermal model were to be used it is essential that the surface heat transfer expressions be based on formulae appropriate for arctic conditions as discussed earlier. It would be necessary to change the thermal portion of the model to follow the suggestions given earlier for surface heat transfer. The finite difference model from Ashton (1979) allows daily variations in meteorology and local variations in river width and mean velocity. Variations in discharge, both from changes at the dam and from stream inflow downstream are not included in the Ashton (1979) model; ice dynamics are also not included. However, the Ashton (1979) model provides a useful framework for the study of transient effects, and is easily modified to include a variety of site specific adaptations. A copy of the Ashton (1979) computer model is included in Appendix A. In the present section, we shall briefly describe the model, its limitations and assumptions and discuss refinements which could be included.

The Ashton (1979) model is a numerical solution of equation 2 in which the width b, depth h and mean velocity U are allowed to vary with downstream distance x; Q the surface heat exchange is calculated according to a simplified air temperature-wind velocity formula, and no other heat transfer terms S' are included. The river discharge (D = Uhb) is assumed to remain constant over the calculation period. The simulations are done in a

Lagrangian reference frame, following a fluid parcel downstream; therefore downstream distance steps are set internally depending on local velocity.

The inclusion of local river geometry in terms of variable U, h and b is clearly an improvement over analytic models in which these terms are held constant. This feature is important for the heat balance since the net heat loss is directly proportional to river width b. Presently, Ashton (1979) assumes that the river hydrology h(x), b(x) and D are known, and calculates U(x) locally assuming a rectangular basin. In principle, any measured river width and depth distribution, including the total river width in a braided section of the river, may be used as data. The extension of the model for alternate basin geometry (e.g., trapezoidal or multi-channel) is straightforward requiring only the inclusion of a flag variable to define basin geometry at each subreach (alter statement 40 in the model to define area discharge relation and statements 10 and 20 to define the basin geometry flag).

In its present form, the model features a simplified expression for Q which is calculated daily based on mean air temperature and wind velocity. For application to Alaskan rivers we recommend using the linearized expressions from Dingman and Assur (1969) (see equation 35). These expressions are only slightly more complicated than those in the Ashton model, and programming changes to the model would be minimal (alter statement 87).

If small streams enter the main channel, they will increase river discharge and alter the thermal balance. In principle, this effect can be handled by solution of equation (1) in which the other heat sources are the known stream input in terms of stream water and ice discharge and water temperature. The solution procedure will "step downstream", and a new increased discharge calculated for the next calculation reach. As a practical matter, information on small stream discharge, temperature and particularly ice content, is usually not available. In addition, if the stream inflow is at a different temperature from the river, it will also be at a different density, and subsequently will not mix instantaneously with the main flow. However, a reasonably good literature exists regarding theoretical and field examinations of transverse mixing in rivers, and a rough estimate can be made of the distance required for complete transverse mixing. If this distance is substantially less than the estimated open water length (from equation 9), then the thermal effects of inflowing streams can be simulated by adding discrete heat and mass sources to the governing equations at the appropriate locations. If the mixing distance is of the same order as the open water distance, then a two-dimensional model involving downstream convection of heat and cross-stream diffusion of heat must be used. An example of such a two-dimensional model is given by Ashton (1979) and is listed in Appendix B.

The determination of whether a two-dimensional model is required hinges on the estimate for transverse mixing length L_t. Transverse mixing for open channel flow is determined by the transverse mixing coefficient ε_t where $\varepsilon_t = chU_*$ and h is depth, U_* is friction velocity and c is a scale constant (Fischer et al., 1978). Ashton (1979) assumes $c \approx 0.2$, but a more recent compilation of typical values suggests $c \approx 0.6$ is more appropriate for the winding rivers characteristic of Alaska. Diffusion theory predicts that a passive tracer will diffuse as $(\text{time})^{1/2}$:

$$\sigma = \sqrt{2\varepsilon t}$$

where σ^2 is the variance of the diffusion and ε is the appropriate diffusion coefficient. Fischer et al. (1979) suggest that a reasonable criterion for substantially complete transverse mixing is when the tracer is diffused to within 5% of its mean value everywhere on the cross-section. Assuming a Gaussian distribution for the tracer, this occurs when $\sigma \approx 0.5b$ where b is river width. The time required for this to occur following a fluid parcel is $T_t \approx \sigma^2/\varepsilon_t = 0.25\ b^2/\varepsilon_t$, and the downstream distance travelled is $L_t = T_t U = .25b^2U/\varepsilon_t = 0.25\ b^2U/(.6U_*h)$. Since a reasonable approximate value for $U_* \approx 0.1U$, we have

(38) $L_t = 4b^2/h$

As a rule of thumb, the river and side stream inflow are well mixed at the distance L_t. If this distance is the same order of magnitude as L the estimated open water length from equation 9, then a two-dimensional model is necessary. If on the other hand $L_t \lesssim 0.1\ L$, a one-dimensional model is acceptable.

