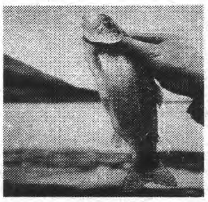
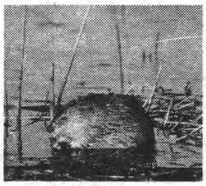
Canada Alberta Northwest Territories

Northern River Basins Study







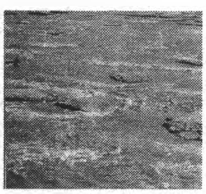


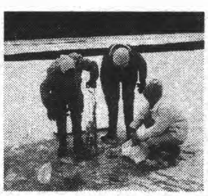


NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 66

PROCEEDINGS OF THE NORTHERN RIVER BASINS STUDY INSTREAM FLOW NEEDS WORKSHOP

OCTOBER 14-15, 1993 AND JANUARY 6-7, 1994






Prepared for the
Northern River Basins Study
under Project 4103-C1

by

Gordon L. Walder
Sirius Aquatic Sciences

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Published by the
Northern River Basins Study
Edmonton, Alberta
January, 1996

CANADIAN CATALOGUING IN PUBLICATION DATA

Instream Flow Needs Workshop (1993/1994, Edmonton, Alta.)

Proceedings of the Northern River Basins Study Instream
Flow Needs Workshop October 14-15, 1993 and January 6-7, 1994

(Northern River Basins Study project report, ISSN 1192-3571 ;
no. 66)
Includes bibliographical references.
ISBN 0-662-24830-9
Cat. no. R71-49/3-66E

1. Peace River (B.C. and Alta.) -- Regulation -- Environmental
aspects -- Congresses.
2. Aquatic habitats -- Peace River (B.C. and Alta.)
3. Aquatic habitats -- Peace-Athabasca Delta -- Congresses.
I. Northern River Basins Study (Canada)
II. Walder, Gordon L.
III. Title.
IV. Series

GB1207.157 1996 574.5'7263231'0971231 C96-980285-4

PROCEEDINGS OF THE NORTHERN RIVER BASINS STUDY INSTREAM FLOW NEEDS WORKSHOP, OCTOBER 14-15, 1993 AND JANUARY 6-7, 1994

STUDY PERSPECTIVE

Regulation of the Peace River has had extensive effects, especially on the aquatic/riparian ecosystem. Many organisms have adapted their life cycles to the natural annual variation in the river flow and changes in the natural flow regime of a river can negatively affect them. One goal of the Northern River Basins Study is to assess the effects of flow regulation on the aquatic/riparian ecosystem of the Peace/Slave river system.

As a preliminary step to field studies on instream flow needs (IFN), two workshops were held to discuss issues, methods and approaches to IFN studies and their applicability to rivers in the study area. IFN studies investigate the water quality and quantity requirements of the aquatic/riparian ecosystem. The first workshop focused on fisheries and aquatic habitats while the second concentrated on riparian and delta habitats. The workshop served to outline appropriate expectations of what studies could be done and what information could be gathered given the time and financial constraints of the NRBS.

The initial workshop concluded that emphasis and priority for IFN studies should be on the Peace River because of the existing flow regulation on this river. Aerial photography or videography to map the various habitat types over different discharges was preferred method for IFN Aquatic Habitat Analysis on the Peace River.

Related Study Questions

3. Who are the stakeholders and what are the consumptive and non consumptive uses of the water resources in the river basins?

6. What is the distribution and movement of fish species in the watersheds of the Peace, Athabasca and Slave Rivers? Where and when are they most likely to be exposed to changes in water quality and where are they're most important habitats?

10. How does and how could river flow regulation impact the aquatic ecosystem?

14. What long term monitoring programs and predictive models are required to provide an ongoing assessment of the state of the aquatic ecosystems. These programs must ensure that all

The subsequent workshop concluded that; science has not sufficiently advanced enough to undertake quantitative predictive modelling of the riparian ecosystem, but modelling at a conceptual level may be useful; there was value in documenting historical changes in river morphology and riparian vegetation; permanent riparian vegetation plots should be established on the Peace River to serve as study sites for long-term monitoring; a database for long-term storage of monitoring data should be established, and biodiversity should be a target in recommending stream flow regimes that will provide protection of riparian environments (i.e., managing for maximum biodiversity).

The study proposals that arose from these workshops when combined with material from other sources provides the basis to comprehensively assess the effect of flow regulation on the aquatic/riparian ecosystem. Although not all the studies proposed in these workshops were achievable in this Study's time frame, the long term objective is that others will take the lead. The workshops set the stage for three follow-up NRBS projects. These projects involved: a pilot study into the use of remote sensing technology to analyze fish habitat on the Peace River (NRBS Report # 81), an assessment of impacts on the Slave Delta (NRBS Report # 74) and changes in channel morphology and riparian vegetation (NRBS Report # 102).

PREFACE:

The Northern River Basins Study was initiated through the "Canada-Alberta-Northwest Territories Agreement Respecting the Peace-Athabasca-Slave River Basin Study, Phase II - Technical Studies" which was signed September 27, 1991. The purpose of the Study is to understand and characterize the cumulative effects of development on the water and aquatic environment of the Study Area by coordinating with existing programs and undertaking appropriate new technical studies.

This publication reports the method and findings of particular work conducted as part of the Northern River Basins Study. As such, the work was governed by a specific terms of reference and is expected to contribute information about the Study Area within the context of the overall study as described by the Study Final Report. This report has been reviewed by the Study Science Advisory Committee in regards to scientific content and has been approved by the Study Board of Directors for public release.

It is explicit in the objectives of the Study to report the results of technical work regularly to the public. This objective is served by distributing project reports to an extensive network of libraries, agencies, organizations and interested individuals and by granting universal permission to reproduce the material.

This report contains referenced data obtained from sources external to the Northern River Basins Study. Individuals interested in using external data must obtain permission to do so from the donor agency.

NORTHERN RIVER BASINS STUDY
PROJECT REPORT RELEASE FORM

This publication may be cited as:

Walder, Gordon L. 1996. ***Northern River Basins Study Project Report No. 66, Proceedings of the Northern River Basins Study Instream Flow Needs Workshop, October 14-15, 1993 and January 6-7, 1994,*** **Northern River Basins Study, Edmonton, Alberta.**

Whereas the above publication is the result of a project conducted under the Northern River Basins Study and the terms of reference for that project are deemed to be fulfilled,
IT IS THEREFORE REQUESTED BY THE STUDY OFFICE THAT;
this publication be subjected to proper and responsible review and be considered for release to the public.

F. J. Wrona ______ 10 Jan 96 ______
(Dr. Fred J. Wrona, Science Director) (Date)

Whereas it is an explicit term of reference of the Science Advisory Committee "to review, for scientific content, material for publication by the Board",
IT IS HERE ADVISED BY THE SCIENCE ADVISORY COMMITTEE THAT;
this publication has been reviewed for scientific content and that the scientific practices represented in the report are acceptable given the specific purposes of the project and subject to the field conditions encountered.
SUPPLEMENTAL COMMENTARY HAS BEEN ADDED TO THIS PUBLICATION: [ ] Yes [ ] No

P. A. Larkin ______ Jan 8/96 ______
(Dr. P. A. Larkin, Ph.D., Chair) (Date)

Whereas the Study Board is satisfied that this publication has been reviewed for scientific content and for immediate health implications,
IT IS HERE APPROVED BY THE BOARD OF DIRECTORS THAT;
this publication be released to the public, and that this publication be designated for: **[ ] STANDARD AVAILABILITY [ ] EXPANDED AVAILABILITY**

Lucille Partington ______ Jan-11/96 ______
(Lucille Partington, Co-chair) (Date)

Robert McLeod ______ 11/01/96 ______
(Robert McLeod, Co-chair) (Date)

REPORT SUMMARY

The need for addressing instream flow needs in the Northern River Basins Study (NRBS) arises primarily from issues related to flow regulation on the Peace River. Flow regulation may have adverse effects on important or critical fish habitats and has clearly affected riparian habitats along the Peace River mainstem and in the Peace-Athabasca Delta.

The purpose of the IFN workshop was to review methods and approaches for conducting IFN analyses, consider there applicability in the Northern River Basins, and develop recommendations for undertaking IFN investigations as part of the NRBS.

The Instream Flow Needs Workshop was divided into two sessions; one on IFN related to fisheries and aquatic habitats, and one on IFN related to riparian and delta habitats. Each session included 20-30 invited participants from universities, federal and provincial government agencies, and environmental consulting companies. Workshop participants included invited speakers as well as other knowledgeable scientists in the areas of fish and fish habitat, aquatic ecology, riparian vegetation and wildlife habitat, river geomorphology and sedimentology, hydrology, and river hydraulics.

The first workshop session, on fisheries and aquatic habitat instream flow needs was held on October 14-15, 1993 in Edmonton. During the first day of this session, presentations were made by several invited speakers on topics that included relevant background information, IFN issues in the NRBS study area, and methods for undertaking IFN analyses. The second day of this session was devoted to group discussions on several selected topics and development of workshop recommendations regarding futures studies.

The major conclusions of the fisheries and aquatic habitats session of the IFN workshop are as follows:

1. Emphasis and priority in IFN studies should be on the Peace River because of the existing flow regulation on this river.

2. Some additional data on fish resources of the Peace River are needed to support instream flow needs analyses. It was generally agreed that the information presently available on general fish distribution and major movements in the mainstem was adequate. However, more specific information on associations with different habitat types (e.g., side channels, stream margins, sloughs, backwaters), locations of critical habitats, and activities associated with the mainstem is needed.

3. The need for a comprehensive, integrated, and effective data management system was emphasized. The importance of this is due primarily to the need for reference to large amounts of a wide variety of data in interpreting results of IFN analyses. Use of a GIS for this purpose was recommended.

4. There was a general consensus that we should probably not pursue IFN studies based on hydraulic modelling to predict microhabitat characteristics (depth, velocity, substrate), at least at the present time. Reasons for this recommendation are related to logistic problems on large rivers, spatial limitations due to the necessarily short length of modelled segments, and difficulty of obtaining adequate data on the microhabitat preferences of the various fish species and life stages.

5. The preferred approach to aquatic habitat IFN analysis was considered to be one based on mapping of various habitat types (e.g., main channel, side channels, sloughs, backwaters) at different discharges. This approach involves taking aerial photography or videography at several different discharges and at a scale appropriate for identification of important habitat features. Surface areas of the various habitat types are measured on digitized images in order to develop habitat-discharge relationships.

6. Sediment transport is a major issue in terms of IFN and fish habitat, and therefore should be included in IFN analyses and evaluations of the effects of flow regulation.

7. The need to consider ice effects was identified.

The second session of the IFN workshop was focussed on how flow and water levels influence riparian and delta habitats and on methods for addressing the question of IFN for protection of these habitats. This session was held on January 6-7, 1994 in Edmonton. The structure and format was similar to the first session of the workshop.

The major conclusions of the riparian and delta habitats session of the IFN workshop are as follows:

1. There was strong support for a historical review of aerial photography on the Peace River (1949 to 1993) to examine changes in river channel morphology and riparian vegetation communities and to interpret these in the context of the historical stream flow record. (This work was undertaken in NRBS Project 1321-C1).

2. Establishment of permanent riparian vegetation plots on the Peace River to serve as study sites for long-term monitoring was strongly recommended.

3. It was suggested that some studies be undertaken to address the need to better understand the response of the system to critical and unusual events (e.g., extreme flow events, ice jam induced floods, ice scouring, fire) because these events are important factors in determining the character of riparian communities.

4. The need to establish a database for long-term storage of monitoring data was identified. Special requirements for a riparian vegetation database include the need to ensure continued accessibility of the data over a period of many decades. Care

needs to be taken to ensure that the computer database does not become inaccessible due to advancing computer hardware and software technology.

5. The temporal resolution of discharge and water level data is an important consideration in IFN analyses for riparian communities and assessment of potential effects of flow regime changes. Monthly data are insufficient and weekly data are probably adequate.

6. It was suggested that biodiversity could be a target in recommending stream flow regimes that will provide protection of riparian environments (i.e., managing for maximum biodiversity).

7. For evaluating the capability of riparian areas to support wildlife, an approach based on habitat suitability analysis was recommended as better than approaches that attempt to model actual wildlife production.

8. There was a general consensus that we are not yet very close to being able to undertake quantitative predictive modelling of the responses of riparian communities to changes in river flow regime. This is due to an insufficient understanding of system functions as well as a lack of specific process coefficients, which cannot be obtained quickly (i.e., in less than 5 years). However, it was suggested that riparian vegetation response modelling at the conceptual level would be a useful undertaking.

ACKNOWLEDGEMENTS

A large number of individuals contributed much time and effort to the instream flow needs workshop. Special thanks are due to the authors of the contributed papers included in these proceedings. Their efforts in preparing presentations for the workshop, assisting in direction of workshop discussions, and preparing a useful collection of papers are greatly appreciated. I would also like to thank the many participants in the workshop, who are listed in Appendix A. Their enthusiastic participation contributed greatly to the success of this workshop. Finally, I thank Christine Finzel, Simon Knight and Stephen Dobson, all of the Strategic and Regional Support Division, Alberta Environmental Protection, and Jim Choles, of the River Engineering Branch, Alberta Environmental Protection for their organizational support and for taking notes and recordings during workshop discussion sessions.

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1.0 INTRODUCTION

Instream flow needs (IFN) may be defined as quantities of water and water quality conditions needed to meet the demands for instream uses of water and to protect both the river ecology and riparian environments. Two types of instream flow needs are generally recognized; IFN for environmental protection (i.e., the requirements for maintenance of ecosystem health/integrity), and IFN for direct human uses (e.g., recreation, navigation, waste assimilation, fishery management objectives). Some of these IFNs can be addressed entirely by socioeconomic analyses (e.g., recreation, tourism) while others require detailed biophysical analyses.

The need for addressing instream flow needs in the Northern River Basins Study (NRBS) arises primarily from issues related to flow regulation on the Peace River. Flow regulation may have adverse effects on important or critical fish habitats and has clearly affected riparian habitats along the Peace River mainstem and in the Peace-Athabasca Delta.

The scope of this workshop was limited to consideration of IFN related to fisheries management and environmental protection issues. IFN issues related to aquatic habitats and to riparian and delta habitats were considered.

The purpose of the IFN workshop was to review methods and approaches for conducting IFN analyses, consider there applicability in the Northern River Basins, and develop recommendations for undertaking IFN investigations as part of the NRBS.

2.0 WORKSHOP STRUCTURE AND PROCEDURES

The Instream Flow Needs workshop was divided into two sessions; one on IFN related to fisheries and aquatic habitats, and one on IFN related to riparian and delta habitats. Each session included 20 to 30 invited participants from universities, federal and provincial government agencies, and environmental consulting companies. Workshop participants included invited speakers as well as other knowledgable scientists in the areas of fish and fish habitat, aquatic ecology, riparian vegetation and wildlife habitat, river geomorphology and sedimentology, hydrology, and river hydraulics.

Presentations by speakers during the workshop were of two types; background presentations were given by some speakers while contributed papers were presented by others. Background presentations included certain background information relevant to the workshop but not appropriate for presentation as a formal paper. The purpose of the background presentations was to inform workshop participants of this information to help prepare them for subsequent workshop discussions. Brief summaries of the background presentations are included in Section 3.0 of this report. Contributed papers included a variety of topics dealing with methods, approaches, and issues related to instream flow needs analysis and effects of flow regulation. These papers are include in Section 4.0 of this report.

2.1 WORKSHOP SESSIONS

2.2.1 Fish and Aquatic Habitats Session

The first workshop session, on fisheries and aquatic habitat instream flow needs was held on October 14 and 15, 1993 in Edmonton. During the first day of this session, presentations were made by several invited speakers on topics that included relevant background information, IFN issues in the NRBS study area, and methods for undertaking IFN analyses. The second day of this session was devoted to group discussions on several selected topics and development of workshop recommendations regarding future studies.

Background presentations in the Fish and Aquatic Habitats session included the following:

1. Hydrology of the Peace River
   by John Taggart, Alberta Environmental Protection, Edmonton, Alberta

2. Water Quality Considerations
   by Patricia Chambers, National Hydrology Research Institute, Saskatoon, Saskatchewan

3. Quantifying the Response of Aquatic Habitat to Stream Flow Changes in Large Rivers
by Woody Trihey, Trihey and Associates, Concord, California

Following are the contributed papers for the Fish and Aquatic Habitats session. With the exception of the paper by Ken Bovee, all papers were presented by their authors during the first day of the session. Ken Bovee was unable to attend the workshop, but copies of his paper were provided to all workshop participants.

1. A Conceptual Approach to Assessing Instream Flows in Large Rivers of the Northern River Basin, Canada
by Thomas B. Hardy, Hardy, Addley and Associates, Logan, Utah

2. A Regional Approach to Planning Instream Flow Studies: Applicability to the Northern River Basins Study
by Dudley W. Reiser, R2 Resource Consultants, Redmond, Washington

3. Maintaining Biological Integrity in Instream Flow Studies in Large Rivers
by Jean E. Baldrige and E. Woody Trihey, Trihey and Associates, Inc., Concord, California

4. Winter Habitat Considerations for Fish in the Peace River
by Bill MacKay, University of Alberta, Edmonton, Alberta

5. Managing Instream Flows for Biodiversity: A Conceptual Model and Hypotheses
by Ken D. Bovee, U.S. Fish and Wildlife Service, National Ecology Research Center, Fort Collins, Colorado

Group discussions during the second day of the workshop were directed by the following list of selected topics. All workshop participants were involved simultaneously in these discussions.

1. Data Organization
2. Critical Habitats
3. Hydrology and Hydraulics
4. Sediment Transport
5. Recommendations and Study Planning

2.2.2 Riparian and Delta Habitats Session

The second session of the IFN workshop was focussed on how flow and water levels influence riparian and delta habitats and on methods for addressing the question of IFN for protection of these habitats. This session was held in Edmonton on January 6 and 7, 1994. It was organized the same way as the first workshop session, with background presentations and contributed papers on the first day followed by group discussions on the second day.

Background presentations for the Riparian and Delta Habitats Session included the following topics

1. Hydrology of the Peace River and Peace-Athabasca Delta
by John Taggart and Andy Deboer, Alberta Environmental Protection, Edmonton, Alberta

2. Increased Water Levels and Expansion of Lake Claire Due to Glacial Induced Regional Tilting
by Derald Smith, University of Calgary, Calgary, Alberta

3. Predictions of Vegetation and Fire Responses to Low Water Levels in the Peace-Athabasca Delta
by Ross Wein, University of Alberta, Edmonton, Alberta

4. Status Report on Vegetation Studies in the Peace-Athabasca Delta
by Pat Fargey, Wood Buffalo National Park, Fort Chipewyan, Alberta

The following contributed papers were presented during the Riparian and Delta Habitats session of the IFN workshop:

1. Post-Regulation Morphological Change and Development of Riparian Vegetation Along the Peace River: Predictions and Initial Observations
by Michael Church and Margaret North, University of British Columbia, Vancouver, British Columbia

2. Implications of Upstream Impoundment on the Natural Ecology and Environment of the Slave River Delta, Northwest Territories
by Michael C. English, Wilfrid Laurier University, Waterloo, Ontario

3. A Model for Managing Emergent Wetland Vegetation: Indicator Species and the Maximization of Diversity
by Irene C. Wisheu and Paul A. Keddy, University of Ottawa, Ottawa, Ontario

4. Instream Flows and Riparian Forests Along Alberta's Southern and Northern Rivers
by Stewart Rood, University of Lethbridge, Lethbridge, Alberta

5. Approaches to Assessing and Modelling Wildlife Habitat in Riparian Areas
by Jeffrey E. Green, Timothy Van Egmond and T. Ross Eccles, Axys Environmental Consulting Ltd., Vancouver, British Columbia and Calgary, Alberta

Group discussions during the second day of the Riparian and Delta Habitats session were directed by the following list of selected topics. All workshop participants were involved simultaneously in these discussions.

1. Responses of Channel Morphology and Riparian Vegetation to Changes in Flow Regime
2. Ice Effects
3. Wildlife Habitat Values of Riparian Vegetation
4. Descriptive Analyses and Monitoring Programs
5. Predictive Tools
6. Recommendations and Study Planning

3.0 BACKGROUND PRESENTATIONS

3.1 HYDROLOGY OF THE PEACE RIVER AND PEACE-ATHABASCA DELTA

John Taggart (Alberta Environmental Protection) outlined the hydrologic data sets available for the Peace River. In addition to the Water Survey of Canada stream gauging data, two other data sets have been developed. These include monthly flows down to the town of Peace River for the period 1937 to 1992 and daily flow data to Peace Point for the period 1960 to 1991. Both the monthly and daily flow databases include naturalized (i.e., unregulated) flows as well as regulated flows. The daily flow database includes regulated flows for three different power generation load scenarios (high load year, low load year, low load year with surcharged reservoir). These data sets are based on application of a SSAR routing model.

The effect of flow regulation is illustrated in Figure 1, which shows mean monthly flows at the Alberta/B.C. border for the period 1940 to 1985. Peak flows during the summer months have been greatly reduced by flow regulation while winter flows have been increased. The regulated flows on this graph represent an average of 16 different load year predictions from a planning model used by B.C. Hydro. Variability of regulated flows in the Peace River at the Alberta/B.C. border is illustrated in Figure 2.

Andy Deboer (Alberta Environmental Protection) described the hydrology of the Peace-Athabasca Delta and reviewed the effects of regulation of the Peace River by the Bennett Dam on water levels in Lake Athabasca. During filling of the Williston Reservoir from 1968 to 1971, the mean annual level of Lake Athabasca was reduced considerably (Figure 3). In 1975, weirs were built on Lake Athabasca outlet channels (Riviere des Roches and Revillon Coupe) in an attempt to restore water levels in Lake Athabasca. Subsequently, lake levels increased but lower levels were observed again in the early 1980s (Figure 3). It was not clear to what extent lake level was influenced by regulation of the Peace River and to what extent it was influenced by natural variation in stream flows.

In an attempt to determine the relative effects of flow regulation and natural flow variation, a one-dimensional hydrodynamic model was used to simulate Lake Athabasca water levels under natural conditions, regulated conditions without the weirs, and regulated conditions with weirs. The results of those simulations, for the period 1960 to 1981 are illustrated in Figure 4. Differences in the simulated average and peak summer water levels in Lake Athabasca are shown in Figure 5. Under regulated conditions without weirs, both the average and peak water levels were reduced from natural conditions. The amplitude of the fluctuation between average and peak was also reduced. Under regulated conditions with weirs, peak water level was nearly the same as under natural conditions. However, the amplitude of fluctuation between average and peak levels remained reduced.

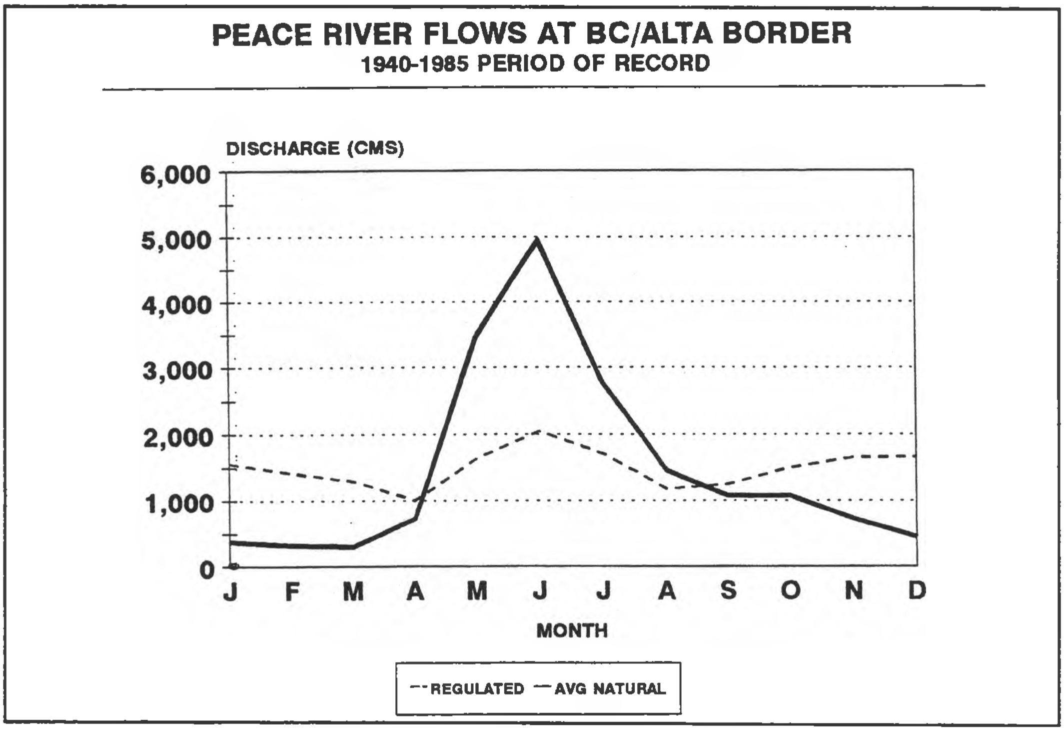

Figure 1. Average natural and regulated flows in the River at the Alberta-B.C. border, 1940-1985.

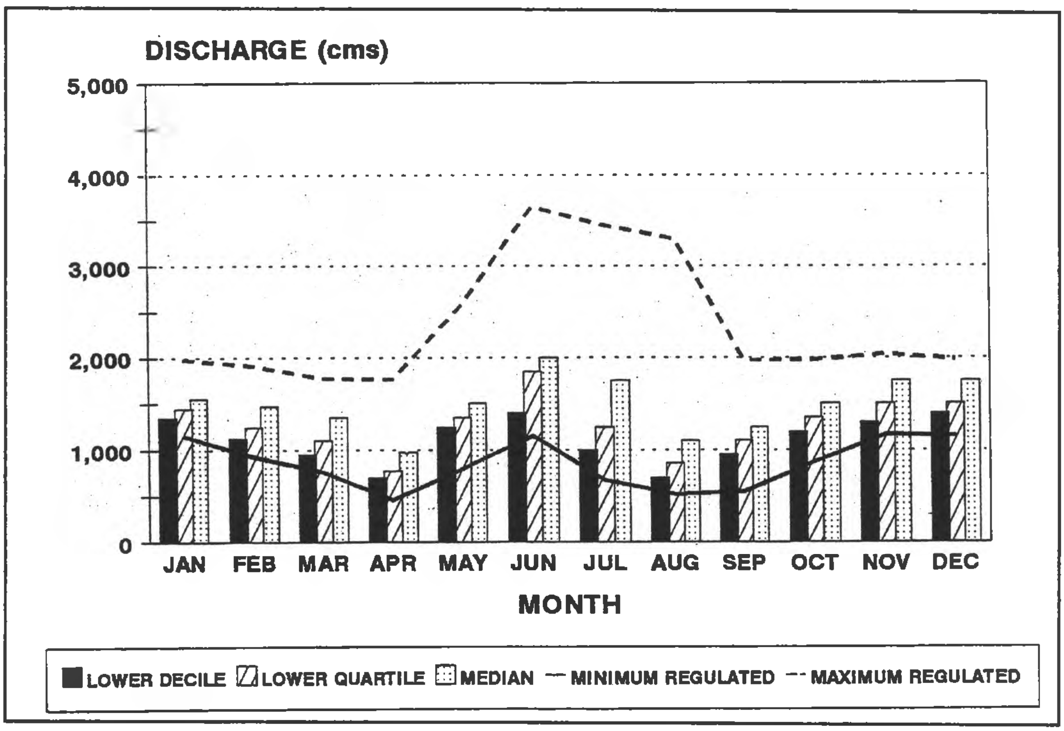

Figure 2. Variability of regulated flows in the Peace River at the Alberta-B.C. border.

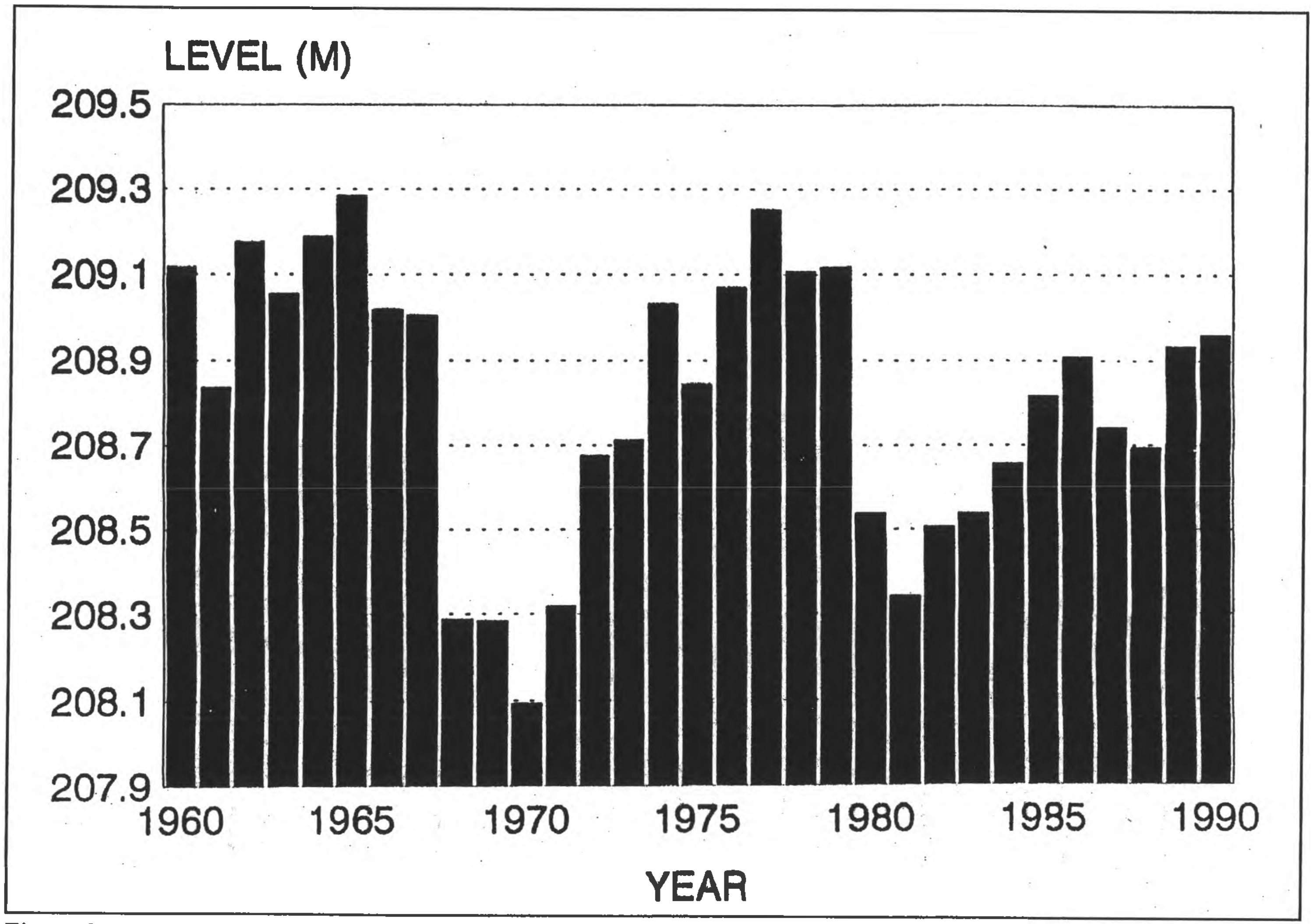

Figure 3. Mean annual lake levels in Lake Athabasca near Crackingstone Point, 1960-1990.

