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Ice on Rivers and Lakes
A Bibliographic Essay

Geological Survey, Reston, Va Water Resources Div

Oct 77

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ICE ON RIVERS AND LAKES-- A BIBLIOGRAPHIC ESSAY

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 77-95

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Ice on rivers and lakes influences design and construction of structures, operation of shipping, flow and circulation, water quality, and other factors related to the use of the water. Human interest in understanding these influences has led to many programs of data collection, research, and investigations for a century or more. The body of literature reporting on these studies includes several thousand items in textbooks, proceedings, journals, and technical reports. By far, the largest portion of the studies were in the United States, Canada, or the Soviet Union. The literature can be classified as dealing with basic characteristics of ice; freezing and melting processes and their prediction and control on rivers, and on lakes; effects of river and lake ice on navigation, flow, and structures; and influences of ice on chemical, biological, and thermal aspects of water quality. This bibliography cites 750 publications, but the body of literature is large and this bibliography is not exhaustive. It does provide, however, a cross section of the scope of work in the field.

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ICE ON RIVERS AND LAKES--

A BIBLIOGRAPHIC ESSAY

By Eleanore R. Ficke and John F. Ficke

U.S. GEOLOGICAL SURVEY

Water Resources Investigations 75-95

A review of some of the more recent literature, mostly from the United States, Canada, and the Soviet Union, describing research, data collection, and investigations of ice on rivers and lakes.

October 1977

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UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

V. E. McKelvey, Director

For additional information write to:

Quality of Water Branch, MS 412
U.S. Geological Survey
Reston, Virginia 22092

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Most of the reports on ice from the United States and Canada, particularly the older ones, report in English units; and metric units are used in most reports from outside America and in many of the more recent U.S. and Canadian publications. Most measurements included in this bibliography are repeated in the units used in the original publications, and the following conversion factors are provided for the convenience of the readers.

Multiply English units	By	To obtain metric units
feet (ft)	0.305	meters (m)
miles (mi)	1.61	kilometers (km)
inches (in)	2.54	centimeters (cm)
pounds (lb)	.454	kilograms (kg)
gallons (gal)	3.78	liters (L)
pounds per foot (lb/ft)	1.49	kilograms per meter (kg/m)

Multiply metric units	By	To obtain English units
grams per cubic centimeter (g/cm^3)	0.0361	pounds per cubic inch (lb/in^3)
kilograms per square centimeter (kg/cm^2)	14.2	pounds per square inch (lb/in^2)
meters (m)	3.28	feet (ft)
kilometers (km)	.621	miles (mi)
centimeters (cm)	.394	inches (in)

ICE ON RIVERS AND LAKES--A BIBLIOGRAPHIC ESSAY

By Eleanore R. Ficke and John F. Ficke

ABSTRACT

Ice on rivers and lakes has many important influences on design and construction of structures, operation of shipping, flow and circulation, water quality, and other factors related to the use of the water resources. Human interest in understanding these influences has led to many programs of data collection, research, and investigations for a century or more. The body of literature reporting on these studies includes several thousand items in textbooks, proceedings, journals, and technical reports. By far, the largest part of the studies were in the United States, Canada, and the Soviet Union. For the sake of this bibliography, the literature can be classified as dealing with basic characteristics of ice; freezing and melting processes and their prediction and control on rivers, and on lakes; effects of river and lake ice on navigation, flow, and structures; and influences of ice on chemical, biological, and the thermal characteristics of water quality.

This bibliography cites about 750 publications dealing with ice. Literature prior to the mid 1960's is summarized in several earlier bibliographies, and therefore this paper concentrates mainly on work over the past decade or so, plus some background from a few earlier reports. The body of literature is large, and this bibliography is not exhaustive; it does provide, however, a representative cross section of the scope of recent work in the field.

INTRODUCTION

Ice has many influences on rivers and lakes within the temperate regions of the United States. The most important economic effects undoubtedly are restrictions of navigation and influences on flooding through the effects of ice jams. Other important effects of ice are on water quality and on the life cycles of aquatic plants and animals, particularly fish. Researchers are studying the basic characteristics of ice and are working on the application of basic knowledge to the solution of problems in nature. Their written observations and analyses form a considerable, but widely scattered body of literature.

Purpose and Scope

This paper presents an introduction to and summary of part of the extensive literature on ice on rivers and lakes. It is a brief summary of the state of the art and of research on understanding and dealing with ice on lakes and streams. It cites as examples some of the papers that describe natural processes of freezing and breakup, factors that cause them, and effects of ice on navigation, water supply, flooding caused by ice jams, and water quality. The scope is limited to effects that are common in the temperate regions of the United States and Canada. Some papers giving data and research results from Alaskan, Canadian, and Soviet polar studies are included, but an attempt has been made to exclude much of the vast amount of arctic research that has limited application in temperature zones.

Several excellent bibliographies and literature reviews have been prepared covering many aspects of ice on rivers and lakes. Therefore, this paper concentrates on reporting many of the more easily available and significant works among the older publications, and especially, the more recent literature. The approximately 750 publications cited here certainly are not a complete, exhaustive survey of the literature; we estimate that at least 2000 additional papers and reports on lake and river ice have been published.

Acknowledgments

A large part of the literature cited in this bibliography was identified through use of the computerized bibliographic data base of the Water Resources Scientific Information Center (WRSIC). The data base is maintained by the U.S. Department of the Interior, Office of Water Research and Technology (OWRT). The assistance from OWRT is gratefully acknowledged.

Manuscripts of this report were reviewed by Philip H. Burgi of the U.S. Bureau of Reclamation, Guenther Frankenstein and George Ashton of the U.S. Army Cold Regions Research and Engineering Laboratory, Robert Wetzel of Michigan State University, and Saul Rantz of the Geological Survey. We acknowledge the many helpful suggestions from these reviewers; but it is the authors, not the reviewers, who take the responsibility for the shortcomings and important omissions which undoubtedly remain in the bibliography.

GENERAL CHARACTERISTICS OF THE LITERATURE ON ICE

Bibliographies and Literature Reviews

Descriptions of ice phenomena and reports on research are widely scattered through the scientific literature. They appear in various journals, proceedings of specialty conferences, reports of governmental agencies of many countries, and a variety of other forms. A significant proportion of the literature is in languages other than English (principally Russian), and a large amount is published outside the United States (mostly in Canada and the USSR). Therefore, the student if ice is greatly aided by several bibliographies and literature reviews that are available. Fortunately, some of the most complete reviews have been assembled during the late 1960's and early 1970's.

An extensive monograph describing ice on rivers and lakes has been prepared by Professor Bernard Michel for the U.S. Army Cold Regions Research and Engineering Laboratory [452][1/]. The monograph includes 164 references, and summarizes findings in a 122-page discussion. The report deals mainly with the physical aspects of ice, its forms, processes of freezing and breakup, and a summary of methods of ice control. Numerous references will be made to Michel's monograph throughout this paper.

A *Review of Current Ice Technology and Evaluation of Research Priorities* [2] by Acres, Ltd., a Canadian engineering consulting firm, contains about 400 references. Engineering problems, such as those with structures, intakes, and power plant facilities are emphasized, but the report also gives attention to research results and the needs for basic research.

A very thorough monograph and literature review, *River Ice Jams--A Literature Review*, has been prepared by S. J. Bolsenga [111] of the U.S. Lake Survey. Bolsenga has assembled the findings of about 400 published studies of river ice jams from all parts of the world, and has included both current and historical information on ice-jam mechanism and methods for prevention and removal. Descriptions of ice-jam characteristics range from mathematical to narrative treatments. References are related to particular topics by arranging them with the discussion, in a chapter-by-chapter format, rather than having the references at the end of the report as is commonly done.

An *Annotated Bibliography on Freshwater Ice* [34], by the Arctic Institute of North America, includes over 2,000 items pertaining to freshwater ice. The bibliography contains an extensive index, with subjects divided into engineering and research categories. A geographic index also is included, showing that more than 30 percent of the references are to studies in Europe and Asia.

[1/] Numbers in brackets refer to references listed in the last section of this bibliography.

A rather short paper, *Ice Formation - A Review of the Literature and Bureau of Reclamation Experience* [143], by Burgi and Johnson, includes 51 references mainly related to ice formation on hydraulic structures in rivers and reservoirs.

Ryder, in his 1954 publication on ice thickness [588], included 186 references that "...yielded ice thickness data, ice break-up dates, or other similar pertinent information on lake and river ice."

Reports on lake ice issued before 1948 are included in the bibliography by Strong [652]. About 150 citations are contained in that report, along with a review of the state of the art at the time of publication.

A survey of literature on the structure of ice, the macro-micro-structure of sea and lake ice, ice chemistry, and phase relations is contained in *Fracture of Lake and Sea Ice* [701]; by Weeks and Assur. The report lists 174 references.

Two additional bibliographical publications, *Bibliography on Cold Regions Science and Technology*, published as Report 12 of the U.S. Army Cold Regions Research and Engineering Laboratory [672], and *Arctic Bibliography* [33], are mentioned in more detail in the subsection of this report on indexes and abstracts. They are called indexes here because they are recurring, annual publications and because they contain references to a far broader range of topics.

Journals

Current literature on ice in rivers and lakes is carried in a number of journals in the fields of hydraulics, hydrology, limnology, geophysics, and biology. The following paragraphs briefly mention a few of the periodicals where ice papers are found most frequently.

Publications of the American Society of Civil Engineers (ASCE), particularly the *Journal of the Hydraulics Division*, carry papers on ice conditions of streams, hydraulics of flow under ice, design of intakes and structures to avoid ice problems, and ice effects on transportation. The *Journal of the Hydraulics Division* published eight articles and discussion papers on ice during the period September 1972 to April 1974.

Soviet Hydrology, a journal published by the American Geophysical Union, contains a large amount of translated Russian literature on river and lake ice. *Water Resources Research*, another publication of the American Geophysical Union, is a prolific journal in hydrology, and contains occasional articles on ice.

The *Journal of Glaciology* is devoted to research on ice, and as its name states, it concentrates on glaciology. However, many papers on ice physics, flow, and other topics that appear in this journal have application to river and lake ice. *Arctic Bulletin,* a journal of the Interagency Arctic Research Coordinating Committee, which has been published since 1973, has articles on a variety of topics pertaining to cold regions, including ice on rivers and lakes.

Limnology and Oceanography frequently has articles about ice on lakes, particularly about thermal and biological effects. Information on biological conditions in ice-covered streams and lakes also is published in *Ecology*. The *Journal of Marine Research,* although mainly concerned with oceanography, may contain articles on research applicable to lakes or estuaries.

Indexes and Abstracts

Each of the journals mentioned in the preceding subsection publishes an index by subject from which the interested reader can find articles dealing with ice. However, several general indexes and abstract publications are available to aid in the search for literature dealing with ice on lakes and rivers.

Selected Water Resources Abstracts, a semimonthly publication of the Office of Water Research and Technology, U.S. Department of the Interior, abstracts most of the U.S. journals that regularly contain articles on water. It also lists most of the water-related publications available through the National Technical Information Service, U.S. Department of Commerce. An annual index by subject is available, using descriptors listed in the *Water Resources Thesaurus* [678]. The publication is relatively recent (since 1968), and therefore does not reference much of the older literature. However, abstracts of many older articles on ice can be found in the several editions of *Annotated Bibliography on Hydrology and Sedimentation* [565, 674, 675, 679, 680].

Government Reports Announcements of the National Technical Information Service (NTIS) includes abstracts of scientific and technical reports prepared by U.S. Government agencies, or by private researchers under Government contract. The abstracts are indexed by subject in *Government Reports Index,* and annual indexes are available.

The *Bibliography on Cold Regions Science and Technology* has been published annually since 1969 as Report 12 of the U.S. Army Cold Regions Research and Engineering Laboratory [672] (formerly Snow, Ice and Permafrost Research Establishment). Earlier volumes (no. 1-22, 1951-68) appear under the titles *Bibliography on Snow, Ice and Permafrost* and *Bibliography on Snow, Ice and Frozen Ground with Abstracts*. The bibliography is prepared in the Science and Technology Division of the Library of Congress and contains a wide variety of materials on many aspects of cold regions.

Biological Abstracts is a source of information on articles regarding biological effects of ice on lakes and rivers. This publication is particularly helpful in locating articles on work published outside the United States.

A broad range of topics is included in the *Arctic Bibliography* [33], which is published approximately every 2 to 4 years by the Arctic Institute of North America. The annotated bibliography has almost total coverage of Canadian publications, and a very good coverage of U.S., Asian, and European work. The user of *Arctic Bibliography* is aided by an extensive subject index. To illustrate the scope of the bibliography--the latest volume, no. 16 (1975), contains about 70 items indexed under the subheading "Ice--River and lake ice," and contains about 35 subtopics under the general topic "Ice." A total of 108,700 publications are cited in the 16 published volumes.

Textbooks

Textbooks in several disciplines, including limnology, hydrology, and geophysics, generally include sections dealing with ice on rivers and lakes.

Two books by Howard T. Barnes from early in the 20th century have been widely used as texts. Barnes' *Ice Formation* [69], published in 1906, tells what the author calls "the ice story of the St. Laurence River." The book reports observations of winter processes on the St. Laurence (St. Lawrence), reviews the physics of ice, provides technical descriptions of the freezing processes and heat transfer, gives the author's theories on the formation of frazil and anchor ice, and includes a short chapter on design of engineering works to avoid ice problems. A second textbook by Barnes, titled *Ice Engineering* [72], published in 1928, is considered by many to be the classic American work on ice. The book, which was widely used as the textbook for more than two decades, is primarily a how-to book for the engineer who has to deal with ice effects on structures, ships, and transportation. A bibliography in the 1928 book listing several hundred books and articles demonstrates the large amount of attention that was paid to ice problems in the period around the turn of the century.

The popular hydrology textbook by Linsley, Kohler, and Paulhus [409] includes a chapter dealing with snow, ice, and frost. The few pages on ice describe frazil and anchor ice and the ice cycle in streams. They give a rough basis for estimating freezing rates at different temperatures and for estimating the ice thrust loads on structures such as dams.

Chow's extensive *Handbook of Applied Hydrology* has a 32-page chapter on ice and glaciers by Mark Meier [445], who has included brief discussions on ice properties and on ice formation. Zumberge and Ayers [752], in the chapter on lakes, present more detailed information on lake ice, including a technique for computing rates of freezing and a means for estimating the ability of ice to support vehicle travel.

Several aspects of lake ice are covered by Hutchinson in *A Treatise on Limnology* [317]. Hutchinson discusses ice density and five different forms of ice in his chapter on the properties of water. Later, in the chapter on thermal properties of lakes he describes granular ice, columnar ice, porphyritic ice, and tabular ice as forms of sheet ice, and he defines agglomeritic ice as a separate type formed by the fusion of separate masses of ice or snow, or by refrozen sheet ice. Hutchinson's treatise includes several references to key literature on lake ice and to some rather remote foreign literature, such as the records on freezing dates for Lake Suwa in Japan which date back to 1443.

In *Limnology in North America,* edited by David Frey [248], lake ice is discussed in several of the chapters which are all geographically oriented. Later sections of this paper will report some of the summaries from Frey's book, such as melting dates in New England [122], salinity effects in Western Canada [482], conditions on the Great Lakes [81], and freezing phenomena in Alaska [412].

Pounder's book on *The Physics of Ice* [537] outlines the state of knowledge regarding the structure and properties of ice at the time of its writing (1965), and also includes information on ice occurrence and movement. The first part of the book contains descriptive material at an elementary level on the properties of ice, sea ice, ice drift, and ice control. Later parts of the book include more technical discussions on ice crystallography, mechanical properties, and thermal and electrical properties. Pounder's final chapter on growth and decay of ice cover presents a mathematical description of the processes of formation and decay of an ice cover on a lake or stream.

An identically titled monograph, *The Physics of Ice* [265], by Glen, is a more recent and more sophisticated treatment of ice physics. The monograph is relatively short (62 pages of text), but it presents detailed discussions of the molecular and crystalline structure and electrical properties of ice. There is a bibliography of nearly 300 publications, mostly from the 1960's and 70's.

Ice and Snow, Properties, Processes, and Applications, by Kingery [353], is a conference proceedings that could be considered a textbook. The publication contains sets of papers on ice properties and solidification phenomena that are applicable in the study of ice on lakes and rivers. The range of subjects covered by the papers is quite complete; the papers seem to follow a systematic outline; and there is very little repetition from one report to the next.

The monograph by Michel [452] was mentioned in an earlier section of this paper as a bibliography; and the style of *Winter Regime of Rivers and Lakes* qualifies the report for use as a textbook. It presents a classification for river and lake ice based on gross macroscopic characteristics and history. Freezing and breakup features are described from the aspect of heat loss and gain and by sketches illustrating the processes, and engineering factors such as ice-jam problems and ice control are dealt with in a textbook-type manner, assuming little prior knowledge on the part of the reader.

Physics of Ice [563], edited by Riehl, Bullemer, and Engelhardt, is a collection of varied papers which would qualify as a textbook. The more than 50 papers included in the book were prepared for an international symposium in 1968. They cover a broad spectrum of topics on the physical properties of ice and seem to be suited to course work or could be regarded as a diversified reference book on basic ice physics.

English abstracts which are available on four Russian publications suggest that the books [148, 519, 667, and 689] could be considered to be textbooks. Books on hydrometry and engineering geology by Bykov and Vasil'yev [148] and by Tushinskiy [667] discuss the techniques for measuring ice conditions on rivers and lakes and the importance of considering river and lake ice in design of engineering works. A 1940 publication by Veinberg and others [689] is a comprehensive summary of the properties of ice and of freezing and breakup processes. Peschanskii's more recent (1967) publication [519] is a general work on the properties of freshwater and sea ice, freezing and breakup processes, and ice engineering.

Proceedings of Symposia and Conferences

Numerous symposia and conferences over the years have been devoted to ice or have included sessions with several papers dealing with ice. The number is large and only a few examples are cited in this subsection.

The oldest series of meetings of this type probably is the Eastern Snow Conference, which has been nearly an annual occurrence and dates back many decades (proceedings volumes start with No. 1 for the 9th Conference in 1952 and run to the present date). Some papers on river or lake ice are included in nearly every Conference, and several of the papers are cited individually in this bibliography. The similarly named Western Snow Conferences have had even a longer run than the Eastern Conferences (44 Conferences through 1976), but the Western Conferences tend to concentrate more strictly on snow and their proceedings are not nearly so rich on the subject of river and lake ice as are those of the Eastern Conferences.

Congresses of the International Association for Hydraulic Research (IAHR) have met approximately every two years for more than three decades, and their proceedings have included several papers on ice, particularly in earlier sessions (through about the 11th Congress, 1965). In the 1970's many high-quality papers on ice subjects have been published in the proceedings of three international symposia sponsored by IAHR [246, 323, 324].

The National Research Council of Canada has sponsored special symposia dealing with ice topics. Two examples are the Symposium on Air Bubbling in 1961 [152], and the Seminar on Ice Jams in 1973 [725]. A Workshop on Snow and Ice Hydrology [676] was held in Colorado in 1969 under the sponsorship of the U.S. National Committee for the International Hydrologic Decade. Symposia on Glaciology sponsored by the International Glaciology Society include material on remote sensing, as illustrated by the proceedings of the 1974 symposium [326]. The International Association of Hydrological Sciences held an International Symposium on the Role of Snow and Ice in Hydrology in Banff, Alberta, in September 1972. The Banff meeting was attended by representatives of 16 countries, and more than 100 papers are published in the proceedings [325]. In 1973 an interdisciplinary seminar on Advanced Concepts and Techniques in the Study of Snow and Ice Resources [592] was held in Monterey, Calif.

Persons interested in ice as it is influenced by or influences environmental pollution should be aware that papers on ice have been included in Joint Conferences on Prevention and Control of Oil Spills. Two papers [344, 386] from the Joint Conferences are cited in this bibliography.

How this Bibliography was Compiled

This bibliographic essay was compiled from (1) primary material--books and reports available to the authors, and (2) secondary sources--abstracts or published summaries of materials not available to the authors. All of the indexes, abstracts, literature reviews, and bibliographies mentioned in earlier subsections of this paper were used to locate publications and as sources of abstracts for reports not available. The most references, especially to recent material, were located through *Selected Water Resources Abstracts* (*SWRA*) and the computer facilities of the U.S. Office of Water Research and Technology and the U.S. Geological Survey. Abstracts published in *SWRA* are stored in a computer accessible file where they can be searched by machine. Computer searching was especially valuable in finding reports on the water-quality effects of ice, particularly in situations where the report title did not indicate that the report included data describing conditions of ice cover.

Many of the older publications cited in this report were located through references in the several editions of the *Annotated Bibliography on Hydrology and Sedimentation* and through the *Annotated Bibliography on Freshwater Ice* [34]. *Biological Abstracts* was useful in locating old and recent reports on water quality, especially those dealing with the biological activity in lakes under conditions of ice cover.

Government Reports Announcements provided information on many recent reports, especially the translations and research results of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). Fortunately for the user, almost all of these reports can be obtained (in paper copy or microfiche) from the U.S. National Technical Information Service, Springfield, Va.

CHARACTERISTICS OF ICE

An understanding of the basic characteristics of ice is critical in applied research and engineering of ice on rivers and lakes. This includes an understanding of the physical properties of ice, and a knowledge of the special terminology used in the literature describing ice.