Assuming that $L_t \ll L$ for all small streams entering the main river, a procedure could be devised to alter the one-dimensional Ashton model (1979) to include these additional thermal sources. The simplest way to do this appears to be: first, make discharge a variable (alter statements 8, 12, 15, 30, 40) in particular defining the subreach velocity by the reach characteristics (statement 40 becomes U(J) = DISCH(I)/(SB(I)* SD(I))), and second, define a new variable giving the temperature increment from the small stream and insert it where the subreach characteristics are defined, say after statement 46. It would be of the form TINC(J) = TINFL(I)*(DISCH(I) -DISCH(I-1))/DISCH(I), and TINFL is temperature of the stream water. This would have the effect of adding the additional heat only where the stream enters and weighting it proportional to the stream discharge. Finally, the third step would require that TINC(J) be added to the local temperature, by altering statement 80 to read TWOUT(J) = TWOUT(J) + DELTW + TINC(J). A few additional alterations would be required to change format statements, and to zero unaffected TINC(J), etc.

A discussion of the Ashton (1979) finite difference model is incomplete without reference to the two modes of thermal equilibrium used in the model. The first mode states that length of the open water reach is coincidental with the position of the zero degree (°C) water temperature. This is the mode that has been assumed throughout this report, and is implicit in the analytic solutions (see equations 9 and 13). The Ashton model uses this definition ($T_w(L) = 0°C$) to define L when the ice cover is newly forming or melting.

When an ice cover is already present, an alternative criterion for ice edge position is adopted in the Ashton (1979) model which is referred to as the equilibrium criterion. The equilibrium criterion is derived from the heat balance equation through the ice cover:

$$(39) \quad (T_m - T_{air})/(n/k_i + 1/h_{ia}) - h_{iw}\,(T_w - T_m) = \rho_i\,\lambda\,dn/dt$$

where n is ice thickness, T_m is the melting point ($T_m = 0°C$), T_{air} is air temperature, T_w is water temperature, k_i is thermal conductivity of the ice, ρ_i is ice density, λ is the heat of fusion and h_{ia} and h_{iw} are the ice/air and ice/water heat transfer coefficients respectively. This equation in turn is derived from the energy balance at the water/ice interface:

$$(40) \quad \phi_i - \phi_{wi} = \rho_i\,\lambda\,dn/dt$$

where ϕ_i is the heat flux by conduction through the ice and ϕ_{wi} is the heat flux from the water to the ice. It is assumed that $\phi_i = \phi_{ia}$ where ϕ_{ia} is the heat flux from the top surface of the ice to the atmosphere. The equilibrium criterion for the leading edge of the ice is determined from the condition that $n = dn/dt = 0$ in equation (39). This condition then defines the equilibrium temperature of the water at the leading edge:

(41) $T_{we} = -h_{ia}/h_{iw}\ T_{air}$

Clearly T_{we} is not in general equal to 0°C; in fact, $T_{we} < 0$ whenever $T_{air} > 0$ and $T_{we} > 0$ whenever $T_{air} < 0$. The first condition is clearly meaningless and therefore in the model the equilibrium criterion is inoperative whenever $T_{air} > 0$; the more standard zero isotherm criterion is adopted for the position of the ice edge if $T_{air} > 0$. The equilibrium criterion is used in the model only when a presently existly ice edge is growing or decreasing in length and the air temperature is less than zero; under all other conditions including the first formation of the ice, the zero isotherm criterion is used.

There are several basic problems associated with the use of the equilibrium criterion. This criterion is determined from equation 40 with the additional assumption that the conductive heat transfer through the ice exactly balances an expression for ice/atmosphere heat transfer. It should be noted that: 1) equation 40 neglects the possibility of surface melt, defining all melting on the water/ice interface; 2) the expression used for conductive heat transfer across the ice is the steady state linear formula ($\phi_i = -k_i T_s/n$ where T_s is the top surface temperature of the ice) which is not realistic during a period of ice growth or decay; 3) the expression used for the ice/atmosphere heat transfer ϕ_{ia} is a simple linearization formula ($\phi_{ia} = h_{ia} (T_s - T_{air})$) and thus ϕ_{ia} effectively ignores effects of melt puddles and short wave radiative exchange; 4) equating ϕ_{ia} to conductive heat transfer ϕ_i is a questionable assumption, particularly when the ice is wet and T_s is close to 0°C while $T_{air} << 0$ °C; and finally, 5) there are no data available which would indicate that the equilibrium criterion is actually an improvement on the zero isotherm criterion.