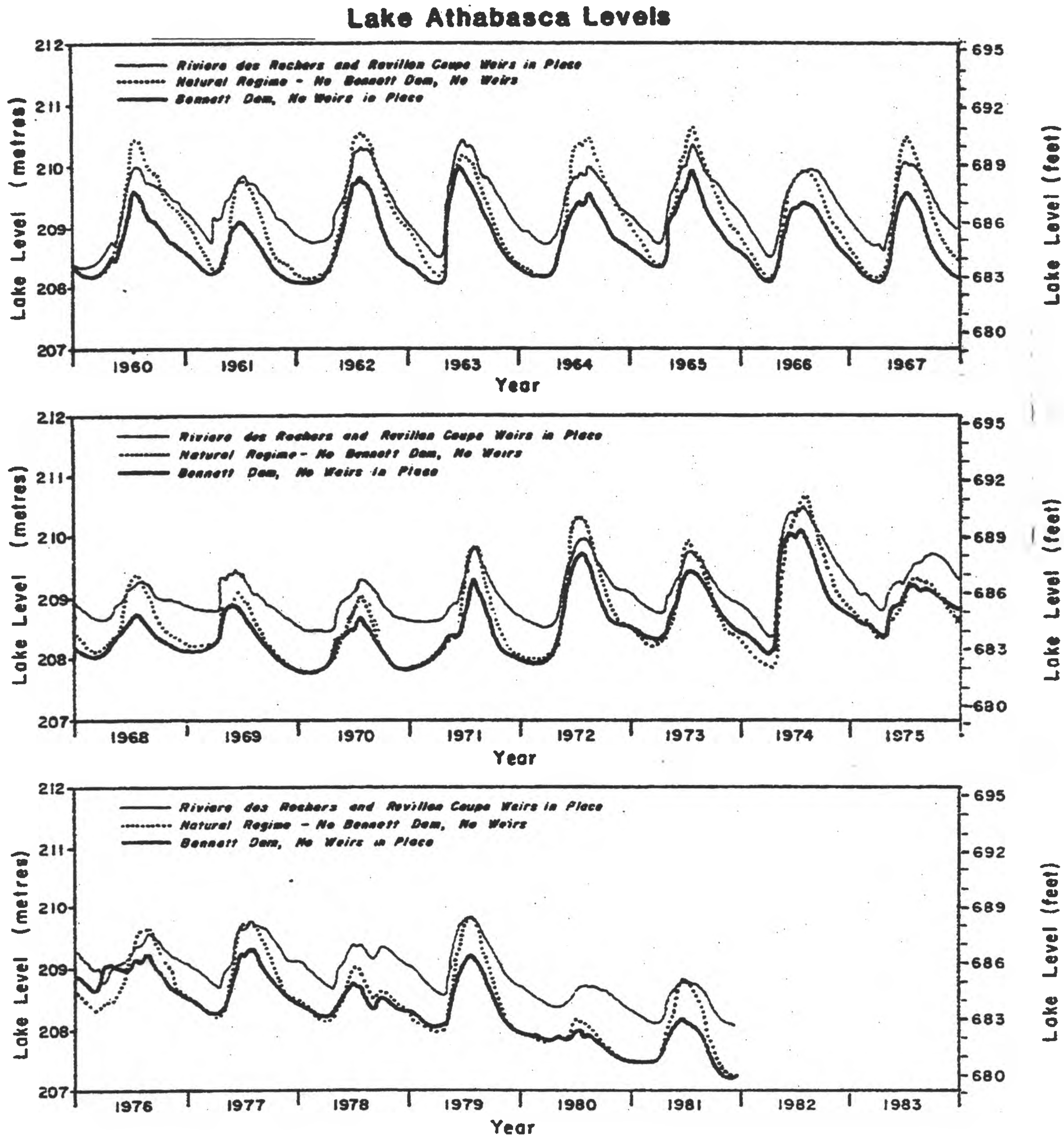

Figure 4. Comparison of simulated Lake Athabasca water levels under natural conditions, regulated conditions without weirs and regulated conditions with weirs.

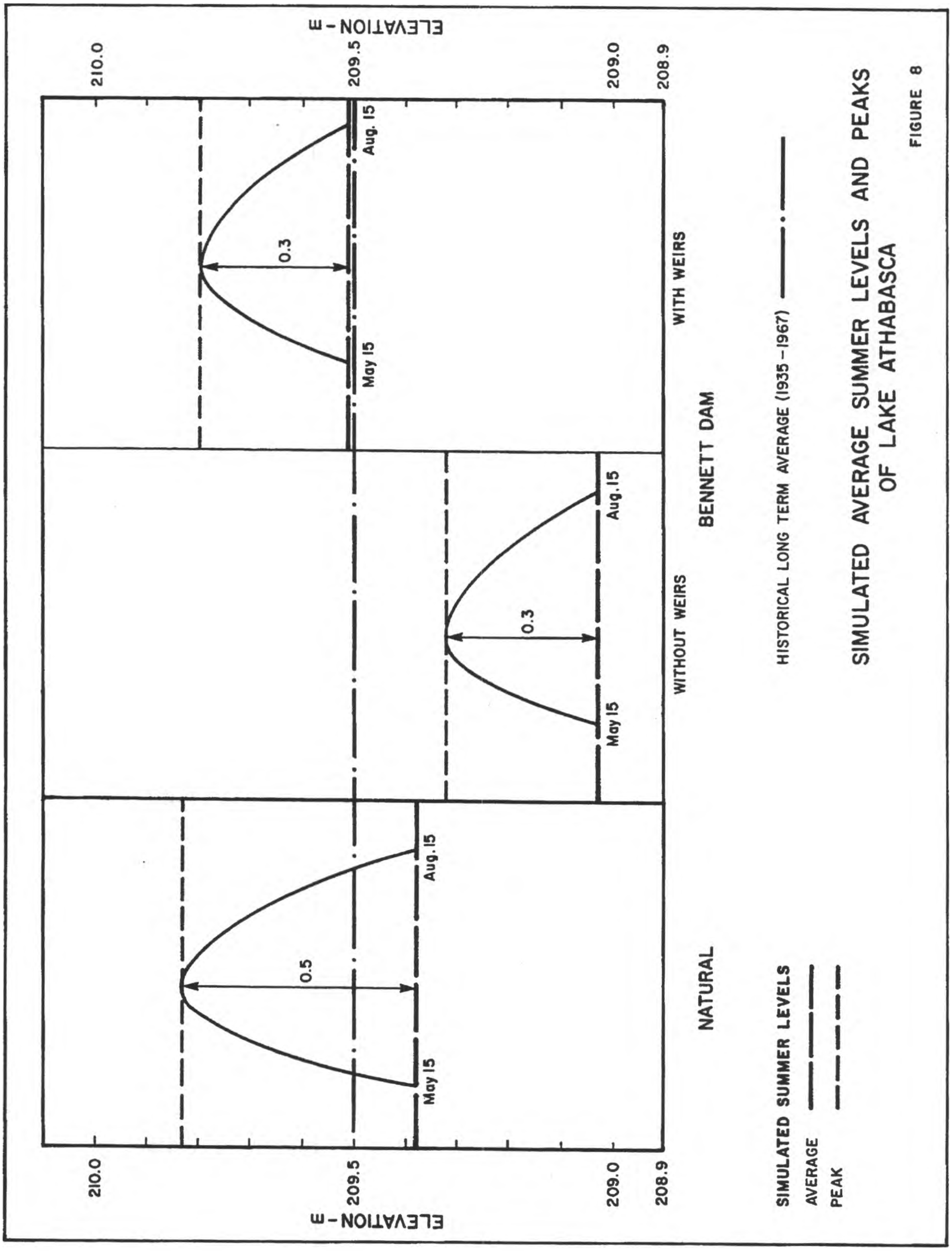

Figure 5. Simulated average and peak summer water levels in Lake Athabasca.

3.2 WATER QUALITY CONSIDERATIONS

Patricia Chambers (National Hydrology Research Institute) presented an overview of water quality in the NRBS study area. This overview emphasized issues related to nutrients, dissolved oxygen, and biological oxygen demand (BOD). Contaminants were not discussed. This presentation outlined the nature and locations of water quality issues in the Northern River Basins, available water quality databases, and current monitoring and modelling activities. A summary of the current and planned activities of the Nutrients Component of the NRBS was also given.

Water quality issues in the Northern River Basins are related primarily to two types of effluent sources; pulp mills and municipal sewage sources. There are more water quality concerns on the Athabasca system than on the Peace River due to the smaller size of the Athabasca River and the fact that there are more pulp mills on the Athabasca system.

Monitoring efforts consist of long-term monitoring programs on both the Peace and Athabasca systems, as well as some periodic synoptic surveys and some continuous dissolved oxygen monitoring. Long-term monitoring programs consist of monthly or bimonthly sampling at several sites, some of which have been monitored since the 1960s. Continuous dissolved oxygen monitoring has been done during winter on the Athabasca River and also to a lesser extent on the Peace River.

It was noted that much less work has been done on the Peace River than on the Athabasca River. This is primarily because the mainstem flow in the Peace River is so large at all times of year that any loadings from effluent sources have little effect. Impacts from nutrient and BOD loadings and impacts on dissolved oxygen in the Peace River do not seem to be significant at the present loading rates.

Dissolved oxygen modelling efforts were reviewed and summarized. Emphasis in these modelling efforts has been on the Athabasca River. No dissolved oxygen modelling has been done on the Peace River mainstem, but some has been undertaken on the Wapiti-Smoky system, which is tributary to the Peace River.

3.3 QUANTIFYING THE RESPONSE OF AQUATIC HABITAT TO STREAM FLOW IN LARGE RIVERS

Woody Trihey (Trihey and Associates) described his experiences working on large river systems and referred primarily to instream flow studies on the Susitna River, Alaska. In those studies, a classification of various habitat types was developed and changes in these habitats in response to changes in mainstem river discharge were quantified.

Habitat types identified were mainstem, side channel, side slough, upland slough, tributary mouth, gravel bar, and vegetated bar. The areal extent of each habitat type in a reach of the mainstem Susitna River was measured on aerial photographs taken for this purpose. Aerial photography was flown at several different discharges and the amounts of each habitat type present at each discharge was measured. These data allowed the development of graphs describing the relationships between stream discharge and surface area of each habitat type. The results of these analyses were then used to develop instream flow recommendations for the Susitna River.

3.4 INCREASED WATER LEVELS AND EXPANSION OF LAKE CLAIRE DUE TO GLACIAL INDUCED REGIONAL TILTING

Derald Smith (University of Calgary) provided a view of changes in the Peace-Athabasca Delta from the perspective of a geologic time frame. The post-glacial history of the area was described and the evolution of Lake Claire was examined. Past and present Peace-Athabasca and Slave River deltas were described.

Evidence supporting the hypothesis that Lake Claire is drowning was reviewed and interpreted to mean that either the basin is receding or the water level is rising. It is believed that the deltaic margins are losing ground in a geologic time frame and that there will be an expanding lake and shoreline over the next 3000 years. These changes are considered to be the result of post-glacial rebounding of the land. The main channel, or the major hydrologic base level for the region, is rising at a faster rate than the Lake Claire basin, causing water levels of the lake to increase.

Three thousand years ago Lake Claire did not exist. It was predicted that 3000 years from now it will be our largest lake, exceeding Lake Athabasca in areal extent but not in water volume.

3.5 PREDICTIONS OF VEGETATION AND FIRE RESPONSES TO LOW WATER LEVELS IN THE PEACE-ATHABASCA DELTA

Ross Wein (University of Alberta) described vegetation succession in the Peace-Athabasca Delta and the role of fires in the vegetation ecology of the area. How low water levels in the delta have affected vegetation communities and altered the effect of fires was discussed.

Through either climate change or human activity, the landscapes are drier and more conducive to fire. The area burned in a fire is related to the degree of drought. It is anticipated that wetland areas will shrink and the uplands will move down in the lowlands. Because many of the upland species, such as white spruce, are very long lived, changes in those vegetation communities tend to be very conservative.

There has been encroachment of willows into areas of the delta that are drying. This is occurring quite extensively, with willows taking over in huge areas. There has been a loss of small mammal biomass due to the extensive willow growth and additional losses are anticipated in the future.

As soils become drier, there is an increase in carbon dioxide release from lower organic soils as they dry out. As a result of this process, there is an increased rate of nutrient release, more oxygen in the soil, and some plants are able to root deeper. Therefore, there tends to be a move from an organic soil cycling

system to a mineral soil cycling system, especially without periodic flood events.
In addition, with the increase in soil drying, fires that occur in late summer can change an organic soil to a mineral soil.

The hypothesis presented was that vegetation communities will not change quickly unless the force of fire changes the system rapidly. The first woody species to come in after a fire are two poplar species, *Populous balsamifera* and *Populous tremuloides*. If poplars overtop the willows, the willows will die out. White Spruce will move down from the uplands lower areas.

3.6 STATUS REPORT ON VEGETATION STUDIES IN THE PEACE-ATHABASCA DELTA

Pat Fargey (Wood Buffalo National Park) provided a status report on vegetation studies currently being under taken in the Peace-Athabasca Delta. Increasing concern over the health of the delta ecosystem prompted the initiation of a program of studies aimed at improving understanding of vegetation ecology of the area.

A three year technical study was initiated in the spring of 1993 to begin to collect information needed to support development of an ecosystem management plan for the Peace-Athabasca Delta. The study has two general objectives:

1. To improve understanding of vegetation community dynamics
2. To experimentally flood some areas in the delta and monitor subsequent vegetation changes

Transects have been established at the top of the hydrological gradient and extended down into the delta. Measurements of vegetation cover were made along these transects and ageing of shrubs and trees was done. Early tentative results of the work indicates that willow encroachment occurs in discrete events and that the rate of succession has slowed. Recently established meadows can probably be distinguished from long established meadows on the basis of soil type.

4.0 CONTRIBUTED PAPERS

A Conceptual Approach to Assessing Instream Flows in Large Rivers of the Northern River Basin, Canada

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Abstract

Due to the large spatial domains of the river systems within the Northern River Basin, Canada, classical instream flow assessment methods may not be appropriate or logistically infeasible to implement. This paper reviews the basic premise upon which current instream flow assessment methods have been developed and then examines several emerging technologies that can likely be applied to meet the needs for the development and implementation of an instream flow assessment methodology for these systems. In particular, utilization of remote sensing platforms such as aerial photography and multispectral videography are capable of providing quality data over large spatial domains that can achieve delineations of key fisheries habitat based on surface characteristics. Delineation of the sub-surface river topography over large spatial domains is also feasible using existing hydro-acoustic sampling strategies that can be directly linked to remotely sensed imagery by differentially corrected Global Positioning Systems. The spatial data obtained from the remote sensing and the hydro-acoustic sampling of the bottom topography can also be used to develop a number of ecologically important metrics for use in understanding the relationship between individual, population, and community use of habitat over large spatial domains. The use of hydro-acoustic technologies also permits direct access to two-dimensional hydraulic simulation models that can provide much higher resolution of the hydrodynamic characteristics of flow dependant attributes within the rivers over spatial domains of interest. Finally, the use of a variety of physical and biotic metrics derived from remote sensing, hydro-acoustic bottom profiling, and two-dimensional hydraulic modeling allows investigations of physical and biological gradients of ecological importance using a variety of parametric and non-parametric statistical techniques in addition to more classical habitat modeling approaches.

Introduction

From the perspective of an individual aquatic organism (e.g., fish), river ecosystems create a temporally and spatially variable physical, chemical, and biological template within which an individual can exist if it possesses the proper suite of physiological, behavioral, and life history traits (Poff and Ward 1990; Orth 1986). The goal of natural resource management is to understand the relationships between organisms and the environment and to be able to predict the effects of resource management actions (Chovanec et al. 1994; Muhar et al. 1995. Before the effect of resource management on aquatic habitat can be measured, however, there must be a thorough understanding of how physical, chemical, and biological components of a stream system interact (e.g., Beanlands and Duinker 1984; Orth 1986). A general principle of ecology is that organisms have a multi-dimensional niche of environmental conditions (e.g., temperature, salinity) and resources (e.g., food, space) within which a viable population can be sustained (May and MacArthur 1972; Pianka 1974; Colwell and Futuyma 1971). The success of a population can be limited by individual components and/or combinations of the physical, chemical, and biological components in the river ecosystem. The factors that limit population success can vary both spatially and temporally, and the factors can occur during different portions of the organisms life cycle. In addition, these limiting factors can be both naturally occurring and man induced. For the resource management of the Northern River Basins there is a critical need to both apply the current knowledge of the ecosystem to current management decisions and to increase the knowledge of how the physical, chemical, and biological components of the ecosystem interact for application in future management decisions.

This basic need for the evaluation of instream flow requirements to protect aquatic resources has resulted in the development and application of a large number of methodologies over the past two decades. The roots of most currently "accepted" instream flow methodologies have their roots in concepts and practices which arose during the mid to late 1970's (Table 1). At present, the application of the Instream Flow Incremental Methodology (IFIM) is by far the most popular in the United States, Canada, and within emerging instream flow programs in Europe (Reiser et al. 1989). Although several "state-of-the-art" methodologies have received some level of institutionalization such as the Instream Flow Incremental Methodology (IFIM), existing tools have come under increasing criticism as to their applicability and validity in resource management. This in part, has been driven by the legal and institutional requirements for methodologies which meet legal defensibility requirements. In past five years however, new research has focused on the development and application of what are viewed as more consistent, reproducible, and cost effective assessment methods which provide "better" quantitative resolution of impacts and evaluation of restoration efforts in aquatic ecosystems (e.g. Johnson and Law 1995; Johnson et al. 1995; Hearne et al. 1994; Capra et al. 1995; Leclerc et al. 1995; Addley 1993). This is especially true in light of current ecosystem management directions by resource agencies and the recognition that to meet ecosystem management objects, more integrated physical, chemical and biological process driven methods will be required.

Unfortunately, most of the existing instream flow assessment methods have been developed and applied primarily within smaller spatial domains and target only the physical habitat components with very little applied work having been undertaken in large river systems such as typified in the Norther River Basins. In addition, as noted above, a growing consensus among both researchers and practitioners is that the disciplinary basis from which the fundamental science and analytical procedures are developed, validated and applied in instream flow assessments needs a broader ecological perspective. Based on experiences over the past two decades, the current trend in applied assessment methodologies is to approach these problems from the perspective of bio-diversity, ecological integrity, and ecosystem management. To this end, and in light of the unique constraints imposed by the spatial scales for the Northern River Basin rivers, new approaches which integrate characterization of the spatial domain over large areas of the river with habitat analysis, community-based habitat measures, and ecological interpretations need to be considered. The objective of this paper is to suggest a rational framework for the integration of spatially explicit delineations of the aquatic environment that will permit the integration of community level approaches to habitat modeling in order to assess the instream flow requirements and/or impact assessments of altered flow regimes in systems typified throughout the Northern River Basins.

Table 1. Basis of Existing Instream Flow Assessment Methods.

Method	Citation
Tennant Method (Montana Method)	Tennant 1975,1976
Hoppe Method	Hoppe and Finnell 1970;Hoppe 1975
Northern Great Plains Resource Program (NGPRP) Method	NGPRP 1974
New England Flow Recommendation Policy (New England Method)	USFWS 1981;Knapp 1980
Connecticut River Basin Method	Robinson 1969
One Flow Method	Sams and Pearson 1963
Washington Base Flow Method	Collings 1974
Oregon Usable Width Method	Thompson 1972
Weighted Usable Width Method	Sams and Pearson 1963
Washington Spawning Method	Collings 1972,1974
Washington Rearing Method (Wetted Perimeter Method)	Collings 1974
Water Resources Research Institute Trout Cover Method (WRRI Cover Method)	Wesche 1973,1974,1976
U.S. Forest Service (USFS) Region 4 Method	Herrington and Dunham 1967
	Dunham and Collotzi 1975;Bartschi 1976
USFS Region 2 Cross Method (Colorado Method, Critical Area Method)	Russel and Mulvaney 1973
	Silvey 1976
USFS Region 6 Method	Swank and Phillips 1976
Waters Method (California Method)	Waters 1976
Indicator Species-Overriding Consideration Method	Bovee 1974
Idaho Method	White 1976;Cochnauer 1976
Instream Flow Incremental Methodology (IFIM)	Bovee 1982

Background

Historically, most applied instream flow assessment methods that incorporated the biological requirements of species relied on information obtained at the individual organism level as a basis to model the quality and quantity of habitat (Bovee 1982). This effort primarily focused on the delineation of individual "preferences" for depth, velocity, and substrate/cover for a handful of target species and life stages. This type of approach also inherently requires that the physical or spatial domain of the river system be measured and/or modeled so that the biological criteria can be used to evaluate the relationship between flow and habitat (e.g. Bovee 1982; Nestler et al. 1993). The incorporation of the temporal variability of habitat was approached from the use of hydrologic time series in habitat time series analyses. This overall approach is not necessarily deficient as long as the target species and life stages have well defined habitat requirements which are known or can be measured and when the physical characteristics of the hydraulic regime in the river can be measured and simulated in a competent fashion using at most a moderate number of cross section profiles. Clearly, given the large spatial domains of the rivers within the Northern River Basin and the logistics for data acquisition in terms of both the physical and biological domains, alternative approaches to delineation of the physical characteristics of the channel, habitat typing, and subsequent biological evaluation of the flow dependant changes in river characteristics need to be considered.

Furthermore, one can approach the problem of linking biology with the physical characteristics of the aquatic environment by integrating spatially explicit delineations of the habitat mosaic with information on community level distributions and abundances (e.g. Aadland 1993). This approach basically examines the relationship between patterns of habitat type use by either individuals, populations, or the community in terms of spatial metrics that can be empirically measured or modeled in large river systems (or small systems for that matter). This approach implies that the aquatic environment can be delineated into meaningful habitat mosaics (or types) which preserve their inherent variation (or lack thereof) with changes in discharge and that one can relate the importance of these individual and habitat mosaics to the biological needs of the individual, population or community. Therefore as a first step in approaching the problem of instream flow determinations, spatial characterization of the river is considered.

Spatial Characterization of the Aquatic Environment

Generally, the first step in any instream flow assessment requires the characterization of the river based on some form of habitat mapping. This mapping usually permits some rational method of justification for the selection of representative reaches, or target habitat types, in which a finite number of cross section profiles are collected. Historically, these cross sectional measurements serve as the basis for the development and application of one-dimensional hydraulic simulation models such as found in PHABSIM. The physical description of the aquatic environment (i.e. habitat mapping) has been approached at the meso-scale (habitat) to macro-scale (reach) levels. Applied metrics within instream flow assessments have classically relied upon linear habitat mapping using simple habitat descriptors such as run, pool, riffle, glide, etc. (Bovee 1982), to more complex habitat descriptors dependant of the physical forming processes for each habitat type (Rossgen 1984; Hankin and Reeves 1988; Hawkins et al. 1993; Kershner and Snider 1992). Some of these techniques relied on the development and application of more quantitative metrics at the meso- and macro-scales based upon a combination of physical attributes such as slope, channel stability, sinuosity, channel type, and habitat formation process (e.g. Rossgen 1984; Hankin 1984; Hankin and Reeves 1988). However, these classification schemes are not likely to be appropriate given the spatial scales associated with typical rivers of concern in the Northern River Basins. Therefore alternative approaches which can delineate habitat features over large spatial scales and which are amendable for integration with on-site field collections of fisheries and other types of data need to be considered. A further consideration in adopting a rational approach should also consider techniques which permits linkages to hydraulic simulation models and can also be utilized to both generate spatial metrics with biological relevance as well as permit integration of biological information at the individual, population or community level rather than only at the individual species level over more extensive spatial domains than historically considered in instream flow methodologies.

Delineation of Surface Spatial Domain in Large River Systems

One of the more likely techniques for use in the delineation of the type and spatial extant of habitat features is the application of remote sensing technologies. Key factors to any remote sensing application should include cost, time, and ability to acquire data a spatial resolutions of between 1-4 meters. Satellite imagery with existing platforms are not well suited to these factors given spatial resolutions of between 10 and 30 meters. Both aerial photography and aerial multispectral videography can achieve these target spatial resolutions and are cost competitive. One advantage of aerial photography is its higher spatial resolution compared to videography systems, however it lacks the inherent advantage of digital multispectral attributes as well as taking prolonged periods for receipt of the imagery for use in near real time field applications. Multispectral videography on the other hand can provide very rapid turn around times for use in ground based mapping and collection of field data for fisheries and image processing. Another advantage of the videography based systems is that it is composed of multispectral digital imagery which can have significant advantages over standard aerial photography. Use of multispectral videography for the delineation of the spatial extent and type of aquatic habitats in river systems has rapidly increased over the past few years. Recent work on larger river systems have employed this type of remote sensing in conjunction with ground based observations to delineate meso-scale habitat features. This has included the delineation of meso-scale hydraulic features in both turbid and clear water systems (Anderson et al. 1993; Panja and Hardy 1995; Panja et al. 1993; Hardy et al. 1994;). Several of these efforts have concentrated on the empirical determination of changes in meso-scale habitat features as a function of discharge with direct linkages to fisheries collection data within specific habitat types (Panja and Hardy 1995; Hardy et al. 1995; Gilver et al. 1995; Snider et al. 1993). Other applications have included use of this imagery for the prediction of species distributions (Hardy and Shoemaker 1995) and the mapping of sediment distributions (Crowther et al. 1995; Gilver et al. 1995).

Figure 1 provides an example of a typical 3-band false color composite from a multispectral videography image of a river based on filter sensitivities in the green, red, and near-infrared band of the spectrum. Figure 2 provides this same view with all land based features extracted from the image and the remaining instream features displayed after a contrast stretch. The amount of detail now visible in the river is significantly improved and can aid in both ground based delineations of habitat as well as computer analyses employing both supervised and unsupervised classification procedures. An example of an unsupervised classification of the masked river contained in Figure 2 for fisheries habitat is provided in Figure 3. It is readily apparent that the computer based classification is quite functional in representation of the spatial distribution of features evident in Figure 2. As noted in the references above, this type of image classification permits the empirical delineation of habitat types over ranges of discharge which can be linked to fisheries collection data by habitat type. The use of GPS during field sampling in conjunction with printed imagery has also been shown to be of value for field crews for location of sampling areas and for ground based delineations of habitat features. Another important feature of the use of digital imagery is for long term change detection in support of monitoring programs. An added benefit of this type of imagery is the ability to quantitatively assess riparian species distribution and responses to long term or episodic hydrologic events. Furthermore, since this type of imagery is compatible with most commercially available GIS software systems such as ArcInfo, GIS

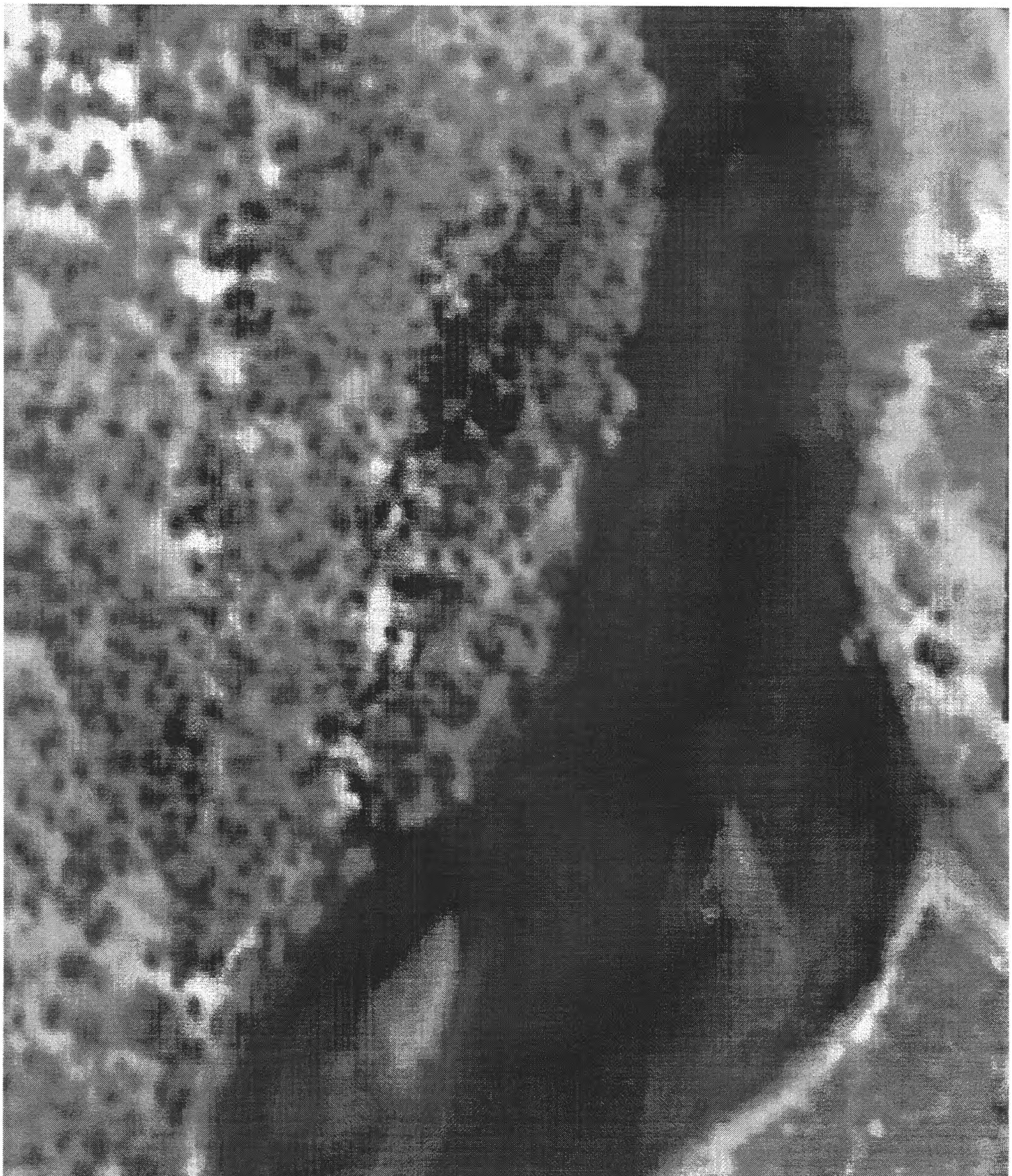

Figure 1. Example of a 3-band false color composite videography image of a river section.

Figure 2. Example of a 3-band false color composite image for isolated river features contained in Figure 1.

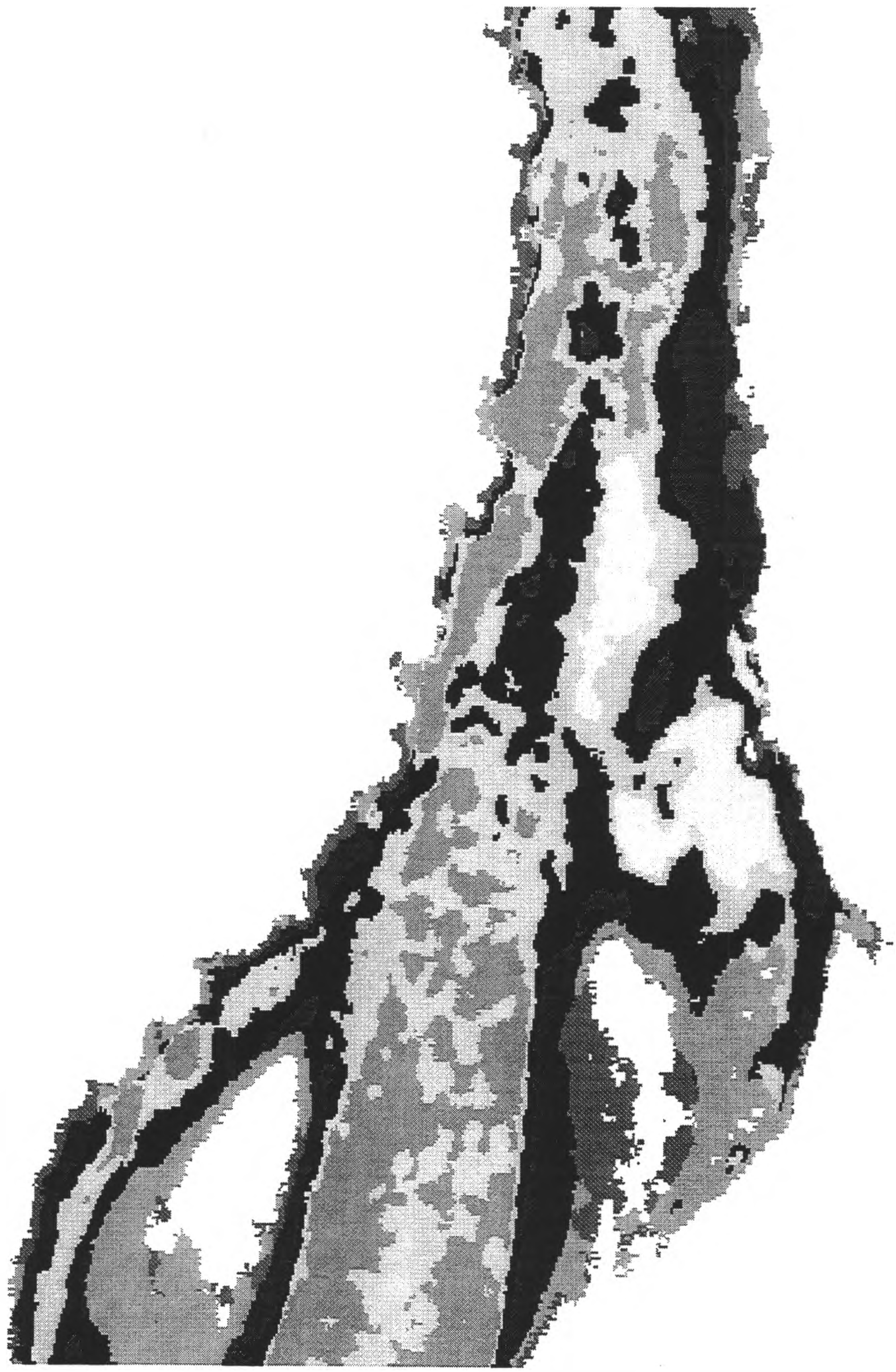

Figure 3. Example of fisheries habitat classifications based on the 3-band false color image contained in Figure 2.

analyses can also be utilized to derive a variety of spatial based physical and biotic metrics such as habitat diversity, contagion, fractal geometries, entropy, etc, as discussed below. Both the 3-band false color composite and classified imagery can also be employed to assist field crews in the location of sampling locations and for the delineation of more spatially explicit habitat mapping. It is anticipated that application of this type of technology would be ideally suited for delineation of the habitat features over large spatial domains within systems of the Northern River Basin. This technology represents a fairly proven technique for these purposes, provides a direct linkage to GIS systems for both the original digital multispectral images as well as the final habitat classifications derived from image processing techniques and ground based measurements, and is cost competitive with more standard aerial photography systems. The technique also implicitly provides a digital media based archiving of the river system for long term historical monitoring activities.