A few publications are available that provide a broad coverage of ice characteristics. The classic work by Dorsey [206] summarizes many of the physical properties of ice. A short paper by Erlander [222] discusses ice structure as a part of a more recent review of research in the structure of water.

General summaries of characteristics of ice and snow are in the proceedings of symposia and in other papers. Kingery's volume [353] containing the papers from a conference in Cambridge, Mass., in 1962, was mentioned earlier in this report as a potential textbook because of its broad coverage of the characteristics of ice. Proceedings of a 1969 conference [676] sponsored by the U.S. National Committee for the International Hydrologic Decade (IHD) contains papers reviewing the state of the art of ice and snow hydrology. Similar IHD conferences were held in Banff, Alberta, in September 1972 [325], and in Monterey, Calif., in December 1973 [592]. Several papers from these meetings are cited separately here. A Russian review paper by Deryugin [191] published in 1971 reported many properties of snow ice. Papers describing many of the characteristics of ice also are contained in the proceedings of a symposium on Ice and its Action on Hydraulic Structures, held in Reykjavik, Iceland, in 1970 [323], and in Leningrad in 1972 [324]. Several papers from the proceedings of the Iceland symposium are cited individually in this bibliography. The proceedings of the Leningrad symposium are printed in Russian. They include 44 papers, with 10 by, or in part by U.S. authors, and 10 papers by, or in part by Canadian authors. The U.S. and Canadian papers undoubtedly were written in English, but were translated into Russian for publication.

The following subsections deal with more specific papers on the many characteristics of ice.

Terminology and Classification

The study of ice is like scientific work in most disciplines, in that it has developed its own special language and terminology. Terms such as *black ice, ice boom, shale ice,* and *polynya* are a few examples.

Wilson, Zumberge, and Marshall [730] were among the first to attempt to develop an ice terminology and classification for lake ice based upon older systems that had been used for sea ice. They divided ice types into two major classes: (1) accretional or sheet ice, and (2) agglomeritic ice. The report of their research contains several clear photographs showing thin sections of the different ice types and views of the ice types on a lake. The classification system of Wilson, Zumberge, and Marshall has been summarized in the treatise by Hutchinson [317], and by Zumberge and Ayers [752].

Armstrong, Roberts, and Swithinbank, in their *Illustrated Glossary of Snow and Ice* [36], have many photographs showing different ice types. Although the pictures generally illustrate sea-ice situations, they certainly have application to lakes, particularly large lakes such as the Great Lakes. Ice terms in the glossary are in nine languages (Danish, English, Finnish, French, German, Icelandic, Norwegian, Russian, and Spanish) with an index in each language.

Michel [452] and Michel and Ramseier [454] have devised a classification for river and lake ice which is based on gross macroscopic characteristics and ice history, but which is not related to the texture and internal structure of the ice itself. Figure 1 shows Michel's classification in model form.

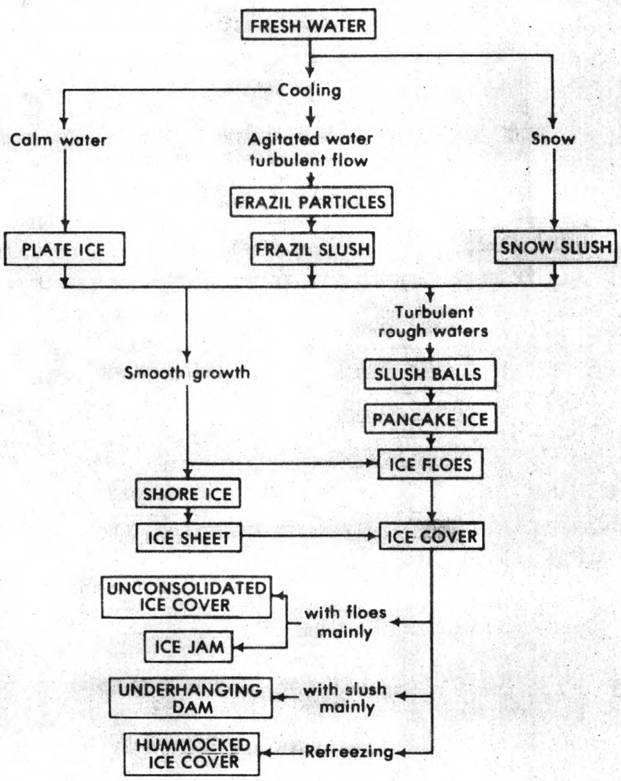

Figure 1.--Model of processes of ice formation; from Michel [452].

Williams [721] has developed a system of field classification of ice. Williams' system is like that of Michel in that is is based on the origin of the ice and draws a distinct difference between ice formed on relatively still water and that formed in flowing streams.

Russian terminology for describing ice has been somewhat different from that used in Canada and the United States. A 1964 paper by Molchanov [458] presents a review of Soviet classification of ice on lakes and reservoirs. Soviet terminology for describing sea ice has been more extensive and more carefully documented than has western terminology. A paper by Dunbar [211] summarizes the sea ice terminology adopted by the World Meteorological Organization (WMO) in 1968, which was strongly influenced by the Soviet terminology.

In a paper for the International Association for Hydraulic Research (IAHR) symposium in 1970, Kivisild [357] summarized the history of river and lake ice terminology, and included definitions of more than 100 terms. Kivisild's paper also arranges the terms by subject, according to obvious features.

Proceedings of the 1975 IAHR symposium on ice [246] contain an appendix listing equivalent English, French, and Russian words or phrases for approximately 115 items of "river and lake ice terminology."

Physical Properties

Many detailed laboratory and field studies have been conducted to study the physical properties of ice. This work on strength, crystalline structure, density, and other features is of value in applied work, such as design of structures, icebreakers, and over-ice transport.

General discussions of the physical properties of ice are found in several books, the proceedings of symposia, and a few articles or papers. Pounder's book [537], mentioned before as a textbook, reviews crystallography and mechanical, thermal, and electrical properties of ice. Glen's monograph [265], which also was mentioned in the discussion of textbooks, reviews similar topics and contains references to 282 publications, mostly from the 1960's. The proceedings [563] edited by Riehl, Bullemer, and Engelhardt, which also was mentioned in an earlier section as a textbook, includes broad subject coverage on physics of ice. *A Review of the Properties of Snow and Ice,* prepared by Mantis [432] in 1951, is an exceptionally complete treatment of the physical characteristics of ice, even though it is more than 20 years old. Fletcher's book on *The Chemical Physics of Ice* [239] is a comprehensive account, based largely on recent literature, of the properties of ice, the connection between them, and the way in which they derive from the structure of the molecule. It has more than 300 references. Two reports, by Brill [120] and by Brill and Camp [121], present detailed laboratory results on studies of crystalline structure, thermal motion, viscoelastic properties, and dielectric properties.

Physical properties are discussed in general in some Soviet publications. *The Physics of Ice* [108], edited by Bogorodskii, is a proceedings of a 1968 symposium with more than 30 papers on several aspects of ice physics. Translations of three chapters from a 1971 book by Bogorodskiy [109] discuss formation, thermal properties, and radiation properties. A recently translated Russian book [598] written in 1963 reviews methods of study for physical properties of ice--structure, salinity, density, strength, and other features. A Soviet publication by Yakovlev [740] is a collection of papers dealing with many physical aspects of ice, including structure and mechanical properties, especially strength.

Research on specific physical properties of ice is reported in shorter reports and articles. High-pressure thermodynamic data were used by Jancso, Pupezin, and Van Hook [328] in calculating and measuring the vapor pressure between -100°C and the triple point. Acoustic attenuation has been reported by Pounder and Langleben [539] to be essentially independent of salinity and structure of the ice. Johnson and Ashworth [332] have reported measurements of thermal conductivity of ice over the temperature range 4 to 360 K (-269° to +87°C), with an accuracy of 0.6 percent or better. Field work on dielectric absorption has been done in the Unitd States, as described by Hoekstra and Spanogle [304], and by British researchers, as reported by Walford [693]. A translation of a Russian paper by Korenouskaya and Tarasov [368] reports on Soviet work on ionic composition and mineralization of ice, relating concentration in ice to concentration in the water from which the ice was formed. Untersteiner [681] also worked on salinity profiles in ice, and the paper discusses four mechanisms, giving greatest credence to the "flushing" or "washing out" effect, and to "brine expulsion" as a result of temperature changes. Shapiro [613] reported on the application of freezing as a technique for concentrating inorganic solutes for chemical analyses, and four papers by Baker [55, 56, 57, 58] describe many experiments and techniques for using freezing as a method for concentrating trace quantities of organic substances for analyses. A paper by Adams [4] describes a method for measuring and computing the densities of sheets of lake ice based on measurements of thickness and the equation of buoyancy.

Crystalline structure.--A review of crystalline structure of ice is presented by Meier [445] in Chow's *Handbook of Applied Hydrology*. The previously mentioned paper by Wilson, Zumberge, and Marshall [730] describes ice texture and presents a statistical study of crystal sizes. Crystals also are discussed in the German paper (English translation available) by Bass and Magun [77], which is concerned with growth patterns, particularly hexagonal modification. Hexagonal and cubic forms of ice were studied in the temperature range -90 to -180°C by Kumai [380], who reported that hexagonal crystals formed at the warmer end of the range and cubic crystals formed at the colder end. Both were detected in the range -130 to -160°C. The popularly styled review article by Runnels [584] describes orientation and structure of ice crystals at the molecular level.

Runnels' paper relates entropy to crystalline structure and briefly describes electrical properties of ice. Delsemme and Wenger [189] have reported on a new allotropic form of ice with a density of about 2.32 g/cm^3 which formed at low pressure at about 100 K (-173°C). Reporting on contributions of the oceans as sources of nuclei of ice crystals, Paterson and Spillane [511] have stated that there is no experimental support for the notion that peptides in the ocean constitute a natural source of ice nuclei.

Mechanical properties.--Jones and Glen have published two papers [334, 335] on mechanical properties of single ice crystals. Their tensile and compression tests found variations of creep rate and a yield-point phenomenon. Deformation of ice has been studied by Barnes and Tabor [75] who reported a deformation in conjunction with pressure melting and by Haefeli, Jaccard, and De Quervain [280] who reported creep rates under compression loading at considerable hydrostatic pressure. Berger, Marshall, Munis, and Fourney [90] used a holographic technique to measure ice strain and determine Young's modulus and Poisson's ratio of ice using the ring test. Nakamura and Jones [467] have described the results of experiments to determine the effects of many different impurities on some of the mechanical properties of ice. A Soviet monograph [351] on ice hardness by Khruschov and Berkovich is available in English translation. Papers by Weeks and Assur [701] and by Milne [455] report on cracking of natural ice. The report by Weeks and Assur analyzes results of several types of testing and includes a list of 170 references. Ingram and Halper [322] have reported on investigations to measure the pressure-time reactions of shock waves caused by explosives detonated in ice. A Russian paper by Proskuryakov and Berdennikov [543] has analyzed horizontal and vertical components of pressure during horizontal expansion of ice onto inclined planes, such as a beach, considering both simple and complex bending. Itagaki and Tobin [327] have reported observations of the relaxation of grooves in ice on a microscopic scale, concluding that viscous flow contributes most to groove decay, and that evaporation-condensation also is significant. In 1971 Soviet papers were published by Proskuryakov [541] and by Shmatkov [623] describing work in electrical modeling of the stresses in an ice sheet. Such work, of course, has application in analyzing ice jams and stresses on structures--subjects to be covered in a later section of this bibliography.

Strength.--Studies of strength of ice seem to be reported in the literature more than any other type of study of physical characteristics of ice. The papers by Jones and Glen [335] and by Khrushchov and Berkovich [351], cited in the previous paragraph, both deal with ice strength. Several papers reporting on strength, appearing 10 to 20 years ago, are significant, including work by Barnes [67] in 1958, substantial data by Frankenstein [244] in 1961, papers on carrying capacity by Panfilov [502, 503] in 1960 and 1961, and relations of strength to other physical properties published by Assur and Weeks [46] in 1963.

More recent publications on strength include the review paper by Pounder [538], descriptions of heavy traffic loads by Stevens and Tizzard [644], and the monograph on strength by Butyagin [144]. Soviet proceedings [134, 542] discuss methods for determining strength of ice as well as studies on the loss of strength during melting. A report by Haynes [290] published in late 1973 contains the results of numerous laboratory tests on specimens stressed under axial tension and radial and tangential compression at the same time. Results showed considerable decreases of tensile strength from values found during simple testing in tension. In another recent paper, Parmerter [508] has analyzed transverse shear and bending stresses in a sheet of floating ice and has derived a dimensionless strength parameter using simple plate theory. Crossdale [183] has developed and demonstrated a method for field testing of ice strength using a large, heavy "nutcracker" device which exerts horizontal forces and can operate in very thick ice. Several researchers have related strength to other properties of ice, including Lavrov [397] who related strength to structure, Frankenstein [245] who related strength to salinity and temperature profiles by means of beam tests, Baily and Macklin [52] who considered strength of accreted ice in relation to impurities, and Buinitskii [132] who considered the effects of diatoms in ice on decreased strength. More than 150 papers on ice strength are cited in a recent (1975) review by Kerr [349] of the literature on the bearing capacity of floating ice plates. Kerr emphasized that ice is elastic until time of failure; a relatively light vehicle parked on the ice is likely to fall through after a certain time interval. In another recent paper, Gow and Langston [274] reported on ice strengths ranging from about 2 to about 7 kg/cm^2 on cantilever beam tests of ice from two New Hampshire lakes.

Optical properties.--The properties of ice in absorbing, transmitting, and reflecting light and radiant energy have considerable influence on the formation and breakup of ice, on the heating of water under the ice, and on biological activity under the ice. Research on optical characteristics has been conducted under both field and laboratory conditions.

Work by several researchers on transmissivity and reflectivity of ice with respect to radiation was summarized by Mantis [432] in a comprehensive report published in 1951. In a later paper published in 1959, Lyons and Stoiber [414] reviewed some of the earlier literature on light absorptivity and presented some new data of their own. They reported that clear, flawless ice has values of light transmittance close to those of distilled water, while bubbly ice like that often found in nature has absorptivities about 100 times greater than those of clear ice. Dirmhirn [201] in 1956 experimented with light transmittance in blocks of ice cut from Lake Neusiedler, Austria. Techniques for measuring the penetration of light through ice and the effects on biological processes are outlined in the 1962 guidebook, in German, by Sauberer [594]. A 1964 paper, also in German, by Albrecht [11] relates penetration of solar radiation in ice covered lakes to the characteristics of the ice and the amount of snow cover. In 1967 Goldman, Mason, and Hobbie [268] reported on penetration of solar radiation into two Antarctic lakes.

Shishokin has studied penetration of solar radiation into ice. Two similar translations (from Russian) of his 1969 paper were published, certainly accidently, by the same journal in the same year [620, 622]. The paper summarizes data collected under many different conditions of ice, radiation, and temperature. In another paper [621], Shishokin analyzed his own and others' data in relation to the Bouger-Lambert formula for penetration of radiation, and a variation of the equation was derived. Karol' [343] also has reported on Russian work to measure the penetration of radiation into ice. The paper by Karol' emphasizes that small and highly sensitive instruments are needed for reliable data. A more recent report on Soviet work on penetration of radiation is contained in the 1972 papaer by Timchenko [660], which reports an empirical equation for radiation absorption developed for the Soviet Far East.

Recent Canadian and U.S. reports on optical properties of ice include the paper by Schindler [602] who presented data on light penetration at several wavelengths and total energy flux at several depths for lakes in northwestern Ontario. Little, Allen, and Wright [411], in a paper titled "Field measurement of light penetration through sea ice," describe a nonoptical, nonelectrical instrument devised for measuring relative light intensity in sea-ice bore holes and report extinction coefficient values. Davis and Munis [185] did laboratory studies of extinction in sea ice using a red helium-neon laser as a light source. They found an exponential relationship between extinction coefficients and salinity. Two recent papers by Maguire [426, 427] report on attenuation of photosynthetically active light by ice and snow cover on Canadian lakes.

Biological effects.--Plant cells and plant pigments in ice can have a pronounced effect on the light transmitting properties. Buinitskii [131] reported on work by Soviet Antarctic expeditions which found large populations of up to 32,700 diatom cells per milliliter in Antarctic sea ice. The diatoms reproduce within the ice, hold back radiation, and cause quicker thawing of the ice cover. Kol and Flint [362], in 1968, and Kol [361], in 1971, identified several algal species in green Antarctic sea ice; and Hoshiai [309] studied the brown layer at the bottom of new Antarctic ice, reporting on chlorophyll-*a* concentration and other chemical properties.

Albedo.--Research on the reflectivity of solar radiation (albedo) has been conducted by several investigators. Work by Koptev [367] on clear water, various forms of ice, and ice covered with snow found that albedo ranged from less than 15 percent to more than 90 percent. Lyubomirova [415] reported on experiments in which a block of ice was tilted to effect various angles of incidence for measuring albedo. Albedo, at angles of incidence from 0 to 80 degrees, ranged from 31 to 58 percent for dry ice and ranged from 24 to 35 percent for wet ice. Langleben [388] measured albedo of nearly 100 percent from snow at a station in the Arctic Ocean. Albedo decreased as snow deteriorated and got as low as 30 percent as the temperature of the air rose to above freezing. Another paper [390] by the same author describes the effects on albedo of puddling from the melting of ice. Two identically titled, similar reports by Bolsenga [112, 113] reported albedo ranging from 10 percent for clear ice to 46 percent for snow ice. Both reports present the data and describe conditions of measurement, and one [112] includes photographs of the ice at time of measurement.

Airborne measurement of albedo provides large-scale data not obtained from measurement on the ground. Spano [640] and Predoehl and Spano [540] have written on measurements over the Ross Sea in Antarctica, with albedo in the approximate range of 60 to 80 percent, except over young ice where it ranged from 10 to 25 percent. Kung, Bryson, and Lenschow [381] made flights over continental North America and reported albedo in snow-covered regions to exceed 50 percent most of the time.

RIVER ICE

Subsections of this discussion of river ice deal with the specific freezing and breakup processes of ice on rivers and with the effects of the ice. In addition to the literature cited in the subsections, there are several reports that describe river ice phenomena and data of a more general nature than will fit into the more specific discussions.

An assessment of research needs, by the American Society of Civil Engineers, Task Committee on Hydromechanics of Ice [347], examines ice problems and places research priorities on formation processes, ice jams, ice forces, and thermal effects. Other problems in river ice also are recognized and the paper concludes that knowledge of river ice lags behind other areas of river hydraulics.

General properties of river ice and the processes of formation are reviewed in the symposium paper by Michel [453]. This paper highlights many of the items in Michel's monograph, which was cited as a textbook in an earlier part of this bibliography.

The proceedings of the International Association for Hydraulic Research (IAHR) 1st (1970) International Symposium of Ice Problems [323] is a publication of more than 60 papers on ice terminology, measurement, ice formation, properties, breakup, control of ice at powerplants, mechanical properties of ice, and ice loads. Proceedings of the 2nd (1972) Symposium [324] contain 44 papers equally diverse, but the proceedings are printed in Russian and therefore have limited value to most researchers outside the Soviet Union. There are more than 50 papers in the proceedings of the third (Hanover, N. H., 1975) symposium [246]. Some of the individual papers from the first Symposium are cited in this report; however many others have not been mentioned specifically.

Two Soviet publications on the hydrology of Siberian rivers [29, 30] are collections of papers designed for a wide circle of readers, including those concerned with forecasts of freezing and ice breakup, aerial reconnaissance of ice conditions, and ice jams. A 1959 Russian publication by Rymsha [589] is a generalization of investigations on winter thermal and ice conditions in rivers and reservoirs. The monograph on ice studies [271] prepared by the State Hydrological Institute, Leningrad, includes reports on several studies of river and lake ice. Ice regime of rivers and reservoirs of the USSR also is discussed in the proceedings edited by Chizhov [166].

Other articles and reports that describe work on several aspects of river ice include the research summary by the National Research Council of Canada [153]. General descriptive summaries of freezing and breakup processes in U.S. streams are contained in the paper by Parsons [510]. Ward [697] has reported that freezing and breakup dates of streams in western United States can be accurately predicted from previous records. Alaska studies of stream icing at the Caribou-Poker Creeks Research Watershed are described in the report of Kane and Slaughter [338]. From an examination of ice records for the Niagara River and air temperatures at Buffalo, New York, Hassan and Sweeney [289] concluded that there is no proof that river ice held by the ice boom significantly affects climate at Buffalo. Descriptions of rivers in Iceland, where large volumes of slush are a problem, are contained in papers by Rist [566, 567]. Freeze-up, winter ice conditions, and breakup in the Mackenzie Delta, Canada, have been described in a paper by MacKay [423].

Far-ranging survey reports on ice conditions in rivers have been assembled by the U.S. Army Cold Regions Research and Engineering Laboratory. The Canadian report by Allen [18], U.S. reports by Bilello and Bates [99, 100, 101], and by Ryder [588], are examples, but many others have been compiled. They are listed in the *Bibliography on Cold Regions Science and Technology* [672].

