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THE MONOGRAPH ON RIVER ICE JAMS

by

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ABSTRACT

A Comprehensive Monograph on River Ice Jams, under preparation by the Working Group on this subject since 1985, is nearing completion. A summary of the contents of the Monograph chapters is presented, outlining the scope and depth of the coverage. Together with presentations by chapter authors, it is intended that this paper will help generate discussion and feedback from the Workshop participants.

RÉSUMÉ

La monographie sur les embâcles à laquelle se consacre le groupe de travail spécial depuis 1985 est en voie d'achèvement. Nous présentons ici le résumé du contenu des chapitres de l'ouvrage en en exposant la portée. Nous espérons que cet exposé, ainsi que ceux que feront les auteurs des différents chapitres, soulèveront la discussion et susciteront des remarques de la part des participants à l'atelier.

INTRODUCTION

The Working Group on River Ice Jams was formed in 1982, under the auspices of the subcommittee on hydraulics of ice covered rivers. The latter is a subcommittee of the Associated Committee on Hydrology, sponsored by the National Research Council of Canada.

The initial mandate of the Working Group comprised four tasks. The first and second respectively dealt with guidelines for collection of field data and for interpretation of existing data sets, such as hydrometric station records (Prowse, 1985; Beltaos, 1983). Definition of research needs was the third task (Gerard, 1984) and a compilation of (mainly Canadian) case studies was the fourth (Petryk, 1985). These four tasks were completed by 1985, at which time the Group's mandate was renewed in order to produce a comprehensive Monograph on Ice Jams. This was prompted by a general lack of detailed and in-depth treatment of ice jams. The state of knowledge on this subject is far below that of other hydrotechnical areas and expertise is concentrated among a few specialized researchers and engineering consultants. The main goal in producing the Monograph is to summarize current knowledge and define serious gaps. The intended coverage is such that both fundamental physical concepts and practical engineering approaches be adequately reviewed and discussed. Thus, the Monograph should be helpful to a wide spectrum of users, including teachers and students, practicing engineers, water resources managers and even specialized researchers.

Initially, it was thought that the Monograph could be completed in three years but, as is usually the case in such endeavours, progress has been slower than anticipated. Nevertheless, first or second drafts are already at hand for most of the Monograph chapters. First drafts are reviewed by all members of the Working Group. It is intended that second drafts be consolidated into a preliminary version of the Monograph for which reviews will be solicited from non-members both within Canada and abroad. When the final revisions are made, possible publication avenues will be explored. Of course, the logical preference is with the National Research Council of Canada, it being the ultimate sponsor of the Monograph.

The fifth Workshop on Hydraulics of River Ice is sponsored by the Working Group and will focus on Ice Jams. Thus, it provides an excellent opportunity for presenting the Group's work to, and obtaining feedback from, a wide audience of professionals with specific interests on the subject. It is recognized that detailed presentation of technical material is not possible within the available time. Instead, it is intended to outline the scope and depth of the coverage and invite comments on its adquacy and ideas on how it might be improved.

CONTENTS OF MONOGRAPH

After extensive discussion and debate among the members of the Working Group and consultation with interested non-members, the following structure was adopted.

CHAPTER	AUTHOR
1. Introduction	R. Gerard
2. River Ice Processes	T. Prowse
3. Ice Jam Processes	S. Beltaos
4. Theory	S. Beltaos
5. Numerical Models	S. Petryk
6. Physical Models	J. Wuebben (with input from F. Parkinson)
7. Mitigation	B. Burnell
8. Field Observations and Measurements	S. Petryk (with input from D. Andres, S. Beltaos, B. Burrell, F. Parkinson, T. Prowse and J. Wuebben)
9. Case Studies	D. Andres
10. Summary and Concluding Remarks	Editors (following review of preceding chapters)

Three members, Andres, Beltaos and Petryk, have agreed to act as editors, respectively responsible for chapters 1, 5, 6; 7, 8, 9; and 2, 3, 4.