Delineation of the Subsurface Spatial Domain in Large River Systems

Another rapidly developing field of "remote sensing" within larger river systems is the integration of differentially corrected GPS and hydro-acoustic arrays for obtaining channel morphometries, spatial data for use in two-dimensional hydraulic simulations, and for vegetation/substrate characterization and distributions (Gubala et al. 1995; Hardy et al. 1995, Tetra Tech, Inc. 1995). Real time mapping of the subsurface spatial domain employing these systems have achieved 1-3 meter spatial accuracy while acquiring data over extensive longitudinal spatial domains covering up to 10 kilometers or more per day. Often, the application of these technologies at high discharge rates is an advantage over more classical field measurement techniques and the subsequent data can be used in simulating hydraulic characteristics at lower discharges of interest. Another important consideration is that these types of systems can also be integrated with the multispectral videography data for use in GIS applications since GPS ground control points can be delineated directly on the videography prints during ground data acquisition. Furthermore, the integration with GPS allows for the rectification of the imagery and subsurface profiling data to standardized map bases in the GIS systems. In addition, integration of the videography based imagery with the GPS and hydro-acoustic data has been utilized to develop ground based stratified random sampling schemes for the acquisition of biological data (Hardy and Shoemaker 1995). At one level of application, the acquisition of channel characteristics by hydro-acoustics has permitted the spatial delineation of the river channel for use in the calculation of habitat heterogeneity and fractal dimensions that were highly correlated with observed biological diversity in the Willamette River (Tetra Tech Inc. 1995).

Figure 4 illustrates a summary of point feature derived interpolated depth contours from GPS integrated hydro-acoustic subsurface profiling and the corresponding interpolated depth contours in a river system derived from the GPS integrated hydro-acoustinc sampling gear. Figure 5 illustrates interpolated depth contours of the subsurface spatial domain for a 1000 foot section of the river system. Figure 6 illustrates a 3-dimensional representation of the subsurface spatial domain using a regularly spaced spatial interpolation scheme and a typical triangular irregular network finite element grid with the simulated velocity vectors derived from 2-dimensional hydraulic simulation within the reach. It is readily apparent that these types of data provide a much improved spatial representation compared to more classical

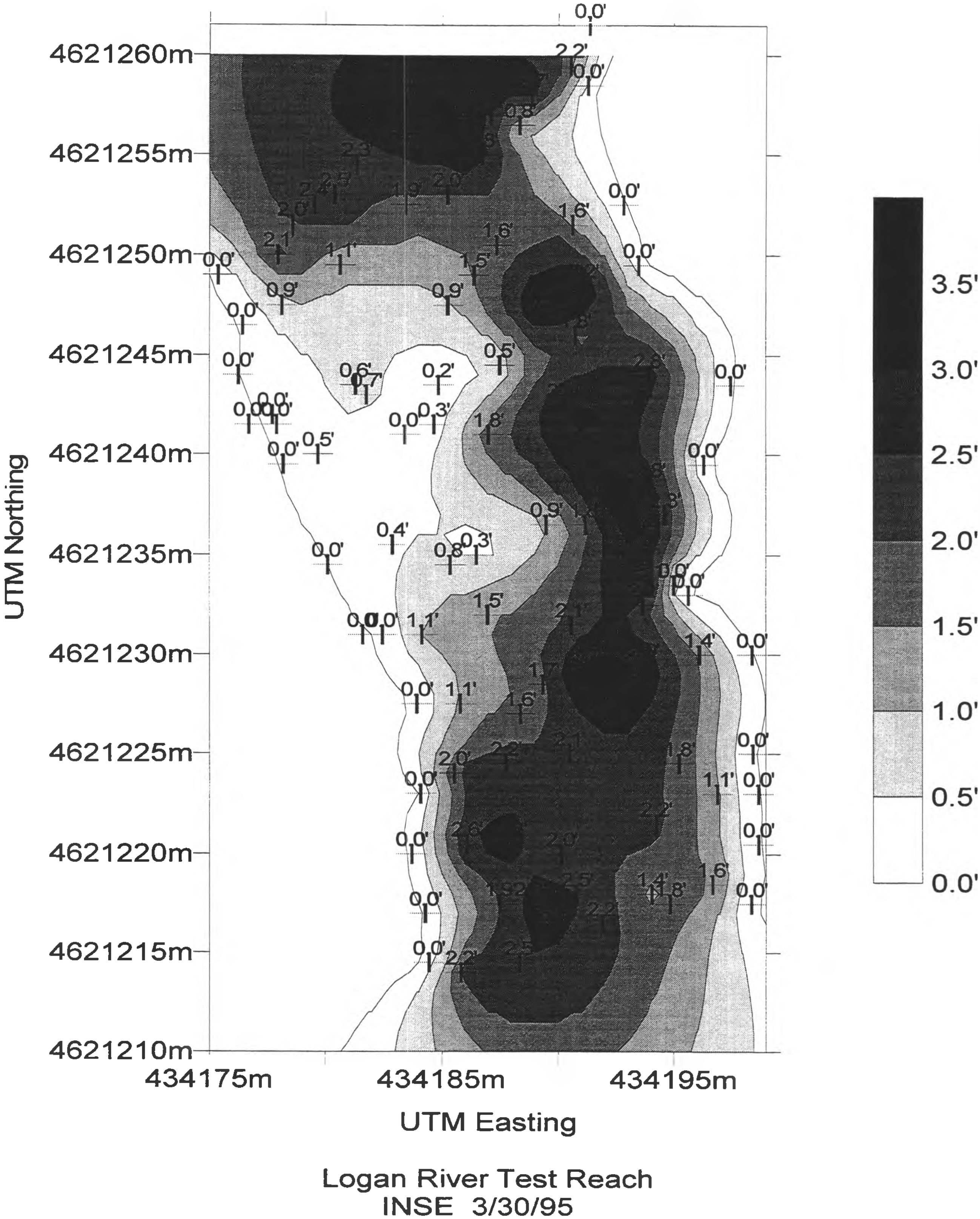

Figure 4. Example of summary point feature derived interpolated depth contours from GPS integrated hydro-acoustic subsurface profiling of a river.

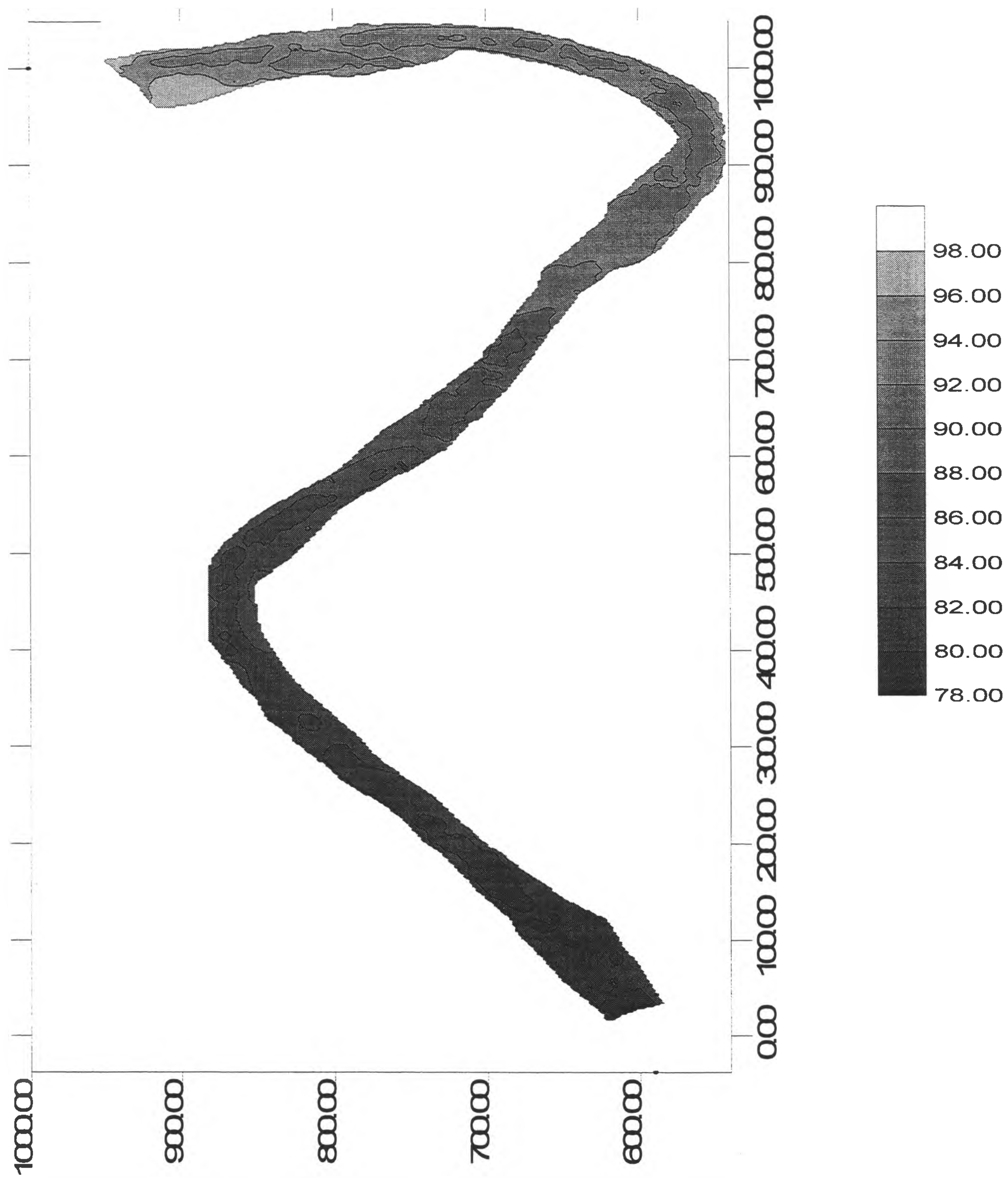

Figure 5. Example of depth contours derived from spatial interpolation of subsurface hydro-acoustic data collected in Figure 4.

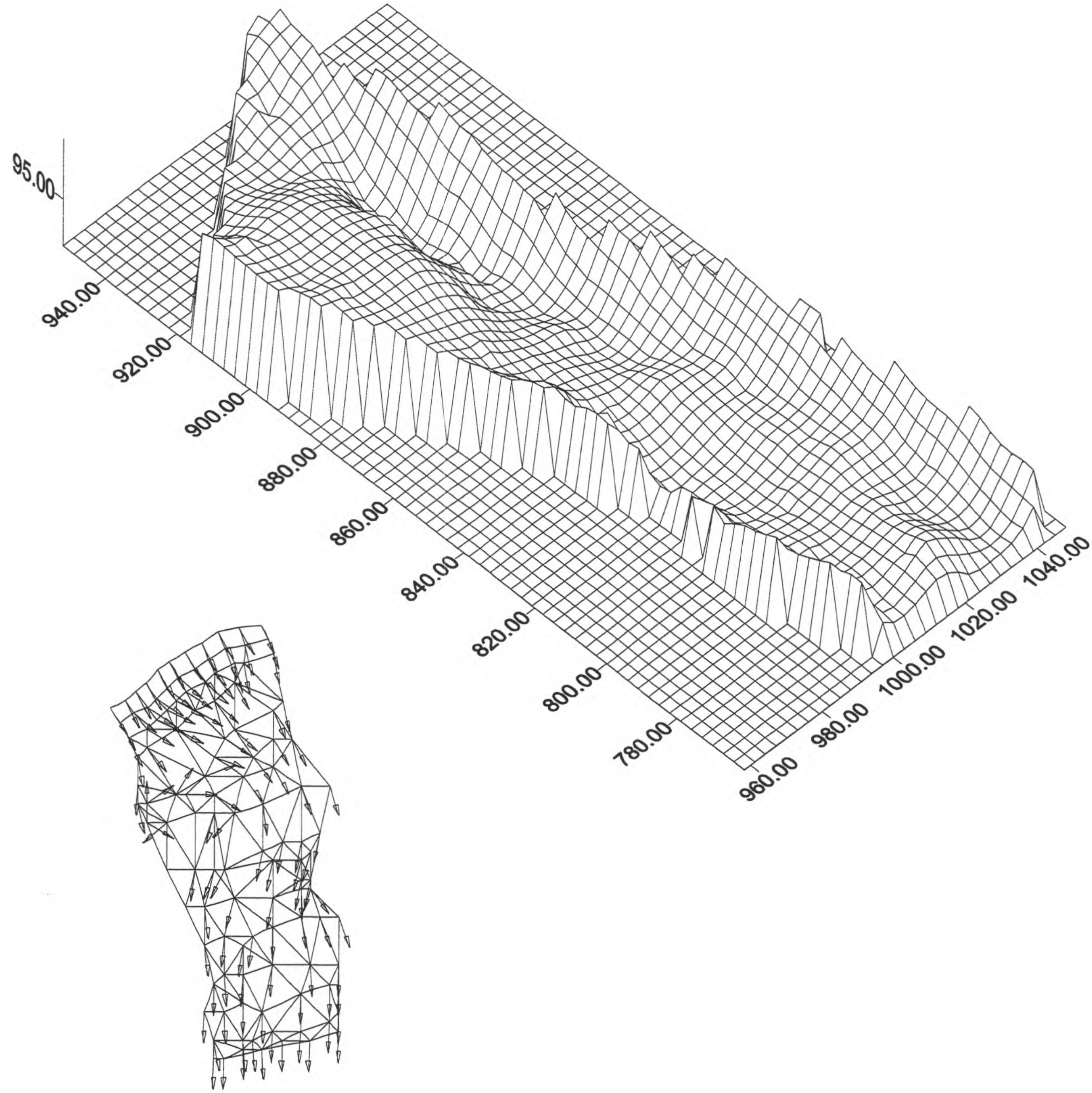

Figure 6. Example of a 3-dimensional representation of a section of the river in Figure 5 using a regular spatial grid (a) and corresponding triangular irregular network finite element solution grid with corresponding velocity vectors (b).

instream flow procedures such as PHABSIM, especially when one considers the spatial scale these results represent. Another feature evident from these Figures derived from the acoustic sampling of the stream geometries is that "habitat" heterogeneity in terms of depth and simulated velocity vectors is implicitly preserved using this approach. This improved spatial representation can also be directly utilized for the calculation of important physical and biometric indices as described below for use in parametric and non-parametric modeling of individual, population, and community level habitat use. What is not illustrated in these examples is the integration of substrate information which is can also be obtained and integrated into the "habitat" representations. Existing hydro-acoustic arrays have been used for the delineation of differential substrate characteristics as well as for the delineation of the distribution and relative density of aquatic vegetation. Incorporation of substrate with output from 2-dimensional hydraulic simulations in habitat analyses has already been demonstrated by Leclerc et al. (1995). The fact that the sub-surface profiling provides data over relatively large spatial domains in a const effective manner that is directly amendable to use in more advanced 2-dimensional hydraulic simulations is discussed further below.

Two-dimensional Hydraulic Simulations of Large Rivers

Integration of the accurate spatial representation of the river topography has resulted in an increasing utilization of 2-dimensional hydraulic simulations in instream flow assessments (Leclerc et al. 1995; Ludlow et al. 1995). Many of the 2-dimensional hydraulic simulation models do not require the measurement of velocities except for the starting conditions at the upstream boundary of the reach and the downstream water surface elevation. This has obvious advantages over existing techniques such as PHABSIM where extensive velocity collections and calibrations are required. Figure 6 illustrated an example of a finite element solution grid obtained from the 3-dimensional spatial domain collected by a hydro-acoustic array for use in 2-dimensional hydraulic modeling. The Figure also provided an example of the simulated velocity vectors for this river reach based on the solution of the finite element grid using a 2-dimensional hydraulic model. Both the finite element grid and resulting velocity simulations can be used for integration of more classical habitat modeling approaches such as in PHABSIM (Leclerc et al. 1995), mechanistic based bioenergetics approaches (Addley 1993), integration of the two approaches (Ludlow et al. 1995) or to compute a variety of spatial and biological metrics as described below. Similar approaches within the Northern River Basins are likely to have greater success than the application of more traditional assessment methods such as one-dimensional hydraulic simulations employing PHABSIM. At present, field validation studies are currently underway which are focussing on the assessment of both the spatial distribution and magnitude of velocity simulation errors based on 2-dimensional hydraulic simulation without use of velocity calibration data and the development of a systematic spatial sampling protocol for data acquisition by the International Aquatic Modeling Group.

Spatial and Biological Metrics

Delineation and quantification of particular combinations of habitat types is a key consideration for using spatially explicit models. Quantifying habitat juxtaposition, extent of edges and habitat connectivity may provide habitat-based measures of ecosystem function in rivers, but will require spatially explicit habitat models such as illustrated in the above examples. The biological importance of accurate delineations of the type, location and extent of habitat features has been recognized by a number of investigators in river systems (Rinne 1991; Freeman and Grossman 1993; Fausch and White 1981; Southall and Hubert 1984; Addley 1993; Stanford 1994; Lobb and Orth 1991; Rabeni and Jacobson 1993; Bovee et al. 1994). Many of the important structural or spatial attributes of the habitat types can be characterized by the amount of contact, or edge, between habitat types, the length of interface or contact zone between two different habitat types and should be accessible using the surface and sub-surface spatial delineation techniques described in this paper. The delineation of the contact zone between two (or more) habitat types as a spatial metric or attribute may constitute a unique habitat type in itself (Ranney et al. 1981, Noss 1983, Lovejoy et al. 1986, Harris 1988, Yahner 1988, Malcolm 1994). Furthermore, spatially explicit models can also be utilized for the development and application of habitat metrics developed in the landscape ecology literature that are now receiving attention in the aquatic community. These metrics describe various aspects of spatial heterogeneity that may be linked to functional responses of various species or community dynamics (Li and Reynolds 1994) such as species dispersal, colonization potential, foraging efficiency, predator avoidance and species replacement. Some of the more commonly applied metrics that may be of value for consideration in the Northern River Basins include fractal dimension (Burrough 1986; O'Neill et al. 1988), dominance (O'Neill et al. 1988), contagion (O'Neill et al. 1988; Turner et al. 1989; Li and Reynolds 1994), habitat diversity and relative evenness (Shannon and Weaver 1962; Pielou 1969; Romme 1982), and edge effect (Malcolm 1994).

Integration of the spatial components described above with these types of physical and biotic metrics opens up analytical approaches classically ignored in instream flow assessments. For example, use of the large spatial data sets potentially obtainable with these technologies would permit the application of statistical techniques such as direct gradient analysis using canonical correspondence analysis, detrended correspondence analysis, principal components analysis, and fuzzy c-means clustering. These approaches can be extremely useful in defining a gradient of environmental variables, such as gradients of depth and velocity, heterogeneity of habitat patch size, persistence of habitat types over ranges of discharges or other biological significant response axes. In addition, to these types of gradient analyses it is also possible to generate gradients of spatial dependant indices, such as contagion, juxtaposition, entropy, or fractal dimension. Exploratory analyses using these indices can often expose previously unknown relationships between the habitat mosaic, community structure, and its function. A key element in these approaches will be the acquisition of species, population, and/or community level use of spatially delineated habitat types which as described above, should be facilitated by the integration of remote sensing of the surface domain in conjunction with the sub-surface profiling of the river and output from 2-dimensional hydraulic simulations.

Summary

Available technologies such as multispectral videography are likely to provide access to surface level spatial delineations of aquatic habitat types that are relevant at the population or community level for use in deriving empirical relationships between habitat availability and discharge. Application of these technologies for similar instream flow questions are currently well represented in the literature. These techniques also provide access to the use of GIS for resource characterizations, impact assessments and long term monitoring data. These techniques also provide an excellent opportunity to acquire data over extensive spatial domains anticipated in throughout the Northern River Basin. Technology also exists for the characterization of the sub-surface topography of the rivers at highly accurate spatial scales using GPS linked hydro-acoustic arrays. This technology can be employed to acquire data over many kilometers of river per day and provide a direct linkage to both the computation of key physical and biotic metrics of ecological importance as well as providing the data for use in advanced two-dimensional hydraulic simulations. Another key element of these two technologies is that data for use in support of ground based fisheries and habitat measurements can be obtained in near real time. Both of these technologies are also compatible with GIS systems commonly utilized today in resource planning. The application of two-dimensional hydraulic simulations is also another important advancement over existing instream flow assessment methods that is potentially ideally suited for use on these large river systems. The inherent advantages are directly related to the data generated from the use of hydro-acoustic array sampling of the bed topography and the lack for extensive collection of velocity profiles within the river. The integration of the spatial and hydrodynamic characteristics of the river from these techniques also permits the application of advanced statistical treatment of the data that can provide better access to results of a biological significance in instream flow determinations.

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A Regional Approach to Planning Instream Flow Studies: Applicability to the Northern River Basins Study

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Abstract

This paper focuses on the planning and coordination aspects of regional Instream Flow Needs (IFN) studies as they relate to the Northern River Basins Study (NRBS). Certain difficulties are inherent when conducting such studies, and these are discussed and potential solutions described. These include; 1) inability to sample all sites within the study area; 2) difficulty in sampling remote locations; 3) problems in integrating all user interests into IFN recommendations; 4) variability in interpreting results of IFN studies; and 5) difficulty in managing and analyzing large volumes of data. Recommendations are suggested for proceeding with the NRBS IFN study.

Introduction

The majority of Instream Flow Needs (IFN) studies pertain to water resource allocations related to single, or in some cases multiple stream systems. The primary environmental concern for these studies typically relates to impacts to the fishery resource local to the streams under study. For these types of studies, the selection and application of a particular IFN method is usually straightforward; a single method is chosen because it is most appropriate for the prevailing conditions, or it is mandated for use by the responsible resource agency. There are IFN methodologies available (both office and field directed) to address a variety of instream flow issues, including fish habitat (Bovee 1982, Wesche and Rechard 1980), channel maintenance (Rosgen 1982), fish passage (Thompson 1974), food production (Weatherred et al. 1981), and others. The Instream Flow Incremental Methodology (IFIM) developed by the U.S. Fish and Wildlife Service (USFWS) is today the most often used IFN method in North America (Figure 1)(Reiser et al. 1989). This method incorporates a variety of instream flow considerations into the assessment of competing water uses, and includes a set of computer programs (termed the Physical Habitat Simulation (PHABSIM) system) for quantifying habitat:flow relationships.

Experience has shown that when IFN studies are constrained by budgets, as all studies are, there is a general tendency to apportion the majority of funds to the collection and analysis of field data; a relatively small proportion of the budget, if any, is allocated to study design development. This logic is based on the premise that the collection of field data is the most important component of the study, since these data form the foundation for resulting instream flow recommendations. However, this

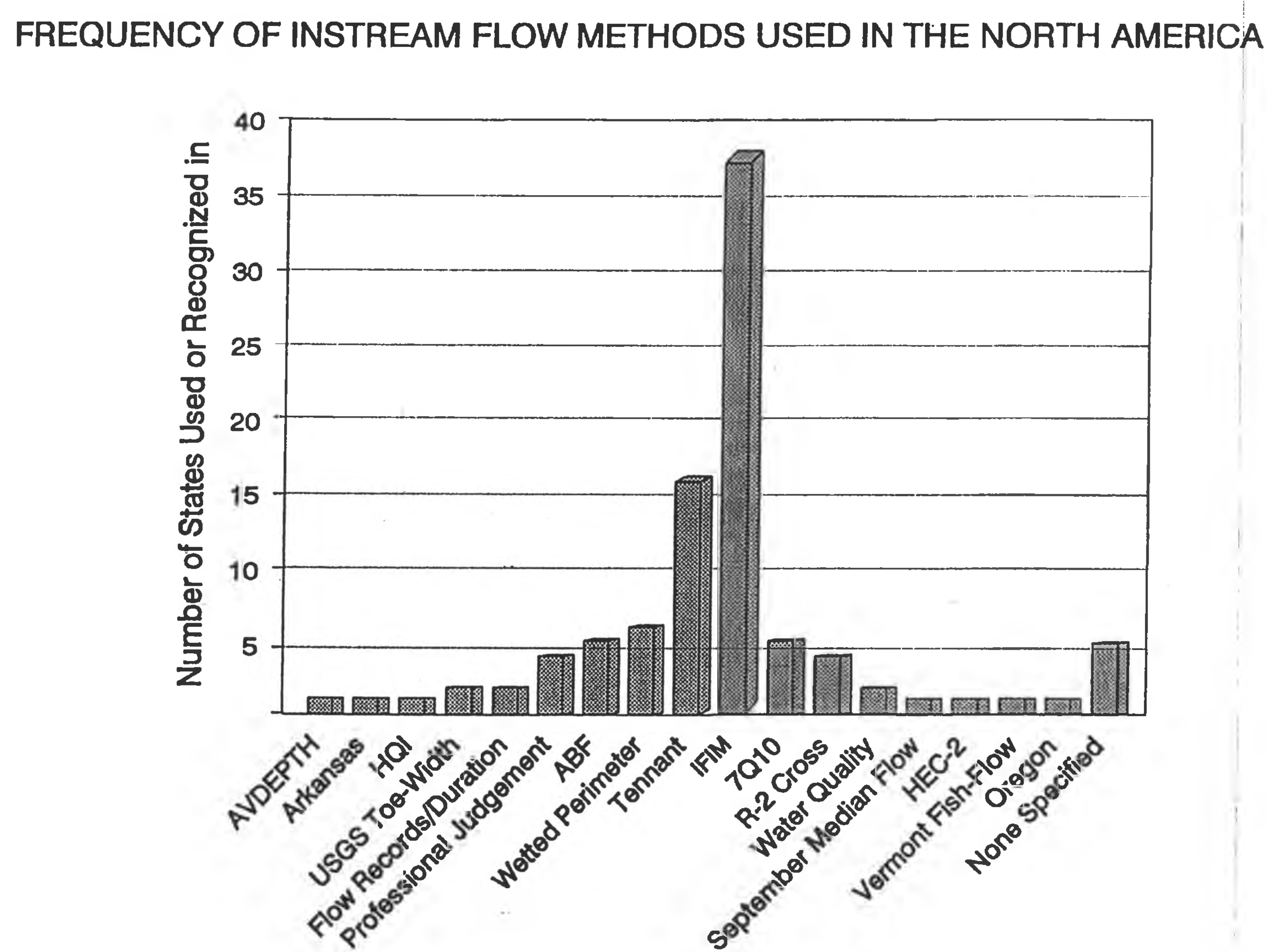

Figure 1. Frequency of instream flow methods used in North America as reported by reiser et al. (1989).

approach can lead to situations where the data collected and analyzed do not address specific study objectives, or were collected inefficiently and with no consideration for quality control and quality assurance.

This paper focuses on an important, indeed critical aspect of Instream Flow Needs (IFN) studies, that being the planning and organization that must precede any field data collection and analysis effort. IFN studies are by nature often controversial, inasmuch as they generally deal with water resource allocation between competing water users. Thus, it is important that IFN studies incorporate sound planning and statistically rigorous procedures from the onset. This can be a difficult process for even the smallest stream or drainage, let alone for an area the size encompassed in the Northern River Basins Study (NRBS); total area exceeds 200,000 km^2. For studies of this magnitude, special attention must be given to the planning, coordination and quality control aspects of the project.

Objectives

The overall objective of the IFN studies for the NRBS is to understand and be able to quantify Fish:Habitat:Flow relationships for rivers and streams in the Peace, Athabasca, and Slave river drainages, so that future decisions regarding water and land use developments can be evaluated in the context of potential impacts on existing fishery and aquatic resources. In the vernacular of today's society, this would be considered "Smart Management," whereby the end product of *existing* analysis can be used in evaluating effects of *future* developments.

The NRBS represents a tremendous opportunity for Alberta Environment to establish a solid database of resource information for the Peace, Athabasca, and Slave river systems. Specific short and long term objectives include:

- Establish a comprehensive database of aquatic information relative to the P-A-S systems to include:
    - Site specific data collection
    - Extrapolation of data (where appropriate) to similar drainages;
    - Integration of "other" parameters into database (as they are collected)(i.e., the database would be dynamic)

- Develop instream flow recommendations for selected (based on resource significance) rivers and streams within study area (based on field and office techniques);

- Maintain and update the database and use in making decisions regarding future resource developments.

The NRBS should be viewed as an important first step in establishing the necessary framework for collecting, compiling, managing, analyzing, and applying the tremendous amount of resource information that has and will continue to be gathered from these systems. The majority of the studies proposed for implementation are focused on the collection of important parameter baseline information. Results of some of these studies will be used immediately to address specific flow and water quality issues related to river regulation. Others are simply collecting first-time information on the systems and will factor into future decisions of resource management. Clearly, the wide ranging use and application of the data which will be generated from the NRBS program underscores the importance of careful interdisciplinary planning and coordination.

IFN Study Components

The components entering into the development of instream flow recommendations can be quite varied and complex (Figure 2). They include certain biological, hydrological, and physical components, which are common to all instream flow studies, as well as several unique to the NRBS; e.g., ice formation, sediment deposition, water quality, and upstream regulation of flows outside of jurisdictional control. The IFN process must also include an institutional component (e.g., management/trustee decisions regarding resource significance) to define and focus study objectives.

The major **biological components** include:

- Fish species distributions (presence/absence of fish in study basins)
- Species - life stage periodicities (defines when fish are spawning, rearing, migrating, etc.)
- Food and feeding habits (considers importance of food chain and maintaining conditions conducive to production of forage base)

Inherent in the above is the spatial and temporal variation which occurs relative to shifts in habitat and river reach use by season, flow condition, and life stage development.