In the past, research on river ice has relied on observation of conditions in natural streams or canals. Laboratory hydraulic model studies, such as those by Burgi [142] and Pariset, Hausser, and Gagnon [507] have used plastic beads to simulate ice. To get better laboratory information, the University of Iowa [44, 346] has constructed a low-temperature flow facility. A flume 40 feet long, 2 feet wide, and 1 foot deep has been built in a temperature-controlled room that can be chilled to -20°F (-29°C). The floor and walls of the flume contain special heat transfer plates through which a temperature-controlled coolant is circulated and the water may also be heated, either directly or through the walls of the flume.

Freezing Processes

Description

Many excellent accounts of river freezeup exist in the literature. The review paper and bibliography by Williams [714], the rather brief narrative by Linsley, Kohler, and Paulhus [409] and the more detailed general account by Michel [452] are a few examples. As figure 1 shows, in flowing turbulent streams, frazil generally is the first ice to form, and formation of slush, shore ice, and an ice sheet usually follow, depending upon temperature and flow conditions. Under some conditions, however, no frazil will form. The following paragraphs, organized on a geographic basis, refer to additional accounts of freezing processes. Many of these detailed data have been used, consequently, to compute factors necessary for the mathematical modeling of the freezing phenomenon.

United States.--One of the earliest U.S. articles on river freezing is the paper published by Francis in 1881 [243]. Francis described formation of ice needles at the surface and their transport by eddies. Many more reports by U.S. investigators have followed. One example is the 1950 paper by Schaefer [599] which contains several detailed photographs of ice crystals and structures of ice deposits. Schaefer's paper includes some of the few published photographs of anchor ice. Discussion of Schaefer's paper by Gerdel [258] offered the convincing argument that anchor ice is not formed, as previously claimed, by long-wave radiation losses from submerged objects. A short paper by Benson [83] in 1955 gave a detailed description of anchor ice in the Pigeon River of Michigan, noting the effect of sunshine in removing anchor ice which had formed at night. Water budget studies of the Heart River, N.Dak., by Erskine resulted in a paper [223] describing freezing processes and included estimates of the volume of ice in the study reach. Brazel's description [119] of winter conditions on the St. Marys River Waterway reports frequent snow-ice layers. Reports from eastern U.S. include the work by Bilello and Smith [102] who described details of freezing of the Connecticut River and descriptions of ice on small streams in northern Virginia, near Washington, D.C., by Pluhowski [528]. Ashton and Kennedy [42], and Ashton, Uzuner, and Kennedy [44] have published detailed accounts of freezing of the Cedar River in Iowa, with detailed data on the amounts of ice, water temperatures in the rivers, and air-temperature conditions during the period of freezing. Burgi and Johnson's summary of experiences of the U.S. Bureau of Reclamation [143] in the West reports briefly on ice formation, associated problems, and some engineering solutions. Published descriptions of freezing processes in Alaskan streams include the report on the Chena River by Frey, Mueller, and Berry [249], the short paper by Gilfilian, Kline, Osterkamp, and Benson [260], and the detailed report by Benson [82] on freezing of Goldstream Creek.

Canada.--The two books by Barnes [69, 72], which were described in the subsection on textbooks, are notable early examples of reporting on ice formation on Canadian rivers. Both books contain numerous reports on the freezing of the St. Lawrence River in the vicinity of Montreal. Also, an early (1917) short paper by Barnes [71] summarizes gravitational and buoyancy forces on crystals of frazil ice. Spence [642] has published a detailed account of freezing of two small streams near London, Ontario, with data on amounts of ice related to air temperature, humidity, sunshine, and stream discharge. Wigle's report on frazil ice, bottom ice, and surface freezing in the Niagara River [710] describes ice forming at the surface when mean temperature is above freezing and the frazil crystals start to attach themselves to objects when the water cools uniformly to the freezing temperature. Additional accounts of freezing of the Niagara are in papers by Russell [586] and by Arden and Wigle [35]. More general Canadian papers include the report by Kivisild [355] on the role of hanging ice dams (ice sheets already formed) in forming a growing cover with packed floating ice.

A report by Pariset and Hausser [506] also describes the function of an ice cover in stopping the movement of frazil ice. Morton's summary paper [463] reviews equations for ice cover formation, including velocity effects and influences of hydraulic gradient. Laboratory studies on ice formation are reviewed by Ramseier [554], who describes formation of crystals on a calm surface as well as the turbulence effect on the size of crystals and on their orientation. Williams [724] summarizes twenty years of record on frazil ice on the Ottawa River and the effects of the ice on power plants. A paper by Tsang and Szucs [666] contains detailed accounts of temperature, ice, and hydraulic conditions on the Nottawasaga River, Ontario, and the Peace River, Alberta.

Europe and Japan.--Ice formation on the lower Rhine is reported by Oudshoorn [496] who describes the formation of the first ice at the head of tide and the upstream growth of the cover. Oudshoorn's observations of formations of ice dams were found to agree well with the observations by Kivisild referred to in the paragraph above. A description of the Netherlands Deltaproject by Santema [593] explains how cooling water, salinity changes, and reduced circulation caused by dams have affected ice formation on rivers and estuaries. Papers by Devik [194, 195] summarize and provide analyses of ice formation on the rivers of Norway. The more recent paper [195] emphasizes effects of ice on the operation of Norway's many hydroelectric power plants. Carstens' report [158] on ice formation in Norway establishes minimum velocities for frazil ice to bridge to a solid ice cover. The paper includes a novel photograph of a meandering narrow open channel in a broad ice-packed river channel. A Japanese paper by Muraki and Kamada [465] describes the condition of ice on rivers where there is heavy snow cover. Snow will overlay the first ice, but will become saturated with water and a second ice cover will form.

USSR.--Soviet work on river ice dates back many decades, but a relatively small amount of the literature is in English; nor is it readily available in the United States. Among the older Russian works recently translated to English is the 1933 paper by Bydin [145] describing the growth of ice. A 1936 paper by Altberg [19] which reviews twenty years (1915-35) of productive Soviet research is called by Gerdel [258], "One of the greatest contributions to be found in the literature on both fundamental and applied research in anchor- and frazil-ice formation." Two papers by Rymsha and Donchenko [590, 591] from the mid 1960's give general descriptions of the freezing process, considering heat loss at the water surface, turbulent mixing, and the intensity of ice formation. These factors are combined into mathematical representation and a nomogram for predicting ice formation. A short papaer by Dyukel' [214], published in 1969 describes slush ice on several rivers of the Soviet Union and shows a relationship between severity of slush and the number of ice jams during a season. Dyukel' concludes that in some regions slush is worst during severe winters and in other areas normal winters have the most slush. Multilayer ice covers are reported by Mel'kheev [446] as occurring in rivers of the Eastern Sayan Mountains, mainly as a result of permafrost effects on runoff patterns. An account of formation of ice lenses in two rivers of the Transbaykal is contained in a paper by Zil'bershteyn [750]. There the rivers freeze in early winter, but the pattern is complicated by increasing flow and a second freezing of the overflowing water in later winter. General descriptions of ice formation in the lower Danube River are presented by Vagin [686], by Vagin, Kovernyy, and Shcherbak [687], and by Shcherbak and Solopenko [614]. The climate of the Danube Delta includes both cold and warm air masses in early winter and ice first appears in shallow arms followed by more general shore ice, ice dams, and total filling with ice. Panfilov's recent paper [505] on thermal cracks in ice cover describes the cracking phenomenon on Soviet rivers and relates it to rates of temperature change in the ice and to deformation stresses. A paper by Polyakova [531] summarizes the dates of freezeup and the characteristics of ice on the Lena River based on detailed data from eight stations.

Climatic Effects and Prediction

Because of problems with navigation, water supply, and power generation, it often is desirable to be able to predict the formation of ice on rivers. Understanding the freezing processes is a prerequisite to predicting dates of river freezing and several authors offer explanations of the heat-transfer or energy-budget factors involved in freezing. As the previous section of this report mentioned, mechanical or hydrodynamic factors such as velocity of the flowing water and slope of the water surface also must be considered in prediction of freezeup. Owing to the complexity of the energy budget of freezing and the hydrodynamic factors that affect river freezing, more simple correlation procedures and statistical analyses frequently are employed in predicting ice formation. The following paragraphs report on some of the literature describing the various predictive methods.

Energy budget.--An energy budget is the most rigorous means of computing ice formation. Budgets consider incoming radiation, net energy loss by evaporation, conduction to the atmosphere, loss by snowmelt, incoming advected energy, outgoing advected energy, and net gain or loss in energy storage. Two good summaries of the equations are presented by Michel [452] and by Burgi and Johnson [143]. Techniques used in the USSR are summarized in *The Manual of Forecasting Ice Formation for Rivers and Inland Lakes* [627], in a short paper by Rakhmanov and Shastin [552], and in the publication on thermal regimes by Pivovarov [527]. Ferguson [230] reported on an energy balance for the Niagara River in the 1967 ice season, and Pruden, Wardlaw, Baxter, and Orr [544] computed one for the St. Lawrence. A summary of energy exchange, water temperatures, supercooling, and frazil-ice formation on the Susquehanna River, appears in a short article by Granbois [275]. Williams [717, 718] reports average monthly values of terms of the energy budget and of heat transfer coefficients for Canadian lakes and streams. Additional

Canadian work includes the report by Michel [450] which shows a good correlation between quantity of frazil ice produced and the rate of water cooling at the freezing point. Another Canadian study is the analysis by List and Barrie [410] of the heat losses leading up to freezing of the Niagara River. Freysteinsson [250] used an energy-budget technique to calculate frazil ice discharge in the Thjorsa River system in Iceland, and reports good agreement with observed quantities of frazil ice. Soviet work with the energy budget includes that reported by Ginzburg [261], in which the energy budget was integrated using predictions of meteorologic variables in order to make predictions of freezing dates. Ginzburg reports a relatively high degree of accuracy. Work by Dyukel' [216], however, stresses that use of any energy budget in predicting and analyzing temperature and ice conditions must consider the heat content of mine, industrial, and domestic waste discharge, as well as the contribution from inflowing ground water.

Hydrodynamic factors.--As figure 1 shows, flow conditions play a major role in deteriming if a solid ice cover will form on a stream. The earlier section of this report on the description of freezing processes referred to several papers reporting on this phenomenon. Pariset, Hausser, and Gagnon [507] conclude that ice-cover thickening is a function of the hydrodynamic forces acting on the cover. Uzuner and Kennedy [684] analyze the critical conditions at which buoyant blocks are swept under downstream floating cover. Their work included experiments and observations in a small laboratory flume which provided data to support their conclusions from a theoretical analysis of forces acting on the ice particles. A discussion of the Uzuner and Kennedy paper by Ashton [37] produces slightly different analyses of the forces acting on the floating ice blocks. Razumikhina [558] derived and confirmed a theoretically based formula describing the competence of ice cover in terms of velocity distribution and turbidity. Papers by Carstens [158], and by Kivisild [355], both referenced in an earlier section of this paper, discuss limits affecting the ability of floating ice to form a part of an ice cover, to be carried under the cover, or to continue to flow. Kivisild states the limit in terms of the Froude number and Carstens reports absolute velocities. The 1973 publication by Hutter [320] presents a comprehensive review of the fundamental equations of floating ice.

Correlation techniques.--The most widely reported predictive methods for ice formation rely on some type of correlation between the date of freezing and other measurable variables, such as air or soil temperatures. Although certainly not so rigorous as energy budget or hydrodynamic methods of computation, they generally are more simple to apply and rely on data that are more easily collected. Ginzburg [263], for example, used records of freezeup dates dating back more than 40 years and developed relationships that 95 percent of the time can predict the beginning date of freezing within three days. The *Guide to Hydrometeorological Practices* [737] of the World Meteorological Organization recommends general procedures in which accumulated degree days below freezing can be used for the prediction of date of freezing. Standard operating procedure for forecasting freezeup of the St. Lawrence River as Massena, N.Y., [45] relies on empirical temperature-decline equations that use measured water temperatures and forecasted flow rates and heat fluxes. A forecasting method developed by Rogers, DeWitt, and Dixon [570] for forecasting ice conditions for the Sugar Island Ferry crossing of the St. Marys River, Mich., uses meteorological and hydrological data, aerial photographs, time-lapse photographs, and probability analyses of data on temperatures and the amount of shipping traffic. A Polish manual on the fundamentals of forecasting [440] and the supporting extensive work by Jarocki [329] on forecasting ice formation in Polish waters rely heavily on empirical relationships between the time of freezing and air temperature or other gross hydrologic variables. Published reviews of hydrologic forecasting techniques used in the Soviet Union [259, 533] report the widespread use of correlation techniques in that country. Some of the many Soviet publications describing these techniques in some detail are discussed in the following paragraph.

In the mid 1930's Bydin [146, 147] worked with the correlation between the temperatures of river water and of the soils on the banks. Using soil temperatures at depths of 0.8 to 1.6 m, he developed correlations for predicting freezing dates. Dyukel' [215] has worked with freezing dates in mountainous areas, grouping the streams by altitude and other hydrologic factors. Dyukel' shows that dates of freezeup are largely determined by channel slopes and to a smaller extent by climatic conditions and rates of discharge. Information on atmospheric circulation and thermal-budget data over large regions were used by Bagrov and Kukhto [51] to predict time of freezing, with the aid of a multiple regression analysis and synoptic analysis. Work by Savchenkova [596, 597] relates the movement of large cold masses to the freezing of Siberian rivers. Using long-term records of several streams and of meteorologic conditions in September and October, a correlation is found between dates of ice formation and changes in atmospheric pressure anomalies. Good forecasts of freezing can be made from 10 to 15 days prior to the time of freezeup. Working with 30-year records from the Dnieper River and macrosynoptic climatic conditions, Solopenko [639] developed a technique for predicting date of freezeup at least a month in advance of its earliest occurrence. Similarly, Vinogradova [690] relates the formation of the Siberian anticyclone in the fall to the freezing dates of the Yenisey and Angara Rivers, developing methods for making long range forecasts. Empirical studies by Zhitskaya [749] on the Pripyat' River related growth of the ice cover to a number of parameters, including snow depth, temperature, length of cold periods, and thickness of ice already formed. Lebedeva [401] worked with climatologic and synoptic information to develop forecasting methods for rivers of the Leningrad region. A paper by Alekseyenko [14] relates dates of freezing of rivers in the Baltic Sea region and Belorussia to hydrologic and meteorologic variables. Polyakova's summary [531] of freezeup of the Lena River gives dates for the probable occurrence of ice in several different reaches and describes the relationships among conditions at eight stations. Data also are included on the rates of ice growth and the time of maximum ice thickness on the Lena River.

Correlation techniques have been used less extensively in the United States and Canada than in the USSR. In 1964 Bilello published two papers [94, 95] relating ice formation on the Mackenzie River at Fort Good Hope and other Canadian river stations to daily air temperatures. Poulin, Robinson, and Witherspoon [536] worked with data from the St. Lawrence River, considering forecasts of river stage and discharge, forecasts of air temperature, and measured temperatures of the river to predict river temperatures and freezing dates. Ward [696, 697] has had considerable success in representing seasonal change in stream temperature by a sine curve. In climates where freezing occurs, the intersection of the curve with freezing temperatures can be used to predict dates of freezing. Arden and Wigle [35], and Ferguson and Cork [231] have predicted freeze-up of the Niagara River based on water temperature and meteorological data, and Williams [724] has used similar data for forecasting frazil ice on the Ottawa River.

Regulation and Control

For decades, the principal method for control of river ice has been ice removal. This was accomplished by icebreakers, salting, explosives, ice booms, and other means. However, consideration also has been given occasionally to attempts to prevent ice formation, usually by heating the water.

Some of the methods for control of river freezing are reviewed in the following paragraphs. For additional discussion of ice control the reader is referred to two later parts of this bibliography (1) the subsection on control of ice jams, and (2) the subsection on regulation and control of lake ice. Some of the techniques reported for use on lake ice also may be applicable to control of ice on rivers.

Heating is an obvious and simple, but usually costly, means of controlling ice. In 1954 the Canadian National Research Laboratories published *A Study of Wintertime Heat Losses from a Water Surface and of Heat Conservation and Heat Addition to Combat Ice Formation in the St. Lawrence River* [544]. The work formulates a rational design procedure for a heater system and estimates the order of magnitude of component costs. A recent paper by Poothrikka, Macagno, and Kennedy [532] develops a closed-form solution of the one-dimensional unsteady convection-diffusion equation to predict temerature effects from added heat and the lengths of ice-free reaches downstream from thermal discharges. A summary by Granbois [275] on the control of frazil ice in hydroelectric power plants recommends the use of heated trash screens, particularly at times of supercooling when the worst of the frazil is forming. Use of heat on a small scale was demonstrated by Doty and Johnston [207] who used propane heaters for keeping a mountain stream gaging station free of ice. Fuel costs, however, of such a system are high. Work with highway culverts in Alaska by Gaskin and Stanley [255] showed that the culverts can be kept open by placing an electric heating cable in the bottom of the culvert pipe. A report on culvert icing by Carey, Huck, and Gaskin [157] concludes that heating, along with channel deepening, probably is the most effective control technique. A thesis by Paily [497] and papers by Paily, Kennedy, Macagno, and Dagan [498] and Paily and Macagno [499] report analyses of the influences of heated discharges in keeping rivers ice free. Work described in these papers was conducted at the University of Iowa, and included laboratory experiments and analyses of field data from the Mississippi River.

One solution to the high-cost problems of preventing freezing seems to have evolved as a by-product of another form of technology--thermal electrical generating plants (coal-fired and nuclear). The power plants often are criticized because they are sources of thermal pollution, which during warm seasons can be harmful to plant and animal life in rivers. In winter, however, the heat may be used effectively in keeping sections of rivers ice free. Dingman, Weeks, and Yen [198, 199, 200, 702] have explored this possibility, analyzed conditions at existing power stations, and concluded that significant portions of the St. Lawrence Seaway can be kept ice free by the installation of nuclear reactors at appropriate locations. Additional reports on the effectiveness of power plants in keeping streams open have been published for the North Platte River in Wyoming [703], and for the Chena River in Alaska [10].

Air bubbling is used for ice control on lakes more than on rivers and is discussed in more detail in a later section of this report. A review of the state of the art on bubbling published in 1961 [152] concludes that success of the technique in rivers depends on flow velocity and upstream sources of heat. A more recent review of the melting processes of bubbling and their effectiveness is in a 1974 report by Ashton [38]. Lauri [396] reports that a channel such as the St. Lawrence Seaway could be kept ice free using special bubble guns at an initial cost of $30,000 per mile, plus an annual operating cost of $750 per mile.

Use of icebreakers still is a common way of controlling river ice. Several papers on breakers are discussed in other parts of this bibliography. A brief review of current Canadian icebreaker methods is contained in a paper by Stewart [645].

Control of freely floating river ice by ice booms is a common way of causing a solid cover to form. A 1938 Russian paper by Pobedonostsev [529] describes a cable boom, and Russell [586] and several other authors describe the boom at the mouth of Lake Erie to control ice flow into the Niagara River. Analyses of some factors affecting the design of booms are in a recent translation of a Russian paper by Latyshenkov [395]. More discussion of ice booms is in the subsection of this bibliography on Interaction with Structures. Increased turbulence at dams is reported by Harich [285] as a means of preventing heavy icing on movable gates. Scherman [601] summarizes that hydroelectric plants should have large upstream basins to trap ice, short deep channels for flow, and intermittent operation during freezeup. Dusting with coal [179] or other materials also is a practice widely used to hasten opening of lake and river ice. Dusting of river channels with sand is also reported [221] as being an effective control technique. A short paper by Johnson and Tabler [331] presents a scheme for keeping sections of small streams in the vicinity of gages and controls open by enclosing the channel and control in a multiplate steel pipe arch. Tveit [668] also reports means of keeping weirs open by housing them in box-like structures. Several photographs are included in Tveit's paper.

Good examples of some of the recent work on ice control are in the section on "Extended Season Navigation" in the proceedings of the Third (1975) International Symposium on Ice Problems [246]. Several of the twelve papers in that section report attempts to improvise new methods or to achieve improved application of older methods.

Melting and Breakup

Description and Prediction

There are about as many published accounts of breakup of river ice as there are published accounts of freezing, simply because many papers report both phenomena. The breakup process usually extends over a period of days or weeks, beginning when the ice in a river starts to move, break, or deteriorate, and ending when the water is completely free of all ice. It is a complex phenomenon, depending on weather conditions that prevail during the ice season and on local variations in channel shape. The review article by Williams [722] attempts to explain river breakup by the model that is shown here as figure 2.