The zero isotherm criterion may be implemented as the only criterion by the following program modification. Between statements 105 and 106 add the statement,

```
IF (ETA(J).GT.0. .AND. TWOUT(J).GT.0.) ETA(J) = 0.
```

Finally, note a correction to the Ashton model; statements 103 and 104 should be reversed.

Conclusions

This report has reviewed several approaches to the problem of the determination of the length of open water downstream from a dam or thermal source in winter.

Open water lengths have been predicted by several Russian studies by statistical approaches based on local data, and are appropriate only for particular locations. More general types of analyses for rivers were introduced by Asvall (1972), Dingman, Weeks and Yen (1967), Paily et al. (1974) and Harleman (1972). These analyses are based on semiempirical formulae for the rate of heat transfer from an open water surface to the atmosphere by evaporation, radiation and sensible heat transfer, and possibly including infiltration of ground water and frictional effects. The heat transfer expressions are applied to the one-dimensional equation for conservation of thermal energy in the river, yielding solutions which predict temperature in the river. Since the formulae for radiative heat transfer are non-linear functions of water temperature, in general numerical methods must be used to determine temperature distributions in the river. However, there are several "linearized" versions of the surface heat transfer expressions, including those by Paily et al. (1974) and by Dingman and Assur (1969). The application of these linear heat transfer expressions greatly simplifies the mathematics involved in the determination of river temperatures, and in fact, allows closed form analytic solutions to be found for a limited number of boundary conditions. The most obvious of these analytic solutions is the steady-state case, given by Dingman and Assur (1969) and defined in this report by equation 9.

We compared the steady-state solution with measured ice-free area in the Chena River and in the Peace River for three linearizations of the surface heat transfer expressions: Dingman and Assur (1969); Paily et al. (1974); and Asvall (1972). The linearizations given by Dingman and Assur (1969) and by Paily et al. (1974) were based on the "Russian winter equation" of Rimsha-Donchenko (1957) and produced the best agreement with the data. However, since the Paily et al. (1974) linearization formulae were derived primarily for air temperatures greater than -19°C, the Dingman and Assur (1969) formulae given by equation 35 are recommended.

Paily et al. (1974) found an additional analytic solution, the transient response of an intially uniform river temperature distribution to a given temperature increment at x = o, with constant air temperature and solar radiation. In equation 20 of this report we introduce a new analytic solution, the transient response of river temperature to periodic air temperature and/or solar radiation. The latter analytic solution provides information on the phase lag between atmospheric forcing and river response, indicating that this lag increases with increasing river depth and decreases with surface heat loss rate and is independent of river width. This closed form solution also includes the effects of spatially varying air temperature and therefore, provides a general model for temperature prediction in rivers with uniform flow and uniform cross-sectional area. Another important use of this transient analytic solution is for comparison with numerical models. Since the analytic solution is exact, it provides a reliable gauge for the accuracy of finite difference or finite element models, thus providing confidence in the applicability of these models.

General finite difference models for arbitrary surface heat loss and changing river basin geometry have been given by Dingman et al. (1967), Ashton (1979), Chaudry et al. (1983) and Bowles et al. (1977). For general applicability in Alaskan rivers where the hydrological data base is sparse, we recommend the Ashton (1979) finite difference model for river temperature analysis. The model predicts the transient response of water temperature for constant discharge, spatially varying cross-sectional area, and temporally varying air temperature and discharge temperature. We have discussed several refinements to Ashton model including arbitrary (non-rectangular) cross-sectional area, the implementation of the Dingman and Assur (1969) heat transfer expressions, heat flux from small streams and an alternative criterion for leading ice edge position. Any of these modifications may be rather simply applied to the Ashton (1979) model.

None of the models discussed in this report are applicable when river discharge is changing drastically. In this case, ice movement and ice front position is a mechanical-hydrodynamic problem, only slightly affected by thermal changes. At this time there is no reliable theoretical or numerical model available for ice front behavior with rapid changes in discharge. For clear strategic reasons, field measurements of these events are rare. In this report we have reviewed the thermodynamic models which are appropriate only for gradually changing discharge when the ice conditions and water temperatures are controlled by the discharge temperature and the local meteorology. Comparisons with data indicate that under these conditions, the appropriate thermodynamic models yield realistic estimates of open water length.