Important **physical components** which must be considered include:

- Channel shape and morphology (energy gradients, slope, general habitat types (pool, run, riffle)
- Substrate characteristics - grain size distribution, sediment concentrations (considers sediment transport, habitat quality, hydraulic modeling)
- Critical/unique habitats - (define important spawning locations, passage corridors etc.)
- Habitat identification/location/quantification (defines locations and condition of important habitats)

NORTHERN RIVER BASINS IFN PROJECT COMPONENTS

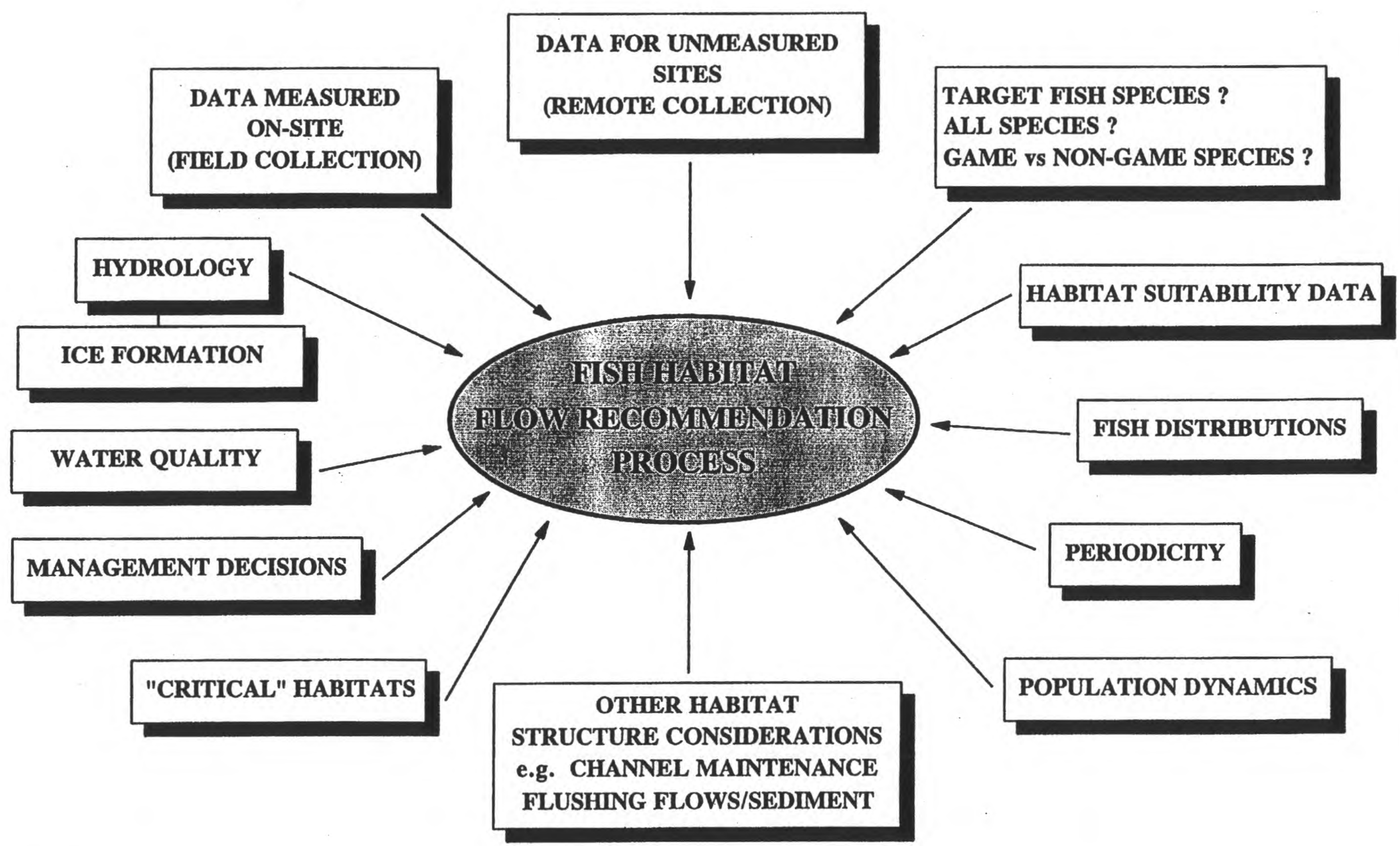

Figure 2. Factors and components which should be considered for thr Northern River Basins Study (NRBS) IFN program.

Hydraulic components are equally important when evaluating IFN requirements, and for the NRBS include:

- Hydrologic Records (gage records - 14 regional hydrometric stations, plus site specific empirical data

- Reach/study site hydraulic information at different flow conditions (stage: discharge relationships → define habitat:flow relationships)

- Timing of ice formation and breakup (considers flow timing, sediment transport, and life history characteristics of fish populations)

The **institutional component** of IFN studies determines how and to what degree the data collected from field and office analysis govern the decisions of resource protection, allocation, and regulation. Institutional decisions are not derived on scientific data alone; they encompass the goals and desires of specific resource management agencies, user groups, and in the case of Indian tribes, treaty guaranteed rights of hunting, fishing, and gathering.

Uniqueness of NRBS IFN

There are several aspects of the NRBS program which makes in unique relative to the more common IFN studies involving a singe river system. These are briefly summarized as follows:

- *Large Study Area* - the NRBS study area encompasses over 200,000 km^2 and involves three major drainage systems (P-A-S);

- *Large Number of Drainages* - although focused on the mainstem Peace River, there are over 3,000 - 4,000 smaller drainages which warrant consideration from a long term management perspective;

- *Multiple Considerations* - instream flows for fish and aquatic biota are but one consideration of the overall program. Others include water quality (contaminant uptake into food chain, fish tainting), riparian protection, and recreation. The NRBS is directed toward an "Ecosystem" management approach (See Figure 2);

- *Multiple Fish Species* - 28 fish species identified, including 11 species of sport fish, 15 species of forage fish, and 2 species of suckers (Paetz 1984). Multiple species management will vary spatially and temporally; consider defining "target" or "indicator" species or fish assemblage, the protection of which will protect all.

- *Flow Control Located in Province Outside of Geographic Area of Concern* - The W.A.C. Bennett hydroelectric dam controls the flows in the mainstem Peace River. This facility is located in British Columbia (upstream from the study area) and is operated by B.C. Hydro. Because B.C. Hydro has apparently elected not to participate in the early stages of the NRBS program, questions remain as to what effect the findings of the study will have on the operation of the dam.

- *Limited Budget* - although not unique to the NRBS, the existing budget is insufficient to evaluate IFN components for all drainages. Assuming the entire budget could be focused on IFN needs for fish would provide an allocation of ‹$3,000/basin for data collection and analysis. Clearly, a prioritization process is required to direct spending to the most important streams and locations (prioritization should consider the applicability/transferability of data collected from such sites to other unmeasured sites).

In this paper, it is assumed that the long range study objective is to derive and maintain data on all of the major drainage basins within the P-A-S systems, notwithstanding that the initial efforts will focus on the mainstem Peace and Athabasca rivers. Thus, the planning and coordination process presented below is much broader than if the NRBS was only focused on two or three study reaches.

IFN Planning Considerations for the NRBS

The planning process offered for the NRBS presupposes that a number of difficulties exist which affect data acquisition, data analysis, and the ability to derive scientifically defensible instream flows. These include; 1) the inability to sample all sites; 2) the difficulty in sampling remote locations and large river systems; 3) the need to integrate all user interests (including trustees) into the IFN recommendations; 4) the problem of maintaining consistency when interpreting results and deriving flow recommendations; and 5) the difficulty in analyzing and managing a large volume of data. These are briefly described below.

Difficulty No. 1 - Can't Sample All Sites

Time and budgetary constraints will not allow the sampling of the more than 3-4,000 basins within the study area, and yet there is a real need to obtain biological, hydrological , and physical data on as many streams as possible, the mainstem Peace River included. Short of developing a prioritization listing of streams for sampling, this problem can be approached through development of an extrapolation process whereby the recommendations and data interpretations developed from measured sites are extrapolated to unmeasured sites. This process can be organized into four steps.

In ***Step 1***, the basin sizes (minima and maxima) are determined and delineated. This is most readily accomplished through the integration of aerial photography and DEM's into a GIS. Once delineated, each of the basins would be assigned a unique identifier number. ***Step 2*** involves the stratification of the sub-basins into unique stratum based on physical, hydrologic and geologic characteristics. These may include such variables as; elevation, aspect, precipitation, geology type, basin slope, channel slope, and drainage area. Through this process, each of the basins will be assigned to a unique stratum which best characterizes its membership. ***Step 3*** includes the sub-sampling of the membership to obtain a statistically representative group of basins for field measurement. Ideally, the number of sites selected should represent a minimum of 10% of the total membership. The selected sites are those for which detailed field measurements are conducted, data are analyzed, and if appropriate, flow recommendations are developed. In ***Step 4***, the results (instream flow recommendations, hydrological characteristics, habitat characteristics, inferential information pertaining to species composition) of the sub-sampling of measured sites are extrapolated to unmeasured sites (within the same stratum). This can be based on normalization of a flow related component such as average annual flow (Q_a), whereby the flow recommended for an unmeasured basin could be computed as follows:

$$Q_{(unmeasured)} = Q_a \times \{(Q_{r(measured)}/Q_a)|\text{stratum}\}$$

An alternative approach would be through regression analysis where the particular flow characteristic is a function of one or more physical variables from the measured sites:

$$Q = f(A_{drainage\ area}, S_{slope}, P_{ppt}, G_{geology} \ldots)|$$

The specific extrapolation procedure used will depend on the data collected and the parameter(s) being extrapolated; this is best handled by a statistician.

Figure 3 exemplifies the basin delineation and extrapolation process for a sub-basin in the Wabasca River Basin. Scaling of data becomes more complex as the level of delineation progresses from the large to progressively smaller sub-basins. Basin stratification allows the]identification of sub-basins having similar physical, hydrologic and biological characteristics. Sub-sampling a set of basins within the same stratum allows the extrapolation of data from measured to unmeasured sites.

Difficulty No. 2 - Remote Locations and Difficult Sampling Conditions

Much of the NRB study area lies within remote terrain which is accessible only by boat or helicopter. This makes sampling difficult and increases the cost per unit of data acquired. In addition, the Peace and Athabasca rivers are large and contain complex islands and sloughs which add difficulty when attempting to collect field measurements. Furthermore, the safety of field crews should always be the number one consideration when formulating field data collection plans. Clearly, time spent in the office planning and coordinating such studies can pay off in dividends by increasing the efficiency and reliability of field data collection. Points to consider include:

- Access can and should factor in the selection of study sites (for sites with similar habitat characteristics, select those which afford best access, unless critical or unique habitats are involved);

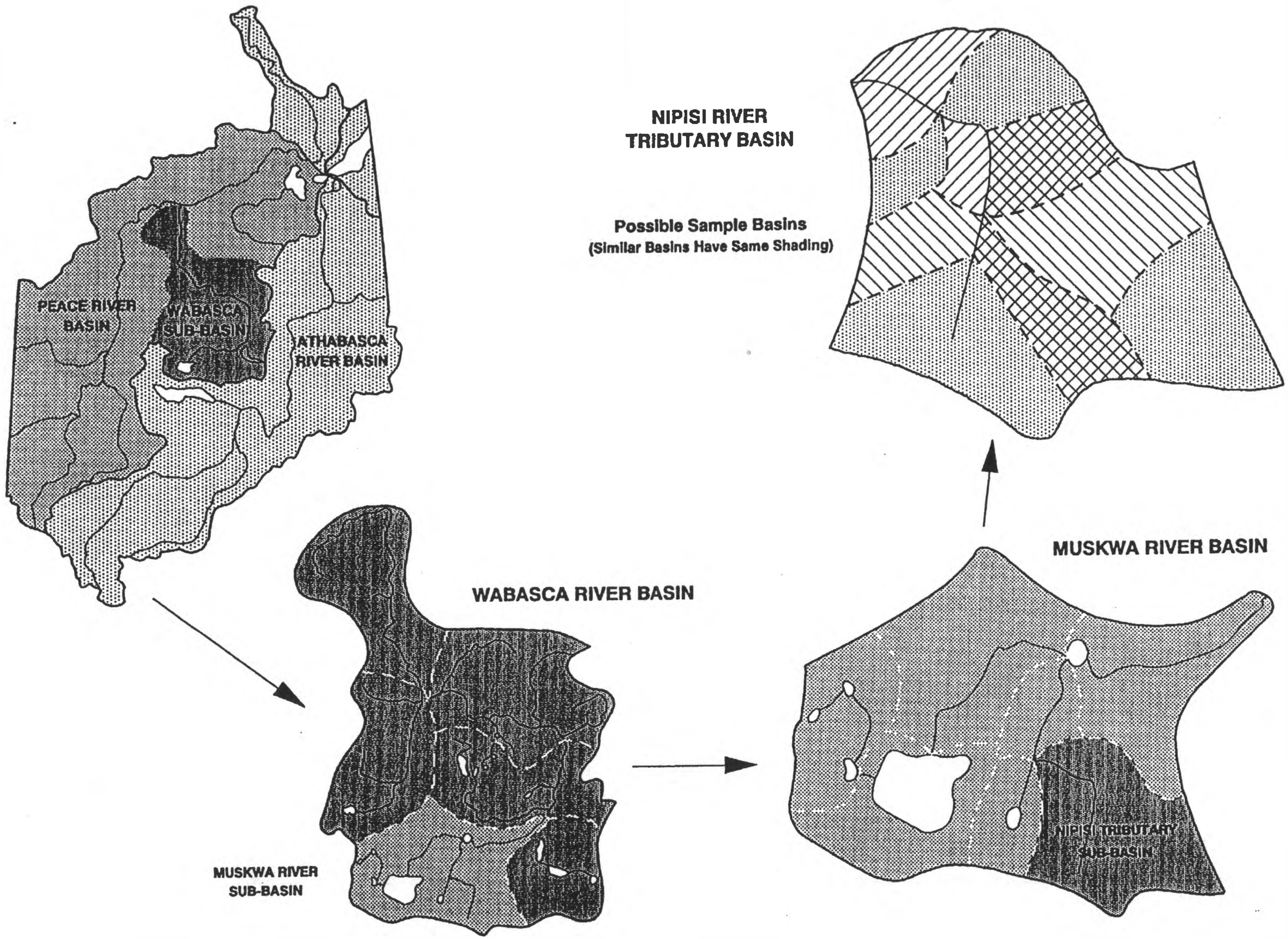

Figure 3. Example of basin delineation and stratification process that could be used for selecting study sites for the NRBS program. The process illustrates the stratification procedures for the Wabasca sub-basin leading to the identification of similar basins (based on certain physical, geologic, and hydrologic characteristics) within the Nipisi River system.

- Field crews should be trained in sampling methods prior to going to the field. When more than one crew is involved, methods should be standardized to ensure comparability of analysis. Develop and use a Field Procedures Manual which provides guidance in field data collection, and serves are field reference for crews.

- Adopt existing/develop new methods for sampling large systems. Don't use "cook book" methods unless they can be shown to be most appropriate for a given site. For the Peace River, analysis based on remote sensing (video imaging, aerial photography) to make surface area:flow comparisons may be the most applicable. Other methods may be better suited for smaller drainages. Evaluate and document methods selection process - prepare summary report describing basis for selection.

Difficulty No. 3 - Integration of All User Interests Into IFN Recommendations

Consideration of the interests and objectives of all entities/trustees for which the instream flow recommendations are being derived is a critical aspect of IFN studies. This may include the selection of target species, the prioritization of life stage components, identification of study reaches based on historical use or location relative to major developments, or other factors which may or may not be of a technical nature. This requires the active solicitation of concerns and ideas from all of the involved parties relative to the objectives/goals of IFN studies and the formulation of specific flow recommendation procedures. This is best handled via the formation of a Technical Advisory Committee (TAC) comprised of members from provincial and federal resource agencies, and the tribes. This committee is in addition to the formal Advisory Board. Depending on the level of activity at any particular time, the meetings should be held at least monthly. The meetings would serve to present and discuss specific methods to be applied, data analysis procedures, flow recommendation techniques, problems and proposed solutions, plans for future actions. The intent of the meetings would be to achieve a consensus on all facets of the project, and to formally document (in writing) the overall IFN process used for the NRBS. This provides a degree of legitimacy and credibility to the study, which can be important when negotiating or litigating specific flow recommendations.

Difficulty No. 4 - Variation in Interpretation of Results

The collection of field data in a systematic and organized fashion is but one of many steps in the development of instream flow recommendations. The analysis and interpretation of data are equally important steps, and ones' that deserve equal attention in defining procedures. Even the collection of data using the same methodologies (e.g., PHABSIM) does not mean that all data will be analyzed the same. There is much room for data interpretation and the setting of biologically important levels of protection.

In the same context that field methods were documented, the analysis and interpretation of data must be standardized within the framework of the overall project objectives. Once established and agreed to by the TAC or coordination committee, the same analytical procedures should be applied to all data falling into similar categories (e.g., all mainstem spawning habitat data would be analyzed the same). The standardization process should focus on fulfilling both biological and institutional objectives.

Because the instream flow recommendations for the NRBS may be controversial, I recommend obtaining a consensus on the final flow recommendations procedures to be used. This can be achieved via simple agreement among the TAC members, or if necessary, the reaching of a consensus of outside experts brought in to specifically review and comment on the proposed methods. Figure 4 represents an example of the data needs, information flow and decision points which feed into the selection of an instream flow methodology.

An important aspect of the interpretation process is documentation. *Document, document, document* each of the steps used in making the final instream flow recommendations. This should include specific aspects of the hydraulic calibration process, selection of appropriate habitat criteria, and the setting of resource protection levels. A good practice is to develop a calculation package for each site, which consists of all the details and decisions made leading to a specific flow recommendation. This is but one aspect of the development of and adherence to an overall Quality Assurance/Quality Control (QA/QC) program.

As a final step, consideration should be given to automating the flow recommendation process. This is especially useful if dealing with a large number of basins, where it is important to maintain consistent analytical techniques.

Difficulty No. 5 - Effective Analysis of Large Volume of Data

Effective and accurate analysis of data is of critical importance when developing instream flow recommendations for a large scale project. This is best achieved through the development of a comprehensive relational database which incorporates all types of data needed in the formulation of instream flow recommendations. This would include data pertaining to fish habitat, hydrology, cross sectional data, fish population and distribution data, habitat suitability criteria (HSC), water quality data, and physical data (e.g., substrate characteristics, sediment data, etc.) (Figure 5). Figure 6 presents a hypothetical database structure illustrating major data fields and categories which may prove useful for the NRBS IFN study. The categories represented pertain to each basin under study (assigned an individual basin number), which is defined by a unique set of basin attributes.

To further streamline data analysis, consideration should be given to deriving linkage programs between specific hydraulic, water quality, sediment transport, and other physical process models and the relational database. This will enable direct computation of results using data from the database, and adds an element of Quality Control (QC) to the data analysis.

NORTHERN RIVER BASINS STUDY: DEVELOPMENT OF IFN FISH HABITAT-FLOW RECOMMENDATIONS

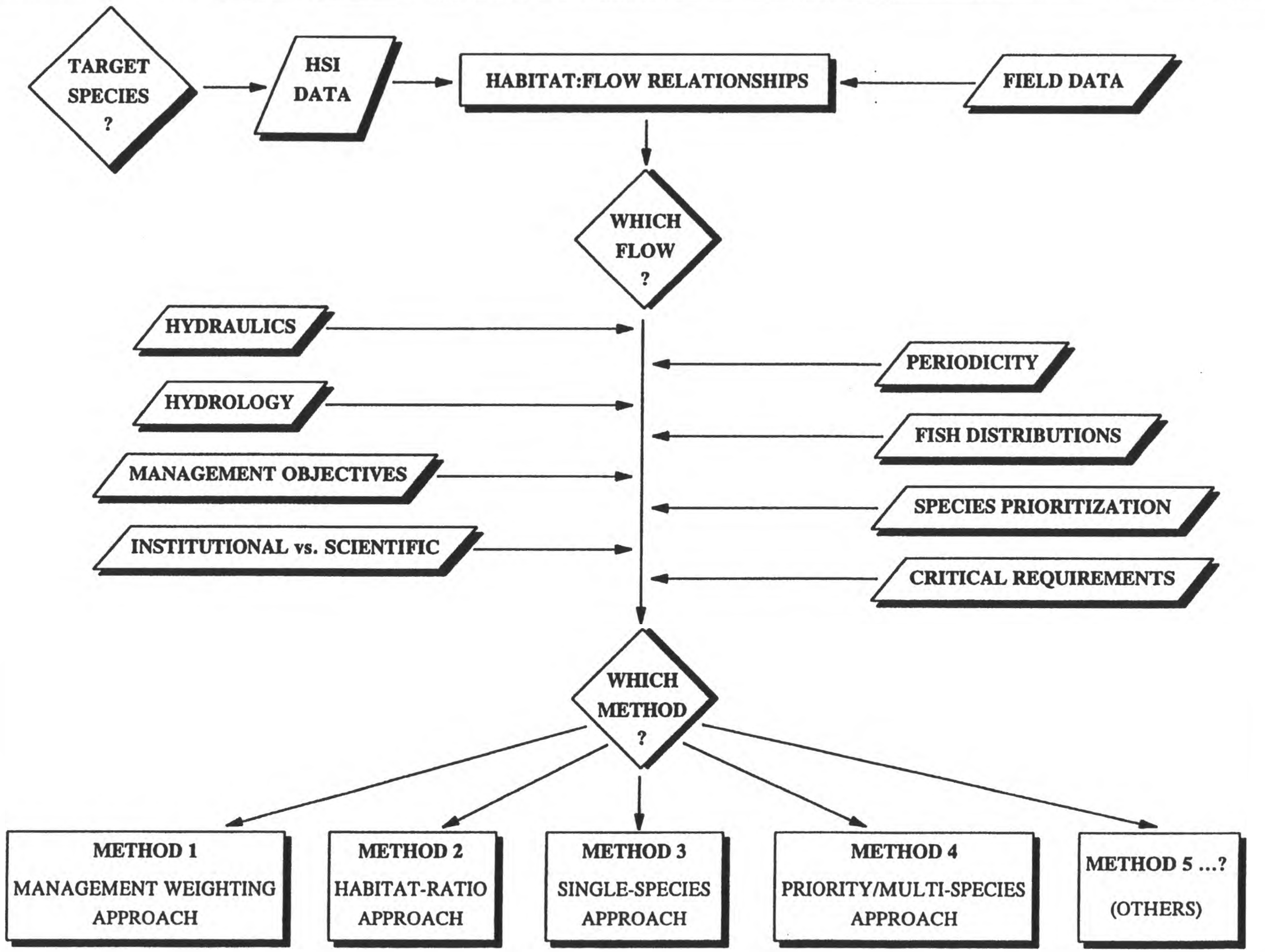

Figure 4. Data input and decision flow leading to the identification and selection of instream flow methods. Different methods are available and may be applicable to the NRBS depending on project objectives, field sampling conditions, and budgetary considerations.

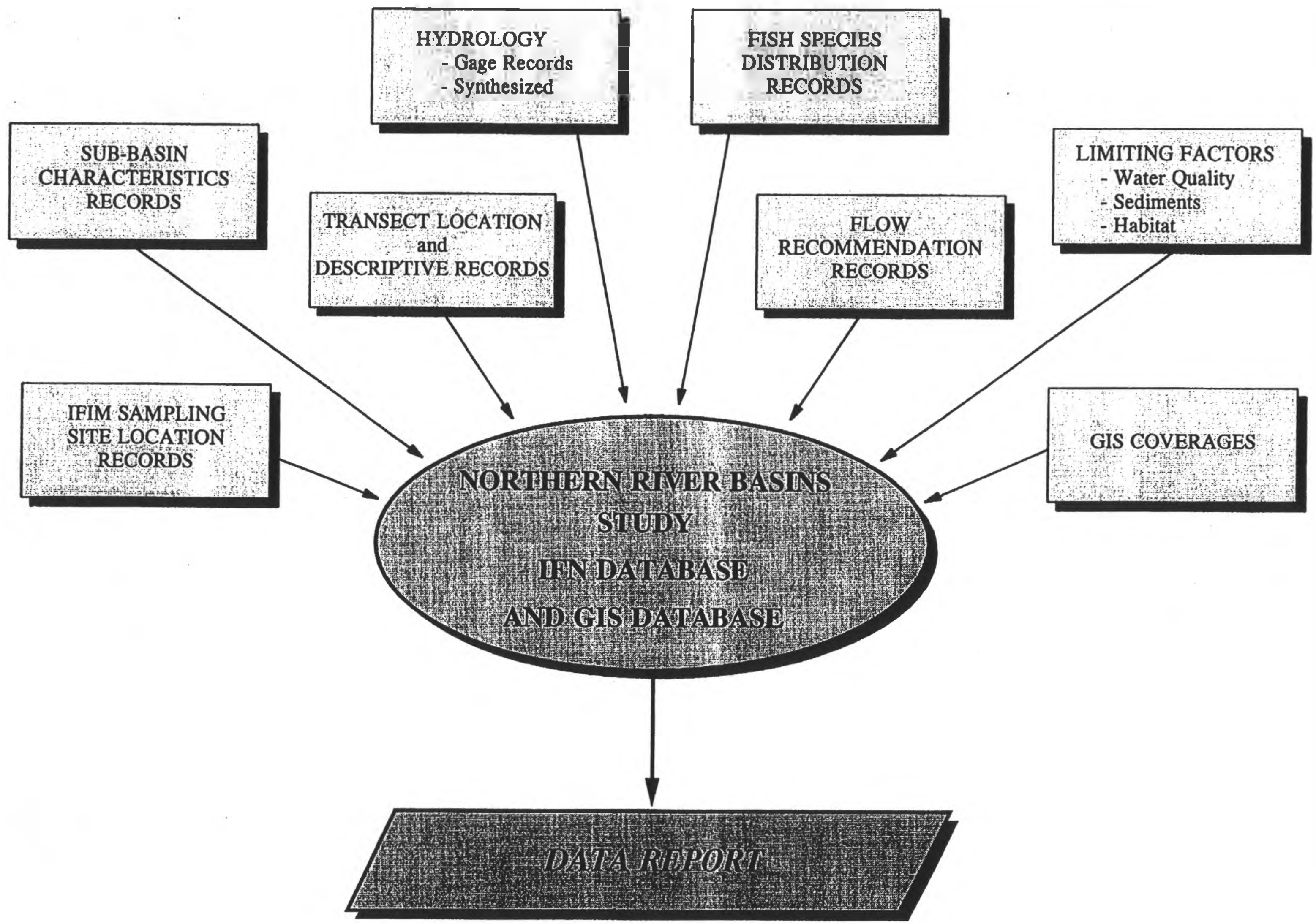

Figure 5. Major categories of data that could be included in a relational database developed for the NRBS IFN study.

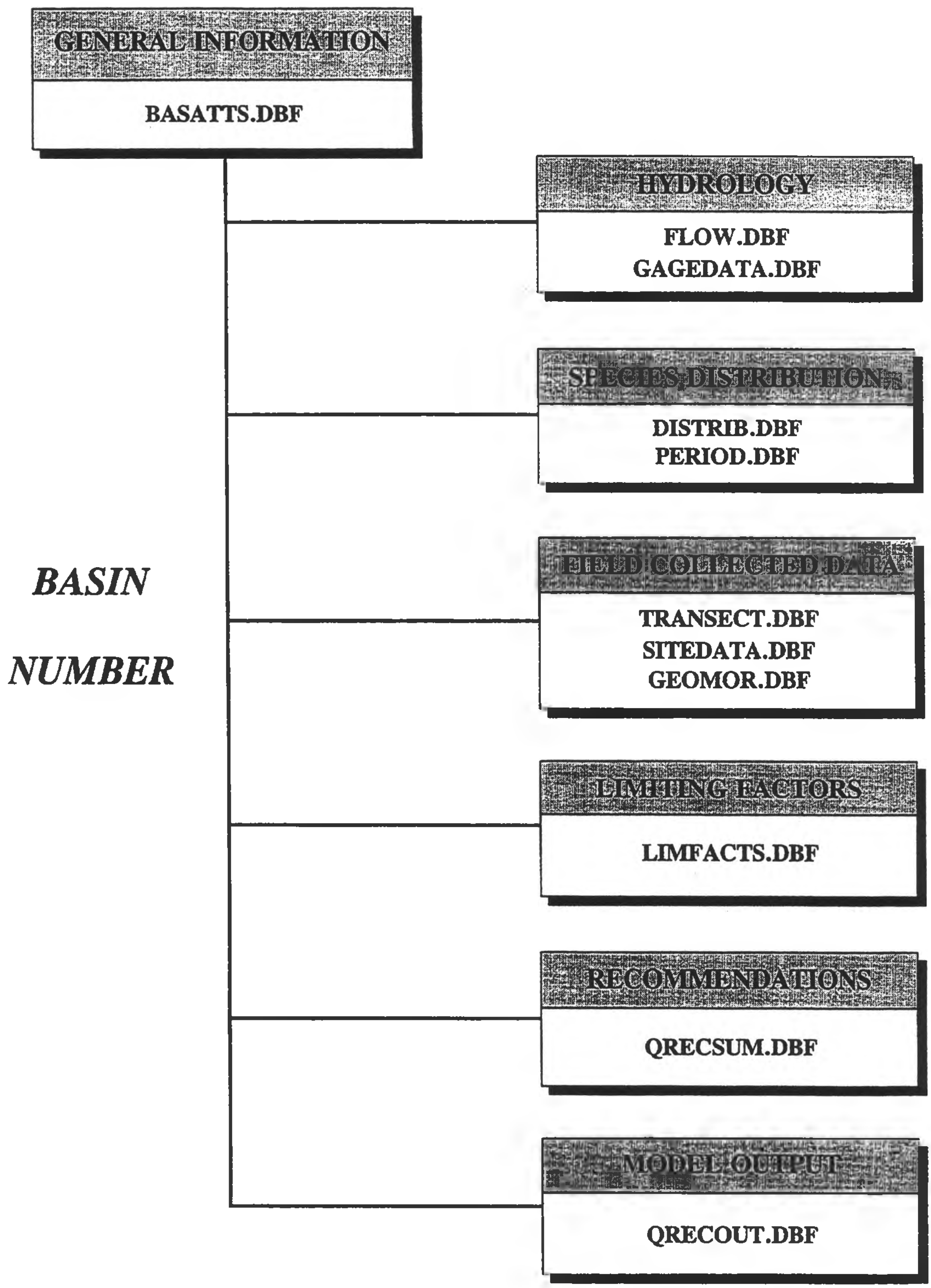

Figure 6. Hypothetical database structure illustrating major data fields and categories which may prove useful for the NRBS IFN study.

As previously noted, the application of a Geographical Information System (GIS) would greatly facilitate data presentation and interpretation, and should be given high priority for the NRBS studies. Likewise, to the extent possible and necessary, automation of the instream flow recommendation process should be considered.

It is my understanding that the NRBS program represents but the start of what will likely be a multi-year if not continuous study of streams and rivers in the Peace, Athabasca, and Slave River systems. In that context, the development of any database should be undertaken with consideration for being able to expand and refine the data base structure to meet future objectives. A data base manager should be hired and placed in charge of all data base aspects for the project.

Instream Flow Considerations - Recommendations

It should be apparent from the preceding discussion that there is no single, irrefutable procedure for conducting IFN studies; many methods exist (Wesche and Rechard 1980, Stalnaker and Arnette 1976, Reiser et al. 1988). Unfortunately, all too often, IFN studies are conducted with little planning or consideration for overall objectives. For a study as large and comprehensive as the NRBS, the planning and coordination process is integral to successfully meeting the stated objectives of evaluating the "Other Uses of Aquatic Resources" component. In this paper, I have identified and discussed the major components and technical considerations of large IFN investigations, and their applicability to the NRBS. Most of the items discussed relate to the planning and organization of IFN studies. A general flow chart which summarizes major steps needed for completing a regional IFN study is presented in Figure 7. I would suggest that a similar flow chart be developed specific to the NRBS IFN program to assist in the planning process.

Considerations

Based on the review of information and the results of the Instream Flow Needs Workshop held on October 14-15, 1993, the following general considerations are applicable to the NRBS program:

* Methodologies should be applicable for each sampled basin

* Management priorities must be established; consider adopting an ecosystem approach as target of protection rather than species level approach;

* Approach needs to reach a solid balance between institutional and scientifically derived decisions;

* Solicit outside expert opinion to assist in selecting "best" approach for deriving recommendations or for addressing other difficult decisions;

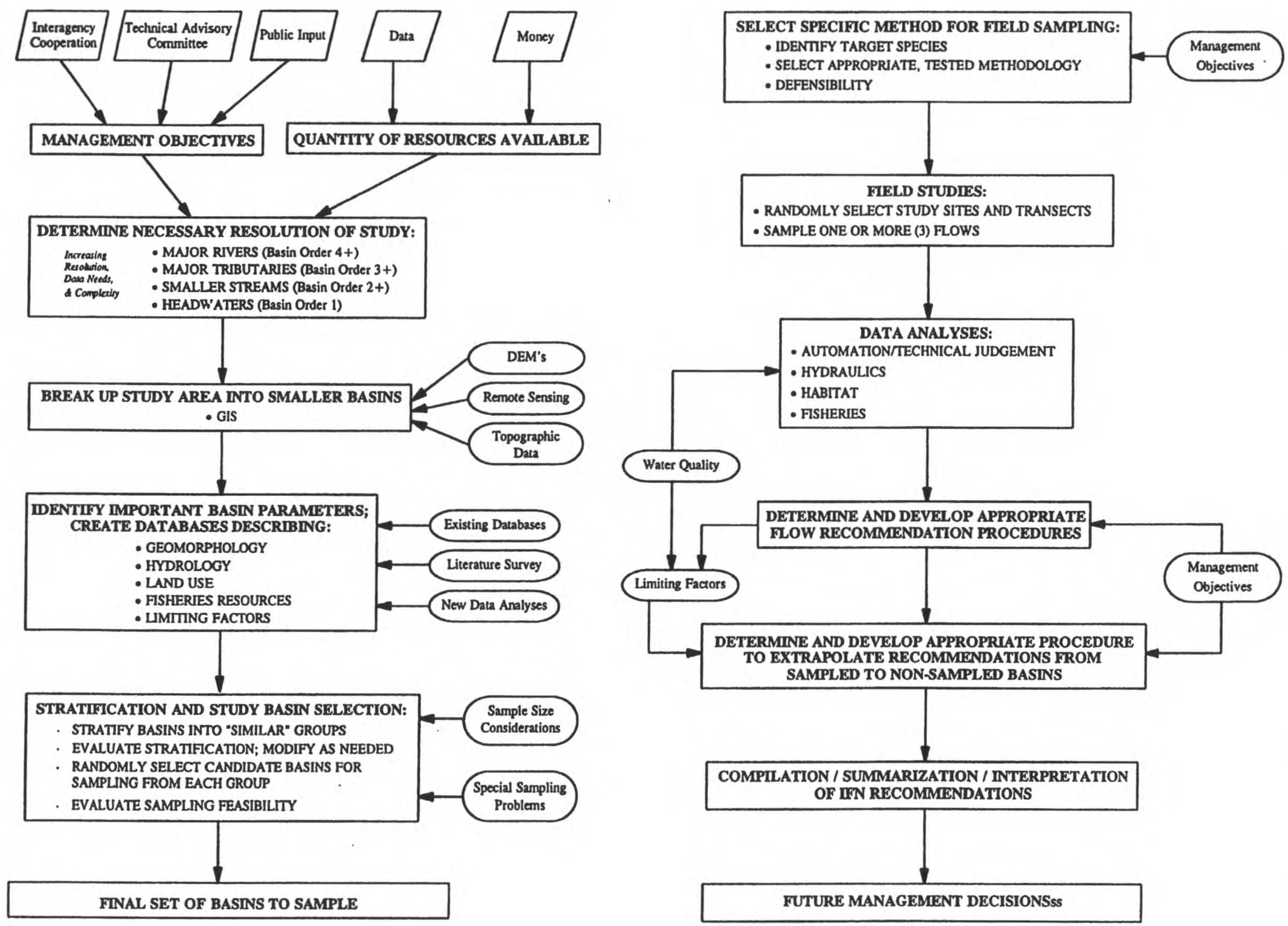

Figure 7. Flow chart depicting major steps and data inputs that should be considered when developing large regional instream flow studies.