Some accounts of river breakup in the recent literature include papers by Burdykina [141] about the Yenisey River in the USSR, by Lehmann [404] describing inland waterways in East Germany, by Slaughter and Samide [633] on the Delta River of Alaska, by Vagin [686] describing the Danube, by Tsang and Szucs on two rivers in Central Canada [666], and by Ashton, Uzuner, and Kennedy [44] on the Iowa River. Four of these papers [44, 141, 633, 666] also include information on air temperature and other meteorological factors affecting the breakup. Bydin's early paper [145] also includes a general account of river breakup in the Soviet Union. An account by Walker [694] describes erosion, sedimentation, and channel scour that accompany ice breakup. Bulatov [134] has described the weakening of ice during breakup on Soviet rivers, including the effects of meteorological conditions and solar radiation

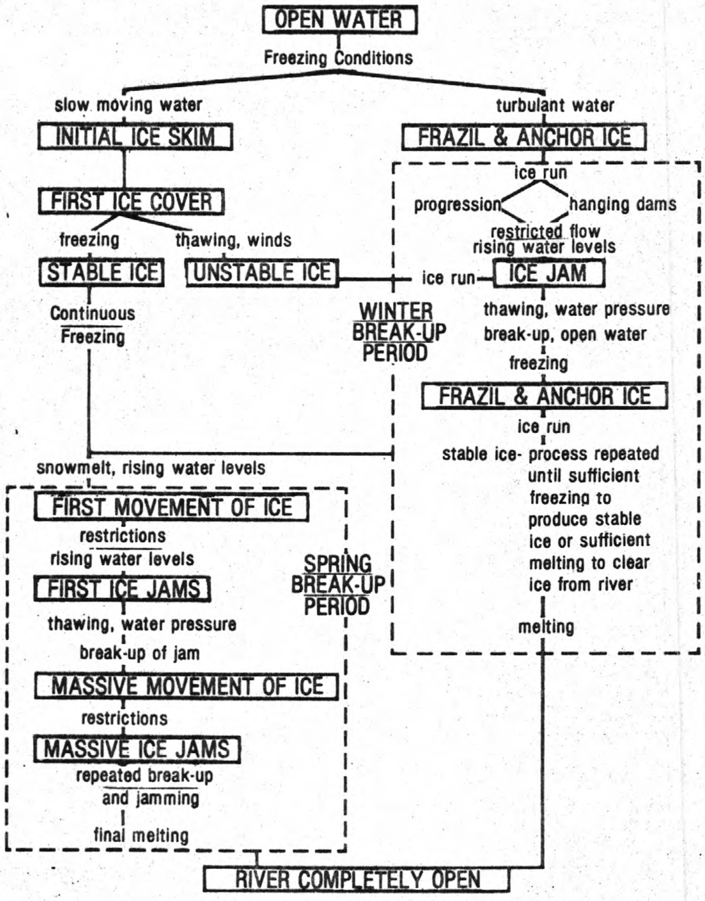

Figure 2.--Model of processes of river breakup; from Williams [722].

in weakening the ice. A report by Walker [695] on the breakup of the Colville River, Alaska, includes a description of the use of a novel procedure whereby the volume of discharge during the breakup period was computed by the use of salinity data on the water under the sea ice at the mouth of the river.

Forecasting breakup is similar to forecasting freezing, in that it relies on an energy balance or on a correlation with air temperature. Russian papers by Timchenko [658, 659], Rakhmanov and Shastin [552], Burdykina [141], Ginzburg [261], and Deryugin and Lazarevskaya [192] report studies where heat budgets were established and hydrologic regime was considered. Burdykina concluded that the flood wave energy and the heat carried by the river water play nearly equal roles in the northeastern half of the Yenisey River estuary, while the thermal state of the river waters mainly affect the ice in the northwestern part of the estuary. Timchenko's studies of the heat balance of the ice found different specific heatflow values in different parts of the Ussuri River basin, and yielded nomograms to determine specific heat exchange as a function of average daily air temperature. The cited paper by Ginzburg reports the application of heat budgets in forecasting river breakups up to a month in advance.

Less sophisticated correlations between air temperature and ice breakup are found much more frequently in the literature than are heat budgets. The World Meteorological Organization [737] recommends a method of breakup forecasting based on estimating the critical sum of degree-days of air temperature sufficient for ice breakup. Applications of this and other correlation techniques can be found in the literature in U.S. papers by Ward [696], by Slaughter and Samide [633], by Schwendeman [607], and by Fobes [241]. Ward's predictions for Colorado streams are based on the shape of an annual sine curve describing temperature; Slaughter and Samide's work in Alaska incorporated the sum of degree days above freezing; Fobes, in Maine, used correlations with long-term meteorological data; and Schwendeman used short-term climatic indicators for the Red River of the North. Soviet reports describing the use of correlation techniques for predicting breakup include several cited in the earlier section of this bibliography on freezing process. These are the papers by Bydin [146, 147] who considered soil temperatures, by Dyukel' [215] who considered altitude and hydrologic factors, by Ginzburg [263] who considered long-term freezing and climatologic records, and by Lebedeva [401] who used synoptic and climatologic information. Additional Russian reports describing correlation techniques include those by Savchenkova [595] and by Ginzburg [262] utilizing data on the winter and early spring patterns of atmospheric circulation. Yefremova [742] used a regression with a polynomial series representing meteorological conditions, and Makarevich, Aniskina, Yefimova, Potapova, and Savina [428] incorporated information on atmospheric circulation as well as local meteorological and hydrologic data for the period before breakup. Makarevich, Yefimova, and Savina [429] have reported that the duration of the winter ice cover on the Danube can be predicted from air temperature and circulation data. Correlations developed from many years of record are better for the Lower Danube than for the Middle Danube because of the regime of the river. Relationships between long records of breakup dates of the Sungari River in Harbin, Northeast China, and air temperatures are summarized in a paper by Murakami [464]. Murakami has developed relationships based on 23 years of data (1919-41), and incorporates some factors that are based on 43 years of record.

Ice Jams

Michel [452] emphasizes the importance of ice jams with the following short summary:

> Breakup is characterized by the formation of ice jams, and numerous icy floods have been recorded. Some of these were severe; for example, the Yukon River rose 65 ft. in the spring of 1930 to flood the village of Ruby. Water-level rises of more than 20 ft. are common when an ice jam is formed.

His chapter on breakup goes on to give accounts of the factors that form ice jams. Again Michel's writing is in a clear textbook style.

The most detailed summary of work on ice jams undoubtedly is Bolsenga's report, *River Ice Jams - A Literature Review* [111]. More than 500 references are cited and reviewed. Bolsenga's conclusions about the state of the art include the following:

> Published information on many aspects of river ice jams is lacking. This is particularly apparent in the area pertaining to the mechanism of formation, growth and decay of ice jams. As a result, techniques of prevention and removal are often inadequate.

Research and investigation continue--and several reports have been published since Bolsenga's review was completed in 1968.

A report by Uzuner and Kennedy [685] of the University of Iowa, in 1974 described an analytical model and experiments on the evolution of ice jams in rivers. The work is limited to cases of rectangular channels. It includes an extensive analysis of compressive and shear strengths and the processes by which jams form and thicken. A later (1976) Iowa report by Tatinclaux, Lee, Wang, Nakato, and Kennedy [656] further summarizes theoretical and lab work on factors that affect if and when ice jams are formed.

Fourteen papers summarizing research and the state of the art in understanding ice jams are summarized in the proceedings of a seminar held at the University of Alberta in May 1973 [725]. A number of case histories are documented on experiences with ice jams and on the methods of dealing with them. One of the papers included in the proceedings is the summary by Atkinson [47] of data on the cost of damage by ice jams in Canada. Atkinson concludes that ice jams in Canada cost from $8.6 to $10 million per year, including damage and additional costs in design against damage. Highest portions of this cost are due to flooding and flood prevention and to additional costs in power generating facilities.

Sixteen papers describing ice jams and their control are included in the proceedings of the Third (1975) International Symposium on Ice Problems [246]. The papers are in a section called "Ice Jam Control," but they cover a broader range of topics than control.

A summary of work on formation of ice jams and engineering applications in the Soviet Union is contained in a collection of 25 papers edited by Chebotarev [164]. A short Russian paper by Dyukel' [214] (also cited in the earlier subsection on description of freezing processes) describes a method of estimating the amount of slush ice flowing in a river during a winter by using data on the number of ice jams. In actuality, the method uses the data on ice jams as an indicator of the severity of the winter--the factor that controls the volume of slush. Berdennikov has written several papers [85, 86, 87] dealing with the stresses in broken ice covers on rivers and on the dynamic conditions and stresses involved in formation of ice jams. The monolithic mass of river ice becomes a broken field or an accumulation of separate ice floes. Within a channel constriction the broken ice comes under compressive forces and forms a field having considerable strength.

Manmade alterations in natural channels often have an effect on the formation of ice jams and on the severity of flooding resulting from the jams. As a result, persons whose properties are damaged attempt to collect compensation from those they believe responsible for the ice jam conditions and the flooding. A few examples of cases in State and Federal courts give some guidelines as to how the law treats the matters of responsibilities and damages in situations involving ice jams. A 1928 case [115] involving a suit against the City of Buffalo, N.Y., charged that the city was liable for damages to flooded property when an ice jam formed at a city-built bridge. The New York Supreme Court held that the ice-jam caused flood was not ordinary and reasonably foreseeable and that the city was not liable. In a 1946 case [456] involving an ice jam and flood on the Mohawk River and Barge Canal, the New York Court of Appeals held the State liable because it had altered a channel causing an ice jam to occur. When the jam did occur the State was negligent when it did not take such necessary action, such as dynamiting the jam in order to protect waterfront property. Many suits have been brought against the United States contending that various Federal projects on river and channel improvements, dam construction, and bridges have caused ice jams to form. Two examples concern a dike on the Missouri River [379] and a lock and dam on the Illinois River [480]. It was the position of the courts that the public works involved were properly designed and that the ice jam conditions that resulted were not foreseeable, but the court also held that the United States was to some extent liable for the damages resulting from the ice jams.

Descriptions of ice jams on selected rivers.--Strand [648] has reported on ice jams on the Upper Arkansas River, Colo., concluding that jams are not expected to occur each year on that river because of the large year-to-year variations in climate and weather conditions. Henry [297] describes ice-jam conditions on the Yukon River; MacKay reports [423] on conditions during breakup and jamming on the Mackenzie River of Canada; and Hladio [303] provides an atlas outlining areas of ice-jam flooding on the Chenango River and Canasawacta Creek at Norwich, N.Y. Among Russian reports, a description of an ice jam on the Lena River in 1969, by Rudnev [583], tells of the worst ice jam in 54 years. The breakup followed a severe winter and late, cold spring which produced an ice cover on the river that was 0.5 m thicker than average. Nezhikhovskiy and Ardasheva [475] report a method developed to calculate maximum ice-jam levels on the Neva River, USSR. Longitudinal profiles of the water surface were used to analyze fluctuations in the water level during ice jams and empirical probability curves were constructed for a number of points. Records of 60 to 80 years were available to construct the curves. Karnovich [341] describes conditions on the Dniester River where severe conditions of ice jams may occur if not controlled and where regulation of discharges of the Dubossary Reservoir and power plant are used to help control the jams. A paper by Nezhikhovskiy and Sakovskaya [476] summarizes that the maximum levels of ice jams in the estuarine reaches of the Severnaya Dvina River is determined mainly by the discharge rate at the time of breakup. Forecasts of levels can be made 5 to 7 days in advance of the peak. Papers reporting on ice jams in the Soviet reaches of the Danube River include the report by Vagin, Kovernyy, and Shcherbak [687] on the entire 171 km of Danube in the USSR and the report by Karnovich and Sinotin [342] describing the lower reaches. Once every 7 to 10 years the lower Danube experiences severe ice jams up to 15 km long and having ice thicknesses as great as 7 to 9 m. An additional Russian report of interest is the paper by Sofer [638] reporting on ice jams in the Lovat' River, which the author describes as typical of the north-flowing rivers of the USSR in its ice-jam characteristics. A recent translation of six papers by Chizhov [167] summarizes Soviet investigations, particularly work on jams on the Dniester River.

Control of ice jams.--The previously-cited review paper by Williams [722] contains a summary of the many methods available for removing or controlling ice jams. Moore and Watson [460] describe experiments with several techniques for ice removal that were tested on the Yukon, including aerial dusting, pumping, blasting, and use of pressure flows. Use of dusting practices in several countries is reported in the literature review by Cavan [161]. In 1956 a Russian paper by Konovalov and Miasnikov [364] reported on effective use of coal dust applied from an airplane in reducing ice problems on the Volga and Irtysh Rivers. The dust on the ice reduced the albedo and increased weakening or melting of the ice and the snow on the ice through increased absorption of solar radiation. Work by Williams and Gold [726] shows that dusting in Canada can, in effect, speed breakup as much as 2 to 4 weeks. Cook and Wade

[179] report that the spreading of coal dust and fly ash on the ice in the Chena River, Alaska, effectively reduced the likelihood of flooding in Fairbanks.

Blasting to control ice jams has been practiced for many years and work continues on determining effectiveness of different types of explosives and on testing means of placement. Work by Froehle [251] and by Frankenstein and Smith [247] regard ANFO (a mixture of ammonium nitrate and fuel oil) as the best material based on effectiveness and cost. Frankenstein and Smith conclude that the diameter of the crater formed by ANFO exploded below the ice is proportional to the cube root of the weight of the charge. A 1973 Canadian paper by Bauer and Workman [79] contends that dynamite or TNT were more desirable. A discussion of their paper by Frankenstein contains his defense of the qualities of ANFO.

Other techniques used in control of ice jams include ice booms, channel improvement, use of ice breakers, and regulation of flow. A general discussion of ice control by Pounder [537] contains a description of icebreakers and operation of the breakers in effecting control of ice jams. In experiments at a generating station in Ontario, Townsend [662] found that proper sequencing of loading of plant units could eliminate most problems with ice jams. Deslauriers [193] describes how remedial work on the bed of the Chaudiere River, Quebec, in combination with shore protection, ice detention, and cover stabilization, minimized damage from ice jams. The ice boom at the downstream end of Lake Erie, as described by Foulds [242], is shown to be effective in preventing lake ice from moving into and causing ice jams in the Niagara gorge.

Research on the control of ice jams continues to have high priority in many countries of the world. For example, there were 16 papers in a session on "Ice Jam Control" at the 1975 Third International Symposium on Ice Problems [246]. The individual papers are not cited in this bibliography.

Effects

Of the many effects of river ice, three have been selected for brief discussion here--navigation effects, flow under ice, and interaction with structures. These seem to be the most frequently mentioned subjects in the literature. The later section of this paper about ice influence on water quality also will mention a few others.

Limitations on Navigation and Solution by Icebreaking

The effect of ice on navigation and efforts to overcome them are subjects too broad for comprehensive treatment in this short paper. There are many reports on the subject and only a few examples have been cited in this bibliography. Dick's account of problems in the Port of

Churchill [196] is one example of complex problems that exist. Data of the type reported by Bilello and Bates [99, 100, 101] and by Ryder [588] have been collected with navigation interests in mind. The previously cited paper by Rogers, DeWitt, and Dixon [570] on techniques for ice forecasting at the Little Rapids Cut is another example of ice forecasting done to facilitate transportation.

Gaither and Dalton's report [254] on an "All-Weather Tanker Terminal for Cook Inlet, Alaska" is an example of special facilities being designed to protect moored ships from flowing ice. Twelve papers in the proceedings of the Third International Symposium on Ice Problems [246] analyze "Extended Season Navigation." Previously cited reports by Pruden, Wardlaw, Baxter, and Orr [544] and by Dingman, Weeks, and Yen [200], which discuss the possible application of heating on the St. Lawrence Seaway, are aimed primarily at lengthening the navigation season. A three-year program to demonstrate the practicality of extending the commercial navigation season on the Great Lakes and St. Lawrence Seaway was operated by the U.S. Army [671]. The work included tests of several means of controlling ice on the waterways, such as tests reported by Oswalt [495] to develop an effective and economical means of flushing ice from lock chambers on the St. Lawrence Seaway. Work by Nowacki and others at the University of Michigan [484, 485] developed a computer model for analyzing the economic benefits to shipowners from extensions of the operating seasons and a model study at ARCTEC, Inc. [373] analyzes many of the technical and operational problems of operating an extended season. A short paper by Boyd [117] elaborates on the savings to one shipper, Dow Chemical Co., that an extended shipping season will produce through reduced capital expenditures and reduced fuel consumption.

Icebreaking.--Removal of ice by icebreakers is the most widely used means of extending navigation periods in cold climates. A report by Hazard [291] states that the Finnish government has decided it is better to keep the Baltic Sea open by the use of icebreakers than to rely on goods stockpiled over the winter or on overland transportation. Icebreaking costs for the Finns amount to about 12 percent of winter freight revenues. A study by Schenker [600] on the economics of icebreaking on the St. Lawrence Seaway found that an extension of the navigation season by four weeks was the minimum necessary to generate significant transportation saving in the regional economy, and that longer extensions also are justified. Wilson [729], in discussing the need for icebreaking on the St. Lawrence, also cites the experiences on the Baltic and points out that iron mines and shipbuilding facilities on the Great Lakes are losing out to foreign competitors because they are not able to make winter deliveries. A short review article by Perrini [518] describes the scope of the current U.S. icebreaking program on the Great Lakes, St. Lawrence, St. Marys, and other parts of the Great Lakes navigation system. The paper summarizes that there are three main features of the program--icebreaking, navigation aids, and commercial vessel operation.

A summary of the involvement of the U.S. Coast Guard in icebreaking and of some of the biggest problems faced by the Coast Guard is in an article by Ehrlich and Welsh [218].

Icebreaker design has improved during recent years, with a tendency toward more powerful icebreakers and innovations in hull design. An example is the Alexbow [491], a device designed for attachement to the bow of a ship to produce icebreaking at relatively high speeds by upward lifting of the ice. A review by Franklin Institute [692] of icebreaking concepts that might best be applied on the upper Mississippi River concludes that the best designs were those that broke the ice by upward forces and then placed the broken ice well back from the broken channel. The principle of the water cannon has been adapted in one reported icebreaker design [177] which uses underwater jets to flush broken ice away from the cleared channel. A new type of "explosive" icebreaker has been tested by the U.S. Coast Guard [673] on the Great Lakes and the upper Mississippi. The icebreaker uses a fuel combustion chamber with high pressure exhausts to break the ice and uses streams of flowing water to remove the broken ice from the channel.

A detailed account of icebreaking by a conventional towboat on the Mississippi River is contained in a 1973 report by Ashton, Denhartog, and Hanamoto [41]. Valuable information is provided on resistance encountered, effects of repeated passages, navigation procedures, and damage to the towboat. A 1974 report by Ashton [39] further analyzes problems of ice management on the Mississippi and shows that most navigational ice problems occur during a small fraction of the period of ice cover.

Flow under Ice

Interest in the volume of discharge of streams flowing under ice cover dates back at least to the early part of this century, as reported by two early U.S. Geological Survey Water-Supply Papers. In 1907 Barrows and Horton [76] published a USGS report on the determination of streamflow during the frozen season. An even more comprehensive Water-Supply Paper on the measurement of flow under ice was published six years later by Hoyt [313]. These papers contain a considerable amount of field data on the stage-discharge relationships of streams under conditions of ice cover, on velocities of flow under ice conditions, on rates of freezing, and on general methods and equipment to be used in measuring and computing winter flow.

For about half a century the art of understanding the flow of streams under ice conditions did not advance a great deal beyond that reported in the two reports cited in the immediately preceding paragraph. Progress during the 1960's and 70's includes the work reported by Fedorov and Sharshukova [228] on the distribution and pulsation of velocities in the Svir' River of the USSR. Chachina [162] reported on computations of winter discharge for the Neva River, USSR, describing use of a simple conversion factor which relates discharge at a certain river stage under ice conditions to discharge at that same stage under conditions of open water. Confirmation studies on the backwater methods used by the U.S. Geological Survey since the days of Barrows, Horton, and Hoyt were reported by Cook and Cerney [178] in 1968. Cook and Cerney make their confirmations by comparing records of stage and discharge from open and ice-cover reaches of the same stream--the Rio Grande del Rancho in New Mexico. Work on simplifying the methods of measuring stream discharges in Canada are described by Strilaeff [650] and by Strilaeff and Wedel [651] who experimented with using the velocity at a single point in the ice-covered stream as an index to cross-sectional velocity and stream discharge.

Tracers, both radioactive and dye, have been used to study the flow of streams under conditions of ice cover. Zimmerman [751] describes the use of a fluorescent dye to determine time-of-travel in a reach of the ice-covered Laramie River in Wyoming and hence to compute the mean velocity of the River from the time-of-travel data. Work with radioactive tracers in north Moravia, Czechoslovakia, was reported by Balek, Ralkova, and Sochorec [61]. They used chromium-51 to determine time of travel and to measure discharge and found that water particles moved faster in an ice-covered channel than they moved in an open channel when other hydraulic conditions remained equal.

Papers also have been published in recent years dealing with the transport of sediment and conditions of the stream bed resulting from ice. Working on the Gana River of Norway, Collinson [176] describes the effects of ice on the stream bed during the period of spring flood as being gouges formed by ice contact, local deposition and scour from separation eddies at grounded blocks, disturbance from collapse of melting blocks, and depressions caused by melting blocks. A paper by Reimnitz and Bruder [559] describes scour caused in arctic Alaska deltas when overflowing meltwater drained through holes in the ice. Short and Wiseman [624] describe observations of ice-slush berms, ice-sediment interbedding, and buried ice boulders along the Alaskan coast. Tsang and Szucs [666] report on transport of stream sediments as a result of the sediments being picked up by ice clusters in the Nottawasaga River, Ontario. Shulits [626] reports how changes in the ice patterns on the Susquehanna River were caused when an airport runway was extended into the river and consequently ice scour produced erosion on the banks of several islands in the river. Tywoniuk and Fowler [669] describe the severe problems in collecting sediment samples from frozen rivers and propose that satisfactory samples might be collected from single verticals in the stream cross sections.