The contents of the Monograph are outlined in more detail in Appendix A. Briefly, Chapter 1 will focus on the definition, characteristics and significance of ice jams while Chapter 2 provides a review of river ice processes in general and identifies their relation to ice jam processes. Chapter 3 presents a qualitative description of ice jam processes and Chapter 4 summarizes the existing quantitative theories. Chapter 5 concentrates on the use of numerical models and outlines their capabilities and limitations. Chapter 6 reviews the background and practice of physical modelling utilized when mathematical prediction is difficult or unreliable. A review, summary and assessment of mitigation techniques is presented in Chapter 7, with emphasis on defining the conditions under which any one technique is likely or unlikely to succeed. Chapter 8 contains guidelines for the type of field data needed in typical engineering projects, along with suggestions on how and when to obtain such data. Chapter 9 will describe two (freezeup, breakup) well-documented case studies illustrating how theory, field observation, modelling and mitigation are utilized in practice.

In the following sections, the contents of Chapters 1 to 9 are described in more detail. Because Chapters 1, 8 and 9 are not available at the time of writing, the descriptions are based entirely on the outlines provided by the respective authors (see also Appendix A).

CHAPTER 1: INTRODUCTION

The first question addressed is, "what is an ice jam?". Though this might at first glance appear trivial, it has been the cause of considerable debate and confusion. For example, terms like ice dam, hanging dam, narrow or wide jam are not fully descriptive, even though they represent specific types of ice accumulations, each forming by different hydraulic, thermal and structural processes.

Next, a brief overview of the evolution of ice jams is presented and differences among various ice jam types are identified (e.g., freezeup versus breakup jams).

A major portion of this chapter follows and discusses the hydro-economic significance of ice jams. Problems caused by jams include flooding, constraints to hydro-power production, interference with navigation, damage to river structures, either by direct impact or by bed scour. The environmental dimension of ice jams is also examined using the Peace-Athabasca Delta example.

CHAPTER 2: RIVER ICE PROCESSES

As background for the more specialized Chapters that follow, a general overview of hydro-thermal and hydro-structural processes is presented, starting from the cooling of rivers in the fall and ending with the final clearance of ice in the spring. Emphasis is on physical concepts and mathematical relationships are only used to illustrate the discussion.

First the various heat losses from the open water surface are described and their relative magnitudes examined. Once the water is cooled to slightly below 0°C (supercooling), ice nucleation occurs and different ice types appear (e.g., border-, frazil- or moving sheet ice), depending on heat flux and turbulence. Progressive flocculation and agglomeration of frazil crystals leads to formation of floating slush and ice pans while supercooling near the river bed may result in large accumulations of anchor ice. Where slush and ice pans are congested ("bridging"), a stationary ice cover begins to form. It may be one or more layers thick, depending on local ice jamming phenomena, as described in later chapters.

As winter progresses, the stationary ice cover thickens by freezing at the bottom or by freezing of water that may seep to the top through cracks in a cover weighted down by deep snow. Another type of ice cover, the icing, formed by freezing of successive thin layers of water, is also described. Conditions known to promote severe icings are identified and their major effects outlined.

The final and often most important phase of the river ice regime, is the breakup. This is shown to be an extremely complex process, dependent on thermal, hydraulic and structural phenomena, all influenced by the highly irregular boundaries of natural streams. Warm weather reduces the competence of an ice cover, directly, by top and bottom melt or by radiative penetration and loss of strength; and indirectly, by increasing discharge which cracks and lifts the cover, thus reducing boundary support. Open water areas develop which further augments thermal deterioration and provides room for large and small ice floes to move into. Small ice jams form at this phase which, upon release, cause further breaking of the ice cover and formation of larger jams. Eventually, the river becomes mostly open with just a few large ice jams held at sites where the winter ice cover has remained intact. The release of such jams produces the "wash", often attended by violent ice runs. Variations in the duration and pattern of breakup, owing to latitude and climate are discussed and conditions are identified that favour the hazardous "pre-mature" events (intense runoff breaking strong ice cover).

CHAPTER 3: ICE JAM PROCESSES

Chapter 3 concentrates on processes directly related to ice jams, that is, initiation, evolution and release. Emphasis is on physical concepts that can explain experience but mathematical treatment is left for Chapter 4.

Ice jams are known to start by congestion of ice floes (typically at freeze up) or by accumulation under an existing ice cover (both freeze up and breakup). Congestion in slow water leads to a surface jam (single layer of floes). Where flow velocity is capable of submerging stationary floes, thickened jams form, either hanging dams (transport under the cover and deposition in low velocity area) or "narrow" channel jams (submergence and immediate deposition under the cover). The "wide" channel jam results from "shoving" or collapse of another type of jam owing to large external forces relative to internal strength.