* IFN recommendations must be scientifically defensible; assume that all data collected and analyzed will be subjected to a rigorous review process;

* Biological considerations: target species/life stage - periodicity/species distributions/habitat requirements and preferences - temporal and spatial variability;

* Other flow requirements should be factored into the analysis:
  - Channel maintenance flow recommendations
  - Riparian Habitat maintenance
  - Sediment transport
  - Ice breakup
  - Water quality conditions (BOD, TDS, TSS)

Recommendations

Specific recommendations include the following:

- **Expansion of the Tennant analysis**: The planning studies completed by Locke (1991) should be expanded to include downstream gaging stations, including gaged tributaries. The same general procedures should be applied to the new sites, with the overall intent of developing a basin wide framework of flow recommendations for important key reaches of the Peace River and major tributaries. Such recommendations can then be used for making comparisons to results from more refined, location specific field analysis.

- **Develop Stratification Strategy for Entire NRBS Region**: Because of the large size of the study area and the need to consider both basin specific and cumulative effects (water quality and quantity, and habitat related) from a long term perspective, a stratification strategy should be developed for the Peace - Athabasca - Slave drainages. This should include: 1) definition of basin size maxima and minima (i.e., scale of stratification); 2) procedures for delineating specific basins (Geographical Information System (GIS), Digital Elevation Models (DEM); 3) determination of basin attributes (e.g., drainage area, channel slope, elevation, geologic type, aspect, precipitation, etc.); and 4) selection and completion of stratification procedure (e.g., cluster analysis, multivariate analysis). The end product of this effort will be the assignment of each basin into one of many different strata; each basin would have a unique identifier to facilitate database entry and tracking. The stratification process would be useful for extrapolating/ inferring results of instream flow and hydrologic analysis from measured to unmeasured basins.

- **Development of Data Collection and Analysis Procedures Manual (Quality Assurance Project Plan (QAPP)**: The results of the Peace River IFN study will likely be subject to scrutiny by both public and private entities, and may result in controversy related to flow recommendations for specified locations and times. One of the ways in which to minimize controversy is to demonstrate the use of standard, commonly accepted (by other IFN practitioners) and applied methods in the collection of field data and in data analysis. The development and use of a Quality Assurance Project Plan (QAPP) should be considered for the NRBS. The QAPP would describe each of the field methods used, equipment requirements and calibration procedures, data logging, transcription, and transfer procedures, and data analysis and flow recommendation techniques (if warranted). Once developed, all participants in the study would be required to utilize (and provide documentation of use) standard procedures described in the QAPP.

- **Development of Data Base Documentation and Data Control Manual**: The IFN study will result in the collection and analysis of data from a variety of sources and disciplines. These data will likely be used by various researchers to address different technical issues, and therefore, the format of the data will likely change depending on specific user and application. To ensure that researchers are consistently using the same data sets; 1) a data base manager should be appointed to oversee the development and maintenance of the IFN Peace River database; 2) a Data Base Documentation and Control Manual should be prepared by the data base manager (with assistance from technical specialists who understand the data types and necessary data fields for computer entry; and 3) all participants in the study should adhere to specified procedures for data entry, transfer, and analysis. This document will be important in demonstrating chain-of-custody of data from the field to data base entry and data validation.

- **Formalize Selection of Methods for Detailed Analysis - Methods Selection Process:** There are many different methods available that could be applied to the Peace River IFN studies. A careful review and evaluation of the methods should be formally completed by appropriate participants, and a consensus reached as to which methods should be applied to the NRBS. The results of the analysis should be documented in a written report listing the methods reviewed and specific methods selected for the Peace River studies. The rationale for the selected methods should be presented in the report. This document does not have to be voluminous and should rely on previously published summary reports for details on specific instream flow methods. The majority detail should be reserved for a description of the procedures and rationale used in selecting methods (or modifications thereof) for application to the Peace River IFN study.

- **Studies Specific to Peace River**: Based on discussions during the technical review meeting and results of preliminary studies, the majority of the initial detailed studies will focus on the mainstem Peace River. The intent of these studies is to develop an understanding of the physical, chemical and biological characteristics representative of all habitat types and conditions in the river. The studies are to determine how populations of fish and their habitats may be affected by flow alterations (direct - habitat loss, and indirect - reduction in habitat quality (sedimentation)).

The major study components identified during the Instream Flow Needs Workshop include;

- ❶ - Habitat mapping of the entire reach of river at different flows (aerial photography, video taping);
- ❷ - Selection of detailed study sites (from habitat mapping: representative/critical/unique habitats);
- ❸ - Development of field methods (habitat specific: mainstem, slough, tributary);
- ❹ - Conduct of field studies;
- ❺ - Data analysis and interpretation; and
- ❻ - Impact analysis.

These initial studies should be conducted in the context of providing a framework for developing follow-on studies to other locations on the river and in selected tributary systems (i.e., consistent with the stratification process described above).

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Maintaining Biological Integrity
in Instream Flow Studies in Large Rivers

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Introduction

Instream flow studies are often conducted to support decisions regarding the allocation of water between instream and out-of-stream uses. Usually, an instream flow study defines the relationship between the magnitude and timing of streamflow and streamflow-dependent physical habitat variables. These relationships are then used to predict the effects of a particular water development or water management proposal on the location, quantity, and quality of various aquatic habitats. The results of a well-conducted instream flow study will feed directly into the decision-making process and provide a technical basis for balancing water between competing uses by identifying potential effects of water allocation on aquatic resources. Or, for making tradeoffs between competing uses that benefit society. Because instream flow studies have a direct link to attaining social goals, their results must be both scientifically reliable and relevant to the decision-making process. Failure of an instream flow study to adequately address the resources at risk may lead to considerable loss to society.

Assuring that biological integrity exists in the instream flow study is an essential part of study plan design. According to Webster, the definition of integrity is the "state of being unimpaired" or of possessing "soundness" (Guralnik, 1972). Aquatic systems are complex. Thus, the design of a well-focused, technically-sound instream flow study can be a very demanding task, which at times, can be more difficult than the actual implementation of the instream flow study. Designing an instream flow study that will adequately represent all of the important components of aquatic habitat and illustrate how these components might change under various water management scenarios requires knowledge of the biology and hydrology of the stream, as well as experience with innovative adaptation of data collection techniques and physical process models. Seldom will the standard application of sampling methods and computer models properly illustrate the response of biological variables to changes in streamflow, stream temperature, water chemistry, sediment transport or ice processes.

In many cases, existing data collection methods and analytical approaches can be modified to meet the specific needs of the river being addressed. In other cases, new approaches and/or methods will need to be developed to properly describe the effects of streamflow changes on a physical process that has significance to the biological integrity of the stream. This means that the biology of the stream must be well understood before physical habitat modeling is initiated. Most instream flow studies are initiated with the intention of applying the Instream Flow Incremental Method (IFIM) (Reiser et al., 1989). The most common physical habitat variables included in this methodology (and its associated physical habitat simulation model, PHABSIM) are depth, velocity, and substrate. Sometimes cover and temperature are also included in the habitat model (Bovee, 1982). Even collectively, these five variables cannot adequately describe aquatic habitat conditions found in large northern rivers. Thus, unless applied within an appropriate biological framework, PHABSIM models are not likely to adequately describe the response of aquatic habitats to streamflow alterations in large northern rivers.

Large Northern Rivers - Special Challenges

Conducting instream flow studies on large northern rivers is a challenging undertaking. Large rivers, in any setting, require innovative sampling methods and modification of analytical approaches developed on small streams. Many investigators focus their attention on adapting data collection methods from small streams to large rivers. On wadeable streams, standard protocol for physical habitat modeling is that replicate hydraulic data are collected at closely spaced intervals along transects that extend across the stream (Trihey and Wegner, 1981). Because the stream is small and wadeable, it is not difficult repositioning one's self on the transect at different streamflows. The problem of locating and then remaining at the desired location on a transect spanning a large river is more difficult, but it can be accomplished by applying modern navigational aids and surveying techniques. So practically, it can be accomplished. But, the first question to ask is not, "Can it be done?" but rather, "Should it be done?". "Does applying this small stream approach for describing instream hydraulic conditions help preserve the biological integrity of hydraulic influences on aquatic habitats in large rivers?" This question can only be answered on a stream-specific basis, but in our collective experience, a standard application of the PHABSIM model to large river systems would not produce sound biological results without tailoring the analytical structure of the study to reflect the specific characteristics of the river studied. This is not as much a short-coming of the IFIM methodology as it is a fault of those who apply it to large rivers without first attempting to understand its applicability.

By using the standard PHABSIM approach in large rivers and placing habitat simulation transects entirely across the river, the instream flow analysis is based on the premise that a suitable combination of hydraulic variables, in the center of the river has the same value to fish as that same combination of variables would have along the stream margin. And since large rivers generally have wide deep channels with high velocities in their center portion, PHABSIM models applied to large rivers often forecast the highest habitat values for fish associated with abnormally low streamflows. In order to maximize wetted surface area with mean-column velocities in the optimal range for fish (usually less than 1 meter per second), the PHABSIM model is indicating large rivers must be converted into wadeable streams.

Studies of fish in large river systems have often shown that fish are quite selective in their use of aquatic habitat. The central portions of large mainstem rivers are primarily used as migration corridors. Deep pools are used by some species during summer and by others during winter. But, the most intensively used aquatic habitats are often peripheral to the main channel: side channels, sloughs, backwater areas, mid-channel islands and tributary mouths. Figure 1 shows the distribution of spawning salmon in one large northern river. These peripheral habitats are often affected by mainstem flow in a variety of ways other than a simple change in depth or velocity. To maintain the biological integrity in the instream flow

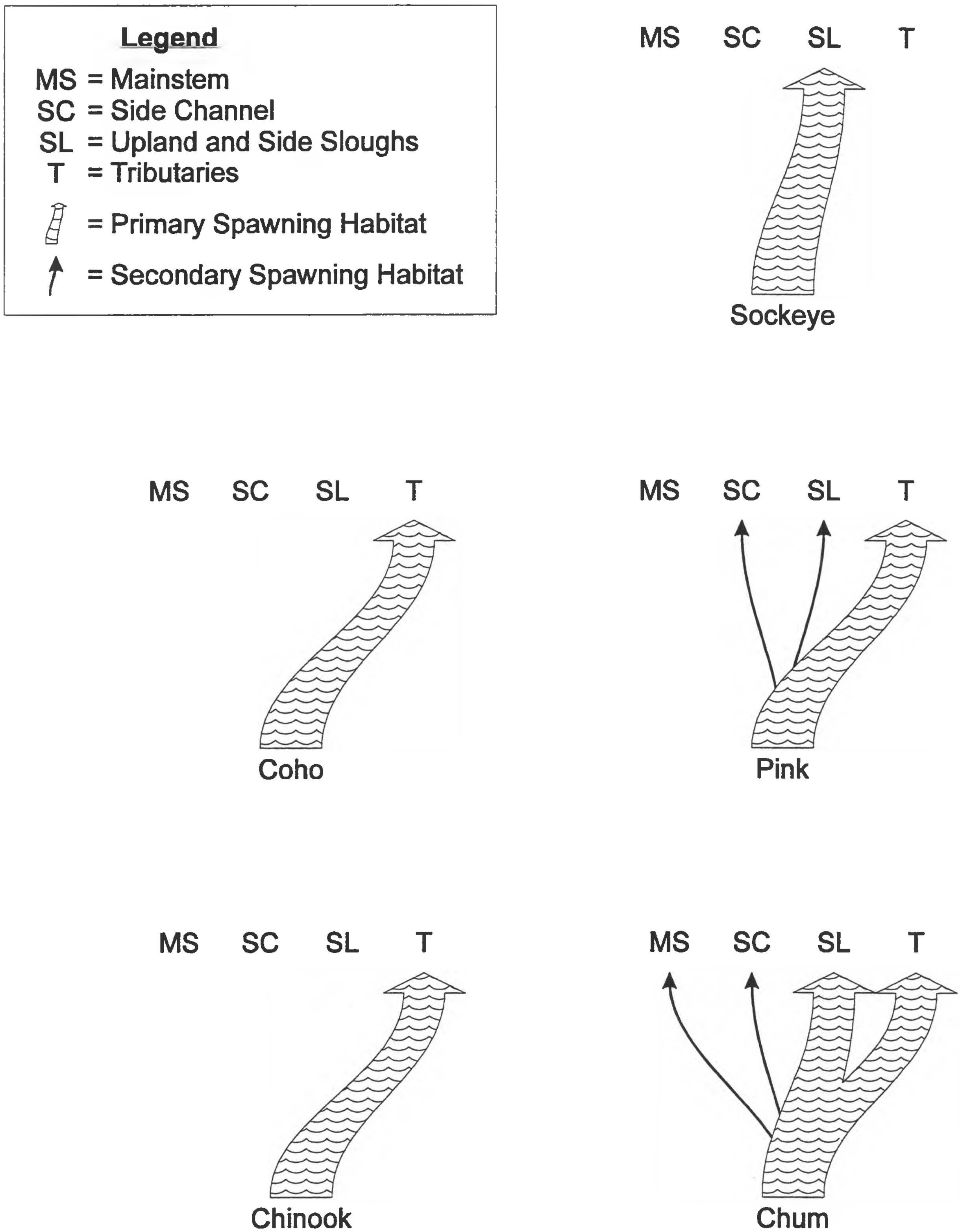


Figure 1. Relative Distribution of Adult Salmon Within Different Habitat Types of the Middle Susitna River. (from: Trihey & Baldrige 1984)

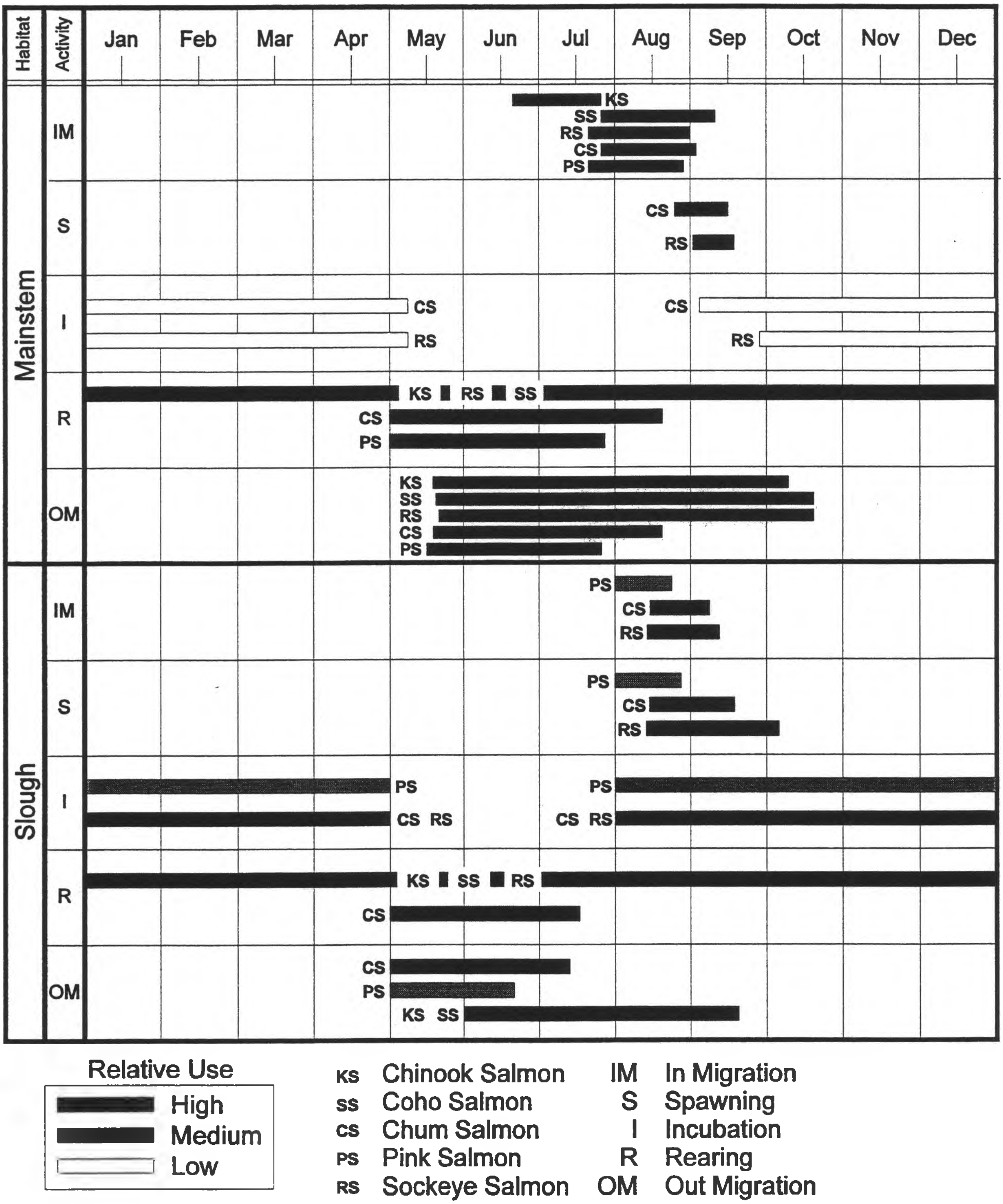
study, we must identify and evaluate streamflow effects on the habitat conditions that are important to fish. We must not allow the habitat models themselves to cause us to select study sites (even randomly selected study sites) because "they can be modeled".

Fish communities in large northern rivers are often complex. They generally consist of multiple species with significantly different life history requirements. Some species mayexist throughout the year in a particular section of river, while other species only use the river segment for a brief portion of the year (Figure 2). Also, the same life history phase (such as spawning) for different species occupying the river segment may occur at different times of year. The distribution of fish in a large river is often patchy. Thus, it is expensive to define habitat use, seasonal movement, and habitat preference criteria. But, understanding such factors is critical to maintaining biological integrity in the instream flow study.

The occurrence of river ice is one physical aspect of large northern rivers that has profound effects on habitat structure and biological systems. Ice cover formation can cause the scouring of deep pools, while ice dams during breakup are often responsible for side channel development. The annual formation and break up of a river's ice cover also profoundly affects the growth of shoreline vegetation and the persistence of large woody debris within the main channel and larger side channels from one year to the next. The transient nature of shoreline cover, both overhead and object, can have a notable effect on the availability and quality of aquatic habitat for cover dependent species.

Secondly, the biological activity that occurs under an ice cover is different from that which exists during the open water season (Barrett, 1975, Campbell and Nuener, 1985, and Stratton, 1985). Because winter sampling is difficult, expensive, and hazardous (Figure 3), very little is known about the behavior or habitat requirements of fish in large rivers during winter. What we do know indicates that fish often occupy very different habitats during winter than they do during summer and they probably have a different survival strategy during winter than during summer. We also know that water development projects in northern latitudes can have a significant effect on river ice processes (Ashton, 1978). None of this is easy or inexpensive to quantify. However, to only address summer habitat conditions in large northern rivers ignores the habitat conditions that fish must inhabit six to eight months of the year at northern latitudes. The omission of a winter habitat assessment can severely compromise the biological integrity of the instream flow study, and negate the ability to maintain pre-development fish populations.

Given the complexities identified above, charting a course through study design, data collection and habitat simulation for large northern rivers must be an iterative process which should be expected to span several years. Along the way we can expect to discover relationships between species distribution and instream habitat conditions that will cause us to add or delete entire study components, or place a different emphasis on how study components will be used in the final analysis.



Based primarily on ADF&G field data.

Figure 2. Phenology and Habitat Utilization of Middle Susitna River Salmon in Mainstem and Slough Habitats. (from: Trihey & Baldrige 1984)

Figure 3. Installing Thermistors in Streambed Gravels Prior to Freeze-up to Monitor Incubation Temperatures Under and Ice Cover.

The key to maintaining biological integrity in instream flow studies for large northern rivers is to first invest sufficient financial resources under the direction of experienced personnel to identify the seasonal movement and habitat utilization patterns of fish, and then consider how the proposed project might alter the availability of habitat conditions that are seasonally important to fish. Figure 4 shows how mainstem discharge affects the surface area of peripheral habitats that supported important fish resources. In this example, focusing on habitats utilized by fish helps us balance between scarce, heavily-utilized habitats (tributary-mouths) and abundant, lightly-used habitat (mainstem).

Attempting to model project effects on a randomly selected suite of physical processes or habitat characteristics is unlikely to provide insight of potential responses of fish populations to water development. It is much better to undertake a deliberate well-focused analysis of a few key relationships between physical processes and habitat requirements rather than to use a "shotgun" approach or attempt to study all the biological factors that might be important.

Scoping Process

The scoping process for instream flow studies often centers around formal meetings with interested parties for the purpose of identifying the appropriate study questions to address during the instream flow study. Bovee (1982) provides a check list to assist with developing a study plan. Such checklists are useful, but they were not developed for large northern rivers. If followed too closely, these checklists can make it very difficult to establish appropriate priorities and study components. In any instream flow study financial resources are limited, and the time allotted for providing input to the decision process is typically much shorter than what is needed to fully evaluate the biological response to physical habitat changes. Therefore, it is important to first allocate adequate resources to identify the key aquatic habitats and physical processes that are likely to be substantially altered by the proposed project. This scoping "team" should include individuals experienced with modeling riverine processes and individuals with local knowledge of the river. In addition, a clear and reliable description of the proposed project is needed. The next step is for the field biologists to determine the seasonal utilization of these aquatic habitats. Concurrently, scientists and engineers should be determining project effects on the physical processes. Thus, the basic elements for a successful study would be available for study design.

For scoping complex instream flow studies, we recommend answering the following questions: Who? When? Where? What? and Why? These questions can be answered at different study levels, but all of these questions must be answered. Answering these questions will assist with identifying interested parties in the decision-making process, and in identifying their principal concerns. Their main purpose, however, is to facilitate maintaining biological integrity in the study design.

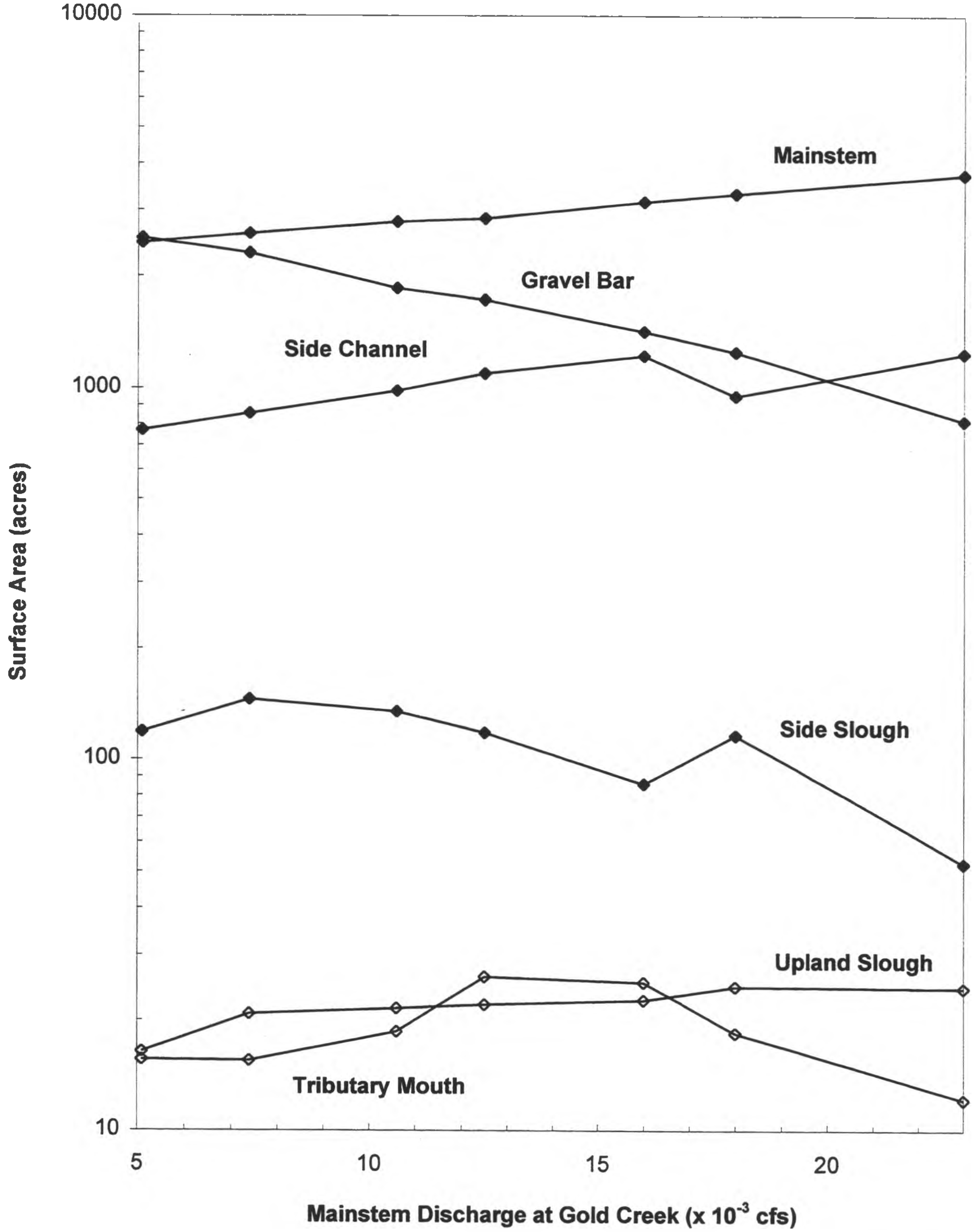


Figure 4. Surface Area Responses to Mainstem Discharge in the Middle Susitna River (RM 101 to 149). (from: Klinger-Kingsley et al., 1985)

Who

Who lives here? Understanding the species composition is an essential first step in maintaining biological integrity in an instream flow study. In many northern rivers, we do not know the species composition. For example, in an instream flow study on a glacial stream for the Alaska Power Authority, the initial information indicated that the stream was inhabited by pink salmon, a few chum salmon, and two resident species. Reliance on this information and the commercial importance of pink salmon relative to the other species resulted in pink salmon being selected as the primary evaluation species. And since pink salmon have a very short fresh water rearing phase, assessing the effects of the proposed project on pink salmon spawning and incubation was the main focus of the original study plan. As a result, the study plan for the instream flow modeling effort concentrated on evaluating project effects on streamflow and aquatic habitat conditions from August through May. Upon implementing a fish distribution and relative abundance study to confirm the initial information regarding species composition, five species of Pacific salmon were found to be using this river. This included a substantial population of sockeye salmon. These findings altered the focus and cost of the instream flow study. Upstream and downstream fish passage, rearing, and summer habitat conditions suddenly became very important considerations. These new considerations, which were essential to maintaining the biological integrity of the study, would not have been identified in time to affect the overall study design had the fish distribution and relative abundance not been conducted as an initial element of the instream flow study.

The other part to the "who" question is who do we focus on? Which species are we going to use as evaluation species. In the above example, it was the commercially important species of Pacific salmon. Very little attention was given to resident species in this river. Selecting species important to commercial, sport, or subsistence harvest is a commonly accepted practice. But just because that practice is commonly accepted, does not mean it will maintain the biological integrity of the instream flow study.

In an instream flow study conducted on a river in the Western U.S., the smallmouth bass was selected as the evaluation species. A very detailed PHABSIM analysis was performed that included careful selection of controlled flows for model calibration, and use of site-specific habitat utilization data to assure that microhabitat conditions were properly considered. Based on the resultant WUA forecasts, the proposed project was expected to be quite successful in achieving complete habitat protection for smallmouth bass. An impoundment and backwater would increase the depth of flow and reduce stream velocities such that the post-project habitat would be near optimal for smallmouth bass. From all appearances, the IFIM study was well executed and the proposed project would enhance smallmouth bass habitat.

After the project was constructed and put into operation, it soon became apparent that the evaluation species was not responding to post-project conditions nearly as well as the IFIM model had predicted. In fact, the smallmouth bass population was notably declining even though physical habitat conditions were "optimal". Subsequent investigation of species composition indicated that the post-project population of sculpin was dramatically less than the pre-project population. Sculpin, one of the main food resources for the smallmouth bass, live mainly in riffle habitat; riffle habitat that had been inundated and converted into deep, low-velocity smallmouth bass habitat. The importance of sculpin as a food base and their habitat needs were not considered in the instream flow analysis. Careful consideration of the stream system as a whole rather than the immediate focus on a routine, single-species application of IFIM modeling techniques may well have maintained the biological integrity of this instream flow study and led to entirely different results.

For large northern river systems, several evaluation species may need to be selected to adequately represent the important components of the fish community. Evaluation species may change between river segments and/or season, and emphasis may need to be placed on lifestage rather than on species. For example, project effects on spawning habitat (regardless of species) may need to be given priority over effects on rearing habitat. The goal is to select evaluation species or lifestages that maintain the biological integrity of the river system, such that decisions based on the instream flow study will achieve the desired results.

When

When are fish here? Most fish in large northern rivers exhibit distinct seasonal movement patterns. Winter habitat is often quite different from summer habitat, and long migrations to spawning habitat are not uncommon. Even the same species of fish can have very different life history strategies for survival. The Kenai River in Alaska has two spawning runs of chinook salmon. The early run spawns in the tributaries and the young remain in these tributary streams for approximately one year (Burger et al., 1982). The late run spawns in the mainstem river and their young move into a downstream lake. In Idaho's Salmon River drainage, cutthroat trout behavior varies with respect to stream size. Cutthroat trout using small tributaries as summer habitat, move to larger tributaries or the mainstem Salmon River to overwinter. Cutthroat trout in the larger tributaries or the mainstem remain in these streams throughout the year (Meehan and Bjornn, 1991). Acquiring such knowledge of habitat utilization prior to establishing IFIM study sites is important for maintaining the biological integrity of the instream flow study. And, such knowledge is not currently available for large northern rivers and can only be obtained by conducting habitat utilization studies at different times of the year during the first phase of study.

Where

Where exactly are they? Which habitats are they using? Considering the instream flow needs of all the fish species (with their various lifestages) present in a complex community can be overwhelming. Many northern rivers have a combination of resident and migratory fish, some with twenty or more species, each with multiple life history stages having separate habitat requirements. Because of these separate habitat requirements, fish often separate themselves by habitat type in large river systems (Figure 5). We refer to this as habitat partitioning. In most large river systems, distinct distribution patterns generally emerge.