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Table 1 - Models of open water area

1) Statistical Models

Investigator	Relationship for open water area
Gotlib and Gorina (1974) Godrotekhnicheskoe Stroitel'stvo, No. 11	1) Graphical relationship between length of open water (L), reservoir discharge (D) and temperature of discharge (T_w) $L = f(D, T_w)$ for cold winters 2) For warm-winter conditions, one specific $L = f(D)$ 3) Graphs for transient response of location of ice edge under warming conditions $L(t)/L(t=o) = f(D, n_i, \Sigma\text{-}T_{air})$ where n_i = ice thickness, T_{air} = air temp. (Note: This graph is not well labeled. The location of the ice edge is not defined clearly. Only qualitative information regarding the effects of variation in D and n_i may be discerned).
Goryunov and Perzkinskiy (1967) Soviet Hydrology; Selected Papers, Issue No. 4	$L = 5.5 \cdot 10^6 (\Sigma - T_{air})^{-2}$ L gives the transient location of ice edge since $\Sigma - T_{air}$ sums over all negative degree days

2) Semi-Empirical Models

Investigator	Surface Heat Loss Definition	Relationship for Open Water Area
Asvall (1972) Proc. of Banff Symposia on the role of snow and ice in hydrology	Tabular values heat loss (Q), as a function of cloud cover (C), wind velocity (w) and air temp. (T_{air}); $Q = f(C, w, T_{air})$. Q can be formulated, $Q = a_o + a_1 T_{air}$ where a_o, $a_1 = f(C,w)$	Area (Lb) times surface loss (Q) equals heat input from reservoir $LbQ = R_o$ $L = R_o/Qb$

Investigator	Surface Heat Loss Definition	Relationship for Open Water Area
Paily, Magagno, Kennedy (1974), Jrnl. of Hydraulics Div., ASCE	$Q = -K (T-T_E)$ where K is a surface exchange coefficient T is local water temperature T_E is "equilibrium temp"., water temp. at which there is no exchange of heat across the water surface with the atmosphere.	Solves the one-dimensional partial diff. equation for conservation of thermal energy. It is assumed that $T = T(x,t)$ only, and the equation is integrated over a cross-sectional area. Since a linear relation is assumed for Q, the equation may be solved analytically, yielding an expression $T = T(x,t)$
Dingman, Weeks, Yen (1967), CRREL Res. Rpt. 206	Q = non-linear function of T, T_{air}, w, e, D, S where new variables are e = evaporation pressures D = discharge S = river slope or Q = non-linear function of T, T_{air}, w, D, S	Numerically integrates the one-dimensional, steady-state partial differential equation for conservation of thermal energy assuming negligible longitudinal diffusion.
Dingman, Assur (1969) CRREL Res. Rpt. 206 Part II	$Q = Q'_o + K (T - T_{air})$ Q'_o and K from regression analysis of the non-linear function in Dingman et al. (1967).	Closed form solution of one-dimensional steady-state ordinary differential equation (linear) for conservation of thermal energy.

Table 2 - Surface Heat Transfer Definitions

Investigator	Surface Heat Transfer Expressions in W/m^2
Asvall (1972)	Cloud cover = 0.0, $Q = 136.05 + 2.09\,w + (12.59 + 1.63\,w)\lvert T_a$ = 0.5, $Q = 77.38 + 2.09\,w + (9.44 + 2.41\,w)\lvert T_{air}$ = 1.0, $Q = 23.00 + 2.09\,w + (10.92 + 2.05\,w)\lvert T_a$ where $Q = [W/m^2]$, $w = [m/sec]$ $T_{air} = [°C]$
Paily, Macagno, Kennedy (1974)	Graphs of ε and η for $Q = \varepsilon T + \eta$ where $\varepsilon = \varepsilon\,(T_{air}, w, R.H)$ $\eta = \eta\,(T_{air}, w, R.H)$ and R.H. = relative humidity It is assumed that barometric pressure = 99.6 mb cloud height = 3,275 ft cloud cover = 6 visibility = 1.87 miles
Dingman, Weeks, Yen (1967)	$Q = Q_R - Q_B - Q_E - Q_H - Q_S + Q_G + Q_{GW} + Q_F$ and Q_R is heat from short wave radiation Q_B net loss of heat by exchange of long-wave rad. w. atmos. Q_E heat loss due to evaporation Q_H sensible heat loss Q_S heat lost by influx of snow Q_G heat added by flow of geothermal heat Q_{GW} heat added by flow of ground water Q_F heat added by friction on stream bottom $Q_R = Q_{RI} - Q_{RR}$ = incoming-reflected short wave radiation and $Q_{RI} = Q_{CL}\,[.17 + .30\,(1-C)]$ Q_{CL} is incoming short wave radiation C is cloudiness in tenths $Q_{RR} = .052\,Q_{RI} - 3.28 \cdot 10^{-5}\,Q_{RI}{}^2$ $-Q_B = Q_a - Q_{ar} - Q_{bs}$ Q_a = long wave radiation from atmosphere $Q_{ar} = .03\,Q_a$ = reflected incoming long wave radiation Q_{bs} = long wave radiation from water surface