Once started, jams propagate upstream in a manner dictated by hydraulic conditions and internal strength characteristics. Eventually, an approximation to steady-state may be established, so that flow and jam properties change little with time. If a steady-state jam is long enough, it may contain an "equilibrium" reach where both jam thickness and flow depth are "uniform" which, in a river, means random and moderate variations about well-defined longitudinal mean values.

Ice jam release is typically a breakup occurrence and may happen within a few minutes to a few weeks after formation. How, why, and when jams release cannot be predicted at present. This has serious repercussions to our understanding of important breakup processes, e.g., surging ice runs and how they break, or are arrested by, intact ice downstream. Moreover, breaching and dislodgement of damaging ice jams requires sound knowledge of release mechanisms. The lack of such knowledge results in a lack of reliable techniques for emergency removal of ice jams.

The factors governing the severity of ice jams are summarized next, as follows from the preceding discussion. They include river width, slope, resistance, and discharge; strength and roughness of the jam; volume of ice available to form the jam; water temperature and heat transfer processes; and competence of the winter ice cover in the case of breakup jams.

As a consequence of the discussion of the various ice jam processes, a classification system of ice jams is presented, based on four criteria, i.e., dominant formation process, season, spatial extent and state. With a few "key" words or initials, an ice jam can be characterized as to its damage potential, expected evolution, relevant physics and possible means of mathematical treatment.

CHAPTER 4: THEORY

This is a natural extension of the previous chapter, containing a critical review of theoretical ideas and equations developed to quantify some of the physical concepts discussed in Chapter 3.

Much of the theoretical literature relates to predicting the thickness of an ice jam, a particularly complex task for wide jams that are formed by collapse. Accordingly, a major part of Chapter 4 deals with the state of stress within a jam, assumed to respond as a granular mass possessing cohesion and internal friction. Starting with the force equilibrium within a "differential"-sized element, successive integrations are performed (vertically and laterally) to obtain the familiar, one-dimensionsl equation of stability in the longitudinal direction. In this manner, the assumptions made implicitly in many previous publications are identified, while the background is established for possible future treatment of two-dimensional aspects.

In the case of equilibrium, the stability equation takes its simplest form and permits analytical solution for the jam thickness and flow depth, leading to a simple prediction of the total water depth. For non-equilibrium sections of a steady jam, numerical techniques must be used. Of particular interest is the toe area (downstream end of the jam) where longitudinal gradients of flow depth and jam thickness are large. Not-so-well-understood factors, suspected of significant effects on jam and flow configuration, include seepage through the voids of the jam, hydraulic resistance of the underside and state of stress in a wide jam. These factors are discussed at some depth in respective appendices to the Chapter.

The release of ice jams, though very important as a breakup phenomenon, is poorly understood at present. The result is a general dearth of quantitative theory and data. The only exception is in predicting characteristics of the surging flow that follows a sudden release. It has been established that the presence of ice that moves along with the water does not significantly alter flow properties, hence open-water models, both analytical and numerical, can be used as a first approximation.

CHAPTER 5: NUMERICAL MODELS

In many river engineering applications, complex predictions about the ice regime and ice jams must be made which can only be handled by numerical, computer-assisted methods. In its most general form, a river ice model would combine existing knowledge of pertinent hydraulic, thermal and structural processes to predict ice conditions and water levels in a study reach, throughout the winter period, given hydrologic inputs and weather conditions. This is not feasible at present, owing to large gaps in the existing knowledge. Nevertheless, several models have already been developed, each concentrating on particular components of the ice regime.

Chapter 5 defines the conditions and project types for which numerical models can be utilized to advantage. The existing models are reviewed next and their strengths and weaknesses pointed out. Some of the more comprehensive models are proprietary, while some of the non-proprietary ones are "narrow" in scope. In most cases, only limited testing of model performance and calibration consistency has been carried out.

To remedy the situation, a three-year, Canadian-led effort is now starting, with the objective of developing a well-tested, comprehensive model of river ice regime. Numerous private and public agencies are involved, with an estimated total project value of about $2 million. After development, the model will pass under the "custody" of Environment Canada and will be made available at nominal charge. The model will be periodically updated as new knowledge becomes available.