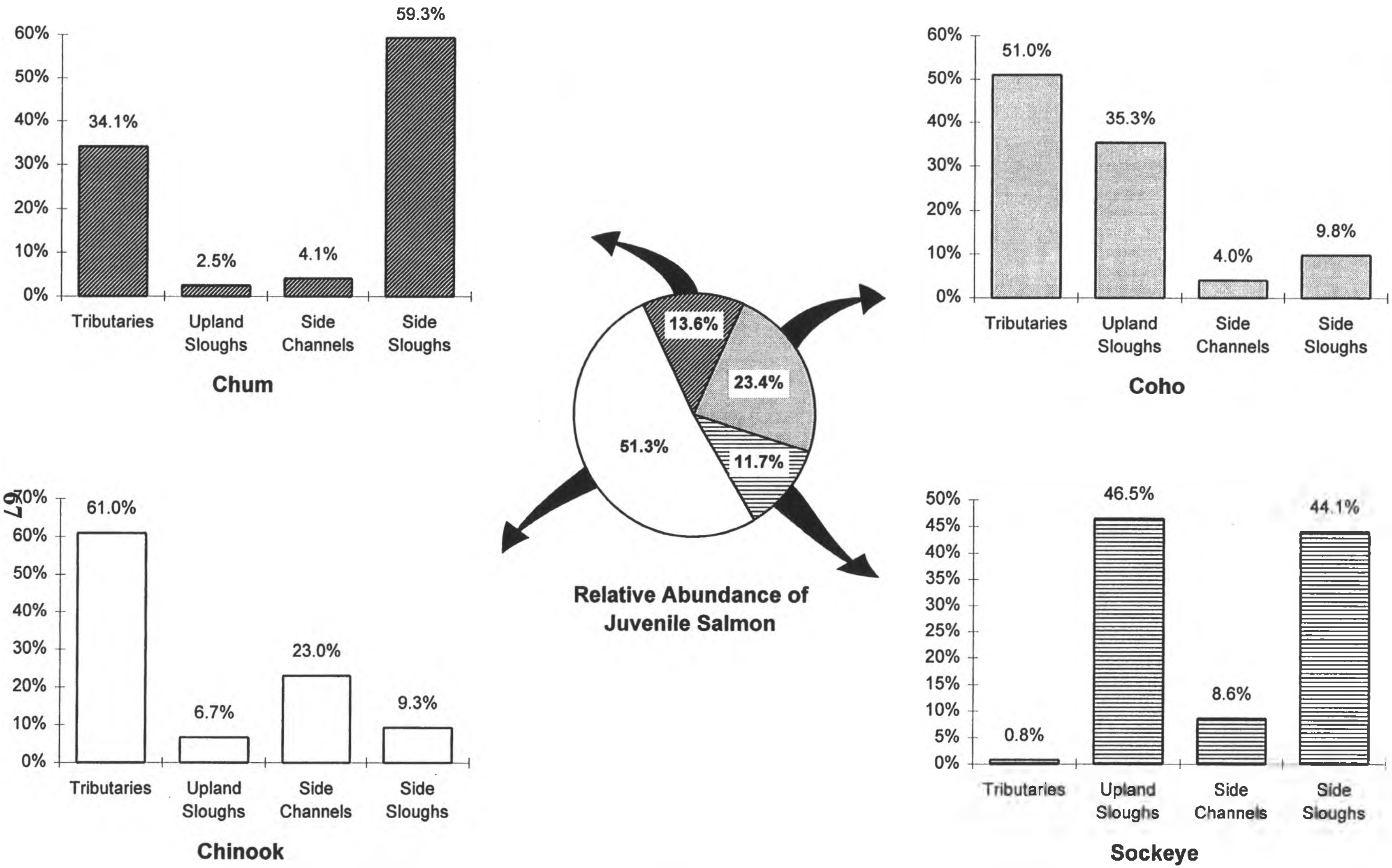


Figure 5. Distribution of Juvenile Salmon Within Different Habitat Types of the Middle Susitna River During the Open Water Period. (from: Milner, 1985)

As a result of a proposed hydroelectric development on the Susitna River, the Alaska Power Authority conducted a baseline fisheries investigation and instream flow study throughout 150 miles of that river. The fisheries investigation for the project spanned a five-year period and identified important habitat utilization patterns for eight evaluation species. We learned in this study that fish so effectively partitioned themselves among different habitat types that the job of identifying project effects on individual fish species was much easier than originally envisioned. Rainbow trout were found in the clear water tributaries and only used the mainstem of the Susitna River during winter when it became clear (Schmidt et al., 1984). Five species of salmon spawned in the Middle Reach of the Susitna River, but distributed themselves in a very distinct and consistent pattern (Trihey and Baldrige, 1984). Pink, chinook and coho salmon used tributary habitats for spawning, pink salmon near the mouths, chinook further upstream in the tributaries, and coho salmon migrating the furthest upstream (refer to Figure 1). Chum and sockeye salmon spawned in side sloughs, but only where groundwater upwelling occurred. Chum salmon were the only salmon to spawn in turbid-water side channels and mainstem shoalareas, but again, only where upwelling groundwater occurred. Having invested the time to obtain this level of understanding of habitat utilization maintained the biological integrity of the instream flow study, greatly simplified the IFIM analysis and increased confidence in application of its results to evaluate project effects. In addition, it greatly reduced the potential overall cost of the IFIM analysis because very little work was necessary on the mainstem or large side channel habitats.

From the available studies of the Peace River, it appears that fish there are also using readily identifiable habitats: snyes (clear sloughs), side channels, shoals, backwaters. Fish may be using mainstem habitat for overwintering and for passage, but most of the more intensely utilized aquatic habitats appear to be peripheral to the main channel. Peripheral habitats respond to hydraulic conditions in the mainstem, and an important component of any instream flow study conducted for the Peace River will be to identify and characterize the dependence of peripheral habitats on mainstem discharge and ice processes. However, this can be done without applying IFIM type models to the mainstem. In fact, developing models based on depth, velocity and substrate composition of the mainstem may only lead to erroneous conclusions.

To properly consider instream flow requirements for large rivers, we need to understand seasonal habitat utilization patterns and the dependence of those utilized habitats on mainstem flow, temperature, sediment transport, etc. Rather than modeling all of the physical conditions and habitat types in a large river system, we can focus our efforts on those habitats of importance that are likely to be changed by the proposed development. Too often we see PHABSIM models for large rivers which do a great job of modeling hydraulic conditions associated with water that fish rarely use.

A good example of this is evident in a review of the IFIM study performed in the Columbia River System. Salmon populations are very depressed throughout the Columbia Basin. And, the abundance of returning salmon was so diminished in the study river that spawning habitats were difficult to identify.

A survey to locate spawning activity found that slightly more than half of the returning adults were observed spawning in mainstem habitats while the remaining fish were spawning near mid-channel islands or in mainstem habitat in the vicinity of islands. The IFIM investigators used the "representative reach approach" to allocate their transects and weight the results of their IFIM modeling according to habitat composition. The mainstem habitat, which comprised nearly all (approximately 90%) of the wetted area in the study reach, dominated the analysis. Since the island habitats comprised only a small amount (approximately 10%) of the wetted area within the study reach, this habitat type exerted very little influence on the overall structure of the IFIM analysis. Within the mainstem habitat, velocities were very sensitive to streamflow, and as streamflow increased, velocities quickly surpassed those deemed suitable for use by spawning salmon. Thus, the instream flow model showed that more spawning habitat would become available if streamflows were substantially reduced.

Upon further evaluation, it was noted that the few salmon returning to spawn appeared to be preferentially selecting island habitat over mainstem habitat when available habitat was considered (approximately half of the spawners were observed in less than 10% of the habitat). At the optimal spawning flows recommended by the IFIM analysis of mainstem habitats, the island areas would not be useable. The island area models indicated that the streamflow required to maintain the complex island habitats were an order of magnitude higher than the flows forecast as providing optimal spawning conditions in the mainstem thalweg. Which IFIM model best maintains the biological integrity of the system? Would salmon spawn in the mainstem if flows were lower and habitat was higher? Are island habitats critical? Careful consideration of such questions would improve the biological integrity of instream flow studies.

In Alaska, the instream flow studies conducted for the Susitna Hydroelectric Project relied heavily on analysis of habitats being utilized by fish rather than randomly selecting mainstem study sites. Only mainstem shoal area and a few side channels areas were used by spawning salmon. Other mainstem habitats were not used by adult salmon except as a migration corridor. Thus, the instream flow modeling only evaluated project effects on areas being utilized by spawning salmon or that might potentially become suitable for utilization. Thus, IFIM transects at mainstem shoal areas and in large side channels, did not span the entire channel (Hilliard et al., 1985). They traversed only the shoal or side channel margin where upwelling groundwater occurred and where suitable substrate existed, or could be placed (Figure 6). In this river, there appeared to be no benefit in expending the effort to model spawning habitat in mid-channel areas or anywhere that upwelling groundwater did not occur. This decision was made on the basis of the biological information on habitat utilization patterns for that system. The analytical structure of the analysis should be firmly grounded in site-specific biology. Fish may respond differently in other systems.

In the Susitna River, tributary-mouth habitat was found to be very important for juvenile and resident fish. Here again, transects were established to permit analysis of the effect of changes in mainstem stream flows (water surface elevation) on the location, surface area, and quality of tributary-mouth habitats. Measurements to describe depth and velocity at the tributary-mouth habitats were obtained at various mainstem flows, which were also documented by high resolution aerial photography. As the mainstem flows increased, the amount of tributary-mouth habitat decreased because the clear water plume was pushed back toward the tributary and the mainstem channel margins. Hydraulic conditions within the turbid mainstem water outside the boundary of the tributary-mouth habitat was not considered

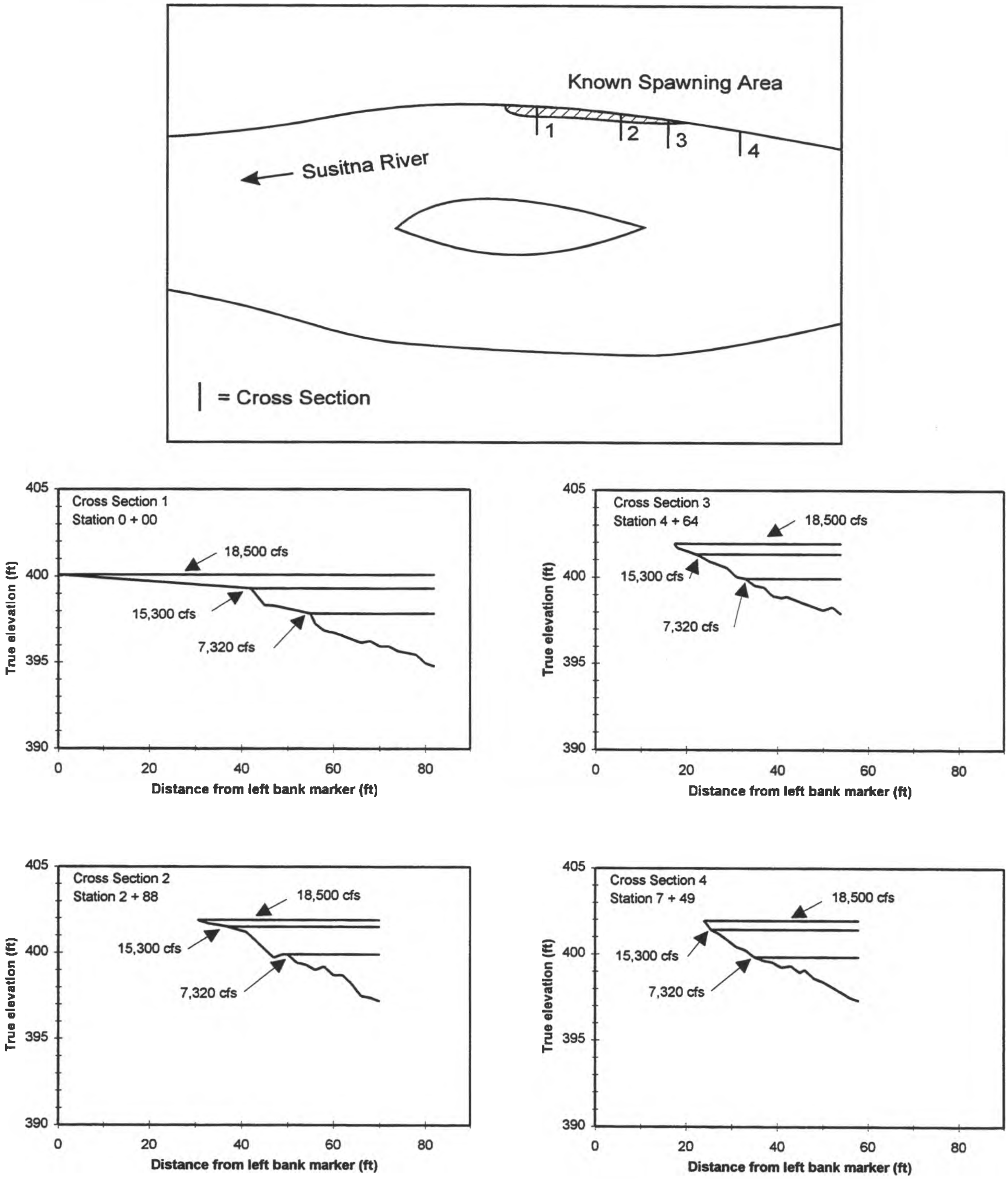


Figure 6. Partial Cross Sections at Site 105.8L for Evaluating Chum Salmon Spawning Along the Left Shoreline of the Susitna River at Discharges of 7,320, 15,300, and 18,500 cfs. (from: Hilliard et al., 1985)

because several years of fish distribution and habitat utilization data indicated resident and juvenile fish were found in the clear water plume (sampling was performed using a variety of methods to confirm this utilization pattern).

The distribution of spawning salmon and of resident and juvenile salmonids in mainstem habitats required modification of the standard IFIM approach and the associated computer models. It required effort to adapt the IFIM models to our situation, but doing so allowed us to maintain the biological integrity of the study and keep the analysis focused on habitats important to fish.

Why

Why are they there? As biologists, we know that it takes more than depth, velocity and substrate to make fish habitat. Many other factors also influence habitat quality and fish populations (Figure 7). Sometimes we can incorporate these factors into PHABSIM. Other times we cannot, and thus we must apply the results of PHABSIM in light of our knowledge of these factors.

During the habitat utilization studies conducted in Alaska, we learned that chum salmon would dig through 20 cm of fine sediment to spawn in the underlying gravels and coarse sand or would spawn among large cobbles and boulders if upwelling groundwater was present. But in one river, the chum salmon would only spawn in upwelling areas along the west side. Three years of investigation by well-qualified biologists and engineers could not explain why this distinct utilization pattern existed.

What implication does the foregoing have on PHABSIM modeling? Groundwater upwelling was known to be far more important than substrate composition to spawning chum salmon. Thus, it was incorporated into the PHABSIM models in such a manner. For these studies, we used ground water upwelling as a binary substrate code. Spawning habitat for chum salmon simply could not exist in areas lacking upwelling. Since we didn't understand why spawning only occurred in sloughs and side channels along the west side of the river, we did not include upwelling groundwater areas along the east side of the river in the spawning habitat analysis.

In glacial systems, juvenile chinook salmon use turbidity as cover (Schmidt, et al., 1984). We found that they preferentially selected much lower velocities in turbid water than they did when they were in clear water. We suspect this difference in velocity preference is associated with the juvenile fish's ability to forage for food, and maintain a feeding position. Thus, to include this information in our PHABSIM analysis for the Susitna River study, we evaluated turbid water habitats separately from clear water habitats. Based on observed microhabitat utilization patterns, we developed one set of depth and velocity criteria for turbid water habitats with higher preferences for low velocity water and another set of criteria for clear water habitats. We also used river stage in the modified PHABSIM models to select the appropriate criteria set since as mainstem discharge increased, groundwater-fed clear side sloughs were overtopped at their upstream end converting them into turbid side channels.

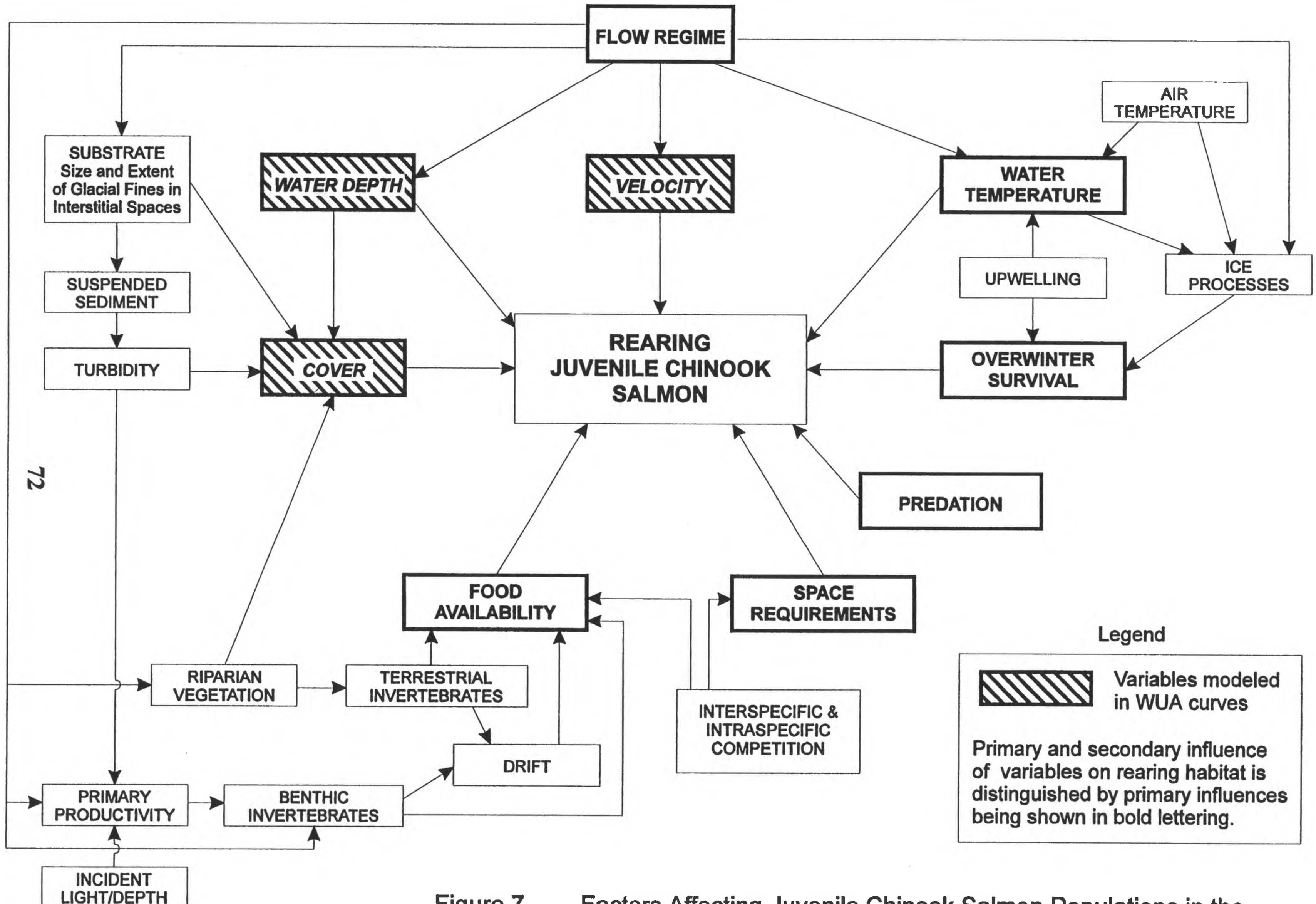


Figure 7. Factors Affecting Juvenile Chinook Salmon Populations in the Susitna River. (from: Milner, 1985)

Summary

The challenge in planning any instream flow study is developing an analytical framework that emphasizes analysis of those habitats and physical processes that are important to fish in the river segment being modeled. Maintaining the biological integrity of instream flow studies for large northern rivers can be very challenging because often little is known about the seasonal distribution and habitat utilization patterns of fish. And acquiring this information is usually difficult, expensive, and hazardous. None-the-less, the biological integrity of instream flow studies for large northern rivers must be established (and maintained) if the study results are to fulfill the expectations of society.

The key to maintaining biological integrity in instream flow studies of large rivers is to first seek to understand the biology of the river system. And then, evaluate project effects on the physical processes that influence that biology. Investigators must guard against the premature application of habitat models and not allow themselves to be drawn into modeling mainstem hydraulics or habitats because that challenge exists.

Had the investigators conducting the smallmouth bass study considered the importance of sculpin in the food chain before commencing their IFIM modeling, they may have been far more successful in protecting the smallmouth bass. And, had the investigators conducting the IFIM study in the Columbia River Basin first described the location and density of adult spawners in a quantitative progress report, the important chinook spawning habitats near island complexes may not have been so quickly subordinated to mainstem habitat in their IFIM analysis.

A more disciplined focus on maintaining the biological integrity in these IFIM studies may have caused the IFIM modeling to proceed more slowly, but the water development community, regulatory agencies and society would all have benefited from more reliable information on potential effect to fish resources.

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WINTER HABITAT CONSIDERATIONS FOR FISH IN THE PEACE RIVER

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Abstract

During winter suitable habitat for fish in north temperate rivers is severely reduced due to ice formation and low water discharge. Surface ice formation can further reduce the amount of habitat available when side channels and backwaters freeze to the bottom. As a result fish aggregate in suitable habitats such as large deep pools. The episodic formation of frazil ice may occur during the winter downstream of dams and in open water areas such as rapids where water flow is turbulent. Frazil and associate anchor ice formation could further restrict over wintering habitat available to fish and may result in the aggregation of large numbers of fish in a relatively small number of locations which are free of the influence of frazil ice. The possible influence of frazil ice on over wintering habitat has received little attention by IFN modellers.

Low discharge which normally occurs in unregulated rivers during winter results in severe reductions in the quantity of habitat available in summer and fall. Winter flows now maintained in the Peace River are considerably above historic winter values so that low flows should not pose a problem for fish during winter.

Introduction

Winter habitat use and winter habitat conditions in running waters is a neglected area of fish biology. The reasons for this neglect are largely the severe climate in winter and the associated difficulties in locating fish and assessing habitat conditions. With the development of radio telemetry it is relatively easy to locate fish carrying radio tags at different times during the year so long as the fish remain in relatively shallow water. Once fish are located the habitat they use at a particular time can be assessed and compared to the types of habitat available in the stream/river at that time.

Most of the work done on fish habitat use during winter has come from studies on small headwater streams used by salmonids (Brown, 1993; Power et al., 1993). The reasons are two fold, first these streams are more amenable to the techniques which are available (SCUBA for open water areas (Cunjack & Power, 1986), radio telemetry for ice covered systems (Brown, 1994)) and the extent of movements of fish in small systems, at least the ones which have been studied, are less extensive than in large rivers and hence they are more easily studied (Brown 1994).

There are no techniques available which can be readily applied to the elucidation of winter habitat use by fish in large rivers. SCUBA is difficult and dangerous in mainstem rivers where open water is usually both deep and fast. Radio telemetry is a useful tool but signal strength is attenuated by water depth and by slush and ice (Sullivan, 1985). In fact the depth limitation, about 5 m without ice cover (Mackay & Craig, 1983), renders radio telemetry an ineffective tool for studying fish habitat use in large rivers during the winter. Nevertheless much of what has been learned about habitat use in small streams can be applied to large, mainstem rivers.

Seasonal Shifts in Habitat Requirements of Fish

Major shifts in habitat use by fish may occur prior to, during or after ice formation. In general fish are dispersed in rivers and streams during summer when they are actively feeding. In late summer (August/September) fall spawners, mountain whitefish, bull trout, and lake whitefish in the Peace River, move to spawning areas (R.L.&L. 1990). In early fall (September/October) spring spawners and post spawning fall spawners may start to move into overwintering areas. Movement to these areas may not be completed until early winter (December). Decreased water temperatures, with reduce food requirements are thought to be a significant factor in triggering movements to overwintering areas in late summer and early fall (Cunjak & Power, 1986).

Large rivers appear to serve as corridors/conduits between habitats which are used at different times of the year. Thus fish may be abundant in the mainstem river at one time of year and apparently absent at other times. In the case of the Peace River large (many hectares), deep (> 7 meters) pools are plentiful and should provide good overwintering habitat for fish (R.L.&L. 1990).

Riverine fish commonly aggregate in large numbers in deep pools during the fall. In small rivers most species seem to prefer pools or other slow moving water which contain cover, usually in the form of log jams or other woody debris as cover provides protection from predators (Cunjak & Power, 1986; Cunjak & Power, 1987; Brown, 1994). Thus fish distribution changes from relatively dispersed to clumped, at least for species for which data have been obtained (Cunjak & Power, 1986, Brown, 1994). In large rivers such as the Peace where pool depths of 7 meters are common (R.L.&L. 1993) cover is not common but protection from terrestrial and aerial predators is provided by deep, turbid water.

Physical Conditions in Rivers During the Winter

In the fall fish generally move out of areas which may become frozen to the bottom in winter and move into deep pools (Chisholm et al., 1987) or areas of ground water discharge into the stream bed (Brown et al., 1994). Springs tend to play a major role in the habitat choice of fish in head water systems (Brown, 1994). Ground water input may not be an important habitat feature in mainstem rivers because they are not common in mainstem rivers and where they do occur their discharge is extremely small relative to river discharge at that point.

It is likely that fish in mainstem rivers such as the Peace undergo large scale migrations as goldeye, walleye and suckers have been shown to do in the Athabasca (Berry, 1986; Donald and Kooyeman, 1974).

Rivers show marked seasonality in discharge with the lowest flows in winter. Winter discharge in the Peace River following construction of the Bennett Dam are considerably above historic winter values (Alberta/British Columbia IFN Sub-Committee, 1991). Thus low winter flows should not pose a problem for fish during the winter in the Peace River downstream of the Bennett Dam.

Rivers differ from lakes in that water depth (stage) increases following ice formation, a hydrologic constraint posed by the friction, and hence decreased velocity of water flowing under ice (Calkins, 1993). Nevertheless large areas of shallow water near shore that were suitable habitat before freeze up are not available to fish following freeze up. Such areas include side channels and backwaters most of which likely freeze to the bottom during the winter.

The unifying feature of most rivers in winter is that water temperature is very near 0 ^{0}C and they are ice covered. Likely them most variable parameter is dissolved oxygen which can vary in both space and time. The most significant physical features of northern rivers with regard to fish habitat in winter is the timing and the types of ice which are formed.

Ice Formation in Rivers

The mean daily water temperature of rivers declines during the fall as a result of decreasing air temperatures until water temperature reaches 0 ^{0}C. When the mean daily water temperature reaches 0 ^{0}C ice permanent surface ice is formed. Surface ice forms first at the margins of running water where water velocities are lowest. This surface ice slowly grows from areas where water velocity is lowest toward the center of the river where velocities are highest (Gerard, 1989a). As air temperatures continue to drop areas of turbulent water becomes slightly super cooled and ice crystals, called frazil ice, begin to form in the water column (Andres, 1982). Frazil ice crystals are either discoid or needle-like and they continue to grow so long as the water is slightly super cooled (Tsang, 1982). Where flows are turbulent frazil ice is suspended throughout the water column. Under these conditions the frazil ice crystals are very sticky and will adhere to objects such as the substrate to form anchor ice (Caulkins, 1993). Under open water conditions fish usually prefer areas of cover in their environment (Brown, 1994). Cover is often provided by woods debris in pools. When frazil and anchor ice form this type of habitat can be completely obstructed by anchor ice driving fish from these habitats (Brown 1994).

Frazil ice only forms in areas of open water since the result of low air temperatures in ice-covered reaches is an increase in the thickness of the ice. Frazil ice formation is an aspect of particular concern downstream of waterfalls, dams and high gradient areas downstream of where warm effluent enters a river.

Under conditions of particularly turbulent flow and extreme cold such as may exist downstream of waterfalls, rapids or the discharge from dams frazil ice may accumulate under surface ice to form very large ice dams (Shumway & Springer, 1992; Gerard, 1989b). The magnitude of such dams may wax and wane with changes in air temperature, the dams building under cold conditions and bursting or becoming reduced when air temperatures warm. Under some conditions the ice dams formed by frazil ice may result in severe flooding or they may suddenly rupture and dewater areas which formerly provided fish habitat resulting in fish mortality (Maciolek & Needham, 1952). The crushing effects of ice which result from the rupture of frazil ice dams can result in fish mortality (Brown et al. 1994).

Where water flows are less turbulent frazil ice is only formed during freeze up. The frazil ice crystals tend to float and to adhere to one another to form pans of ice which float downstream (Caulkins, 1993). Ultimately the pans will jam in constricted regions (usually a bend) where surface ice has been growing outward from the sides. The jam of ice pans will form a solid mass of surface ice which will prevent further frazil ice formation during the winter (Caulkins, 1993).

Frazil ice formation is episodic, it occurs only in open water reaches when air temperatures reach some critical lower value. The air temperature which triggers frazil ice formation depends on discharge, turbulence, extent of open water, etc. (Ettma et al., 1982). It is unlikely that fish would be able to breath in water which contains a very high density of frazil ice as the ice crystals would either damage the gills if they were small enough to pass through the gill rakers or they would block the pharyngeal cavity if they were too large to pass through the gill rakers. Either consequence would not be positive for the fish and they would likely be forced out of areas with active frazil ice generation even if the event only lasted a few hours. Displacement of cutthroat trout has been observed as the result of an episodic event of frazil ice formation (Brown 1994).

In reaches of streams and rivers where frazil ice formation is a regular event in the winter only a small portion of the total habitat may be suitable for overwintering fish. Frazil ice has been reported to virtually fill pools as deep as 8.9 m on the Miramichi River in New Brunswick (Cunjak & Caisse, 1994). Thus on the Peace River one might not expect to find fish in the area of the open water/surface ice covered region downstream of the Bennett Dam or for a few kilometres down stream of the Vermilion Chutes.

Physiological Considerations for Overwintering

Food requirements for most fish are very low in winter as a consequence of low metabolic rate, decreased activity and little body or gonad growth. Since body temperature of fish is the same as that of their environment the low water temperatures which exist during winter reduce resting metabolic rates to very low levels. In addition most fish species in the Peace River are likely inactive and undergo little body or gonad growth during the winter. All of this results in low energy expenditure and food requirements which may be as little as 10% of summer requirements.

Biological Considerations

Predators

Habitat preferences of fish are dictated by a balance between obtaining protection from predators and at the same time optimizing feeding or reproduction. In the winter food requirements are generally low, even for species which feed and grow during the winter, as a result of very low metabolic rates seen in all fish at extremely low temperatures and few species are engaged in reproductive activities. Thus protection from predators is an important biological consideration for fish in their habitat preference. Besides other fish the major predators of fish in rivers are migrating birds - mergansers, and other fish eating ducks, ospreys and eagles. Fish often seek cover from predators in running water. In winter surface ice provides cover from avian predators. During the winter mammals such as mink and otter can be major fish predators. Otters are limited to areas where open water occurs. To avoid capture by predators fish tend to use habitat with cover in the form of boulders or log jams in small rivers and streams. In large, relatively turbid rivers like the Peace water may to too deep for predators to be effective and cover may not be a significant habitat requirement (R.L.&L., 1993).

Competitors

Since fish do not have high energy requirements in the winter inter and intra specific competition does not appear to have a major impact on habitat selection.

Spawning/Spawning Requirement

Some fish such as burbot spawn in late winter under the ice. They appear to be mass spawners, that is males and females engage in a spawning frenzy rather than individual pairings. They do not appear to have specific substrate requirements for spawning (Boag, 1989).

Cold water fish such as burbot, northern pike and lake whitefish actively feed and grow during the winter. They are more likely to move and to seek out areas where food is abundant than are cool water species such as walleye which are not so metabolically active 0 °C which is experience in NRBS waters during winter.

Conclusion

Winter habitat suitability is an area which has been largely ignored in IFN models and in field studies of habitat suitability in regulated rivers such as the Peace. The formation of various types of ice can profoundly reduce available habitat for fish. The formation of surface ice on low gradient reaches can increase stage and expand habitat availability. Episodic formation of frazil ice during extreme cold periods below areas of high turbulence would exclude fish from reaches down stream of the open, turbulent water.

The maintenance of winter flows at levels higher than historic values should increase the availability of over wintering habitat. Higher flows would likely have little effect on the formation of frazil ice.

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Managing Instream Flows for Biodiversity: A Conceptual Model And Hypotheses.

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Introduction

Biological diversity has become an important topic in the management of natural resources. An entire session of the 57th North American Wildlife and Natural Resources Conference (McCabe, 1992) was devoted to problems and opportunities related to biological diversity in the aquatic environment. One of the main themes of several of the authors was the lack of attention paid to biodiversity in aquatic systems. Pister (1992) attributes this phenomenon to a tendency of fish and wildlife agencies to manage for individual species rather than for communities or ecosystems. However, Snyder (1990) asserts that the management for individual species is often deficient because managers concentrate on habitat requirements for adults, ignoring or "assuming away" habitat requirements for early life history phases.

The importance of evaluating habitat requirements for multiple species and life stages is recognized in applications of the Instream Flow Incremental Methodology (IFIM) and its component subunits, such as PHABSIM (Stalnaker, 1979; Bovee, 1982; Bovee, 1986). In actual practice, however, most applications of IFIM have tended to concentrate on one or two target species considered to be important by the fish and wildlife agencies involved with the study. These applications commonly focus on important sport or game species, and decisions are often based primarily on habitat requirements for adults.