$Q_a = (a + be_a)\ \sigma\ T_{air}^4$

$a = .36 + .12\ C \exp[-1.92 \cdot 10^{-4} Z]$
$b = 2.8 \cdot 10^{-3} - 26.1 \cdot 10^{-4} C \exp[-1.97\ 10^{-4} Z]$
e_a = vapor pressure of air (mb)
Z = cloud height (m)

$Q_{ar} = .03\ Q_a$
$Q_{bs} = .97\ \sigma\ T_w^4$

Q_E and Q_H were estimated by two approaches:
Kohler formulae:
$Q_E = (1.52 + 3.55\ w)\ (e_{SW} - e_a)$
$Q_H = (.92 + 2.16w)\ (T_w - T_{air})$
w wind velocity at 2 m.
Rimsha and Donchenko formula
$Q_E = (1.56\ k_N + 2.94w)\ (e_{SW} - e_a)$
$Q_H = (k_N + 1.89w)(T_w - T_{air})$
$k_N = 3.87 + .17\ (T_w - T_{air})$
e_{SW} = saturation vapor pressure (mb)

$Q_s = A\ [\lambda + C_i\ (T_w - T_{air})]$
A is snow accumulation rate
$A \approx 7.85\ V^{-2.375}$
V is visibility in km
C_i heat capacity of ice
λ latent heat of ice

Q_G by local measurements of geothermal gradient

Q_{GW} by local measurements of ground water flows

$Q_F = D\gamma S/Jb$
D is river discharge [m^3/sec]
γ is weight density of water = $\rho_w g$ = [$kg/m^2\ sec^2$]
S is water surface slope
b is river width

Dingman, Assur (1969)

Clear (C=0.) $Q = 50.93 + 11.21w + (16.99 + 2.05w)\ (T_w - T_{air})$
Cloudy (C=1.0) $Q = -35.28 + 4.40w + (17.97 + 2.22w)\ (T_w - T_{air}$
w = wind velocity
T_w = local water temperature, T_w (x)
T_{air} = ambient air temperature

APPENDIX 5

REPORTS

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PENDIX A: UNSTEADY FULLY MIXED
E SUPPRESSION

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A *06/05/78-09:24
      C           G ASHTON 26 APRIL 1978  UNSTEADY FULLY MIXED ICE SUPPRESSION
      C           THIS PROGRAM COMPUTES DOWNSTREAM EVOLUTION OF AN ICE COVER
      C           IN RESPONSE TO RELEASE OF A FULLY MIXED THERMAL EFFLUENT
      C           AND VARYING AIR TEMP; RIVER FLOW IS ASSUMED TO BE STEADY
      C           AL,D,U,ETA, TWOUT, B  ARE LENGTH,DEPTH,MEAN VELOCITY,
      C           ICE THICKNESS,WATER TEMPERATURE, AND WIDTH FOR EACH SUBREACH
      C           DAT AND STW ARE DAILY AIR TEMPSAND EFFLUENT SOURCE TEMPS
            DIMENSION SAL(60),SB(60),SD(60),DAT(60),STW(60)
            DIMENSION AL(100),D(100),U(100),ETA(100),TWOUT(100),B(100)
            DIMENSION CWAR(70),V(70)
      C           CWAR AND V ARE DAILY HEAT TRANSFER COEF & WIND SPEED
            READ 900,NT,NSR,ALTOT,DISCH
      900   FORMAT(2I10,2F10.0)
            PRINT 816,NT,NSR,ALTOT,DISCH
      816   FORMAT(1H1,5X,'NT  NSR  ALTOT  DISCH  ',2I4,2F12.3)
      C           ALTOT IS LENGTH OF STUDY REACH (M), DISCH IS DISCHARGE (M3/S),
      C           NSR IS NUMBER OF SUBREACHES FOR WHICH VALUES OF WIDTH OF
      C           CHANNEL AND DEPTH ARE AVAILABLE
      C           NT IS NUMBER OF DAYS OF SIMULATION
            READ 901,(SB(J),SD(J),SAL(J),J=1,NSR)
      901   FORMAT (3F10.0)
            PRINT 817,(SB(J),SD(J),SAL(J),J=1,NSR)
      817   FORMAT(3X,' SB = ',F10.3,' SD = ',F10.3,' SAL = ',F10.3)
      C           SB AND SD ARE WIDTH AND DEPTH AT SUCCESSIVE X DISTANCES SAL
      C           SUBDIVIDE TOTAL REACH INTO SUBREACHES WITH DELT TRAVEL TIME
            DELT = 3600.
      C           CALCULATE NL AND TOTAL TRAVEL TIME
            TRAV = 0.0
            DO 10 J=1,NSR
      10    TRAV=TRAV+SB(J)*SD(J)*SAL(J)/DISCH
            NL=TRAV/DELT
            TRAV=TRAV/3600.
            PRINT 810,TRAV
      810   FORMAT(10X,' TOTAL TIME OF TRAVEL = ',F10.2,' HOURS')
      C           CALCULATE NEW SUBREACH LENGTHS WIT DELT TIME OF TRAVEL
            SUMSAL=SAL(1)
            SUMAL=0.0
            I=1
            DO 15 J=1,NL
            U(J)=DISCH/(SB(I)*SD(I))
            AL(J)=DELT*U(J)
            D(J)=SD(I)
            SUMAL=SUMAL+AL(J)
            DELAL=SUMAL-SUMSAL
            IF(DELAL)15,15,12
      12    I=I+1
            SUMSAL=SUMSAL+SAL(I)
      15    CONTINUE
      C           ROUTINE ONLY GOOD IF ALL SAL LONGER THAN DELT*U(J)
```