Effects of ice roughness.--In recent years a major emphasis in ice research has been placed on the analyses of the effects of roughness of the bottom side of an ice cover on the flow in the stream. Most of the earliest papers on the subject were written by Soviet scientists. Dul'nev [210], in 1962, evaluated and derived a combined roughness coefficient for a channel with an ice cover. In 1964, Nezhikhovskiy [474] reviewed equations for combining Manning's roughness coefficients for the streambed and the underside of the ice and discussed the effects of slush on the ice roughness as well as changes in the roughness of ice through the winter season. Dul'nev and Nezhikhovskiy also cite some Russian references from the 1930's which were not available to the compilers of this bibliography. Other Soviet papers [579, 630, 631] from the mid 1960's deal with roughness values of ice as they affect the volume of discharge and the velocity distribution in the stream.

Three paper by Kevin Carey [154, 155, 156] in 1966 and 1967 presented the first American work on ice roughness and its influences on flow and velocity. Carey's first paper [154] includes data on the dimensions of roughness features of ice on the St. Croix River in Wisconsin, suggests use of the Karman-Prandtl resistance equation for computing discharges, and computes values of the Darcy-Weisbach friction factor and Manning's roughness coefficient. In a later paper [156], Carey describes the underside of the St. Croix ice as having ripplelike and dunelike features and confirms the Belokon-Sabaneev formula, as reported by Nezhikhovskiy [474], for relating the roughness coefficients for the ice, the bed, and the total channel. After extensive work with channel roughness using pipe-flow equations, Carey [155] concluded that streamflow under ice conditions could better be computed using a stage-fall relation and the concept of backwater.

Several additional American papers on ice roughness appeared shortly after Carey's publications. Yu, Graf, and Levine [746], in 1968, reported roughness coefficients for the St. Clair River, Mich., and developed a relationship between the Manning coefficient and stage of the river. In 1969, Larsen [393] reported a technique for using a rational formula for composite roughness based on the velocity distribution pattern. Studies on the Nottawasaga River of Ontario are reported by Tsang [664] in 1970. Tsang's paper includes many data on vertical velocity distribution and computes the variations in shearing resistance caused by the presence of frazil ice in the stream. A summary report of ice studies on the Iowa River and in the laboratories of the University of Iowa was released in 1970 [44]. This report by Ashton, Uzuner, and Kennedy describes temperature and velocity conditions in the river during freezeup and the ice season, shows photographs of sections of river ice, and reports on several experiments performed in the University's cold flume.

Work on ice roughness performed outside North America and the USSR includes the studies by Ohashi and Hamada [490] on Hokkaido, Japan, which found the Manning's coefficient to range from about 0.012 to 0.062. Tesaker [657], reporting on work in Norway, found average coefficients for the ice to be in the range 0.013 to 0.020, with many values being considerably higher.

Papers within the last five years show that work on the roughness of river ice and the mechanics of flow under ice is becoming more widespread and more sophisticated. Ashton and Kennedy [43] describe an analytical model to predict the occurrence and describe the properties and behavior of ice ripples that form on the underside of ice covers. They note that ice ripples do not form during the initial freezing process, but appear later; and their appearance and form can be predicted by the heat transfer and hydrodynamic considerations of the model. Larsen [394], in 1973, reported on roughness conditions observed in Sweden, and on differences in ice thickness and character between the edges and center of the channel. Larsen postulates that the differences in ice cover were caused by heat transfer from the bottom and suggests that other factors such as variations in heat-transfer coefficients and other sources of energy are more likely to be involved. However, Ashton [40] and Rantz [556], who cite the heat-transfer computations by Baines [53], were quick to criticize Larsen's contention about the heat transfer from the bottom and suggested that other factors such as variations in heat-transfer coefficients and other sources of energy are more likely to be involved. A comprehensive review paper on ice roughness by Uzuner [683], in 1975, summarizes and evaluates the techniques proposed by several authors for computing a value for composite roughness. Uzuner recommends the procedures proposed by Hancu [284] and by Larsen [393].

Interaction with Structures

Engineering works often are located so they have to withstand pressure from floating ice. Examples include ice booms which are intentionally designed to catch and hold ice, as well as dams, bridge piers, and harbor facilities. Other structures, such as power plant intakes or diversion tunnels, have to allow floating ice to pass with minimal problems.

The most frequent and most feared problem associated with the interaction of ice with structures is the failure of the structure. At times these failures can be blamed on faulty design; and at other times, such as that of a dam failure in New York [468], the blame can be placed on improper maintenance or negligence in regulating flows.

Literature in this subsection can be divided into two types: (1) analyses of the problems caused by ice, such as forces or pressures that the ice places on the structures, and (2) descriptions of design strategy employed to achieve maximum effectiveness of the structures with minimum risk of damage. In addition to the publications cited here, there are 23 papers on the subject of "Effects of sea ice on marine structures" in the proceedings of the Third International Symposium on Ice Problems [246]. Many of these papers, which are not cited individually in this bibliography, contain materials that are applicable to interaction between structures and river and lake ice.

Analyses of forces, pressures, and problems.--Probably the most comprehensive publication available on the forces involved in the interaction of ice with structures is the monograph by Korzhavin [371] which was compiled in 1962 and recently has become available in an English translation. More recent (1970's), shorter monographs are *Ice Pressure on Engineering Structures,* by Michel [451], and *Pressure of Thermal Origin Exerted by Ice Sheets on Hydraulic Structures,* by Drouin and Michel [209]. In addition, many short papers exist in the literature, predominantly by Russian and Canadian authors. Soviet contributions include the papers by Panfilov [504] and by Korzhavin [372] describing pressures on bridge piers, an analysis of ice pressures on structures, especially dams, reported by Petrunichev [522], descriptions of pressures caused by ice drift on separately standing structures in coastal areas [6], and the critical survey by Shadrin and Panfilov [612] on published formulas for computing ice pressures on structures. Publications describing work in Canada include papers by Allen [16, 17] on forces from floating ice and piles of ice, summary papers on problems from ice pressure on structures by Kivisild [356], by Gold [267], and by Atkinson, Cronin, and Danys [48], a report on potential problems of drifting ice hitting drilling towers on the Grand Banks [106], a description of a structural-hydraulic model used to determine forces which sea ice cause on bridge piers in the Northumberland Straight [182], and a summary by Williams [719] of laboratory studies of frazil ice adhering to the surfaces of structures under varying conditions. A report by Perham [517] printed early in 1974 contains the results of measurements of forces acting on two ice booms in the St. Lawrence Seaway, N.Y. The complex of data in the report includes measurements of tension in several ropes, as well as information on river flows, ice conditions, and meteorologic conditions. Additional short papers on forces from ice include Löfquist's report [413] on studies in Sweden of temperature variations and their effects on ice pressure against dams, a summary report from the U.S. Army Cold Regions Laboratory [473] describing ice forces on piles, a paper by Rose [580] summarizing laboratory experiments and field studies to estimate maximum probable thrusts for the continental United States of 5000 to 20,000 pounds per linear foot, and an account by Schwarz [606] of laboratory studies and field measurements on the Eider River, Germany. An interesting, related publication is the account by Wikstrom [711] of extensive damage caused to bark of littoral trees on the Gulf of Finland resulting from high water and the breaking up of ice in a storm.

Structures designed to withstand ice.--The monograph by Korzhavin [371] which was mentioned in the preceding paragraph contains material on features to be considered in the design of structures which will be in contact with ice. Other general reports which cover the subject include the summary of current research published by the Canada National Research Council [153], and summaries by Burgi [142] and by Burgi and Johnson [143] of experiences of the U.S. Bureau of Reclamation on design of ice-control structures used by the Bureau. Papers presenting descriptions of the use of ice booms and features of boom design include the summary by Lawrie [398] of the use of booms on the St. Lawrence River, and descriptions of booms on the Niagara River in articles by Foulds [242], by Bryce and Berry [130], and by Bryce [129]. A Russian paper by Latyshenkov [395] describes model studies conducted to test factors affecting design of booms for protecting ships that are wintering in rivers. Accounts of original schemes used to protect piling from damage by ice include the description by Muschell [466] of the use of special pile points and barbs to prevent uplift of the piles by ice and rough water, Cloyd's report [173] of a piling "jacket" to form a "monopod" design used on drilling platforms in Cook Inlet, Alaska, and the paper by Wortley [738] describing the use of an air-bubbling system to keep piling and pontoons free from ice attachment and destruction. A patent issued to Howard [310] covers a method of protecting structures by means of an ice-trenching machine mounted to remove ice in a circular path around a structure at a rate equal to the rate of movement of the ice toward the structure. Reports on the design of water tunnels so as to minimize problems with ice include the paper by Michel [449] on the handling of frazil ice, particularly in power plants, Dirom's description [202] of free-flowing diversion tunnels used during the construction of Bennett Dam in Canada, and the account by Willey [713] of unique facilities for passing sediment and ice in the Burfell project, Iceland.

LAKE ICE

Literature on lake ice can be divided into two groups--that which is mainly descriptive and that which includes analyses of the factors controlling freezing, breakup, and properties of the ice. The subsections that follow treat the literature according to this type of division. There are, however, a few publications which are of a very general nature, including both description and analyses, which are cited here to avoid including them in both categories. These include Strong's bibliography [652] on lake ice published in 1948, a short review article on studies of sea and lake ice prepared by Weeks [700] in 1963, the recent summary of current research by Canada National Research Council [153], a review of Antarctic limnology by Heywood [301], and three collections of Russian papers [166, 271, 589] for which English translations are not available.

Observation and Description

Discussions that follow are organized into three groups: (1) the literature on observation methods, and particularly on remote sensing technology, (2) reports on observations on the North American Great Lakes, and (3) descriptions of ice phenomena on smaller lakes. Again, it is necessary to first refer to a few publications of a more general or related nature which do not fit well into these subdivisions. An example is the *Ice Atlas of Arctic Canada,* by Swithinbank [654], which deals mostly with coastal waters and sea ice. This large atlas, with page sizes of 20 x 34 inches, presents data back to the year 1900, using an ingenious system of colored symbols on maps and large matrixes summarizing the data broken down into two-week periods throughout the year. Another major Canadian publication of importance for both large and small bodies is the summary of breakup and freezeup dates compiled by Allen [18]. Reports by Skov [632] on ice conditions in the Greenland Sea and by Barber [64] on James Bay describe conditions more of oceanographic than of limnologic nature, but they have applications to lakes, particularly to larger ones. The paper by Molchanov [458] on typology and classification of ice covers, which was referenced in the earlier subsection on terminology and classification, has equal application both to large and small lakes.

Observation Methods

Michel [452] summarizes that qualitative descriptions of the formation, evolution, and breakup of an ice cover can be made by visual observations along the shore or by aerial observations and photographs. Phenomena have a strong tendency to repeat themselves year after year at the same location, therefore a few general surveys will show the most advantageous overall plan. Techniques employed today still rely on many measurements made directly on the ice, but there even have been marked improvements during the past decade in methods for making such measurements. Stewart [646], for example, describes the use of a flotation-equipped helicopter to obtain data on ice thickness and other characteristics at more than 50 stations on Lake Erie. Ramseier and Weaver [555] developed a heated wire ice thickness gage that can be placed in freshwater or saltwater ice and can be used to make quick and accurate repeated measurements.

As the following paragraphs demonstrate, there is a considerable effort being placed on developing methods of remote sensing. An example is to be found in the short paper by Aver'yanov [49] in which he reviews the techniques for ice study being adopted in Antarctic studies, including radioelectronic surveying equipment, radar soundings of ice thickness, new drilling techniques, and isotope studies of the ice itself. Some general descriptions of the application of the several forms of remote sensing to ice observations are contained in articles by Harwood [288] and by Biache, Bay, and Bradie [92], and in several papers in the proceedings of the Symposium on Remote Sensing in Glaciology [326] and the Interdisciplinary Seminar on Advanced Concepts and Techniques in the Study of Snow and Ice Resources [592]. Ehrlich and Welsh [218] summarize the use of remote sensing data in directing the icebreaking program of the U.S. Coast Guard, and Bilello [98] reports on a network established by the U.S. Army Cold Regions Research and Engineering Laboratory to collect surface data for correlation with data collected by remote sensing.

Aerial photographs have been used advantageously to describe ice conditions on both large and small lakes. The University of Wisconsin demonstrated a unique method in an aerial reconnaissance of lake ice conditions in October and November 1961, over Manitoba, western Ontario, Minnesota, and Wisconsin to measure albedo and observe lake ice. The fast-motion film [733] shows migration of the freezing zone as it moves southward. Many of the data observed in that same Wisconsin study are reported in the progress report by Ragotzkie and McFadden [550]. Near the southern end of Lake Michigan, Seibel, Carlson, and Maresca [611] used a time-lapse photographic system to provide a nearly continuous record of ice conditions. Marshall uses photographs to great advantage to get an interpretation of Great Lakes features [435]. Marshall's report contains more than 60 photographs with explanations of the many features and the factors that cause them. Wilshaw and Rondy [728] describe the aerial ice reconnaissance program used on the Great Lakes, with a photomosaic on the northern end of Green Bay. More references to the data from the Great Lakes surveys also are included in the subsection of this bibliography which follows this one.

Multispectral sensing, whereby radiated energy in the visible, infrared, and near ultraviolet bands are measured simultaneously and recorded separately, is a significant advance in remote sensing technology. Most multispectral equipment, however, is extremely expensive and its application is considered as being mostly experimental at this time.

An example of multispectral tests conducted over ice is reported by Horvath and Brown [308].

The advent of space flight has made possible photography or imagery from much greater altitudes than were possible from aircraft. Recent articles by Wiesnet, McGinnis, and Forsyth [709] and by Hagman [281] report the use of satellite imagery to describe ice conditions on the Great Lakes and snow cover in the basin. Marshall's report on "Lake Superior Ice Characteristics" [436] shows ice distribution as interpreted from Tiros II imagery. Ferguson, Cork, and O'Neill [232] have evaluated the application of weather-satellite photography in Canada, including its use to determine freezeup and breakup dates for lakes; and McClain [416] has reported on the use of data from U.S. environmental satellites to delineate freezing. Reports on the use of satellite observations in the study of sea ice have been recorded by McClain [417], by Wendler [708], by Aber and Vowinckel [1], and by Barnes and Bowley [73]. Again, working with data on sea ice, Barnes, Chang, and Willand [74], have described schemes for image enhancement of infrared data from satellites to more clearly define the edges of ice shown on the images.

Moderate success has been experienced in attempts to study ice using airborne sensors that measure thermal infrared energy. For example, Melkov and Rublev [447], in 1965, reported on work in the USSR; and in 1972 the results of a 4-year study on Georgian Bay were reported by Webb [699].

Several researchers believe that sensing of passive microwave radiation has possible application in ice studies because the imagery works well in distinguishing ice--from water--from dry land. Edgerton and Trexler include ice studies among the list of possible applications in their 1969 paper [217] on the applications of microwave sensing. Results of later studies on the microwave emission from ice are reported by Gloersen [266] and by Wilheit, Nordberg, Blinn, Campbell, and Edgerton [712].

Efforts also have been reported in recent years on the use of active remote sensing--radar and lasers--in the mapping and study of ice. Rouse [582] reports that a radar scatterometer could be used with some success to identify types of sea ice. A paper by Farmer [225] describes the use of side-looking airborne radar by the U.S. Coast Guard in locating and classifying icebergs.

Radar responses from lake ice are different from those from sea ice, but radar has some very definite advantages over other sensing methods in mapping lake ice. Spellman, Weeks, and Campbell [641], for example, used side-looking airborne radar (SLAR) to categorize tundra lakes according to whether or not they were frozen completely to the bottom. Two papers by Bryan [127, 128] review the application of radar for measuring characteristics of lake ice and demonstrate the application of radar methods on studies of Silver Lake in central Michigan. Larrowe and others, in a short paper [391] and a detailed report [392], have reported on experiments with fine-resolution, side-looking radar in mapping the extent and types of ice cover on the Great Lakes. Work with airborne lasers still is highly experimental, as demonstrated by the paper by Tooma and Tucker [661]. Work by Tooma and Tucker on the Lincoln Sea tested laser profiles of ice roughness against measurements by other means and found agreement within about 23 cm.

Work is continuing on attempts to find rapid means of measuring ice thickness. In 1972 the *Guide to world inventory of sea, lake and river ice*, published by UNESCO [670], recommended that ice thicknesses be determined only by direct measurement through holes in the ice, with one exception. The UNESCO guide concedes the use of a Canadian developed electrode which could be placed in the ice in order to measure resistance changes and give measurements of ice thickness with an accuracy of about 1 cm. Two papers resulting from research at the University of Wisconsin [91, 337] report on mapping of the underside of an ice cover by the use of a transit sonar device lowered through a hole in the ice. Clough [172] reports on the results of radio echo sounding collected during a zig-zag traverse over sea ice. The paper shows that the modulated radio signal can be used to map the extent to which brine has percolated into the edge of thick sea ice.

Although the advantages of a sensor in the ice and of sonar measurements are obvious, a principal research goal remains to find a means of measuring ice thickness and other properties remotely from an aircraft. The use of radar seems to offer the greatest hope for success, as indicated by available papers. Ten reports describing research on remotely measuring ice thickness are included in the proceedings [151] of a seminar held in Ottawa in 1970. One of the reports in that proceedings is the paper by Adey [5] titled, "A survey of sea-ice-thickness measuring techniques." Adey reports that at that time there had not yet been proved a technique for quantitatively measuring ice thickness remotely, but that there is promise for four different types of radio and acoustic devices (some advances in these methods have been achieved since the time of Adey's paper). Hartz [286] describes a radiometer method which was tested with some success in the Arctic and Swithinbank [655] reports on the use of a radio echo sounder for measuring ice thickness on McMurdo Sound, Antarctica. A 1976 paper by Cooper, Mueller, and Schertler [180] reports the use of short-pulse radar mounted aboard an all-terrain vehicle for measuring ice thickness in the Straits of Mackinac. The maximum difference between radar and auger measurements was less than 9.8 percent at 25 sites in ice ranging in thickness between 29 and 60 cm.

Another interesting device of potential value in measuring ice properties remotely is the sea-ice penetrometer reported by McIntosh, Young, and Welsh [421]. The device is pencil-shaped, weighs 50 pounds, and is designed to be dropped from an aircraft. An accelerometer sends a signal back to the dropping aircraft so that penetration or ice thickness (in the case of complete penetration) can be computed. It is reported to measure thickness or penetration within about 3 inches accuracy.

Despite the prevalence of research on remote sensing, advances also are being made on other means of collecting ice data. Soviet research on measuring the movement of ice sheets includes work with leveling and tensiometers, as reported by Berdennikov, Deryugin, and Khaminov [88], and the use of doppler lasers, as summarized by Bogorodskiy, Trepov, and Fedorov [110]. New types of equipment for monitoring ice thickness and the thickness of frazil ice were developed in Iceland and are reported in a paper by Kristinsson [378]. Procedures for measuring light penetration in lakes in winter were considered in a symposium of the International Union of Biological Sciences and are reported in the guidebook by Sauberer [594]. A summary of principles to be used in the design of hydrologic networks for monitoring ice conditions is contained in a Soviet paper by Karasev [339]. In a related paper concerned with the relationship of ice on lakes and rivers to other hydrologic systems, Heinemann, Myers, and Moore [296] describe how observations of the ice-melting patterns serve as indicators of aquifer presence and conditions of ground-water inflow.

Work on the Great Lakes

Both Canadian and U.S. researchers have been working on the Great Lakes for several years. Most of the refined limnological studies, however, have been made in the summertime, and most of the reported work on ice is more descriptive than analytical. This subsection discusses some of the papers on Great Lakes ice completed over the past few years.

Marshall [436] reports measurements of ice thickness on Lake Superior and ice distribution data based upon aerial reconnaissance and satellite imagery. From mid-February to mid-March the ice pack reaches its maximum areal development with 60 to 90 percent of the lake covered. Ice is heaviest along the shores and in the bays, where it may be thicker than 0.5 m. Marshall's study of Whitefish Bay, Lake Superior [437], reports that the Bay is covered for a period of 3½ to 4½ months each year; and that maximum ice thicknesses vary from 0.4 to 0.6 m. Brunn and Straumsnes report the piling up of ice on the shores of Lake Superior [126]. At Duluth, where northeasterly winds cause westward ice movement, piles of ice from 9 to 15 m high have been observed. Wortley [738], in an article cited earlier in this bibliography, writes of the damage that may result to marinas along Lake Superior as a result of ice action and describes a technique for averting the damage. A paper by Green [277] reports observations of finger rafting of ice on Lake Superior--a phenomenon commonly observed in sea ice, but usually not found on lakes. Other work on Lake Superior includes the albedo measurements by Bolsenga [112, 113], which were mentioned in an earlier section.