CHAPTER 6: PHYSICAL MODELS

In some applications, pertinent predictive techniques are either unavailable or unreliable due to lack of knowledge or complexities introduced by irregular boundaries. Physical modelling might then provide a practical alternative either by itself or combined with approximate or empirical predictions. Chapter 6 discusses general similitude requirements when river ice is present. Guidelines for the design of river ice models are included and address various modelling scenarios, as defined by the primary objectives of the study and availability of suitable modelling materials.

There has been considerable success in simulating hydraulic and structural processes that are directly related to ice jams (e.g., narrow-wide jams) using plastic beads or blocks. However, only rarely has it been possible to model indirectly related structural processes such as the breakup of the winter ice cover which can be both a cause and a consequence of ice jamming (cause, when it furnishes ice blocks to form a jam; consequence, when the cover breaks up due to an ice jam release). A major obstacle is the general lack of (non-proprietary) materials that adequately represent the required, scaled-down, ice properties for inexpensive applications. In turn, this derives from the very low strength needed for use at laboratory scales.

Modelling of thermal processes where they are at work simultaneously with hydraulic and structural areas is also problematic owing to (a) uncertainty as to scaling of thermal parameters and (b) occurrence of phenomena in the model that do not appear in the prototype (e.g., formation of anchor ice due to small depth or due to large roughness elements used to induce fully rough flow).

The chapter ends with a collection of case studies illustrating the usage of physical models to solve site-specific problems caused by river ice and ice jams.

CHAPTER 7: MITIGATION

Ice jam mitigation is a major aspect of river ice management and includes all activities carried out to prevent or dislodge ice jams or to reduce the damages that may result from them. Mitigation measures have been subdivided into ice jam prevention; flood damage reduction; and ice jam breaking and removal.

Ice jam prevention can be accomplished by structural and non-structural methods. In the first instance, river structures are built to prevent or delay the movement of ice floes or intact ice cover into critical areas (e.g., ice control and storage dams; ice booms). Non-structural methods apply mainly to breakup jamming and aim at weakening or destroying the winter ice cover in areas known for their jamming potential. Such methods include thermal regime and flow regime modification, surface treatment, blasting, ice cutting, and use of ice breakers. Non-structural methods are less expensive but less reliable than structural ones.

Much like with open-water conditions, flood damage reduction aims at reducing the likelihood of a flood event or minimizing damages should a flood occur. Flow control structures (e.g., dams, diversions) are effective but very costly so that they only become economical where extensively developed flood plains are to be protected. Dykes can also provide effective protection but the design should consider that (a) the water level rises much more steeply with discharge when ice is present and the flow is confined between the dykes; (b) overtopping or bypassing might have much more serious consequences than the corresponding events in the absence of dykes. Flood proofing can reduce damages and includes flood plain management and flood forecasting and warning. The latter is a very complex matter when ice is a factor and usually is based on highly empirical, site-specific approaches.

Though it is far preferable to prevent ice jams than to have to remove them, the latter occurrence is very common. Explosives, construction machinery and ice breakers have been used with varying success. Construction equipment can be effective in accessible, very small streams by physically removing ice from the jammed area and thus reducing head losses. Blasting and ice breaking is most effective when the jam is held in place by a short section of intact ice cover, followed by a long reach of open water. It should be recognized that ice jam removal is essentially an emergency operation and success depends on quick mobilization of resources and personnel.

CHAPTER 8: FIELD OBSERVATIONS AND MEASUREMENTS

The chief objective of this chapter is to present guidelines for field observations and measurements required to assess ice jamming aspects of engineering projects such as hydro-electric, water supply, flood plain, flood control effects on river structures, etc. The key to any field program is to tailor it to the project at hand by considering (a) the importance of ice jams to the study; (b) the level of the engineering study (reconnaissance, preliminary, pre-feasibility, feasibility, detailed design, construction, operation); and (c) the potential benefits of broadening the scope of work beyond the minimum requirements, e.g., adding a research component that is likely to produce important practical results for the project and possibly for similar future studies.

Procedures and instruments that are typically used to measure relevant parameters are discussed in detail. This includes meteorologic data, river bathymetry, water levels and river profiles, water temperature, frazil ice types and floating sheet ice, ice discharge, border ice growth, ice cover type and thickness, water velocity and discharge, progression and regression of ice covers, ice strength and ability to resist breakup.