```
              PRINT 811
        811   FORMAT(3X,' AL(J)',3X,'U(J)')
              PRINT 813
        813   FORMAT(3X,' METERS',3X,'M/S')
              PRINT 812,(AL(J),U(J),J=1,NL)
        812   FORMAT(2F10.2)
        C        READ AIR TEMPERATURES AND SOURCE TEMPS FOR NT DAYS
              READ 902,(DAT(I),STW(I),V(I),I=1,NT)
        902   FORMAT(3F10.0)
              PRINT 815
        815   FORMAT(3X,' I',3X,' AIRT',3X,' WATER T)
              PRINT 814,(I,DAT(I),STW(I),I=1,NT)
        814   FORMAT(I5,2F10.4)
        C        NOW INITIALIZE PROPERTIES AND COEFFICIENTS
              CP=4215.
              AKI=2.24
              ALAM=3.34E5
              AMU=1.79E-3
              RHOI=916.
              RHOW=1000.
              CWI=1622.
              CWA=25.
        C        SET ICE COVER THICKNESS AND WATER TEMPERATURE AT ZERO
              DO 25 I=1,NL
              ETA(I)=0.0
        25    TWOUT(I)=0.0
              NTD=86400./DELT
              DO 30 I=1,NT
        30    CWAR(I)=4.5+3.8*V(I)
        50    DO 400 IT=1,NT
              CWA=CWAR(IT)
        100   DO 390 IDT=1,NTD
              TWOUT(1)=STW(IT)
        C      ESTABLISHES WATER TEMP FOR INLET 1ST SUBREACH
              DO 380 J=1,NL
              IF(ETA(J))250,250,300
        C      NO ICE COVER
        250    QW=CWA*(TWOUT(J)-DAT(IT))
              DELTW=-QW*DELT/(RHOW*CP*D(J))
              TWOUT(J)=TWOUT(J)+DELTW
        C        OUTLET TEMPERATURE FOR SUBREACH AT END OF IDT TIME STEP
              IF(TWOUT(J))260,270,270
        260   TWOUT(J)=0.0
              ETA(J)=DELT*CWA*(-DAT(IT))/(RHOW*ALAM)
        270   GO TO 380
        C      ICE COVER PRESENT
        300   QW=CWI*((U(J)**0.8)/(D(J)**0.2))*TWOUT(J)
              DELTW=-QW*DELT/(RHOW*CP*D(J))
              TWOUT(J)=TWOUT(J)+DELTW
              IF(DAT(IT))306,305,305
        305   QI=0.0
```