Nestler (1990) summarized four major impediments to using IFIM in a more ecologically challenging setting, especially in the warmwater streams of the southeastern U.S.:

1. The hydrology of warmwater streams is driven by rainfall rather than snowmelt, resulting in greater temporal variation in streamflow;

2. Channel structure is more complex in warmwater streams, providing a greater variety of potential microhabitat niches;

3. The biology of many organisms in warmwater streams is poorly known, making it difficult or impossible-to develop habitat suitability criteria necessary for IFIM analyses; and,

4. If habitat requirements for a large number of species are evaluated, interpretation and assessment becomes unwieldly due to conflicting habitat requirements and the volume of information that must be processed.

The last two items mentioned by Nestler are particularly vexing to an investigator trying to manage a community instead of a population. Bain and Boltz (1989) suggested a strategy of developing habitat suitability criteria for guilds of animals that share comparable habitat requirements. This approach reduces the volume of information to be processed in an IFIM analysis, but it retains many of the same attributes associated with population-oriented uses of PHABSIM (e.g., managing for a particular habitat type).

The basic premise of this paper is that management at the community or ecosystem level requires a different perspective compared to management at the species or population level. Entirely different metrics (e.g., richness, diversity, evenness, and persistence) are used to evaluate community attributes. If IFIM is to be used in the context of community-level management, it should be adapted to provide output that is meaningful at the community level. My objectives are to describe how PHABSIM can be used to provide such output, to illustrate how this approach could be used to manage rivers for biodiversity, and to suggest some testable hypotheses that might be associated with these metrics. While the importance of habitat diversity to stream communities has been recognized (Gorman and Karr, 1978) the role of habitat diversity has not generally been considered in instream flow need assessments.

Formulation of the Conceptual Model

Underlying Assumptions

Several assumptions have been made in the development of this conceptual model. First, it is assumed that the well-being of an individual species depends directly on many habitat types during different parts of the life history, but our understanding of the relative importance of the different habitat types is incomplete. Second, it is assumed that habitat types not directly used by a species are equally important as sources of food, as living space for competitors or predators, or may contribute to a species' well-being in more subtle ways, such as increasing dissolved oxygen concentrations through mechanical reaeration. Third, it is assumed that quantification of the interactions between the biological and physical mosaics in a lotic environment may never be achieved; such quantification would come at great expense, with low transferability to other stream systems, and would likely be infeasible for most operational studies.

Microhabitats as Species

This model is based on the premise that all habitat types are potentially important to the structure and stability of the community. Therefore, the objective of this model is to manage for a mix of heterogeneous habitat types without regard to which species may or may not use a particular type. This is done by defining discrete, non-overlapping combinations of microhabitat characteristics and treating these in the same manner as individual species in developing community metrics.

Bain and Boltz (1989) introduced the concept of developing habitat suitability criteria to define habitat use guilds. The same concept can be applied to defining microhabitat types; in fact, the definitions used by Bain and Boltz (1989) fit nicely in this conceptual model. Depth can be classified as shallow, moderate, and deep (or very shallow, moderately shallow, moderately deep, and very deep). Likewise, velocities can be partitioned into slow, medium, and fast classifications. Substratum can be considered fine, medium, or coarse, and cover can be designated by function (e.g., velocity shelter, visual isolation, combination) or simply by presence or absence.

To implement this model, boundaries to each of the variable classifications must be assigned. This is comparable to the development of habitat suitability criteria in regular applications of IFIM. Table 1 illustrates one set of divisions I used to delineate sub-classes of variables in this study.

Table 1. Arbitrary divisions of velocity, depth, and cover to delineate microhabitat types and microhabitat classes used in conceptual model.

Microhabitat variable	Classification	Range
Velocity	Slow	O - 45 $cm.sec^{-1}$
	Moderate	46 - 90 $cm.sec^{-1}$
	Fast	91 - 150 $cm.sec^{-1}$
Depth	Shallow	3 - 45 cm
	Moderate	46 - 90 cm
	Deep	> 90 cm
Cover	Present	Present
	Absent	Absent

Each combination of variable sub-classes listed in Table 1 describes a unique microhabitat type. For example, one combination is shallow and slow with no cover, whereas another combination is deep and fast, with cover. Using the subdivisions of variables listed in Table 1, there are 18 unique combinations of depth, velocity, and cover (Table 2). One habitat type was added to the habitat matrix. This class was defined as uninhabitable but part of the habitat matrix nonetheless: where depth was less than 3 cm (including streambed areas above water) or where velocities exceeded 150 $cm.sec^{-1}$.

Because each combination of habitat attributes is unique, it can be treated much the same as a species in traditional community ecology. For example, habitat richness is a count of the number of unique habitat types present in the stream at a given discharge. Habitat diversity is an index of the heterogeneity among habitat types present at a certain streamflow. Habitat evenness is the ratio between calculated habitat diversity and the maximum habitat diversity possible.

Many of the indexes commonly used in community ecology have their origins in mathematical information theory. Pielou (1969) describes the Shannon-Weaver Index (Shannon and Weaver, 1949) as a measure of information content per symbol of a code composed of s kinds of discrete symbols whose probabilities of occurrence are P_1, P_2....P_S. The diversity index, H', is a measure of uncertainty. If an individual is picked at random from a many species population, there is uncertainty as to which species will be picked; the greater the diversity, the greater the uncertainty.

If a series of random or systematic measurements are made in a stream and classified into unique habitat types, the result is a population of s kinds of discrete symbols whose probabilities of occurrence are P_1, P_2,...P_S. Therefore, at any discharge Q it is possible to calculate a value for H'. In my conceptual model, I used a variation of the Shannon-Weaver (Wiener) index that is formally the same as the maximum likelihood estimator of H' (Pielou, 1969):

$$H = -\sum (N_j/N) \ln (N_j/N)$$

where,

N_j is the number of measurements in the jth classification and
N is the total number of measurements in the population.

Application of the Conceptual Model

Data from the Cache la Poudre River, near Rustic, Colorado, were used to calculate habitat richness, diversity, and evenness for discharges ranging from 0.4 $m^3.sec^{-1}$ to 86 $m^3.sec^{-1}$. This represents the range of discharges present in the Cache la Poudre River over a 30-year period from 1954 through 1983.

Table 2. Microhabitat types defined as combinations of three depth and velocity sub-classes and two classifications of cover.

Microhabitat class	Description
A	Shallow, slow, cover absent
B	Shallow, slow, cover present
C	Moderate depth, slow, cover absent
D	Moderate depth, slow, cover present
E	Deep, slow, cover absent
F	Deep, slow, cover present
G	Shallow, moderate velocity, cover absent
H	Shallow, moderate velocity, cover present
I	Moderate depth, moderate velocity, cover absent
J	Moderate depth, moderate velocity, cover present
K	Deep, moderate velocity, cover absent
L	Deep, moderate velocity, cover present
M	Shallow, fast, cover absent
N	Shallow, fast, cover present
O	Moderate depth, fast, cover absent
P	Moderate depth, fast, cover present
Q	Deep, fast, cover absent
R	Deep, fast, cover present
S	Uninhabitable (depth < 3 cm or velocity > 150 $cm.sec^{-1}$

Stratified random sampling was used to select ten transects from an existing database for the Cache la Poudre. Transects were sampled from six pre-defined mesohabitat types in proportion to the amount of river segment they represented (e.g., three transects from high gradient riffles, one from a deep pool, and so on). Measurements of microhabitat characteristics were made systematically across each transect. By adhering to this sampling strategy, each set of measurements represented the same amount of surface area.

Bed elevations at measurement locations (verticals) were determined by differential levelling and water surface elevations were surveyed at 0.7, 4.3, 7.1, and 20 $m^3.sec^{-1}$ to develop empirical stage-discharge relationships for each transect. Measurements of cover, substrate, and mean column velocity were made at approximately 7.1 $m^3.sec^{-1}$. The IFG4 hydraulic model (Milhous *et al.*, 1989) was used to simulate the cell-by-cell hydraulic characteristics of each transect for discharges ranging from 0.4 $m^3.sec^{-1}$ to 86 $m^3.sec^{-1}$. Results from the hydraulic simulations were then entered into a spreadsheet, where each cell was classified according to microhabitat type and the number of cells in each type determined. These data were then used to calculate habitat richness, diversity, and evenness for each discharge (Table 3).

Results

Habitat Richness

In the Cache la Poudre River, habitat richness remained relatively stable (18-19) at all discharges above 7 $m^3.sec^{-1}$, but decreased rapidly at lower flows. Figure 1 is very similar in appearance to a plot of wetted perimeter versus discharge, but represents a significantly different phenomenon. A reduction in wetted perimeter at lower discharges is due to the loss of wetted area over riffles; the reduction in habitat richness represents the loss of areas having moderate to high velocities.

Habitat Diversity

It was postulated that habitat diversity would be lowest at extremely low and extremely high discharges, with the highest diversity at some intermediate discharge. At low discharges, most of the cells will either be shallow and slow or high and dry. At high discharges, most of the cells will be deep and fast. In the Cache la Poudre River, this is the pattern that emerged (Figure 2).

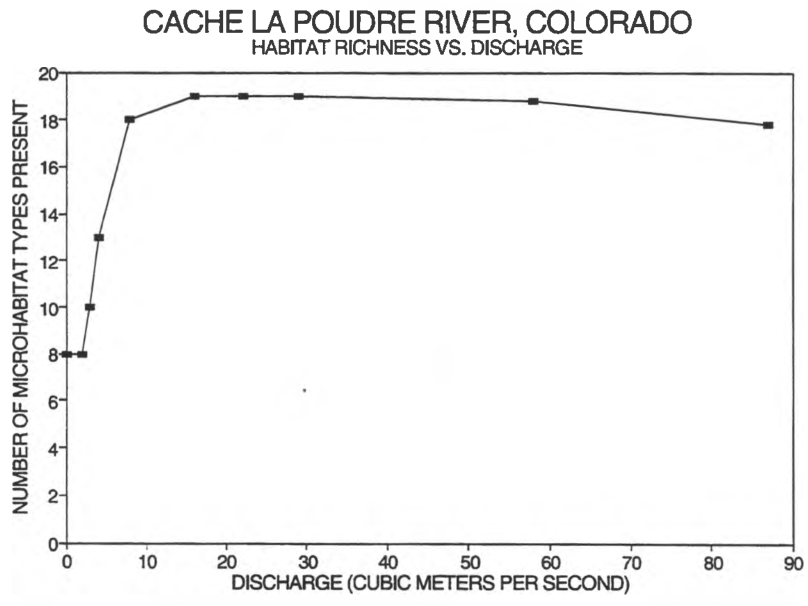

Figure 1. Habitat richness versus discharge , Cache la Poudre River , Colorado.

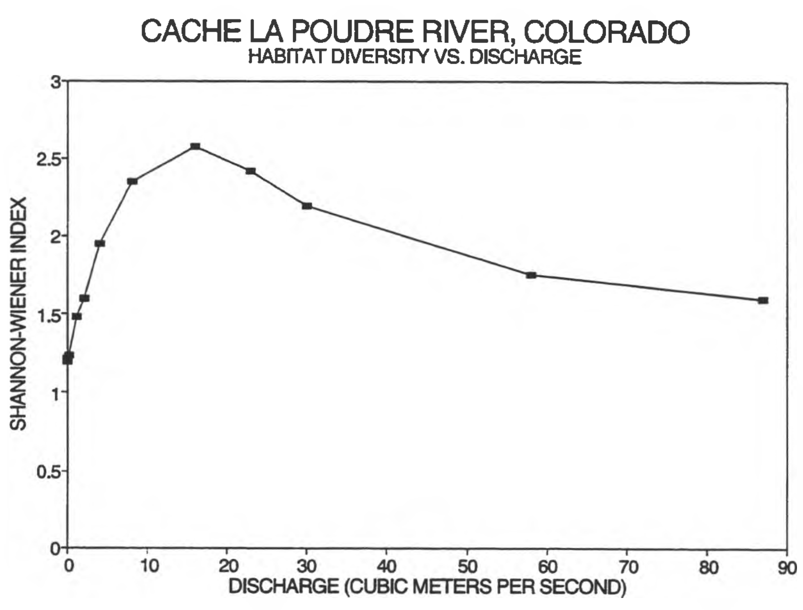

Figure 2. Habitat diversity versus discharge, Cache la Poudre River, Colorado.

Table 3. Numbers of stream cells in each microhabitat classification (Table 1) at 10 simulated Discharges, Cache la Poudre River, Colorado.

	Discharge in $m^3.sec^{-1}$										
Microhabitat Type	0.1	0.3	0.7	1.4	2.9	7.1	14.3	21.4	28.6	57.1	85.7
A	53	56	66	53	49	44	25	21	19	11	12
B	55	52	66	55	43	39	32	24	19	13	16
C	13	15	18	25	28	5	4	5	6	3	5
D	14	17	22	29	25	18	17	21	16	9	5
E	3	5	7	7	9	2	1	1	1	2	3
F	6	7	7	8	18	4	6	9	11	10	10
G	3	3	8	18	27	33	29	6	9	5	6
H	0	0	0	4	3	9	11	7	7	7	4
I	0	0	0	0	5	45	24	12	8	11	7
J	0	0	0	4	10	30	23	15	20	15	12
K	0	0	0	0	0	9	8	2	1	2	5
L	0	0	0	0	10	13	9	12	9	17	18
M	0	0	0	0	2	2	6	10	5	1	0
N	0	0	0	0	0	2	3	3	2	2	3
O	0	0	0	0	0	15	55	61	53	13	11
P	0	0	0	0	0	10	23	23	20	8	2
Q	0	0	0	0	0	0	11	32	22	17	3
R	0	0	0	0	0	1	21	21	16	20	23
S	249	241	202	193	167	115	88	111	152	230	251
Richness	8	8	8	10	13	18	19	19	19	19	18
Diversity	1.203	1.268	1.463	1.643	1.94	2.32	2.558	2.434	2.246	1.800	1.613
Evenness	0.58	0.61	0.70	0.71	0.76	0.80	0.87	0.82	0.76	0.61	0.56

It is interesting to compare Figure 2 with the more familiar relationships between weighted usable area (WUA) and discharge. Although the scales are quite different, the shapes of the functions are very similar. This suggests that for any of the uses of the WUA-Q function in IFIM (such as time series analysis and comparison of alternatives), the diversity-Q function could be substituted and used in exactly the same way.

Evenness

Evenness is a second measure of diversity that describes the equitability with which members of a population are distributed among the total number of species present. A convenient method of determining evenness is to divide the observed diversity by the maximum diversity possible, given the same number of species. Although somewhat counter-intuitive, maximum habitat diversity also varies as a function of streamflow, even though the number of cells remains the same. This is because habitat richness changes as a function of discharge. Because both observed and maximum possible diversity vary as functions of discharge, it should not be too surprising that evenness does too (Figure 3).

Although similar in appearance to the functional relationship between diversity and discharge, the scale for evenness ranges from zero to one. In this sense, the relationship between evenness and discharge may actually be the more useful because it is normalized, providing some meaningful boundaries on the amount of diversity that can actually be attained in a river at any discharge. If the objective of a study is to equalize the distribution of microhabitat types to the extent possible, evenness might be a very appropriate index by which to judge alternatives.

Stability and Persistence

Stability is considered a quantitative measure of constancy in abundance of taxa over time, whereas persistence is a qualitative measure of continued presence of taxa (Connell and Sousa, 1983). In biological communities, there are several metrics that can be used to measure stability: Morisita's index of similarity, Spearman's rank correlation, and Kendall's W (Matthews, 1986; but see Grossman *et al*, 1990). A major difference between biological communities and "physical communities" is the attribute of memory. In biological systems, there is an inherent memory because antecedent events are reflected in relative abundance, species diversity, or other community characteristics. Thus, a species assemblage can be measured today and the metrics obtained can be assumed to reflect the recent history of the community. With the exceptions of catastrophic events or chronic watershed disequilibria that result in changes to the stream channel, the same cannot be said about the structural and hydraulic characteristics of a river. The habitat diversity measured today is independent of the habitat diversity that would have been measured yesterday. Although it would be possible to use Morisita's similarity index to compare last month's habitat diversity with this month's, the result may not be very informative.

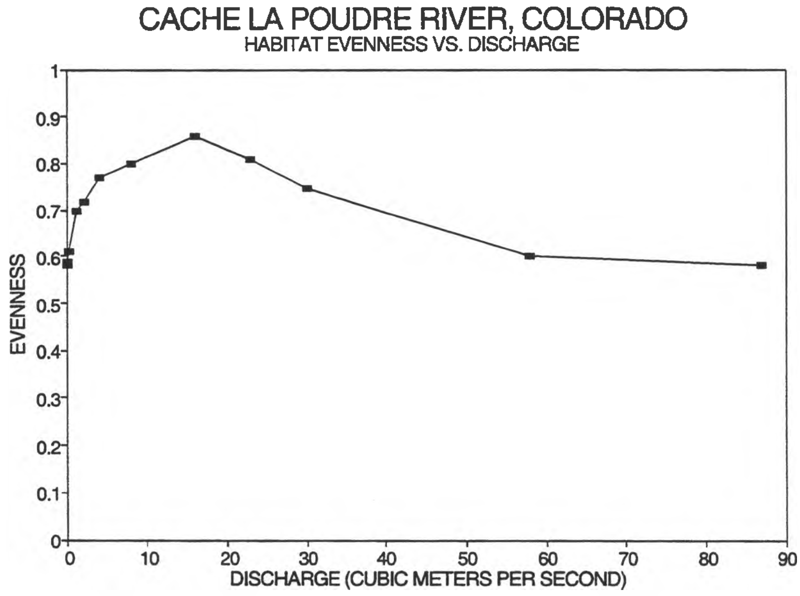

Figure 3. Habitat evenness versus discharge, Cache la Poudre River, Colorado.

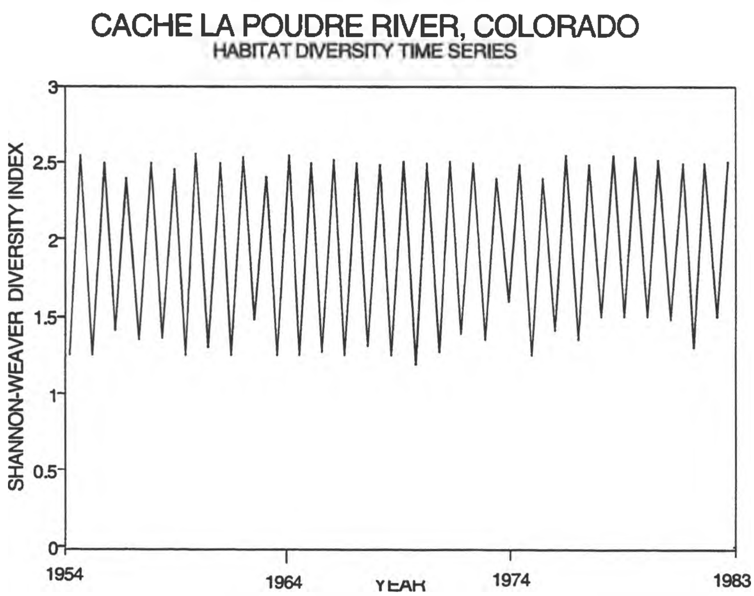

Figure 4. Habitat diversity time series, Cache La Poudre River, Colorado.

Other tools are available, however, to analyze temporal variability: time series and duration analysis. A time series of habitat diversity can be developed, for example, from the habitat diversity-discharge function and a hydrologic time series. The result is a chronology of habitat diversity for each period in the hydrologic time series (Figure 4).

A duration curve is constructed by ordering events in the time series from highest to lowest and assigning a rank to each event from 1 to n. The probability of an event being equalled or exceeded is calculated as:

$$p = m/(n+1)$$

where,

m is the rank of an ordered event, and
n is the total number of events.

The magnitude of the event is then plotted versus its corresponding exceedence probability to generate a habitat diversity duration curve (Figure 5). This contains the same information as the habitat time series, but is ordered according to probability rather than chronology.

The time series and duration plots both illustrate something about the stability of microhabitat structure in the Cache la Poudre River. In Figure 4 it is evident that there is considerable variation in habitat diversity over the course of a year, but that this variation is cyclic. That is, habitat diversity changes, but the variability is approximately the same year after year. Second, the magnitude of low diversity episodes are similar every year. This pattern is reflected in the habitat diversity duration curve (Figure 5), which is relatively flat for all habitat diversity values with exceedence probabilities greater than 50%. The slope of the curve is indicative of the variability of the system. A horizontal plot indicates a completely stable phenomenon, whereas a vertical plot indicates total chaos. Based on Figure 5, we can say that there is considerable variability in the events providing greater habitat diversity, but the events resulting in low habitat diversity are relatively consistent over time.

A Practical Example

The current pattern of streamflow in the Cache la Poudre River reflects its historical use as a source of water for irrigation. Several small reservoirs with a combined capacity of approximately 30,800,000 m^3 are located in the headwaters of the river. Under current operation, storage of base flows begins at the end of the irrigation season (during early October) and continues throughout the winter months. As a result, streamflows during the winter are generally depressed compared to natural baseflow conditions. During the spring runoff period, high flows cannot be buffered significantly because the reservoirs are small and usually filled to near-capacity.

In this example, two different operations of the headwaters reservoirs were considered. Under the baseline condition, it was assumed that no formal instream flow release is required from the reservoirs. Any streamflow in the Cache la Poudre is due to downstream demands. Under the alternative to be tested, the reservoirs would be slowly evacuated during the winter to supplement baseflows, and refilled during the spring runoff period.

A simple reservoir operation model was used to determine the feasibility of various release and storage patterns. A two-stage instream flow rule appeared to be workable. When reservoir storage was greater than 12,335,000 m^3, the instream flow release was set at 1.7 $m^3.sec^{-1}$. When reservoir storage was less than 12,335,000 m^3, the instream flow release was set at 0.7 $m^3.sec^{-1}$. If releases for downstream delivery requirements exceeded either instream flow release rule, the instream flow release was set to zero.

The result of implementing such an operational strategy on the headwaters reservoirs would result in an increase in habitat diversity of approximately 25%, during the lowest 10% of the episodes (i.e., exceedence probabilities greater than or equal to 90%; Figure 6). Over the lowest 50% of the habitat diversity values, the alternative would have resulted in an increase of 14%. Obviously, habitat diversity could have been increased dramatically if the instream flow release were increased to 7 to 14 $m^3.sec^{-1}$ (Figure 2), but the reservoirs were too small to accomplish a release of this magnitude.

Discussion

1.The foregoing example illustrates that habitat diversity could be used as a replacement to the standard WUA-Q function typical of IFIM applications. The use of a habitat diversity index could solve at least some of the problems associated with IFIM in complex warmwater streams that were summarized by Nestler (1990). Habitat diversity indexes can be generated from rather general and arbitrary divisions of microhabitat types (as in Table 1), negating the requirement for highly detailed habitat suitability criteria. When using habitat diversity indexes, interpretation is greatly simplified because there are only a few functional relationships with discharge that need to be considered. Even a "simple" biological system such as the Cache la Poudre contains several species of fish and numerous species of invertebrates. It would not be unrealistic to evaluate a dozen WUA versus discharge relationships in the Cache la Poudre example, if a standard IFIM analysis were to be conducted. In fact, this example has been used for several years in our training courses, and the conclusions derived from using the habitat diversity time series and duration statistics were essentially the same as those obtained by evaluating species and life stages separately.

Unfortunately, it seems that every solution spawns new problems and this approach is not without uncertainties. Two issues deserve special attention here: the effects of scale and the biological relevance of habitat diversity. Effects of scale on the calculation of habitat diversity

Diversity indexes, regardless of which are used, are sensitive to the number of discrete units of code used to calculate them. By dividing microhabitat variables into ever smaller intervals, the effect is to increase the number of units. Inevitably, this will result in an overall increase in computed diversity. One of the

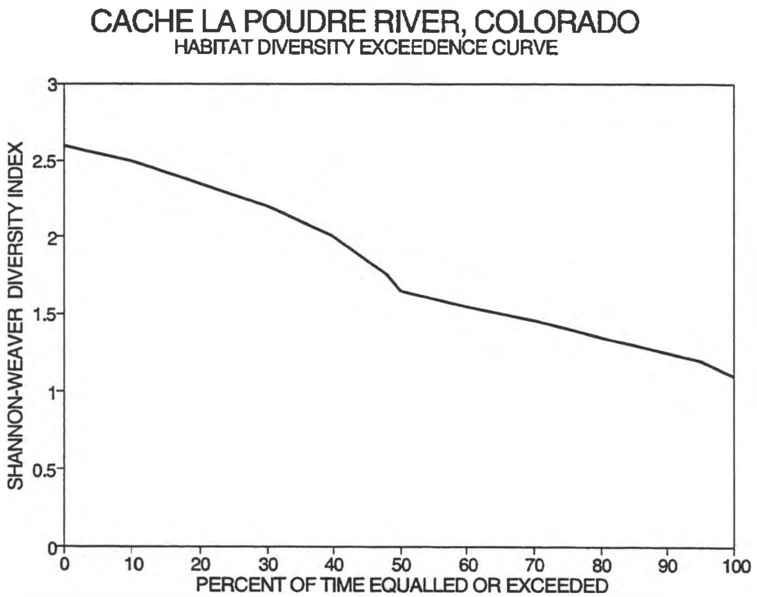

Figure 5. Habitat diversity duration curve, Cache la Poudre River, Colorado.

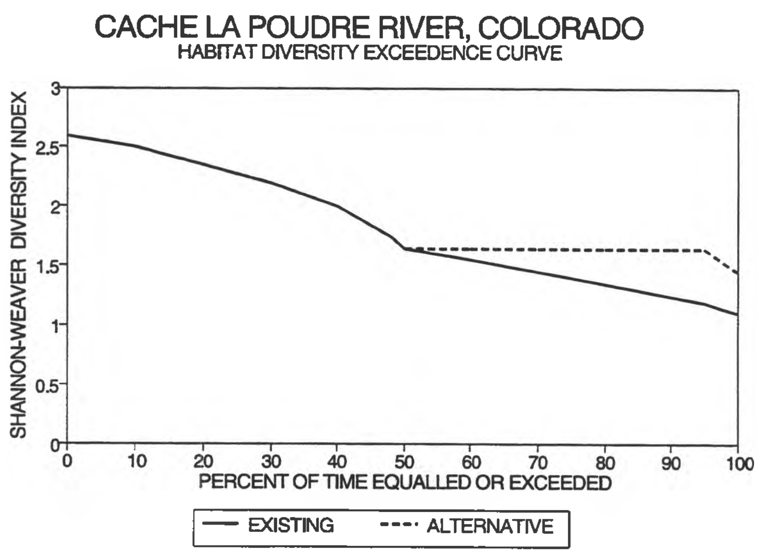

Figure 6. Comparison of habitat diversity under two alternative operating regimes, Cache la Poudre River, Colorado.

disadvantages of diversity indexes is that it is impossible to tell from the index alone, when one species has been replaced by another. It is conceivable that by subdividing a variable too finely there will be so many microhabitat classes that the number of classes remains about the same regardless of the discharge. The net result would be a loss in sensitivity to changes in discharge. As an experiment, I increased the number of microhabitat classes from 19 to 32 and recalculated the habitat diversity versus discharge function (Figure 7).

Although the two curves in Figure 7 are similar, there is one subtle difference that might be important: the differential between the minimum and maximum diversity values was considerably greater when 32 classes were used. Consequently, the improvement illustrated by the example would have appeared to be greater if diversity had been computed on the basis of a larger number of classes. Whether this difference would have altered the conclusions regarding the alternative is debatable, but the effect of larger numbers on decision makers is not. This finding suggests that the results can be manipulated by changing the scale of the analysis...at least up to the point that using too fine a scale results in the same diversity at all discharges.

To resolve this problem, I recommend that the divisions for microhabitat scales be defined following the general approach for habitat guilds as proposed by Bain and Boltz (1989). Where the actual cut-off points occur between shallow and moderate depths or between slow and moderate velocities is probably less important than the number of increments used to define shallow or slow. The guidelines provided by Bain and Boltz (1989) may be useful in defining these increments.

Biological Relevance of Habitat Diversity: Some Hypotheses.

From the late 1970's to the late 1980's, a debate emerged among community ecologists regarding the causative mechanisms regulating community structure. At the centre of the debate was the importance of equilibrium (deterministic) and nonequilibrium (stochastic) processes to assemblage dynamics.

The deterministic school maintained that species assemblages are generally at equilibrium and that species avoid competitive exclusion through biological processes such as resource partitioning or predation on ecological dominants (Grossman *et al.*, 1982). According to this hypothesis, one process by which competition is avoided is through diversification of the realized niches among species. Consequently, one could expect that an environment providing a wide variety of physical niches would support a diverse food base, suitable reproductive habitat for a variety of species, and living spaces for all life stages of many species. In short, a diverse physical environment should support a more diverse biological community than a simpler environment that provides less variety.

The hypothesis that community structure is regulated through nonequilibrium processes emerged during the late 1970's. Connell (1978) presented evidence that biological diversity in tropical rain forests and coral reefs is a function of disturbance. According to this school of thought, competitive exclusion only occurs in a stable environment and in nature, the physical environment is rarely stable long enough to allow an equilibrium to develop. Species assemblages are determined through differential responses to

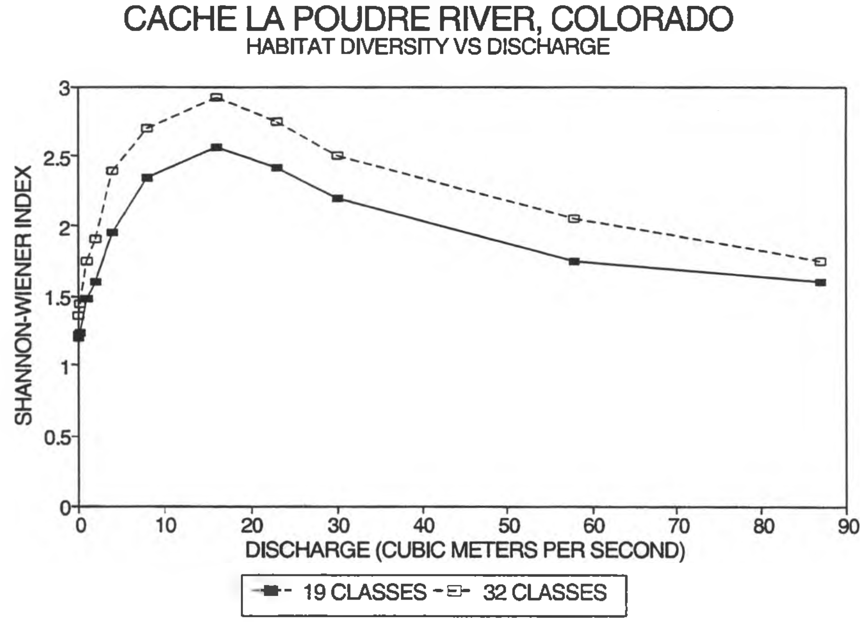

Figure 7. Effects of scale on the habitat diversity versus discharge function, Cache la Poudre River, Colorado.

unpredictable environmental changes rather than through biological interactions (Weins, 1977). The intermediate disturbance hypothesis predicts that communities subjected to intermediate levels of disturbance will maintain a higher diversity than those experiencing either less frequent or more frequent perturbations (Connell, 1978; Ward and Stanford, 1983).

Grossman, *et al.* (1990) reviewed ten studies conducted since 1974 to test the mechanisms by which species assemblages were determined in streams. The authors of four studies (Moyle and Vondracek, 1985; Matthews *et al.*, 1988) concluded that the stream fish communities they investigated were regulated by deterministic processes. Two others (Meffe and Berra, 1988; Ross *et al.*, 1987) suggested deterministic regulation. One (Grossman *et al.*, 1982) concluded that the stream fish community was regulated by stochastic processes, and one (Freeman *et al.* 1988) suggested a possible stochastic connection.

Gelwick (1990) presented evidence of both processes at work in a stream in Oklahoma. The pattern of species richness and abundance in pool assemblages was associated with habitat size and complexity, whereas temporal variation was a more important determinant in riffle assemblages. Gelwick's (1990) findings suggest that both sides may be right. Perhaps community structure in some streams is determined through stochastic processes, and by deterministic processes in other streams. Perhaps species diversity is related to the physical diversity of the stream and to the relative stability of that physical diversity over time. The habitat diversity time series and duration models proposed in this paper may provide a means of testing these relationships. Accordingly, I propose the following general hypotheses and encourage their testing by the ecological research community:

1. Streams having high habitat diversity will support more diverse biological communities than streams having low habitat diversity (in the same ecoregions).