The formation and evolution of ice jams in the study reach requires careful documentation by frequent or continuous monitoring during critical periods such as freeze up and breakup. The observations would (a) establish the location(s) of ice jam formation, typically by bridging at freeze up or by intact ice cover at breakup; (b) define the manner of progression upstream so as to classify the jam (e.g., surface jam, hanging dam, narrow jam, wide jam); and (c) identify the time, manner and conditions leading to the release of the jam, as well as document attendant surge effects downstream. The role of thermal and mechanical erosion should be identified where possible. Water levels upstream, along and downstream of a jam, taken within a short period of time would define corresponding river profiles, a crucial input to mathematical modelling. Aerial or ground photography, combined with follow-up surveys later on, are often the only practical means of obtaining water levels, especially where ice jams are very long, inaccessible or short-lived.

Discharge is also required and, where it cannot be reliably estimated from existing sources (e.g., hydrometric station records), must be measured directly. This is not a simple task during ice-jam periods when ice floes are being transported by the flow. Thus, it can only be accomplished as opportunity permits (e.g., open water areas upstream of the jam or fully covered, intact ice cover areas downstream). Timing of floating objects can also be used for rough estimates. Another crucial piece of information is the thickness of a jam. However, measurement at breakup remains elusive, except in the rare cases where jams freeze in place. A rough idea of the thickness can be obtained by measuring the height of shear walls exposed upon release of a jam and the subsequent drop in water level.

The opportunities and limitations associated with the ice-jam season are discussed in detail in a separate section of the chapter. This includes observations specifically applicable to (a) freeze up jams; (b) winter jams (formed after a winter thaw and breakup); (c) spring breakup jams; and (d) post-jamming measurements. The chapter closes by briefly reviewing examples of field data collection programs on a spectrum of rivers, i.e., La Grand, St. Lawrence, Peace, Thames, Salmon (U.S.A.), Mackenzie, Restigouche.

CHAPTER 9: CASE STUDIES

This chapter provides descriptions and in-depth discussions of two case studies (freeze up jams and breakup jams, respectively) to illustrate how the information presented in previous chapters can be utilized in practice. First, several potential cases are considered in the context of the range of hydro-climatic conditions of Canadian rivers. Selection criteria are then established and the final selection comprises the lower Nelson River for freeze up and the Thames River for breakup.

The lower Nelson case study starts with detailed descriptions of the area, channel, climate and flow regime and proceeds to outline the results of freeze up observations, e.g., border ice growth, lodgement sites, upstream progression of the ice cover and modes of formation. River profiles and cover thickness measurements are included. Both mathematical and physical modelling work has been carried out and it is reviewed next. The mathetmatical modelling focused on ice production, upstream progression of the cover, roughness of the cover and considered both narrow- and wide-jam stability criteria. Model extrapolation is also discussed.

The breakup case study pertains to the Thames River in S.W. Ontario and, again, starts with descriptions of the area, channel, weather conditions and general breakup patterns. Breakup observations, carried out over several years, are outlined next. They comprise breakup progression patterns, ice jam locations and ice jam characteristics. Quantitative data on ice jams pertain to formation, profiles, stages, thickness estimates and flow discharges. The analysis of the data provides values for the hydraulic roughness and internal frction of the jams.

The chapter closes with a summary highlighting not only the contents of the case studies, but also the information gaps encountered and their implications.

SUMMARY

The Monograph on River Ice Jams, under preparation by the NRCC Working Group on this subject, is nearing completion. The depth and scope of the coverage provided in the Monograph Chapters have been outlined in the preceding sections. Together with the pertinent presentations scheduled for the fifth Workshop on River Ice and Ice Jams, it is intended that this paper will help generate discussion and feedback from the participants.

ACKNOWLEDGEMENTS

This paper was prepared on the basis of chapter drafts and chapter outlines prepared by members of the Working Group on River Ice Jams. Authorship of the chapters is indicated in the main text.

The membership of the Working Group is as follows: D. Andres (Secretary), Alberta Research Council; S. Beltaos (Chairman), National Water Research Institute; B. Burrell, New Brunswick Department of Municipal Affairs and Environment; R. Gerard, University of Alberta; R. Halliday, Inland Waters Directorate; F. Parkinson, La Salle

Hydraulics Laboratory; S. Petryk, Tecsult; T. Prowse, National Hydrology Research Institute; and J. Wuebben (observer), Cold Regions Research and Engineering Laboratory, U.S.A.

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Petryk, S. 1985. Casebook on Ice Jams. Draft Report, NRCC Working Group on River Ice Jams (see also pp. 113-125 of above noted Workshop Proceedings).