```
      GO TO 307
306   QI=-DAT(IT)/((ETA(J)/AKI)+(1./CWA))
      DETA=(DELT/(RHOI*ALAM))*(-QW+QI)
307   CONTINUE
      ETA(J)=ETA(J)+DETA
      IF(ETA(J))320,380,380
320   ETA(J)=0.0
380   CONTINUE
C     PRINT 801,(J,ETA(J),TWOUT(J),J=1,NL,20)
      DO 385 J=NL,2,-1
385   TWOUT(J)=TWOUT(J-1)
390   CONTINUE
      ALO=0.0
      DO 395 J=1,NL
      IF(ETA(J))391,391,395
391   ALO=ALO+AL(J)
395   CONTINUE
      PRINT 802,IT
      PRINT 851
851   FORMAT (3X,'ICE THICKNESSES')
      PRINT 801,(ETA(J),J=1,NL)
      PRINT 803,ALO
      PRINT 852
852   FORMAT(3X,'WATER TEMPERATURES')
      PRINT 801,(TWOUT(J),J=1,NL)
400   CONTINUE
803   FORMAT(10X,' ALO = ',F12.3,' METERS')
802   FORMAT(1H0,'END OF DAY',I5)
801   FORMAT(10F7.3)
      END
```

APPENDIX B: UNSTEADY LATERAL MIXING ICE SUPPRESSION

```
'1A *05/23/78-08:06
C          G ASHTON 22 MAY 1978
C            UNSTEADY LATERAL MIXING ICE SUPPRESSION
           DIMENSION AL(100),ETA(100,20),TW(100,20),DAT(60),STW(60)
           READ 401,NT,NSR,NSW
           READ 402,DELT
           READ 403,(DAT(IT),IT=1,NT)
           READ 404,(STW(IT),IT=1,NT)
           READ 405,UM,DM,BW
           READ 406,NTW
   401     FORMAT (3I10)
   402     FORMAT (F10.0)
   403     FORMAT(F10.0)
   404     FORMAT (F10.0)
   405     FORMAT(3F10.3)
   406     FORMAT(I10)
C            NOW INITIALIZE WATER TEMPERATURE AND ICE THICKNESS
           DO 50 I=1,NSR
           DO 40 J=1,NSW
           ETA(I,J)=0.0
           TW(I,J)=0.0
   40      CONTINUE
   50      CONTINUE
C            PRINT OUT INPUT DATA
           PRINT 501,NT,NSR,NSW
   501     FORMAT(3X,' NT  NSR  NSW = ',3I10)
           PRINT 502,DELT
   502     FORMAT(3X,' DELT = ',F12.1,' SECONDS')
           PRINT 503
   503     FORMAT(3X,'DAY  TA(DEG C)   TW,0')
           PRINT 504,(IT,DAT(IT),STW(IT),IT=1,NT)
   504     FORMAT(3X,I4,2F10.2)
           PRINT 505
   505     FORMAT(3X,' INITIAL ICE THICKNESSES')
           PRINT 506,((ETA(I,J),J=1,NSW),I=1,3  )
   506     FORMAT(20F5.3)
           PRINT 507
   507     FORMAT(1H0,' INITIAL WATER TEMPERATURES')
           PRINT 508,((TW(I,J),J=1,NSW),I=1,3  )
   508     FORMAT(20F5.2)
C            NOW ESTABLISH LENGTHS WITH TIME OF TRAVEL EQUAL TO DELT
           ALSR=UM*DELT
           PRINT 509,UM
   509     FORMAT(1H0,3X,'MEAN VELOCITY = ',F10.3,' M PER SEC')
           PRINT 510,DM
   510     FORMAT(3X,'MEAN DEPTH = ',F10.3,' METERS')
           PRINT 511,ALSR
   511     FORMAT(3X,' SUBREACH LENGTH = ',F12.1,' METERS')
           DO 60 I=1,NSR
           AL(I)=ALSR
   60      CONTINUE
           PRINT 512,BW
   512     FORMAT(3X,'TOTAL WIDTH = ',F12.1,'METERS')
           DELB=BW/NSW
C            NOW DETERMINE NUMBER OF TIME STEPS PER DAY NTD
           NTD=86400./DELT
C            NOW INITIALIZE PROPERTIES AND COEFFICIENTS
           CP=4215.
           AKI=2.24
           ALAM=3.34E5
           RHOI=916.
           RHOW=1000.
           CWI=1622.
           CWA=25.
           HWA=CWA
           HWI=CWI*(UM**0.8)/(DM**0.2)
```