Heap [293], in 1962-63, made one of the first attempts to describe the ice on Lake Michigan using data from observers and aerial flights. He was able to define the dates of freezing and breakup, the percentage of the lake that froze, and the regions of ice cover. A later report by Heap and Noble [294] includes data for three winters, 1962-65, and an analysis of cooling factors and possible techniques for predicting ice conditions on Lake Michigan. The work by Noble [478] and Noble and Ewing [479] on Lake Michigan complements that of Heap by providing information on the temperature structure of the lake water during winter periods. A short paper by Hughes [315] reports details of temperature patterns along a cross section of the lake through the winter season and describes freezing over of the lake as "a rare event." Time-lapse photographs by Seibel, Carlson, and Maresca [611] at the site of the Donald C. Cook Nuclear Plant in sourtheastern Lake Michigan provide a nearly complete seasonal coverage of ice conditions. Analyses of the photographs lead to categorizing of ice conditions into five distinct stages: no ice, static, accretion, deterioration, and breakup.

Work on the other Great Lakes includes Webb's description of temperature and ice conditions on Georgian Bay (Lake Huron) [699], as well as papers on the Dunkirk, N.Y., region of Lake Erie [118, 224]. Fahnestock, Crowby, Wilson, and Schneider [224] apply the term *ice volcanoes* to the conical mounds of ice that form in shore ice in the Dunkirk area, and Braun and Jones [118] document the effects of heat from a power plant in Dunkirk harbor, where they feel that winter effects generally are beneficial. Two papers by Palmer and Izatt [500, 501] present information on studies of circulation of Lake Erie under conditions of partial ice cover. Data on Lake Erie ice thickness, extent of ice coverage, and thermal conditions, as measured at more than 50 stations during the period February to April 1972, are included in a paper by Stewart [646]. Stewart's work found little or no vertical stratification and water temperatures generally less than 0.1°C. Russell [586] reports on the complex relationships between ice conditions on Lake Erie and problems with ice in the Niagara River and on the steps to control the problem, particularly through the installation of a large ice boom. A report of the extent of ice on Lake Ontario, based upon observations from a research ship during the winter months, is included in a paper by Anderson, Bruce, Sporns, and Rodgers [20]. A summary of work on Lake Ontario performed as part of the International Field Year is contained in a bibliography compiled by Baldwin and Sweeney [60]. Another summary of the activities of the Field Year is contained in a report by the U.S. National Oceanic and Atmospheric Administration (NOAA) [677].

Several other reports on the Great Lakes describe general conditions or relate to more than one lake. Among these is the series of data reports and atlases describing winter ice cover on the Great Lakes, prepared by the U.S. Lake Survey Center, and assembled by Leshkevich, by Rondy, and by Wilshaw and Rondy [406, 572, 573, 574, 575, 576, 577, 578, and 728]. Marshall's publication of photographs of Great Lakes ice [435] contains pictures from all of the lakes. The paper, "Meteorological Factors Affecting the Great Lakes," by Richards [561] contains ice data and correlations with degree-days of air temperature for lakes Superior and Erie. These data also have been included in another paper by Richards [562]. Many data on several of the lakes, a review of old data-collecting programs, and some detailed temperature information have been analyzed to produce the *Manual of Great Lakes Ice Forecasting* [637]. Beeton and Chandler's description of the Great Lakes [81] in *Limnology in North America* includes brief summaries of ice conditions on all of the lakes. Nowacki and others [484, 485] have analyzed the economics of extending the shipping seasons of Great Lakes' bulk carriers, including work on optimizing ship designs for ice operations.

Some older descriptive papers on Great Lakes' ice include the short paper by Oak [487] and the summary of engineering effects by Striegl [649]. A paper by Humphreys [316], published in 1932, gives a theoretical analysis of the effect of snow on the rate of freezing, and is intended to dispel common disbeliefs about the rates of freezing on the Great Lakes. A review summary of current data-collecting activities has been prepared by Chase, Baker, and Lewis [163]; and a report on the use of radar in mapping ice cover has been published by Larrowe and others [392]. Davis [186] reports on the short-term, but marked effects that ice along the coastlines of the Great Lakes can have on beach forms, causing significant ridges and depressions which disappear after the ice goes off the lakes.

Publications dealing with Great Lakes ice during the last two or three years have dealt mainly with results of remote sensing surveys and with forecasting of ice conditions. Papers by Wiesnet, McGinnis, and Forsyth [709] and by Hagman [281], for example, report on the use of data from satellites to delineate ice coverage of the Great Lakes and the coverage of snow in the Great Lakes basin. Papers on forecasting include those by Rogers [568, 569] on long-range forecasting of the percent of maximum ice extent and by Rogers, DeWitt, and Dixon [570] on forecasting of ice conditions at the crossing of the ferry at Little Rapids Cut on the St. Marys River. Forecasting techniques generally use historical correlations between ice conditions and accumulated freezing degree days in conjunction with current records of air temperatures. Along a slightly different line, a 1974 paper by Welsh and Kingsbury [707] describes Great Lakes slush ice, a phenomenon of great importance in restricting shipping. The study of slush ice includes analyses of photographs, measurements of ice draft from sonar transducers set in the bottom, and study of ice samples and measurements collected with the aid of a helicopter.

As there has been a push for extending the navigation seasons on the Great Lakes, there also has been a growing demand for more, better, and more timely information on the extent and characteristics of Great Lakes ice. A paper by Quinn [545] reviews the activities of the Ice Navigation Center, operated by the Lake Survey Center in Detroit, in gathering and disseminating data during winter seasons.

Ice on Smaller Lakes

Ice on smaller lakes generally forms according to the "calm water" and "smooth growth" paths shown in figure 1, as described by Michel [452]. Several accounts exist of the process, and that of Wilson, Zumberge, and Marshall [730] is considered by several authors to be one of the first careful studies of lake ice formation.

Older studies of lake ice are summarized by Hutchinson [317]. Among the interesting early papers are those by Barnes [70] and by Birge [104] in 1910 in which they debate the mechanisms of the breakup and melting phenomena. A recent translation of a 1925 Soviet paper by Molchanov [457] provides an interesting account of some early Russian work on the composition of ice in nature. Simojoki [629] describes ice conditions on lakes in Finland in a report published in 1939. Northcote and Larkin [482] summarize a study in western Canada in the early 1940's in which duration of ice cover on small lakes was related to salinity, and where salt precipitates were observed to form as a result of freezing. A study of ice-temperature data collected at Eleven Mile Canyon Dam, Colo., during the 1940's is reported by Monfore [459].

A significant and extensive report on studies of more than 40 Wisconsin lakes during the 1950's is contained in the three-part report by Bunge and Bryson [135]. The three volumes contain numerous maps and photographs of observations, together with an ice budget and a partial heat budget. Other papers of interest published at about the same time are the report by Piotrovich [523] of melting in a Russian reservoir and a paper on thermal classification by Hutchinson and Loffler [318].

Publications from the early 1960's include the short paper by Barnes and Hobbie [68] describing the rate of melting of Lake Peters, Alaska, and the monograph by Henson, Bradshaw, and Chandler [298] on the physical limnology of Cayuga Lake, N.Y. Livingstone [412] includes a summary of some work in Alaska in the early 1960's that found that small lakes in that area use almost all of their heat income to melt ice and therefore remain very cold all summer.

Other ice research on small lakes in the early 1960's includes two very thorough studies of heat budgets of Wisconsin lakes by Scott and by Scott and Ragotzkie [609, 610]. At about the same time the University of Wisconsin [733] was conducting photographic and aerial reconnaissance of lake ice conditions over large areas in the U.S. and Canada. Summaries of freezing processes in U.S. and Russian lakes were published at about this time by Ragle [546] and by Rymsha and Donchenko [590, 591]. In 1965 Marshall [434] wrote on the observed sheet ice and snow ice conditions on 10 small lakes in Michigan, and Woodcock [736] reported observations of cell-like melt centers in Grass Pond, Long Island, N.Y. Woodcock believed that convection, as well as pressure, caused the cells. Mathews [438], also in 1965, described the occurrence of two ice-dammed lakes in British Columbia.

Billelo, in the late 1960's, published two similar papers, both titled *Water Temperatures in a Shallow Lake during Ice Formation, Growth, and Decay* [96, 97]. Both have detailed documentation of water temperature and ice conditions. About the same time, Weeks and Assur published an extensive review and report on *Fracture of Lake and Sea Ice* [701], and Williams [720] wrote a paper on temperature during melting that was similar to Billelo's. A unique, brief paper by Ragotzkie and Ruzecki [551] reports on ice accumulations in a boat house that depict a standing wave phenomenon in Lake Mendota. In 1968 a report was published by Manson, Schwartz, and Allred [431] describing hydrologic features of lakes in Minnesota, a paper by Kirby, Donaldson, and Bond [354] described Crater Lake, Oreg., and a Russian report by Aledsandrov and Kozlovskiy [12] reported on conditions in some Antarctic lakes. Hoopes, Zeller, and Rohlich [306], in 1968, describe the effects of a steam-generating plant in keeping open the waters of Lake Monona, Wis.

Since 1970, several more publications have appeared on ice conditions in small lakes. Thse include the collection of more than 20 papers in the proceedings of a Canadian symposium [3] on ice cover in Labrador-Ungava, and a review by Williams [727] of waters in the Umiat area, Alaska. Papers by Lazier and Metge [400] and by Lazier and MacLachlan [399] report work in Ontario on temperature gradients and movements in ice cover. A paper by Parrott and Fleming [509], in 1970, reports observations of freezing and thawing of ice on Post Pond, N.H., and a 1971 report by Post and Mayo [534] describes the floods caused by breaking of glacier-dammed lakes in Alaska. Hammer's 1971 report [283] on lakes in the upper Qu'Appelle River system of Saskatchewan describes an ice cover occurring from late November until late April, with ice thicknesses rarely exceeding 1 m. Ficke [234], in 1972, reports data on evaporation rates from an ice-covered lake in northern Indiana. A 1973 report by Browman [124] details temperatures during cooling, ice formation, ice melt, and breakup of Holland Lake in western Montana. Papers from 1974 include an account by Bilello [98] of the U.S.-Canadian network to collect ice and snow observations from more than 100 stations at latitudes of about 45°N., a detailed account by Bryan [128] of ice conditions on a small lake in central Michigan, and a significant contribution by Browman [125] explaining the formation of snow-slush and the occurrence of channels in the ice on Holland Lake, Mont. In 1976 Bates [78] published an account of ice conditions and elaborate measurements of water temperature in the top 8.5 m of Lake Champlain, Vt. Adams [4], also in 1976, reports on thickness and density of ice on Knob Lake, Quebec, and on Gilles Lake, Ontario.

Russian papers from the 1970's include the reports by Donchenko [204] describing freezing rates on 25 reservoirs in the USSR, and by Alekseyenko [13] reporting on freezing in the Volga reservoirs. Filippov's paper [237] on ice in a Ukrainian reservoir pays special attention to the conditions which determine frazil ice formation near the intakes to a powerplant. Karelin and Timokhov [340] report on the results of measurements of wind stresses on ice flows on Lake Lodoga. In another recent paper, Deryugin [190] quantitatively described the processes of snow-ice formation on Soviet reservoirs. A short paper by Yelshin [743] in 1971 reports a good inverse relationship between breakup data and the "lake area index." According to Yelshin, the lake area index is the ratio of surface area of the lake to drainage area of the basin feeding the lake.

In addition to the chronologically listed research reports described in the previous paragraphs of this subsection, several reports have been written describing ice thicknesses and freezing and thawing dates in North America [99, 100, 101, 547, 588]. Others have been prepared by the U.S. Army Cold Regions Research and Engineering Laboratory.

Factors Affecting Lake Ice

Climatic Effects and Prediction

Because of navigation, recreational use, and water quality factors, it often is desirable to be able to predict times of freezing and breakup and amounts of ice that will be formed on lakes. Techniques used for lake ice forecasting are similar to those used for forecasting on rivers, namely energy balances and correlations with air temperature. Many papers have been published describing the use of both techniques.

Energy considerations.--Studies of the transfer of heat from freezing lake ice to the water or the atmosphere date back many decades. An interesting older paper by Humphreys [316] from the *Monthly Weather Review* of February 1932 discusses the old fisherman's saying, "The colder the air the thinner the ice." The author of the article points out that, indeed, freezing rates may be slower at colder air temperatures if the ice at the colder temperatures is covered with a thin layer of snow. A 1949 paper by Huff [314] reviews the theoretical considerations of ice freezing rates, including equations for diffusion and heat conduction. An extensive, and significant Soviet review of the heat transfer phenomena involved in lake freezing was published by Piotrovich in 1958, and is available in English translation [524]. Piotrovich's method of predicting ice freezing and melting is based upon detailed solutions of the heat transfer equations for daily computational period. The publication cites more than 30 Russian papers on ice. Another significant Russian monograph on forecasting ice is the manual edited by Shulyakovskii [627] which was cited in the earlier section of this bibliography dealing with river ice. Shulyakovskii's manual contains considerably more mathematical detail and more examples than does the monograph by Piotrovich.

In the American literature, there has been a tendency to seek simplified expressions of heat transfer phenomena, such as the equation of Assur, as explained and demonstrated by Zumberge and Ayers in the *Handbook of Applied Hydrology* [752]. Lee and Simpson [403] also describe a method which uses ice potential calculations and heat budget equations for computing ice growth in terms of known or predicted meteorological data.

Application of energy-budget and heat-transfer techniques to predicting ice conditions has been aided by the results of a number of studies that were performed and reported during the 1960's. These reports present the results of many detailed analyses of ice conditions on several lakes, along with information on water temperatures and meteorological conditions. Williams [718] reports measurements of heat losses and heat transfer coefficients from studies of McKay Lake, Ontario. Related articles by Williams [715, 717] deal with additional measurements of rates of heat loss from Canadian lakes and with the phenomenon of evaporation from frozen lake surfaces. Publications by Scott and others describe heat budgets of lakes in Wisconsin--one of these [609] being a report on the heat budgets of 53 Wisconsin lakes, and another [610] containing a detailed budget of the heat energy of Lake Mendota during a winter period. Ragotzkie and Likens report on the heat balances of lakes Vanda and Bonney [549], and Parrott and Fleming [509] published a detailed account of conditions in Post Pond, N.H. Reports dealing with the heat budgeting or transfer in sea ice have been published by Weller [705, 706], by Langleben [389], and by Schwerdtfeger and Pounder [608].

Several Russian papers on heat transfer from ice exist, in addition to the two extensive works [524, 627] mentioned in a previous paragraph. Donchenko [203, 205] reviews several Soviet techniques in short papers published in 1966 and 1972. Blinov [107] discusses the equations of heat exchange in a short paper written in 1971, and Shuliakovskii, Ginzburg, and Balashova [625] report on results of a heat-loss predictive technique applied to about 250 different cases. Other Russian papers published in the last few years include the one on heat budgets by Pivovarov [527], an account of micrometeorology in the vicinity of two rather large lakes by Konovodov [365], Bulatov's paper [134] containing heat budget data collected in connection with a study of strengths of ice, and a paper by Piotrovich [525] on accretion and melting of ice crystals and formation of snow ice. Russian papers often incorporate complex ways of computing or estimating energy terms that are not measured.

In addition to heat energy, turbulent action sometimes plays a role in the formation of ice on lakes. Papers such as the one by Hutter [320], which was cited in the discussion of freezing in rivers, may have application in considering the formation of lake ice. Wind shear and turbulence induced by the wind play a significant part in the breakup of lake ice and at times influence the freezing process. Hutter's general approach to the mechanics of shearing action on ice blocks could be of value in sophisticated attempts to consider wind effects in predicting lake freezing.

Correlation techniques.--Several papers about forecasting ice on the Great Lakes [163, 294, 561, 562, 637] rely on correlations between time of freezing and air temperature. Air temperature is treated in most cases as the sum of degree days, usually above or below freezing, and wind conditions are considered in some of the methods, such as that of Chase, Baker, and Lewis [163]. Snider's *Manual of Great Lakes Ice Forecasting* [637] includes tables for referencing degree-days data for several areas in the Great Lakes basin and also has maps showing the probabilities that specific areas will be frozen on certain dates throughout the ice season. The large, deep lakes store tremendous amounts of heat; therefore the relationships for all the lakes are different from each other, and allowances must be made for antecedent heat [561]. Recent (1976) evaluations by Rogers [568, 569] of correlation techniques for long-range forecasting of ice conditions on the Great Lakes consider regression equations and other statistical methods and climatology methods and found that the "best" techniques were not the same for all the Great Lakes and that multiple methods worked best in some cases.

Among the works on smaller lakes in North America, Williams [723] did a multiple regression analysis on data from several Canadian lakes and got equations that would predict dates of breakup with standard errors of estimate of from 1.6 to 4.3 days. Other relationships between time of freezing and climatic factors exist in the work of McFadden [420], who analyzed the Wisconsin flights over the U.S. and Canada, and in a paper by Ragotzkie [547], who concluded that freezing time is related to an integrated time series of a number of climatic parameters. Bilello [94, 95] developed sets of curves whereby he could use daily temperature records to predict freezing dates in the Mackenzie River basin of Canada. Breakup dates for some lakes in Maine are described by Fobes [240, 241], who devised an empirical predictive technique based on air temperatures, sunshine, wind, and correlation with the breakup date of a river in the area. Relationships of freezing and melting time to temperature and other meteorological factors are valid predictive methods, but other factors, such as altitude, have to be considered. Brooks and Deevey [122] report the study by Cooper in New England, where an excellent correlation was found to exist between time of breakup and altitude.

Russian methods for predicting ice conditions based on correlation with meteorological conditions are reviewed in the paper by Popov [533], and in a manual on forecasting [259] published in 1970. Papers reporting the application of the methods to specific lakes include the account by Kozhankova [375] of use of long-term meteorological data for predictions on Gorkovskoye Reservoir, and the account by Yefremova [741] of forecasts for Votkinskiy Reservoir based on large-scale atmospheric circulation patterns. The paper by Yelshin [743], which was cited in a previous subsection, reports the prediction of freezing dates based on a relationship between surface area of the lake and size of the drainage area of the basin above the lake.

Regulation and Control

Books by Michel [452] and Pounder [537] both contain excellent summaries of techniques available for controlling ice on lakes. Icebreaking and heating methods apply to lakes in slightly different manners than they apply to rivers because lakes do not have the continuous flow of water. Dusting with dark material and chemical melting also can be used on lakes, and Michel has included lengthy tables for evaluating different chemicals and estimating amounts required.

Icebreaking techniques on lakes are similar to methods used on rivers and therefore are not described in this section. More discussion of the subject is included in the sections of this bibliography on (1) regulation and control of freezing processes on rivers, (2) ice jams on rivers, and (3) limitations on navigation on rivers.

Air bubbling and pumped artificial circulation are ice-removal techniques which can be quite effective on lakes. Pounder [537] dates bubbling back to 1923, but many descriptions of the method have been published more recently. Frozen lakes usually are thermally stratified, with the water just beneath the ice at 0°C, and the deeper water at about 4°C. Stored heat in the warmer water is utilized by the bubbling method, wherein an air line is placed at the bottom of the lake so that the escaping air will force a circulation of deep, warmer water against the ice. Similarly, the pumping method achieves circulation by means of a surface or bottom pump which forces the bottom water against the ice. Circulation of warm water past a spot in the ice will open a hole and the hole will remain open as long as pumping or bubbling continue and as long as there is sufficient heat stored in the lake water and the water remains at least a fraction of a degree above freezing.

Two rather extensive publications dealing with methods and results of work in bubbling and pumping are the proceedings of a symposium on bubbling [152] which was held in Ottawa, Canada in 1961, and a Russian review and handbook on bubbling and pumping by Balanin, Borodkin, and Melkonyan [59]. A short Soviet paper on bubbling was published by Petrov [521]; Canadian papers include those of Williams [716], Smith [635], and Ince [321]; and U.S. publications include the ones by Bier [93], Schmitz and Hasler [605], and Wortley [738]. The paper by Koike and Koike [359] on the application of air bubbling in Japanese reservoirs illustrates the world-wide use of the technology.

As in the case of rivers, the discharge of heated water to lakes is considered to be a potential environmental problem. On the other hand, desirable effects such as ice removal can be achieved. The paper by Policastro [530] on thermal discharges--called a *minicourse* by the author--includes recommendations for consideration of ice effects by engineers in the design of discharges to lakes or cooling ponds. Fortunately, there has been some documentation of several cases of heated discharge to lakes, such as the work by Hoopes, Zeller, and Rohlich [306] and by Neill [470] on Lake Monona, Wisconsin. Spreading of heated discharge in Lake Monona in the winter time is restricted by baffles; and temperatures in the discharge area are about 14°C. Some species of fishes are attracted to the heated area; and others avoid it. Effects of a discharge in Dunkirk Harbor on Lake Erie are described in the paper by Braun and Jones [118], which was cited in the earlier subsection on the Great Lakes. The paper concludes that the discharge has generally desirable effects, including good fishing and the ability of boat owners to leave their crafts in the water. A report by Witt, Campbell, and Whitley [734] on discharge of heated water and acid pollution to a reservoir in Missouri documents wind effects by changes in the open water pattern in the reservoir during the winter season. Temperatures in the arm of the reservoir that received the heated water did not drop below 10°C.

An interesting ice-removal technique somewhat different from those mentioned in the paragraphs above is the breaking of ice by compressed gas blasting, as reported by Mellor and Kovacs [448]. Carbon dioxide shells, of the type used in coal mining, were tested in lakes in New Hampshire and in Alaska and were found to be effective in breaking ice having thicknesses up to about 20 inches.