Prowse, T.D. 1985. Guidelines for River Ice Data Collection Programs. Draft Report, NRCC Working Group on River Ice Jams (see also pp. 69-86 of Proceedings, 6th International Research Basins Symposium/Workshop, 1986, Michigan Technological University; and pp 111-125 of Proceedings, Eastern Snow Conference, 1985, Montreal).

APPENDIX A: OUTLINE OF MONOGRAPH CONTENTS

1. INTRODUCTION

   - What is an ice jam?
   - Characteristics of ice jams
   - Significance of ice jams (flooding, hydro-power, scour, ice cover formation and breakup, environmental aspects, summary)
   - Outline of Monograph contents

2. RIVER ICE PROCESSES

   - Introduction
   - Heat loss from open water
   - Ice formation (nucleation, crystal growth, border ice, moving sheet ice, frazil ice, ice production, floc development, anchor ice)
   - Cover formation
   - Ice growth
   - Ice cover resistance
   - Ice decay and breakup (heat transfer, internal melt and ice strength, hydrothermal melt, cover changes, breakup, forecasting, ice clearance, ice effects, breakup duration and patterns)

3. ICE JAM PROCESSES

   - Initiation mechanisms (congestion, surface restriction, other typical sites)
   - Evolution (surface jam, thickened jam, grounding, steady state and equilibrium, rate of ice edge advance - effects on discharge)
   - Release
   - Factors affecting the severity of ice jams
   - Classification

4. THEORY

- General
- Initiation
- Development (surface jam, thickened jam, forces and stresses in a jam, strength of ice jams - collapse)
- Steady state and equilibrium (stability of a wide jam, equilibrium reach, upstream transition, downstream transition, non-equilibrium jam)
- Release (release mechanisms, consequences - surges)
- Major unknowns and research needs
- Appendix A: Strength Characteristics of Ice Jams
- Appendix B: Limits to Stability of Ice Jams Due to Erosion
- Appendix C: Applicability of the Pariset *et al*. Theory of Wide Jams
- Appendix D: Hydraulic Resistance of Flows Under ice Jams

5. NUMERICAL MODELS

- Introduction
- Application of Numerical Models
- Status of Existing Models (overall objectives, list of known models, applications on specific rivers, background and limitations of existing models)
- Perspective of future improvements (development of a comprehensive model in the short-term objectives, participants, phases, long-term perspective)
- Appendices A to J. Descriptions of existing models (SIMGLACE, LASALLE, ICESIM, ICEROUTE, HANGING DAM, RIVERICE, RHIVER, IOWAICE) and User Experience

6. PHYSICAL MODELS

- Introduction
- Significant ice processes
- General similitude considerations (scaling parameters, scaling ratios, distorted models)

- Design of river ice models (modelling scenarios - stationary cover, accumulation of fragments, ice cover breakup; model ice materials - rigid ice substitutes, synthetic ice, natural ice)

- Case studies

7. MITIGATION

- Introduction

- Prevention (ice control-fixed structures, ice booms, channel cleaning, ice suppression, blasting, cutting, breaking)

- Flood damage reduction (flood control works, flood proofing, flood plain management, forecasting and warning)

- Breaching and removal (explosives, ice breakers, ice removal)

8. FIELD OBSERVATIONS AND MEASUREMENTS

- Introduction (objectives, uses, typical projects)

- Measurement of parameters affecting ice jams (meteorological, bathymetry, water levels and river profiles, water temperature, frazil ice types and floating sheet ice, ice discharge, border ice, ice cover types and thicknesses, water velocity and discharge, progression/regression of ice cover, ice cover strength against breakup)

- Documentation of the evolution of ice jams (bridging, progression upstream, collapse and reformation, melting and erosion, release, water levels during jamming)

- Seasonal considerations (observations during freeze up jamming, during and after winter breakup, during spring breakup, post-jamming observations)

- Examples of field data collection programs (La Grand River, Project Archipel, Peace River, Thames, Salmon, Mackenzie, Restigouche Rivers)

9. CASE STUDIES

- Introduction (objectives, variety of hydro-climatic regimes, potential case studies, criteria for final selection)

- Lower Nelson River (study area, hydro-climatic regime, with emphasis on freeze up, freeze up observations and data, mathematical modelling, physical modelling)