```
      F=0.05
C        F IS ARBITRARILY CHOSEN FOR EXAMPLE CASE
      USTAR=UA*SQRT(F/8.)
      EK=0.2
C        CALCULATE STABILITY PARAMETER
C        STABLE = 2.*EK*USTAR*DM*DELT/(DELB*DELB)<1
      STABLE=2.*EK*USTAR*DM*DELT/(DELB*DELB)
      IF(STABLE-1.)70,71,71
70    PRINT 515,STABLE
515   FORMAT(3X,'STABILITY PARAMETER = ',F6.3,'  STABLE')
      GO TO 72
71    PRINT 516,STABLE
516   FORMAT(3X,'STABILITY PARAMETER = ',F6.3, ' UNSTABLE')
72    CONTINUE
      PRINT 517,EK
517   FORMAT(3X,'EK = ',F6.3,' M2 PER SEC')
      PRINT 518,USTAR
518   FORMAT(3X,'USTAR = ',F7.4,' M PER SEC')
      PRINT 521,DELB
521   FORMAT(3X,'DELB = ',F7.1,'  METERS')
      EO=EK*USTAR*DM
      EI=EO/2.
      RCD=RHOW*CP*DM
      DT=DELT/(2.*DELB*DELB)
C*****************************
      DO 700 IT=1,NT
      DO 650 ID=1,NTD
C        INITIALIZE UPSTREAM WATER TEMPERATURE VARIATION
      DO 130 J=1,NSW
      TW(1,J)=STW(IT)
130   CONTINUE
      DO 630 I=NSR,2,-1
C        CALCULATE J=1 NODE
      IF(ETA(I,2))133,133,134
133   EJP1=EO
      GO TO 135
134   EJP1=EI
135   CONTINUE
      IF(ETA(I,1))136,136,137
136   EJ=EO
      B=1.-(DELT*HWA/RCD)-DT*(EJP1+    EJ)
      D=DELT*HWA/RCD
      GO TO 138
137     EJ=EI
      B=1.-DELT*HWI/RCD-DT*(EJP1+    EJ)
      D=0.
138   CONTINUE
      C=DT*(EJP1+EJ)
      TW(I,1)=B*TW(I-1,1)+C*TW(I-1,2)+D*DAT(IT)
C        CALCULATE J=NSW NODE
      IF(ETA(I,NSW-1))151,151,152
151   EJM1=EO
      GO TO 153
152   EJM1=EI
153   CONTINUE
      IF(ETA(I,NSW))154,154,155
154   EJ=EO
      B=1.-DELT*HWA/RCD-DT*(EJM1+    EJ)
      D=DELT*HWA/RCD
      GO TO 156
155   EJ=EI
      B=1.-DELT*HWI/RCD-DT*(EJM1+    EJ)
      D=0.
156   CONTINUE
      A=DT*(EJ+EJM1)
      TW(I,NSW)=A*TW(I-1,NSW-1)+B*TW(I-1,NSW)+D*DAT(IT)
C        CALCULATE INTERMEDIATE NODE POINTS
```

```
      DO 600 J=2,NSW-1
      IF(ETA(I,J-1))165,165,166
  165 EJM1=EO
      GO TO 167
  166 EJM1=ET
  167 CONTINUE
      IF(ETA(I,J))168,168,169
  168 EJ=EO
      GO TO 170
  169 EJ=ET
  170 CONTINUE
      IF(ETA(I,J+1))171,171,172
  171 EJP1=EO
      B=1.-DELT*HWA/RCD-DT*(EJP1+2.*EJ+EJM1)
      D=DELT*HWA/RCD
      GO TO 173
  172 EJP1=ET
      B=1.-DELT*HWI/RCD-DT*(EJP1+2.*EJ+EJM1)
      D=0.
  173 CONTINUE
      A=DT*(EJ+EJM1)
      C=DELT*(EJ+EJP1)
      TW(I,J)=A*TW(I-1,J-1)+B*TW(I-1,J)+C*TW(I-1,J+1)+D*DAT(IT)
  600 CONTINUE
  630 CONTINUE
C        NOW CALCULATE ICE THICKNESSES AT J NODES
      DO 206 I=1,NSR
      DO 205 J=1,NSW
      IF(DAT(IT))200,200,201
  200 QI=-DAT(IT)/((ETA(I,J)/AKI)+1./HWA)
      GO TO 202
  201 QI=0.
  202 CONTINUE
      QW=CWI*(UM**0.8)*TW(I,J)/(DM**0.2)
      DELETA=(QI-QW)*DELT/(RHOI*ALAM)
      ETA(I,J)=ETA(I,J)+DELETA
      IF(ETA(I,J))203,204,204
  203 ETA(I,J)=0.0
  204 CONTINUE
  205 CONTINUE
  206 CONTINUE
  650 CONTINUE
C        PRINT OUT DAILY RESULTS
      PRINT 519,IT
      PRINT 520,((TW(I,J),J=1,NSW),I=1,NSR)
  519 FORMAT (1H1,' TW DAILY END OF DAY ',I5)
  520 FORMAT(10X,10F6.3)
      PRINT 529,IT
      PRINT 530,((ETA(I,J),J=1,NSW),I=1,NSR)
  529 FORMAT(1H1,'      ICE THICKNESSES END OF DAY ',I5)
  530 FORMAT(10X,10F6.3)
  700 CONTINUE
      END
```