INFLUENCES OF ICE ON WATER QUALITY

Information about effects of ice on water quality is not so abundant in the literature, especially the older literature, as is information about the physical aspects of ice formation. In 1969 Vallentyne [688] attempted to prod his colleagues into doing more winter work through a short piece titled "Definition of a Limnologist":

> A limnologist is a zoologist who, during the summertime, studies chemical and botanical aspects of geological problems in readily accessible lakes, 15 m deep, located in the vicinity of universities.

Vallentyne's prodding, humrous statement is out of date today, and probably was a decade or more out of date at the time it was published. Indeed, the limnologists in U.S. universities, almost all of whom work on small budgets, have provided most of the data and almost all of the recent important advances in this country in knowledge of influences of ice on water quality.

Discussions of the effects of ice on water quality have been divided into four subsections dealing with the chemical effects, biological effects, temperature under the ice, and circulation under the ice of lakes. One subject that seems to cross the lines of all four of these subsections is that of sampling techniques. Peculiar problems associated with sampling under ice have led to the development of special techniques and equipment, some of which are reported here. Babcock [50], for example, developed and reported on a power-driven ice auger with an adjustable slide which he mounted directly on a snow vehicle. A flow-through sampling system mounted in a portable shelter which could be pulled about on the ice was reported by Ficke and Lipscomb [235]. Sampling at very close intervals just beneath the ice is a problem which can be solved by a syringe sampler developed and described by Clasby, Reeburgh, and Alexander [170]. Sly and Gardener [634] report their development of a vibro corer and portable winch for collecting cores in sand and gravel bottoms through holes in the ice. The corer uses a pneumatic impactor of the type designed for breaking concrete on construction jobs. To avoid cutting holes in the ice each time a point is resampled during a season, Noth [483] reports that insulated plastic pipe frozen into the ice can be quickly released for easy access. Applegate, Fox, and Starostka [31] used a sampling device made from lengths of 6-inch aluminum irrigation pipe to sample zooplankton beneath ice when metered townets could not be used. A device similar to a periscope was developed and used by Magnuson and Karlen [425] to observe the movement of fish throughout the winter in a frozen lake.

With care, scuba can be used for sampling and observations under ice. A paper by Ray and Lavallee [557] discusses the results of testing and experimenting with equipment and diving techniques under Antarctic ice. Clasby, Horner, and Alexander [169] describe work under Arctic ice by scuba divers. The divers implanted incubation chambers into the underside of the ice in order to collect data on primary productivity within the ice.

Chemical Effects

Winter Data from Year-Round Studies

Water-quality information on lakes and rivers covered with ice is much more abundant than was suggested by the quotation from Vallentyne in the opening paragraph of this section. Many data exist as parts of reports dealing generally with summer conditions, but including winter observations. In most cases there is little in the title or abstract to show that information on water quality under ice is included. The following paragraphs cite several papers on limnology and water chemistry that do include descriptions of winter conditions.

General limnologic studies.--Limnologic studies or reviews usually include discussions of temperature, pH, specific conductance, dissolved oxygen, alkalinity, and common ions. Some recent reports of Canadian studies with winter data included are the one by Northcote and Halsey [481] on four lakes in British Columbia, one by Schindler [602] on lakes in northwestern Ontario, and a paper by Harvey and Coombs [287] describing lakes on Manitoulin Island, Ontario. The paper by Schindler reports studies on rates of oxygen depletion under ice, while Harvey and Coombs describe a lake with oxygen levels less than 1 mg/L causing winter kills of yellow perch and northern pike. The report by Northcote and Halsey contains data on purple sulfur bacteria. An article by Duthie and Carter [212] reports on nutrient and oxygen conditions in meromictic Sunfish Lake, Ontario, where the monimolimnion acts as a nutrient trap and has reduced levels of dissolved oxygen in winter. Kerekes and Nursall [348] describe conditions in five eutrophic lakes in Alberta where considerable increases in dissolved solids as well as oxygen depletion were measured in the winter. Barica [65] reported on the nutrient levels and geochemistry of the waters of 79 saline winter-kill pothole lakes in southwestern Manitoba.

Studies in the U.S. include the one reported by Alexander and Barsdate [15] on Smith Lake, Alaska, which demonstrated high concentrations of organic acids in winter. An investigation by Howard and Prescott [312] of Alaskan tundra lakes found that after freezeup all chemical properties except pH and concentration of dissolved oxygen increased, to a maximum at the time of maximum ice thickness. Solutes were concentrated up to about 30 times by the thick ice cover, but the lakes did not become anaerobic. In fact, oxygen supersaturation was found in some lakes in January. Two papers by Anderson [22, 23] report winter conditions as part of year-round studies of saline lakes in Washington. Reports of work on lakes in South Dakota include Nickum's description [477] of peak chemical concentrations under ice, and the paper by Petri and Larson [520] which also reports high concentrations under ice in 26 lakes, 17 of which also showed absence or depletion of dissolved oxygen. In Minnesota, Megard [441] describes increases of calcium and alkalinity and undersaturation of calcium carbonate in a productive lake under ice, and Schindler and Comita [603] report on fish kills from complete oxygen depletion in Severson Lake. Weimer and Lee [704] report on Lake Mary, Wis., with detailed data on nitrogen and methane, and Potash [535] describes Vermont farm ponds, where nutrients are at highest levels in winter when phosphate is the limiting plant nutrient. Winter lake conditions also have been described by Hergenrader and Hammer [299] in eastern Nebraska and by Nelson [472] in Colorado. Waddell and Price [691] studied the quality of the Bear River basin in Utah, Wyoming, and Idaho throughout the year, including winter information.

Winter river conditions in England, as reported by the Trent River Board [663], include fish kills resulting from high ammonia and low oxygen during ice cover. Sewage inflows to the river play a key role in producing the adverse water-quality conditions. Mortimer's review paper [462] on possible mechanisms for exchange of materials between lake waters and sediments in the North American Great Lakes relies heavily on reports of conditions in English lakes.

Data on dissolved gases, particularly oxygen and carbon dioxide, in the Vilyuy Reservoir, USSR, are reported in a paper by Labutina [383]. In the winter, concentrations of dissolved oxygen ranged from 1.3 to 9.9 mg/L in the epilimnion and from 0 to 5.4 mg/L in the hypolimnion. Carbon dioxide during the winter was in the range 5.7 to 26.4 mg/L in the epilimnion and in the range 7.9 to 36.1 mg/L in the hypolimnion.

Studies of nutrients.--A report by Gahler [253] on exchange of nutrients in Oregon lakes includes the results of measurements made in separate plastic pools isolated in the lake. Under ice conditions, the pool isolated from the lake sediments had higher oxygen content than did pools in contact with the lake bottom. Nursall's paper [486] on analyses of a eutrophic system concludes that lakes in Alberta under ice operate as closed systems, in contrast to periods of open water. Smith [636] describes the effectiveness of adding N-P-K fertilizer to a lake in New Brunswick and states that the induced eutrophication was largely reversible. Work in Sweden attempted to reduce phosphorus in lakes by precipitation using aluminum sulphate, as described by Jernelov [330], and studies by Riger [564] in Ontario found that turnover time of phosphorus increases as much as 1000 times under ice conditions. Work on nitrogen fixation in an Alaska lake [103] is described by Billaud, who states that ammonia is the most important nutrient source. Other nitrogen studies include the report by Rusness and Burris [585] on acetylene reduction in Wisconsin lakes and the report of laboratory studies on denitrification by Dawson and Murphy [187], who conclude that considerable denitrification can take place beneath ice in winter. Stiff and Gardiner [647] considered the hydrolysis of urea in rivers; the urea is used in preventing formation of ice on airport runways and eventually finds its way into rivers. It was concluded that some, but incomplete, hydrolysis takes place. Summerfelt [653] describes winter conditions related to the eutrophication of lakes in several of the Great Plains states as a result of increased use of commercial fertilizers and runoff from livestock feedlots.

Studies of minor nutrients include the work reported by Hutchinson and Setlow [319] on niacin in Linsley Pond, Conn., where high concentrations were found only when ice is present or breaking up. Information on copper in Knights Pond, Mass., as reported by Kimball [352], shows decreased concentrations in late winter and spring. McMahon [424] reports data on year-round variations in ferrous and total iron in a lake in Ontario.

Radioactive materials.--Uranium concentrations in lake water in Saskatchewan were measured by Macdonald [419], who found unusually low concentrations at time of breakup as a result of dilution from melting ice. Dyck and Smith [213], describing uranium prospecting in Ontario, report relatively constant year-round levels of uranium in lakes and streams, but report increases in radon-222 beneath the ice of frozen lakes. The radon level remains fairly constant in streams.

Aeration and purification.--Air bubbling in a reservoir in Wisconsin produced general improvement in water quality in all seasons, as described by Wirth, Russell, Uttermark, and Hilsenhoff [731]. During the winter aeration increased dissolved oxygen, reduced high concentrations of dissolved material near the bottom, allowed invertebrate life in the muds, and caused warmer waters to flow to the stream below the reservoir. Fast [226, 227] aerated two Michigan lakes, using a system that aerated only the hypolimnion of one of them. Aeration was stopped on September 7, but winter oxygen levels were increased and biochemical oxygen demand (BOD) was lowered as a result. Winter work on the natural purification processes in the Odra River, Poland, is reported by Manczak (also spelled Manzack) [430, 433], who states that purification processes are greatly hindered under ice conditions.

Sewage lagoons are efficient means of treating waste waters, particularly from small communities. However, their operation can be impaired by an ice cover. A report by Olson, Van Heuvelen, and Vennes [493] on lagoon operation in North Dakota points out that summer capacity is considerably greater than capacity during critical winter situations, and that there is a tendency for lagoon waters to drop their suspended solids more quickly in winter. Pearson [512] documents problems with lagoons at high altitudes, where low oxygen saturation conditions and ice may cause problems, and where mechanical aeration seems to be required. Studies of three-stage lagoons by Goswami and Busch [273] include evaluation of performance under ice cover, when they noted marked decreases in photosynthetic activity.

Specialized Studies under Ice Conditions

Some of the dissolved materials in water usually precipitate when the water is frozen. The phenomenon can be demonstrated in the laboratory and indeed has been put to use by Shapiro [613] in a technique for concentrating dilute solutions of inorganic substances. Concentration of organic compounds in dilute aqueous solutions was reported in four papers by Baker [55, 56, 57, 58], and also by Kammerer and Lee [336]. Lake and Lewis [385] report this same phenomenon as it relates to "Salt Rejection by Sea Ice During Growth." Research reported by Applied Science Laboratories [32] found that the partial freezing of mine drainage water reduced some metal and acid components as much as 85 to 90 percent and reduced the hardness by nearly 100 percent.

Northcote and Larkin [482] report an extreme case of precipitation, in which salt crystals were observed to be deposited on the bottom of freezing saline lakes in Canada. In prairie-pothole ponds in North Dakota, Ficken [236] found a temporary loss of more than 25 percent of dissolved tonnage during winter. The lost solids seemed to be stored temporarily in the bed material and were slowly returned to solution after the ice melted. Measurements by Hill [302] of hardness of water just beneath the ice cover of a Minnesota lake demonstrated that dissolved materials were coming out of solution as the ice froze and were dissolving in the water just beneath the ice. Later they returned to solution in melt water as the lake warmed in late winter. Measurements of strontium-90 in the ice of an experimental pond in Russia by Pisarev and Koloskov [526] revealed that strontium concentrations in the ice were only about one-fourth as great as the concentrations in the water. Another Russian paper, by Kuzenkova [382], reports an empirical method for computing salinity of shallow water in winter based on increases caused by freezing.

Dimitriyeva has put the principle of salt rejection by freezing water to good use by devising a technique for "Determination of the Volume of Seasonal Ice Formation in River Basins by the Hydrochemical Method" [197]. Dimitriyeva has designed an elaborate mass-balance scheme which estimates the amount of ice formed by measuring the increases in dissolved salts in the remaining water.

Detailed analyses of the chemical composition of ice have been reported by several authors, including Groterud [279] who published data on three lakes in Norway. Groterud found that, compared with open water, concentrations of nitrate, nitrite, ammonia, and phosphate were high in some of the frozen lakes, and phosphate possibly was being released from cells frozen in the ice. Laboratory studies by Grant [276] on chemical reactions, principally organic, in frozen systems suggest that ice acts as a catalyst in controlling the rates of reactions. Korenouskaya and Tarasov published a rather complete set of data on the chemical composition of ice on a reservoir, and on water below the ice [369]. He reports that mineralization of the ice decreased by a factor of six during winter, and that many complex changes in the chemical composition of the water and ice occurred. Another paper by Korenouskaya [370], with Tarasov, reports mineralization in three ponds with results similar to those reported for the reservoir study. Laboratory and field studies of ice salinities, particularly as related to the salinity of the water from which the ice formed, are described in a paper by Fertuck, Spyker, and Husband [233]. Field studies by Barica and Armstrong [66] in Ontario found large amounts of nutrients (carbon, nitrogen, phosphorus, and minor nutrients) in the ice and snow covering a lake. Most of the nutrients came from the snowfall and of course became available to the lake flora upon melting of the lake cover. Concentrations of chlorophyll-*a* and chloride and measurements of pH in the colored layer of Antarctic sea ice are reported by Hoshiai [309], who found high chlorophyll levels and high chlorinity and pH near the top of the layer.

Chemical conditions under ice cover frequently are affected by the biological process of photosynthesis and by decay of plant and animal material. Many papers dealing with these processes are described in the next subsection on biological effects.

Publications describing winter nutrient loading in rivers include the report by Hegg [295] on the Red River of the North, where maintaining critical oxygen levels of 5 mg/L under ice is a major concern. Kluesener and Lee [358] describe organic loading during ice cover in the Wisconsin River and Pentwell Reservoir. Paper mill wastes were responsible for most of the oxygen demand, and natural aeration and photosynthesis did not overcome the deficit. Canadian studies of organic loading and oxygen levels include the work on the Red Deer River in Alberta as reported by Bouthillier and Simpson [116] and work on the South Saskatchewan River as described by Landine [387]. Landine's paper includes consideration of oxygen sag equations and models for predicting oxygen levels.

Winter studies of air bubbling in a Wisconsin lake report [732] that the lake was stirred by the bubbling, that oxygen levels remained high throughout the winter, and that total freezeover of the lake was prevented.

Lackey and Levandowsky [384], in Virginia, compared the effectiveness of aeration scheduling in preventing winterkill, considering whether it was better to begin the aeration early in the winter compared with starting when oxygen levels get low. They found that early aeration is more effective and warned that commencing aeration when oxygen levels are low should be done with considerable caution. In a study of winter bubbling in a lake near Moscow, Rossolimo and Shil'krot [581] found that thermal stratification was prevented, the usual formation of hydrogen sulfide was curtailed, continuous mixing resulted, and some areas of open water were retained. The Russian study found no carryover of the results of winter aeration into the summer.

Several papers have been written on the chemical features of Antarctic lakes Bonney and Vanda under ice cover. Data on chemical concentrations are in reports by Angino and Armitage [27] and by Goldman, Mason, and Hobbie [268]. Deuterium in Lake Vanda is reported by Ragotzkie and Friedman [548] to be at low levels because of fresh-water origin of the salts and effects of evaporation. Another related paper, this one about Arctic rather than Antarctic waters, is the description by Kelley [345] of carbon dioxide in the seawater under the ice.

Konrad, Keeney, Chesters, and Chen [366] describe nitrogen and carbon content of sediment cores collected through the ice on Wisconsin lakes as part of a program to evaluate the lakes' potential for eutrophication control by means of sediment removal.

Increasing attention is being given in recent literature to the problems of handling oil spills on rivers and lakes. Ice and cold can cause extraordinary problems in handling spills, but in a few cases cold can be helpful. For example a patent was issued to Cole and Hess [175] on a process for handling oil spills on water by freezing in order to harden the petroleum. In more general reports, Chen, Keevil, and Ramseier [165] and Keevil and Ramseier [344] analyze the behavior of oil spilled in ice-covered rivers. Their reports include descriptions of laboratory experiments, calculations on dispersion, and a summary of reported oil spills on Canadian rivers. Examples of the extreme difficulties that may be experienced are summarized in the report by Lamp'l [386] describing the cleanup of a spill of 44,000 gallons of fuel oil from beneath 5 feet of ice on Lake Champlain during a period of severe winter weather. Attempts also are being made to develop plans for handling oil spills in frozen waters, as illustrated by the report by Tsang [665] describing schemes for handling a possible spill on the Detroit River, St. Clair River, and Lake St. Clair.

Biological Effects

Different types of biological conditions are found under ice covers of rivers and lakes than exist during open water. This subsection contains examples of some of the many papers that deal with some of these conditions, including (1) growth of algae and productivity of phytoplankton, (2) other plant growths including macrophytes and bacteria, (3) fish life, and (4) other fauna such as zooplankton and insects. Some of the reports cited cover several phases of winter aquatic life, but are mentioned only in one of the discussions. Examples of broad publications include the volume of Kol [360] on crybiology, the biology and limnology of snow and ice, and the extensive report covering the year-round biology of Lake Wingra, Wis. [80].

Algae and Productivity

Among the many reports by U.S. authors on algal life in ice-affected waters is the report by Alexander and Barsdate on Smith Lake, Alaska [15], which describes a succession of plankton blooms and concludes that about one-fourth of the annual productivity occurs under ice cover. Data on chlorophyll and phytoplankton, as well as chemical data, on two saline lakes in Washington are in a paper by Anderson [22]. Maciolek [422], in the study of the microseston of a California mountain stream, found that changes in the seston population correlated with flow patterns induced by ice formation. In Deer Creek Reservoir, Utah, Gaufin and McDonald [256] found winter populations of *Fragilaria capucina*, *Asterionella formosa*, *Stephanodiscus*, and *Cyclotella*. Pennak [515] reports that three Colorado mountain lakes had negligible winter populations of diatoms and green and bluegreen algae, but had microalgae up to 14,500 cells per milliliter. In the Dakotas, Anderson and Armstrong [21] describe phytoplankton in Devils Lake, N. D., and Nickum [477] reports work on the algae in two prairie lakes in South Dakota. Changes from year to year in the algal population beneath the ice of a Minnesota lake are reported in a brief paper by Hill [302]. In Lake Mendota, Wis., Wohlschlag and Hasler [735] found that the algae growing in the course sediments were most productive in winter. A late winter bloom of phytoplankton and nanoplankton is reported for Lewis and Clark Lake in Benson and Cowell's paper on Missouri River reservoirs [84]. Data on phytoplankton in a Massachusetts lake collected by Wright [739] show that the winter population distribution is affected by snowfall, and that possibly some of the plankton can grow without light. A study of limnology and trophic status of Mountain Lake, Va. [488, 489] found high winter production, with the population dominated by *Cyclotella compta* and including many small flagellates. Work by Mattoni, Myrick, and Keller [439] on algal growth on waste treatment tanks in Indiana found that during short periods of ice cover the algal growth rates were comparable with those during warmer seasons.

In Canada, Hammer [282] found planktonic bluegreen algae the year round in a group of lakes in southern Saskatchewan. Smith [636] reports that in a fertilized lake in New Brunswick there was a bloom of *Anabaena* and *Spirosyra* after fertilization, with the *Anabaena* continuing to bloom under the ice.

From Sweden, work on lakes Erken [514] and Norrviken [8] shows heavy growths of planktonic algae under the ice of the eutrophic lakes. Ahlgren [7] describes winter dominance in Lake Norrviken by the Cryptomonads. A paper by Keynas [350] describing the four archipelago zones of southern Finland states that ice is one of the environmental factors that strongly influence algal distribution among the zones. Kristiansen [377] investigated the phytoplankton in two Danish lakes and found that winter populations were quite small and were dominated by *Cryptophyceae* in one lake and by *Chrysophyceae* and *Chlorophyceae* in the order. Comparisons by Lechewicz, Sokolowska, and Wojciechowski [402] of the numbers and biomass of the phytoplankton in three Polish lakes identified a strong relationship between winter growth rates and light penetration.

From a study of algae in Lake Baikal, Botintsev [114] found strong winter dominance of *Melosira* and also found that 34 percent of the total annual production by phytoplankton took place during the period of ice cover. In another Russian report, Kozhova [376] describes the planktonic composition and production in Bratsk Reservoir, reporting significant biomasses, but no blooms under ice cover.

Abundant growths of diatoms can be found under the fast ice of Davies Sea, Antarctica, as discovered during scuba diving exploration and reported by Andriyashev [26]. Scuba divers in the Antarctic Ross Sea, reported by Zaneveld [748], found large beds of red algae at depths from 6 to 35 m.

Productivity studies of Howard and Prescott [311] in lakes of the Brooks Range and coastal plain of Alaska found that highest production rates occurred after the period of maximum radiation, either under the ice in June or when the lakes opened in June to September. Anderson [24] reports that winter productivity of small lakes in eastern Nebraska is a large portion of the annual total. According to Anderson, the lakes are so eutrophic that their production soon will be in a class with sewage lagoons. Megard [442] found that algal photosynthesis under 1 m of ice in Shagawa Lake, Minn., is almost equal to that of open water on cloudy summer days. Schindler and Comita [603] describe productivity in another Minnesota lake, Severson Lake, where respiration consumes most of the oxygen under ice. A controlled study of productivity in two experimental ponds in Wisconsin is reported by Siewert [628], who made measurements on a control lake and on one that was elevated 5°C above ambient. Productivity data under ice from lakes in Michigan include the data collected by Greenbank [278] on the effects of ice and snow cover, as well as the papers by Ball [62, 63] describing the effects of fertilizing several lakes in southern Michigan. Olive, Morrison, and Riley [494] measured productivity, phytoplankton populations, and chemical concentrations year round in an Ohio lake. Winter productivity rates of 4 to 5 mg of carbon per square meter per day were several hundred times smaller than the summer rates. Studies by Potash [535] of productivity of Vermont farm ponds by algal culture with *Kirchneriella subsolitaria* found high nutrient levels in winter, with phosphate being the limiting nutrient. In work with sewage treatment ponds, Goswami and Busch [273] found photosynthetic activity low in winter because of ice cover and an increase in algal populations with melting.

Measurements of productivity in two mountatin lakes in Alberta, one alpine and one subalpine, are described in a paper by Anderson [25], who found lower production in the subalpine lake as a result of heavier snow. The previously referenced work by Nursall [486] on kettle lakes in Alberta describes levels of winter productivity. Maguire [426, 427] analyzed amounts of light transmission through the snow and ice cover on some Canadian lakes and studied the effects of light attenuation on rates of photosynthesis and decreases in dissolved oxygen.

Work with productivity measurements outside North America includes Gelin's [257] studies of nanoplankton in Lake Vombsjon, Sweden. In the period right after breakup the nanoplankton accounted for 90 percent of the lake productivity. Two Soviet papers [618, 619] report large biological productivity during winter in lakes of the Transbaikal, where growth of phytoplankton and higher plants is due to high levels of solar radiation passing through the very clear ice, which is free of snow cover. Productivity data collected by Clasby, Horner, and Alexander [169] using elaborate techniques in the Arctic Ocean produced detailed descriptions of the relationships between productivity rates and levels of illumination. From studies in Antarctica , Bunt [136] describes productivity of microalgae in McMurdo Sound as it relates to light and other factors; and Goldman, Mason, and Hobbie [268] report similar types of data from lakes Vanda and Bonney. Research in Germany by Albrecht [11] relates degree of snow cover on frozen lakes to amount of light penetration, rates of production by algae, and oxygen levels in the lake water. Albrecht's work led to the conclusion that winter oxygen production in lakes could be increased significantly by removing about one-third to one-half of the snow cover in a striped pattern. The whole topic of measuring light penetration in winter and its relationship to biological factors has been of considerable concern to researchers and was the topic of an International Union of Biological Sciences symposium and led to a general guidebook by Sauberer [594].

Algal cells in water can produce changes in the optical properties of the water column; measurements of light penetration and secchi disk transparency frequently rely on this phenomenon as the basis for estimating algal density. Among the few detailed data on optical density and plankton populations under ice are the results reported by Baker and Brook [54] for ten lakes in north-central Minnesota. The work found turbidity associated with microstrata of specific populations of phytoplankton. The strata were present during summer, disappeared during autumnal overturn, and reappeared under ice. In a detailed study of optical transparency of Lake Baikal under ice, Sherstyankin, Kaplin, and Maksimov [615] collected information on transparency, as well as data on plant pigments and populations of phytoplankton, zooplankton, and microbial plankton.

Attached algae also play a role in the winter ecology of waters. This was demonstrated by Castenholz [160], who found in lakes of the lower Grand Coulee, Wash., that *Ulothrix,* for example, grew on rocks, even under ice cover. Another attached form, aufwuchs growing on inundated trees, were studied and reported by Claflin [168] who describes winter populations that were as much as 100 times less than the summer populations.

Arctic seaweed is an algal form that frequently is exposed to an ice-covered condition. Healey [292] conducted laboratory and in situ studies on the ability of the seaweed to show positive net photosynthesis and growth under ice. The work found that no growth can be expected beneath snow-covered ice, but could occur beneath 70 cm of clear ice.

Dense algal growths frequently cause problems in sewage treatment plants, and treatment with copper sulfate often is a way of controlling the algae. These problems and treatment are not confined to warm weather, as demonstrated by the work on Lake Ramsey, Ontario, as described by Brouse [123]. Treatment to control taste and odor caused by *Aphanizomenon* consisted of copper sulphate application before freezing. The treatment brought down the algal population and reduced taste and odor problems by late December. Another report [698] dealing with a similar problem, describes application of copper sulphate from a barrel anchored in the stream of a reservoir leading to the intakes of a water treatment plant.

Papers mentioned in the preceding paragraphs have dealt with algae and algal productivity in water under ice. Algae also are known to grow within ice, as described in several papers on studies conducted in Arctic and Antarctic regions. Two papers by Buinitskii [131, 132] report algal populations, mostly diatoms, of from 11 to 32,700 cells/cm^3 in Antarctic ice, with *Fragiliariopsis cylindrus* being most widespread. The diatoms act as a radiation filter in the ice and affect its strength. Meguro, Ito, and Fukushima [443, 444] describe the diatom growth in Antarctic ice as being mostly in small fissures near the bottom of the ice. They measured a chlorophyll concentration of 120 μg/L in the diatom layer. Work by Bunt, by Lee, and by Boggs [137, 138, 139, 140] has concentrated on the growth and production of microalgae in Antarctic ice, and particularly on the growth of the algae under different light conditions. Results show that the algae have an extreme capacity for shade adaptation, retaining their viability during darkness periods of up to six months.

Green algal species in Antarctic ice were studied and reported by Kol [361] and by Kol and Flint [362], who named *Chlamydomonas ballenyana* and *Bracteacoccus minor* as dominants. Complex algal populations in the bottom few centimeters of Arctic ice were reported in a paper by Horner and Alexander [307]. They also reported on populations of protozoans, bacteria, and other organisms and stated that heterotrophic metabolism by the algae was negligible.

Macrophytes and Bacteria

Although algae are the most studied plant forms found in lakes and rivers under ice conditions, other forms such as macrophytes and bacteria play significant roles in lake ecosystems. The following paragraphs cite a few of the many published descriptions of these plant forms.

In Lawrence Lake, Mich., Rich, Wetzel, and Nguyen-Van-Thuy [560] found macrophyte flora dominated by *Scirpus subterminalis*, which showed a high, viable biomass under ice cover. Cameron and Lambert [150] described the vegetation on a Rideau River island near Ottawa, where three floristic units were found. The composition of these units is governed by degrees of exposure to the scouring effect of ice and by spring flood waters.

Publications dealing with bacteria include the paper by Upadhyay and Grecz [682] on the survival of spores of *Clostridium botulinum* in ice at temperatures down to -190°C. Studies on the survival of fecal indicator bacteria in a frozen Alaska river are reported by Gordon [269]. Waters from a single source of pollution were followed for seven days, after which total coliforms were reduced to 3.2 to 6.5 percent of the initial count, fecal coliforms were reduced to 2.1 to 4.2 percent, and enterococci were reduced to 18.1 to 37.3 percent.

Johnson's data [333] demonstrate that ice cover in Green Bay could concentrate bacteria from untreated sewage and interfere with water taken nearby for a water supply. In a study of Lake Balaton in Hungary, Olah [492] found small changes in the bacterial populations under ice, with stable stratification and population of several million cells per liter.

Drabkova's paper [208] on iron bacteria in lakes is an example of the Russian work on bacteria under winter conditions. In one lake, Drabkova found that iron bacteria comprised up to 20-25 percent of the total bacterial population. Work on biochemical uptake of oxygen in Klyaz'ma Reservoir, USSR, was described by Bylinkina [149], who attributed 80 percent of the oxygen demand to oxidation of dissolved organic matter, with additional effects from oxidation of decomposition products of sediments and from respiration of plankton. Laboratory studies of BOD tests on water from Rybinskii Reservoir were conducted by Romanenko [571] to determine the effect of container size on test results. Bottles ranged in size from 60 mL to 20 L, and tests showed that bottle size had little effect and that oxygen consumption rates in the bottles were representative of those found in the water of the ice-covered reservoir.

Fish

By far, the greatest percentage of papers on fish in ice-affected waters is devoted to description of the influences of decreased oxygen levels--a problem that occurs both in streams and in lakes. Other papers mentioned in the paragraphs that follow have to do with activities and habits of the fish, as observed under winter conditions.

Bjornn [105] reports on the movement of trout and salmon in Idaho streams in coincidence with changes in temperature and flow regime. An evaluation by Alabaster, Garland, and Hart [9] of potential problems from heated water in the River Trent in England concludes that fish can be killed by sudden exposure to water heated 6 to 9°C above ambient. There also is a danger that fish living in heated water could be killed if the water suddenly cools, such as with the shutdown of a power plant and warm zones in rivers tend to restrict fish migration. Another report on the River Trent [663] states that winter fish mortality results from deoxygenation from sewage discharges and prolonged cover by ice and snow. A related article on winter conditions affecting fish in streams is the paper by Pennak [516] on a system for classifying lotic habitats. Pennak states that for most purposes, winter temperatures in mountainous streams or in those at latitudes greater than 35°N. can be considered to be 0°C.

Many reports document the responses of fish to and fishkills by reduced oxygen levels in lakes. In Ontario, for example, Harvey and Coombs [287] found winterkilling of yellow perch and northern pike in three lakes, but also found old fish which led to the conclusion that total winterkilling is not common. Fry [252], in another Ontario study, describes stresses on trout and other fish caused by low oxygen levels, both in the hypolimnia of eutrophic lakes and beneath ice covers. Work by Schindler and Comita [603] on Severson Lake, Minn., found complete fish kills during some winters. Detailed observations of fish activity by Magnuson and Karlen [425] in a winterkill lake, Mystery Lake, Wisc., found that the least active species, northern pike, survived longer than did the more active bluegill and yellow perch. Berg and Magnuson [89], in comparing two other Wisconsin lakes, found that fish from the winterkill lake were more tolerant of low oxygen levels than were fish from the lake that did not kill. In Siewert's study [628] of two experimental ponds in Wisconsin, one heated and one unheated control, it was found that the control pond showed fish kills in summer and winter, while the heated pond did not. Greenbank [278], based on a survey of fishkill lakes in Michigan, concluded that removal of the snow cover may be one logical solution to the problems. In other Michigan studies, Ball [62, 63] found winterkilling in lakes that had been artificially fertilized, but not in unfertilized control lakes. Winterkill of trout in small mountain lakes of Colorado is reported by Pennak [515]. However, Nelson [472] found low oxygen levels in several larger Colorado lakes, but did not observe winterkill. McDonald and Schmickle [418] describe a winter fishkill in Coralville Reservoir, Iowa, which occurred when sudden runoff from a frozen drainage basin washed plant matter and agricultural pollution beneath the ice of the frozen lake. In Missouri, Fisher, Smith, and Enns [238] studied the winter survival of fish that had been stocked in sewage lagoons for insect control. They found that mosquito fish could not tolerate cold water, that other types of fish survived under clear ice, and that all fish as well as tadpoles were killed when snow cover over the ice limited photosynthesis and caused anaerobic conditions. Studies by Barica [65] of winterkill pothole lakes in Manitoba found that many also had summer fish kills owing to anoxic conditions. Summer kills occurred in lakes with chlorophyll-*a* concentrations exceeding 100 μg/L and with specific conductance between 800 and 2000 micromhos per centimeter. A paper by Zachwieja [747] summarizing several years of study on Lake Wąrniak, Poland, describes varying severity of winterkills depending on meteorological conditions, thickness and structure of ice and snow cover, and oxygen contents before freezing. Casselman and Harvey [159], in Ontario, studied selective mortality of pike and other fish and found that the larger, older, and faster growing pike were killed while the younger and slower growing pike were more likely to survive. A paper by Summerfelt [653] attributes the increasing number of winterkills in lakes of the Great Plains and North Central States to increased use of agricultural fertilizers and to runoff from livestock feedlots.

As mentioned in earlier subsections of this bibliography, some studies in Wisconsin [731, 732] have experimented with air bubbling during winter in an effort to prevent fishkills. Wirth, Russell, Uttermark, and Hilsenhoff [731] found that bubbling not only improved fish conditions in the aerated lake, but also aided winter survival of brown trout in the stream located below the reservoir outlet.

Studies on Lake Monona, Wisconsin, reported by Neill [470] and by Neill and Magnuson [471], found varied reactions among different fish in response to a discharge of heated water to the lake. Some fish avoided the outfall area and others gathered, and thermoregulation behavior was overriden by feeding behavior.

Papers reporting on fish behavior under ice include the summary by Lelek, Libosvarsky, Panaz, Bezdek, and Machacek [405], which states that movement is much reduced from summer standards, alertness is diminished, and fish do not feed. This compares with the report by Moroz [461] on the metabolism of hibernating carp during an especially severe winter. The study includes elaborate analyses of tissue from the fish having greatly reduced metăbolism rates. In contrast, Elliot and Jenkins [219] report that brook and rainbow trout in lakes at high altitude in the Sierra Nevada were active and could be caught under the ice using bait. Analyses of stomach contents found that the fish fed poorly compared with summer because of the loss of surface food forms. Hergenrader and Hasler [300] describe a bimodal diel pattern in the activity of yellow perch in Lake Mendota, Wisc. There generally was considerably more activity during daylight periods.

Zooplankton, Insects, and Other Fauna

Fish certainly have been the subject of most of the zoological studies of frozen water, but several investigations of various other animal forms also have been reported. Papers have been written on a range of subjects, the animals varying in size from microscopic to as large as waterfowl. The greatest numbers of papers describe the zooplankton and benthic forms in streams and lakes. A few examples are cited here.

Reports on planktonic forms include Canadian papers by Schindler and Noven [604] on the zooplankton in two experimental lakes in northwestern Ontario, and by Clifford [171] on drifting organisms in a brown-water stream in Alberta. In the Ontario lakes, populations of *Daphnia* and of *Diaptomus* are reported to have winter peaks. From the study of a shallow saline lake in the state of Washington, Anderson [23] reports year-round plankton data, concentrating on the zooplankter *Artemia salina*. Descriptions of the winter zooplankton in Devils Lake, N. D., are made by Anderson and Armstrong [21] and the plankton in Lewis and Clark Lake on the Missouri River in South Dakota are described by Benson and Cowell [84]. Cunningham [184] reports on migrations under ice in a lake in northwestern Connecticut, where copepods showed nocturnal migration and *Daphnia* showed little vertical migration. From studies of eutrophic Russian lakes of the Ivano-Alekseisk group, Gorlachev [270] concluded that zooplankton biomasses under ice may exceed summer maxima. A paper by Fenchel and Lee [229] reports on the protozoa, especially cileates, found in Antarctic pack ice, and concludes that the ice population is distinctly different from the plankton community in the underlying water.

Aquatic insects and benthic fauna have been studied under ice conditions several places in the world. Papers describing the work include Nebeker's account [469] of laboratory experiments with 10 species of stoneflies, mayflies, and caddisflies removed from Minnesota streams during the winter and taken into warm laboratories. All forms emerged early with stoneflies and burrowing mayflies coming out five months early and with increased separation of emergence time of the sexes. Nebeker concluded that the water must cool significantly and heat according to a normal pattern in order to get a proper hatch. A study by Holmquist [305] on five shallow lakes in northern Alaska was designed to evaluate the ability of bottom-living organisms to survive in frozen environments. It concludes that it is not possible to predict the possible survival of invertebrates based upon knowledge from studies conducted in temperate regions. In the Trinity Fork of the Logan River, Utah, Pearson and Kramer [513] studied benthic and drift invertebrates and found that reproductive products are stored in areas relatively safe from anchor ice and late-winter floods. Studies by Cowell and Hudson [181] found heavy migration of *Hexagenia* nymphs in two reservoirs in the Missouri River system at the time of and following ice breakup. In two Polish papers, Gizinski and Toczek-Boruchowa [264] report on the advantages of winter sampling to get representative bottom fauna samples from a lake, and Kownacka and Kownacki [374] describe devel-lopment of bottom fauna in streams during ice cover. Dayton, Robilliard, and Devries [188] report Antarctic observations showing influences of rising anchor ice in lifting epibenthic organisms. Persistence of bottom snails in a Wisconsin lake was one of the effects observed to result from artificial aeration of a lake, as reported in a paper [732] cited in earlier parts of this bibliography.

Accounts of some rather unusual studies include the description by Emery, Berst, and Kodaira [220] on actions of hibernating leopard frogs in ice-covered lakes. Observations made with the aid of scuba found that the frogs move about somewhat, keeping themselves from becoming covered by mud, but exposing themselves to predation by fish. Another unusual study was the work by Ryder [587] on the waterfowl wintering in Colorado lakes. Ryder observed numbers and habits of ducks and noted that they demonstrated considerable increases in rates of activity and metabolism during cold winter nights in order to maintain spots of open water.

Observations of many types of organisms dwelling under Antarctic ice were made by Russian biologists using scuba, as reported by Andriyashev [26]. Another report on Antarctic fauna is the paper by Rakusa-Suszczewski [553] on the amphipod *Paramoera walkeri*, which lives on shallow bottoms and beneath sea ice.

Water Temperature Under Lake Ice

Very small variations in water temperature usually occur under lake ice. However, by the end of a winter, conditions can change considerably from those that existed at time of freezing. In some cases, relatively high temperatures build up under the ice.

Data on water temperature under ice are included in several of the other subsections of this section on Influences of Ice on Water Quality. References to only a few of these and a few other examples are repeated here.

Pennak [515] reports temperatures of up to 5.4°C under ice in mountain lakes in Colorado. Hill [302] reported temperatures as high as 6.1°C just beneath the ice of a lake in Minnesota. Temperatures as high as 7.5°C were observed by Williams [720] under the melting ice cover of White Lake in Ontario. A paper by Anderson [23] reports temperatures greater than 20°C at the end of the three-month ice period in the bottom layer of meromictic, saline Hot Lake, Wash. Papers by several authors

[27, 616, 617] describe temperatures as high as 8°C and 24°C in two Antarctic lakes, lakes Bonney and Vanda respectively, both of which are permanently ice covered.

Detailed accounts of winter temperatures in several Japanese lakes are recorded in an article by Yoshimura [745]. Data on temperatures under the ice in four lakes in British Columbia are reported by Northcote and Halsey [481]. Most of the temperatures recorded in these articles fall in the range of 0° to 6°C.

Two Russian papers [272, 363] analyze some of the factors influencing temperature under ice, including heating from the bottom from inflowing water and by radiation through the ice. Bilello [96, 97] found that water temperatures near the bottom of a Michigan lake increased nearly 3°C during a 25-day period in December and concluded that the water was being warmed mainly by heat transfer from the bottom muds. Heating of the bottom water of Lake Tornetrask, England, by transfer of heat from the bottom is described in a paper by Mortimer [462]. Schwerdtfeger and Pounder [608] describe energy exchange through sea ice cover by conductive heat flux and radiative fluxes.

William [716] has analyzed data on temperature phenomena under ice and has incorporated the findings into the design of a system for ice prevention by air bubbling.

Circulation Under Ice

Water currents under ice are important because they transport dissolved material and sediment and also may influence floating organisms. Likens and others [407, 408] used a radiosodium tracer to collect detailed data on movement of a solute in a small ice-covered Wisconsin lake. Transport distances were 15-20 m the first day and up to 30 m in three days. The overall pattern of circulation is consistent with convective motion caused by heating from below, suggesting important contributions as a result of water heated by the bottom sediments. Stanislav and Mohtadi [643] report a mathematical simulation model to predict the dispersion of a pollutant stream entering an iced lake, and Chen, Keevil, and Ramseier [165, 344] describe the movement and dispersion of oil spilled beneath ice. Laboratory studies by Yen [744] describe details on temperature and circulation of melt waters from masses of ice heated from the top and on masses heated from the bottom.

Anisimova and Speranskayava [28] describe the statistical characteristics of velocity and temperature fields in ice-covered lakes, concluding that the turbulent structure of flows is similar to two-dimensional confined flows. Another Russian paper, by Bulatov [133], describes an interrelationship between the vertical temperature pattern and velocity distribution. The report describes the formation of a thermocline in a frozen reservoir and develops equations for describing velocity and temperature.

Observations recorded by Walker [695] and by Reimnitz and Bruder [559] on discharges of the Colville River, Alaska, into the Beaufort Sea have led to an interesting method for estimating flow volume. The river freezes completely in the winter and sea water occupies the delta front. As the river breaks up, the fresh water displaces the sea water under the sea ice, and Walker has been able to use salinity data to calculate the volume of spring discharge. Reimnitz and Bruder observed that the river discharge was confined by the sea ice and the shallow bottom causing considerable scour of the sea bottom.

Another interesting report dealing with sedimentation is the paper by Coakley and Rust [174] on sedimentation in Stanwell-Fletcher Lake, located 400 mi north of the Arctic Circle. Most of the lake surface is ice-covered year-round, minimizing sediment-transport currents and causing poorly sorted sediments and little seasonal sediment pattern near the center of the lake.

On a larger scale, Palmer and Izatt [500, 501] have studied water movement under shore ice of Lake Erie. The studies, which were made with a current meter at a point 700 m from shore, found that currents generally moved in the same direction, and that dispersion coefficients with an ice cover were significantly less than without an ice cover.

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