2. Streams exhibiting a moderate amount of temporal variability in habitat diversity (as determined from the habitat diversity duration curve) will support more diverse biological communities than streams exhibiting either very high or very low temporal variability.

3. Biological communities in streams exhibiting little variation in habitat diversity over time will be stable and persistent.

4. Biological communities in streams exhibiting large variation in habitat diversity over time will not be stable or persistent.

In one of A.A. Milne's stories, Winnie-the-Pooh and Piglet discuss the Heffalump. Although neither could describe a Heffalump, they were sure of its existence and were of like mind that they would recognize one if they ever saw one. In some respects, biodiversity may be the natural resource manager's Heffalump of the 1990's. The example presented in this paper shows how various outputs from IFIM can be translated into community metrics, and how such metrics might be used in a management context. Developing the metric or applying it is relatively easy. Testing the aforementioned hypotheses will be more difficult, but achievable. The real difficulty may be in making the philosophical leap from managing for species to managing for diversity and convincing decisionmakers that it is a worthwhile thing to do.

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Post-regulation Morphological Change and Development of Riparian Vegetation Along Peace River: Predictions and Initial Observations

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Abstract

Predictions are made of the downstream effect of regulation of Peace River at W.A.C. Bennett Dam on the morphology and riparian vegetation. Anticipated changes in channel morphology are estimated from regime equations for Albertan gravel-bed and sand-bed rivers. Projected changes in riparian vegetation communities are based upon observed patterns of change around Taylor, British Columbia, and upon succession theory. A longer term view of vegetation changes is gained by mapping from air photos. Flow regulation will reduce the river width by about 40 per cent in the gravel-bed reach and about 25 per cent in the sand bed reach; mean depths will decline by 25 per cent and 15 per cent; mean velocities will be reduced by less than 10 per cent. The channel will be stable in the gravel-bed reach, except in the vicinity of tributaries delivering significant volumes of sediment. Active adjustments will occur in the sand-bed reach. The riparian succession will be complex and will depend upon both prior history at the site and contingencies such as fire, disease, and animal activity. The potential habitat that the riparian communities will provide will depend upon their distribution and connectedness, as well as the species present.

Introduction

Since 1968, Peace River has been regulated at W.A.C. Bennett Dam, constructed in Peace Canyon near Hudson's Hope by the British Columbia Hydro and Power Authority (Figure 1). The purpose of this paper is to present some preliminary estimates of the effect of regulation upon the morphology and riparian vegetation of the river along the 1250 km downstream course.

The estimates are preliminary because they are based upon predictions from alluvial river regime relations, and from observed patterns of riparian succession in only a small number of sites. Field work thus far has been restricted to the 155 km reach between Hudson's Hope and the British Columbia-Alberta border, and field studies of vegetation succession have been conducted in an even more restricted reach near Taylor, British Columbia. Moreover, the time scale for adjustment of such a large river is on the order of centuries, so that only the early part of this adjustment has so far been observed. The adjustments of the riparian vegetation are not necessarily synchronous with the morphologic

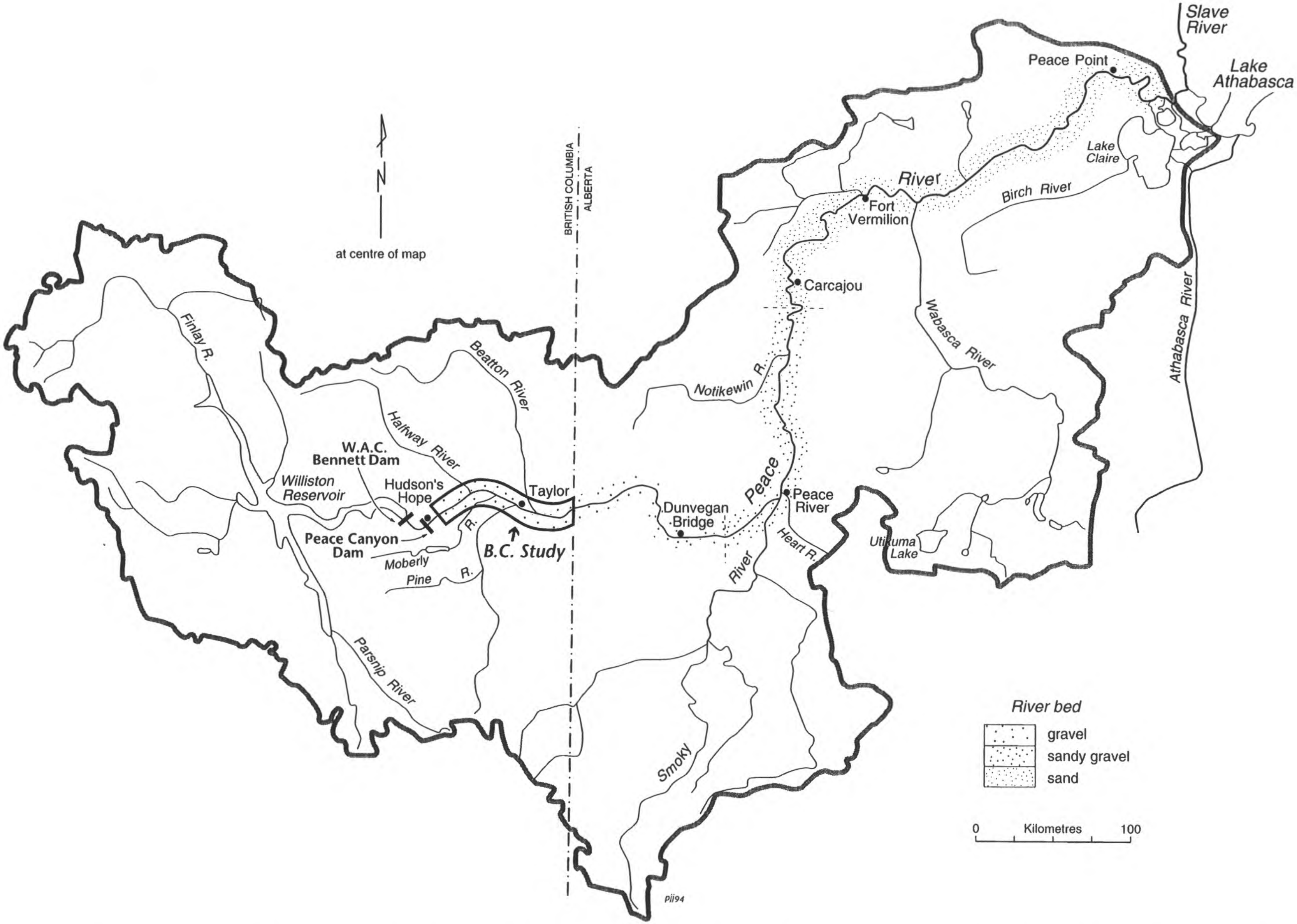

Figure 1: Peace River basin, showing principal places mentioned in the text, and the extent of the gravel, transition and sand reaches downsteam from Bennett Dam.

changes as the different plant species have different lifespans and different response times to altered environmental conditions.

Peace River along most of its course flows in a major valley that is incised several hundred metres below the adjacent prairie level. The river is partly confined and so the floodplain is narrow and discontinuous. The river frequently flows against the valley walls. The bedrock is composed of poorly lithified Mesozoic and Cenozoic sediments which are relatively easily eroded. Consequently, basal erosion by the river has induced frequent major landslides. The incidence of failures is perhaps one every few decades at some place along the river.

The questions of morphological and riparian adjustments along the river are of substantial scientific interest. The opportunity to observe a major regime adjustment in a large river, uncomplicated by other human activities, is relatively exceptional. Consequently, alluvial regime relations -- originated in the study of unlined irrigation canals -- have rarely been critically tested in application to rivers. Furthermore, riparian succession in boreal ecosystems remains a largely uninvestigated topic. The closure of the dam represents something of a large-scale experiment, insofar as the regime change is known and is relatively simple. The river downstream exhibits both cobble-gravel and sand bed reaches, and a sandy gravel transition (Figure 1), so that contrasting styles of adjustment determined by different alluvial substrates may be observed. This comparison is not perfectly well controlled inasmuch as the sandy reaches occur downstream from the confluence of Peace River with Smoky River. The latter is the largest single tributary of Peace River and the effect of the flow regulation is substantially diminished downstream.

Imposed Hydrological Change

For most water resources purposes, mean flows and minimum flows are the focus of concern. However, in considering morphological changes along the river, the incidence of relatively high flows that are competent to move the sediments which make up the bed and lower banks of the river is of central interest. Furthermore, the development of riparian vegetation is sensitive to the incidence and persistence of high stages which saturate soils or inundate sites. Accordingly, the flood regime of the river is analysed briefly.

The incidence of floods is modulated by short-term fluctuations of climate. Such fluctuations are well-known in the climate records of western Canada (cf. Barrett, 1980), so it is useful to restrict comparisons to specific periods. The gauging history along Peace River practically restricts pre-regulation flow analysis to the ten year period 1958-1967. A post-regulation comparison is based on the years 1980-89. This avoids the peculiar regime of the first two post-regulation years when the reservoir was being filled and also the significant climate transition that occurred in the mid-1970s. The comparison periods are very short and little significance should be invested in the details of the comparison.

Figure 2 illustrates the magnitude of the mean annual flood (MAF) measured at gauging stations along the river during the two periods. At Hudson's Hope the post-regulation MAF is only 32 per cent of the pre-regulation figure. At Peace Point, it is 58 per cent of the pre-regulation value.

Figure 3 displays flood frequency graphs for the principal hydrometric stations based on the same 10-year periods. It is apparent from this figure that the magnitude and variability of flood flows are much more severely reduced in the cobble-gravel reach upstream of the Smoky River confluence (just upstream of the town of Peace River) than below it. Nonetheless, at Peace River town, the former MAF has become a 20-year event after regulation, and a former 10-year event is now a 90-year flood.

From the perspective of riparian vegetation, high stage is more significant than high flow. The relation between high stage and high flow is not simple on Peace River. As a northward flowing, boreal river, ice jams are prone to create high water during the early spring ice-drive when the flow is not particularly high. A comparison between open-water flood levels and breakup levels during the pre-regulation period for Peace River at Fort Vermilion (Gerard and Karpuk, 1979) reveals that, eventually, the highest water levels are associated with breakup. Regulation will have influenced the character of winter ice formation and breakup as well as water levels during the open water season. It remains to perform comparable analyses for the post-regulation period.

These data form the basis for some predictions about the eventual mean morphology of the river in the regulated regime.

Predicted Changes in Mean Channel Geometry

Alluvial river channels conform to alluvial regime scales first developed for the design of unlined irrigation canals (Lindley, 1919; Lacey, 1930). Relevant equations, which have also been called -- in application to river channels -- equations of "hydraulic geometry" (Leopold and Maddock, 1953) are as follows:

$$w_s = aQ^b \quad (1)$$

$$d_* = cQ^f \quad (2)$$

wherein w_s is river surface width; $d_* = A/w_s$ is hydraulic mean depth and A is cross-sectional area of flow; Q is a "channel-forming flow", and the other notations indicate coefficients. Because $Q = w_s d_* v$ by definition, wherein v is mean flow velocity, equations (1) and (2) induce a third relation

$$v = kQ^m \quad (3)$$

The coefficients, a, c and k take on values that vary according to the nature of the bed and bank materials of the river. However, the coefficients b, f and m appear to be well-constrained.

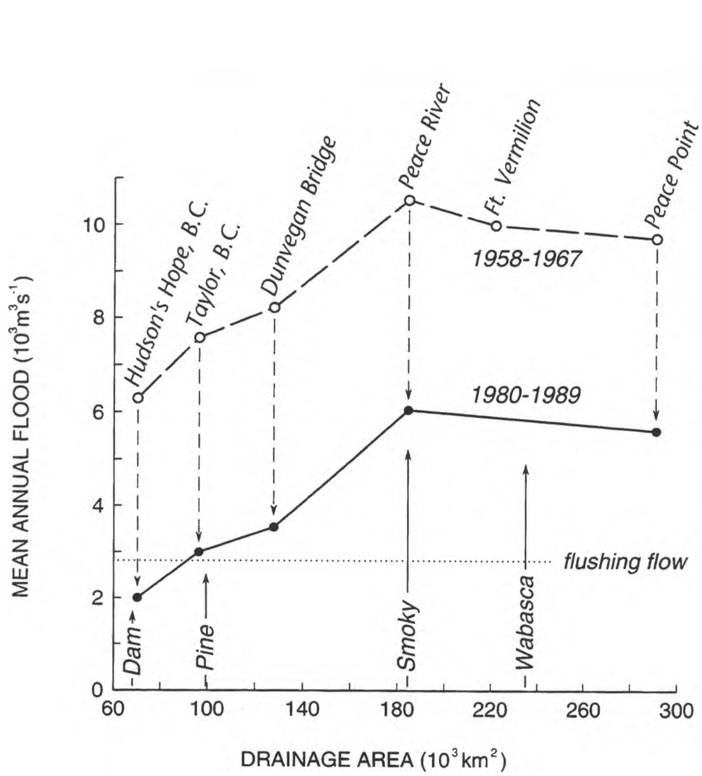

Figure 2: Observed mean annual flood in Peace River downsream of Bennett Dam for periods before and after regulation. "Flushing flow" indicates the minimum flow specified for maintaining aquatic habitat and water quality.

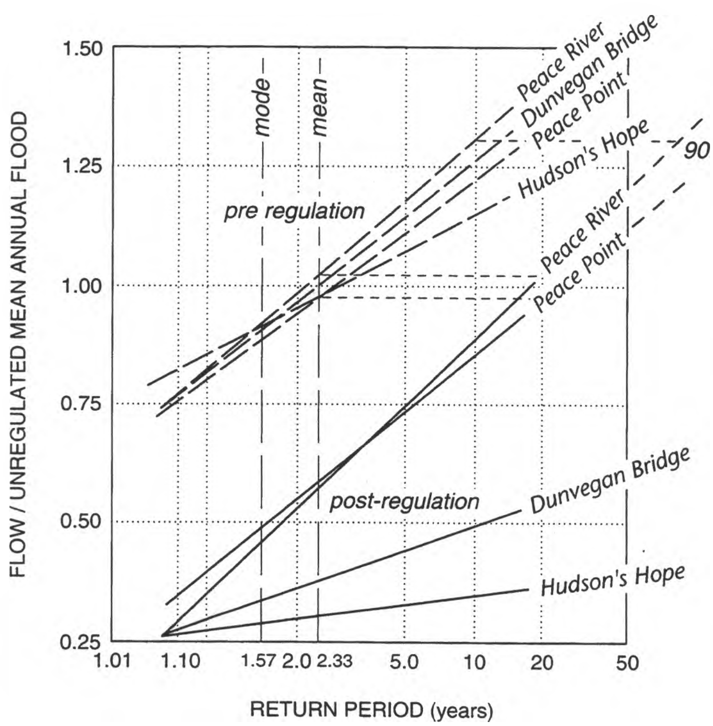

Figure 3: Flood frequencies at principal gauges on Peace River, before and after regulation. Each plot is based on a 10-year record only and should not be interpreted to indicate long-term conditions.

In fact, expected morphological adjustments can be calculated by forming the ratio of regulated (r) to unregulated (u) values; e.g.,

$$w_{sr}/w_{su} = (Q_r/Q_u)^b \qquad (1a)$$

The coefficients cancel provided that the regime type (i.e., bed and bank material) does not change.

A scale equation of the same form is available to describe the relation between flow and meander or riffle spacing. In this relation, the exponent is accepted as 0.50.

In canals, the channel-forming flow is well-defined (it is the full design flow), but in rivers it is clear only that, to predict a morphologically meaningful result, we require a flow that closely approximates the "bankfull" flow of the river: that is, the flow when the wetted cross-section occupies the entire channel between the trimlines of terrestrial riparian vegetation. Some analysts have claimed that this is equivalent to MAF, but it is clear that this is not true everywhere. For present purposes, the exponents of the equations are set by adopting results from analyses of Albertan rivers (i.e., of rivers in the same hydroclimatic zone as Peace River: see Figure 4). The gravel-river data are related to MAF, but those for sand-bed rivers are related to "bankfull", which varies in recurrence frequency from 2 to 20 years in the sampled rivers. For predicting changes, MAF values are used. Predicted changes are based upon the ratios of regulated to unregulated flows, and the ratios will be closely approximated by the MAF values even if the actual flows appropriate for Peace River should have a somewhat different frequency. Because of this, the procedure is conservative.

Results are presented in Table 1. In the gravel-bed reach above the town of Peace River and the Smoky confluence, widths are predicted eventually to be about 60 per cent of present widths, and depths about 75 per cent. Downstream of the Smoky confluence, width and depth adjustments are expected to be about 75 per cent and 83 per cent of preregulation values respectively. The change in velocity will be of order 10 per cent or less everywhere along the river.

Predicted Changes in Channel Pattern

Details of how these changes may be achieved are more difficult to quantify, because they depend upon the competence of the regulated river to move alluvial sediments supplied by the tributaries and resident along the main river. The response of the gravel-bed reach is apt to be quite different than that of the sand-bed reach.

Table 1. Predicted changes in mean channel dimensions: Peace River

Station	Q_r/Q_u	w_{sr}/w_{su}	d_{*r}/d_{*u}	v_r/v_u	L_r/L_u
exponent		0.540	0.333	0.125	0.500
Gravel reach:					
Taylor, BC	0.39	0.60	0.75	0.90	0.65
Dunvegan Bridge	0.43	0.63	0.75	0.90	0.65
Transitional reach:					
Peace River	0.58	0.74	0.83	0.93	0.75
Sand reach:					
Fort Vermilion	*0.59*	*0.75*	*0.84*	*0.94*	*0.76*
Peace Point	0.58	0.75	0.83	0.93	0.76

Estimates for Fort Vermilion based on Q_r for the period 1970-79, for which there are 8 years of record. Gauging discontinued.

The river in the gravel-bed reach was formerly a wandering channel -- frequently split about channel islands whilst maintaining an identifiable main thread along its course. Width adjustment is occurring by the following means, listed in order of relative significance:

- abandonment of formerly seasonally inundated channel bar surfaces;

- abandonment of secondary channels in split reaches;

- accretion of sand and silt to channel edges.

One result of these processes is a reduction in the total length of channel. This can be measured by the "braid index", the ratio of total channel length to the main channel length. Observations in the British Columbia reach of the river during the period immediately following regulation are summarized in Table 2.

Table 2. Change in the braid index of Peace River in British Columbia: 1967-1977 (channel length data in km)

Reach	Main channel		Back channels		Braid Index	
	1967	1977	1967	1977	1967	1977
u/s Pine River	78.5	78.8	141.4	74.7	2.80	1.95
d/s Pine River	48.7	48.7	145.7	85.2	3.99	2.75
Total (in B.C.)	127.2	127.5	287.6	159.9	3.26	2.25

Braid index = (thalweg length + backchannel length)/thalweg length

The river is no longer competent to move the cobble-gravel delivered by the major tributaries. This material is being deposited into the channel of Peace River as an "in-channel alluvial fan", which then pushes Peace River toward the opposite valley wall and also acts as a low weir. Peace River is backwatered upstream for several kilometres whilst a steepened reach is developing on the downstream side of the tributary deposits (Figure 5). Over a period of many decades, Peace River will develop a "stepped profile" between successive fans. This pattern has developed naturally in rivers in many mountain valleys of British Columbia, where tributaries draining steep mountain sides have built alluvial fans across the main valley floor. The most notable development to date is at the confluence of Pine River, at Taylor, British Columbia. Here, the channel is aggrading (Figure 6) as Pine River deposits develop. Elsewhere along this reach, there are no systematic changes in the channel cross-section. The cobble-gravel bed remains static, whilst downstream from the Pine River confluence, sand deposits are developing on bar tails and, in places, along the channel margin. Because the bed is static, the predicted adjustment in riffle spacing may not actually occur. The river is, in effect, no longer an alluvial channel.

The sand-bed reach will, however, remain active. Here, adjustments may be expected to occur as sand bars continue to build and erode.

What will happen to the gradient and planform pattern of the river is a more complex question. These two characteristics are intimately related because the easiest way for a gradient adjustment to occur is for the river to become more or less sinuous. The necessity for adjustment is mediated by the concentration of mobile sediment in the river: the greater the sediment load, the higher must be the gradient to maintain the ability of the flow to move it downstream.

In Peace River, the bulk of the sediment load enters the river from tributaries east of the mountains, so the Bennett Dam itself has had no major impact upon the sediment budget. In the gravel reach, the

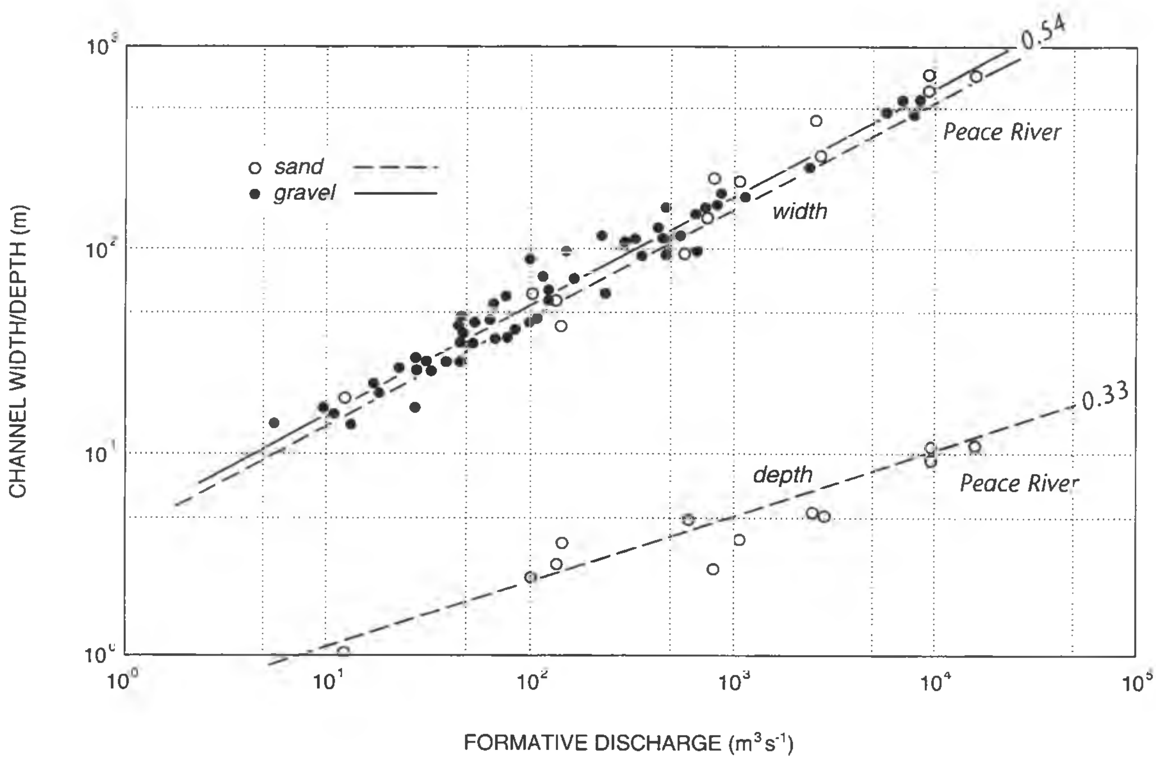

Figure 4: Regime equations for Alberta rivers (from Neill, 1973; Bray, 1982).

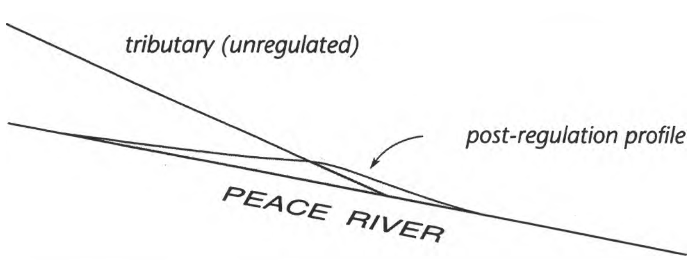

Figure 5: Sketch to indicate the effect on the gradient of Peace River of gravel accumulation at tributary mouths following regulation.

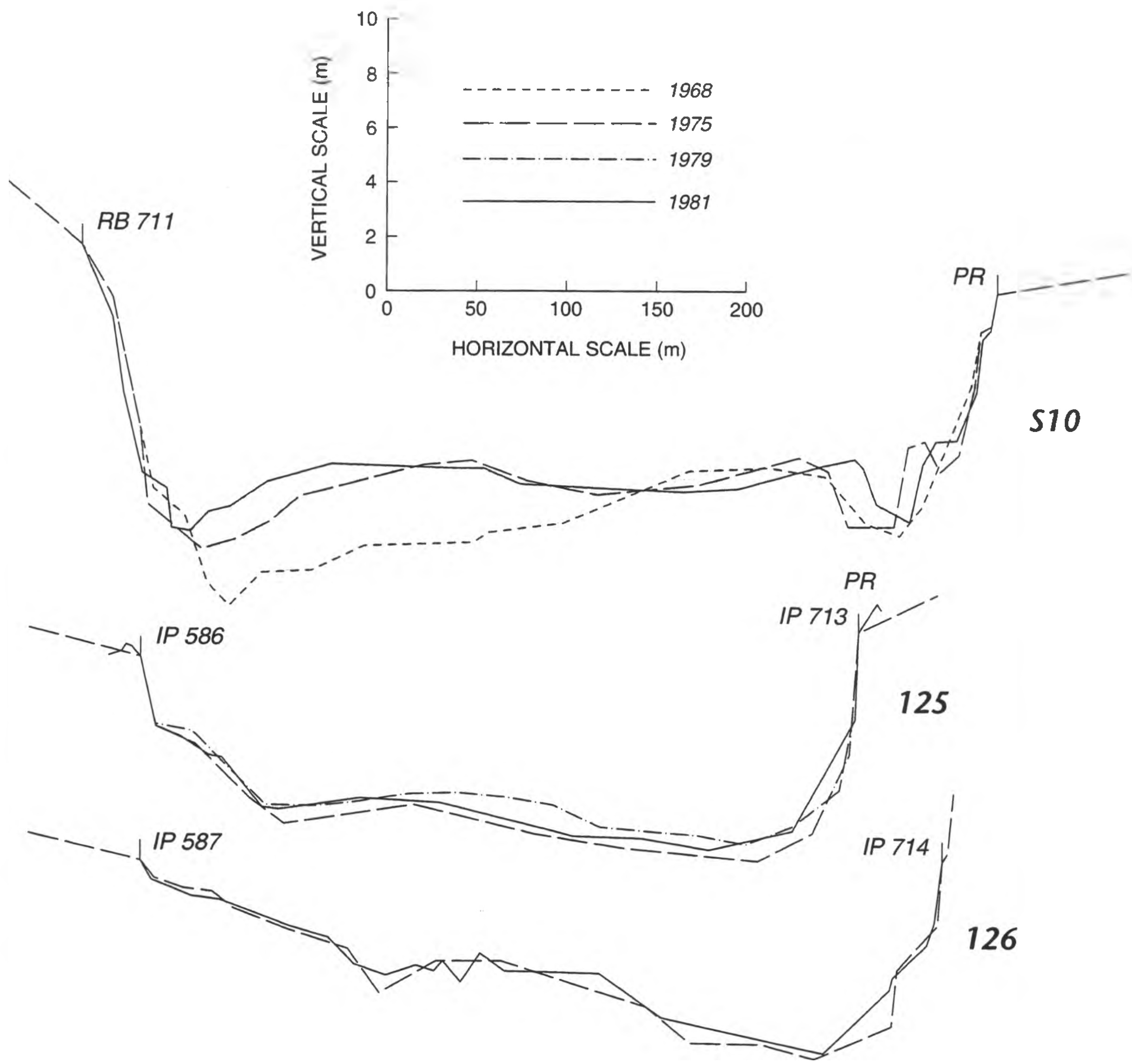

Figure 6: Cross-sections in the vicinity of the Pine River confluence.

tributaries are delivering gravel which is being deposited at their confluences. Whilst the concentration of sand will have increased (as the result of the reduction in flow), the relatively high gradient of the river is sufficient to pass the sand downstream, except for channel-side accumulations. Downstream of the Smoky confluence, however, there probably has been a significant change in the sediment balance toward higher concentrations. This will encourage an increase in gradient, or it will promote increased deposition of sand along the channel. The river is not now highly sinuous, so in the long run, a tendency for increased shoaling and island formation, and irregular lateral instability, may be detected. The predicted reduction in riffle spacing will be accomplished as part of this process. The reduction in overall channel width may in fact not be observed if, instead, channel division increases so that the total channel width conveys water less efficiently. This would, in effect, amount to a regime change in the river.

The eventual impact of these changes on the incidence of major landslides is an interesting question, but the answer cannot yet be discerned. It will depend upon whether the channel pattern changes lead to increased attack by the river on the valley walls.

The implications of the predicted morphological changes -- some of which we already see underway in the gravel reach -- are that the old floodplain will become a low terrace everywhere along the river, that former bar surfaces will become the sites of new floodplain development, and that sand accretion along the channel edges and in former backchannels will provide sites for progradation of semiaquatic and shoreline vegetation.

Riparian Vegetation

The riparian vegetation, like any vegetation, provides an historic record of the past environment as well as indicating the current environmental conditions, both for plants and for the animal species dependent on them. The plants that occupy any community are present because their seeds or propagules were able to reach these sites, the environment was suitable for their growth, and they were able to compete successfully for the available space with other plants. The conditions that allowed colonisation of a site in the past may not exist today, but once plants are established their presence may exclude the invasion of the site by other species. It is this ability of established plants, particularly the longer-living tree species, to persist in sites where they can no longer survive at the early seedling stage, that enables the use of vegetation to interpret past environmental conditions.

Because the riparian vegetation is composed of a number of more or less distinct communities, each dominated by plant species of different ages and with different tolerances to environmental conditions, the information that can be inferred about both past and present conditions along the Peace is considerable. For example, the existence of undisturbed mature coniferous forest lacking any substantial ground cover of older fallen logs would suggest that the present trees are the first generation to occupy these surfaces. The surfaces underlying these forests may be only a bit older than the trees on them. However, there is an alternative: the forest may have been subject to some regular disturbances such as flood, fire or human use that has regularly removed all large fallen trees. If this has been the case then the the underlying surfaces may be considerably older than the trees now growing there. Evidence to support the occurrence of such disturbances should exist in the soil profiles and in the traditional knowledge of the indigenous users of the area. If such evidence is not found then assumptions could be made about the minimal ages of some of the riparian surfaces.

Species distribution and composition of communities provides other useful information. Correlation of species with soil texture in the rooting zone indicates that certain species preferentially colonise on certain textures. These textures are inherited characteristics from the river deposits. Analysis of the present species composition forms the basis for prediction of the future species on that site. These two types of information allow the development of a hypothesis about plant succession. The hypothesis has generated a model of succession on different substrates (Figure 7). Normally plant succession is slow and thus it takes a long time to observe and to validate a model, but observation periods can be extended by the interpretation of air photographs that date back to the 1940s. The crown composition of a community identified in 1981 can be compared with the same site in every decade since 1945 (Figure 8) and the validity of the successional model can thus be checked by post-diction.

Interfacing known habitat values of different plant species with animal species present in the area allows an estimate to be made of carrying capacity. Many of the requirements for such habitat evaluations depend not only on the plants' presence but their age, position in the structure of the community, coverage of the area and relative health. This information is gathered as a standard part of complete vegetation inventories. The spatial display of the vegetation allows the extraction of habitat potential data as well as data on the connectivity and width of these potential sites, information essential to establishing the actual usefulness of the sites for wildlife. Prediction of changes in the morphology of Peace River coupled with the ability to model the plant succession on these changing surfaces suggests that future areas of potential habitat could be forecast as well as changes in spatial dimensions that might make potential habitat useful. This type of spatial forecasting is greatly facilitated by use of a GIS system.

Vegetation Survey: 1981-1991

A survey of the vegetation of the islands and bars of the Peace River floodplain between Moberly River and Beatton River was started in June 1981. The purposes of the survey were to establish the ground truth for air photo mapping of riparian vegetation along Peace River in British Columbia, to locate permanent plots in the main vegetation types identified, to sample the plots in order to describe the vegetation accurately, and to provide benchmark data for further study. The plot data were used to develop a model of succession of the riparian vegetation and to establish links between plant cover and geomorphic processes.

Air photo interpretation and mapping was initially based on infra-red photography flown in 1977 at 1:46,000 scale. False colour IR provided sharper definition of dominant deciduous trees and shrubs than does conventional photography. Twelve cover types were delimited on the 1977 photos (Table 3) and were examined in the field in 1981. Ground truthing involved rapid reconnaisance from the river and

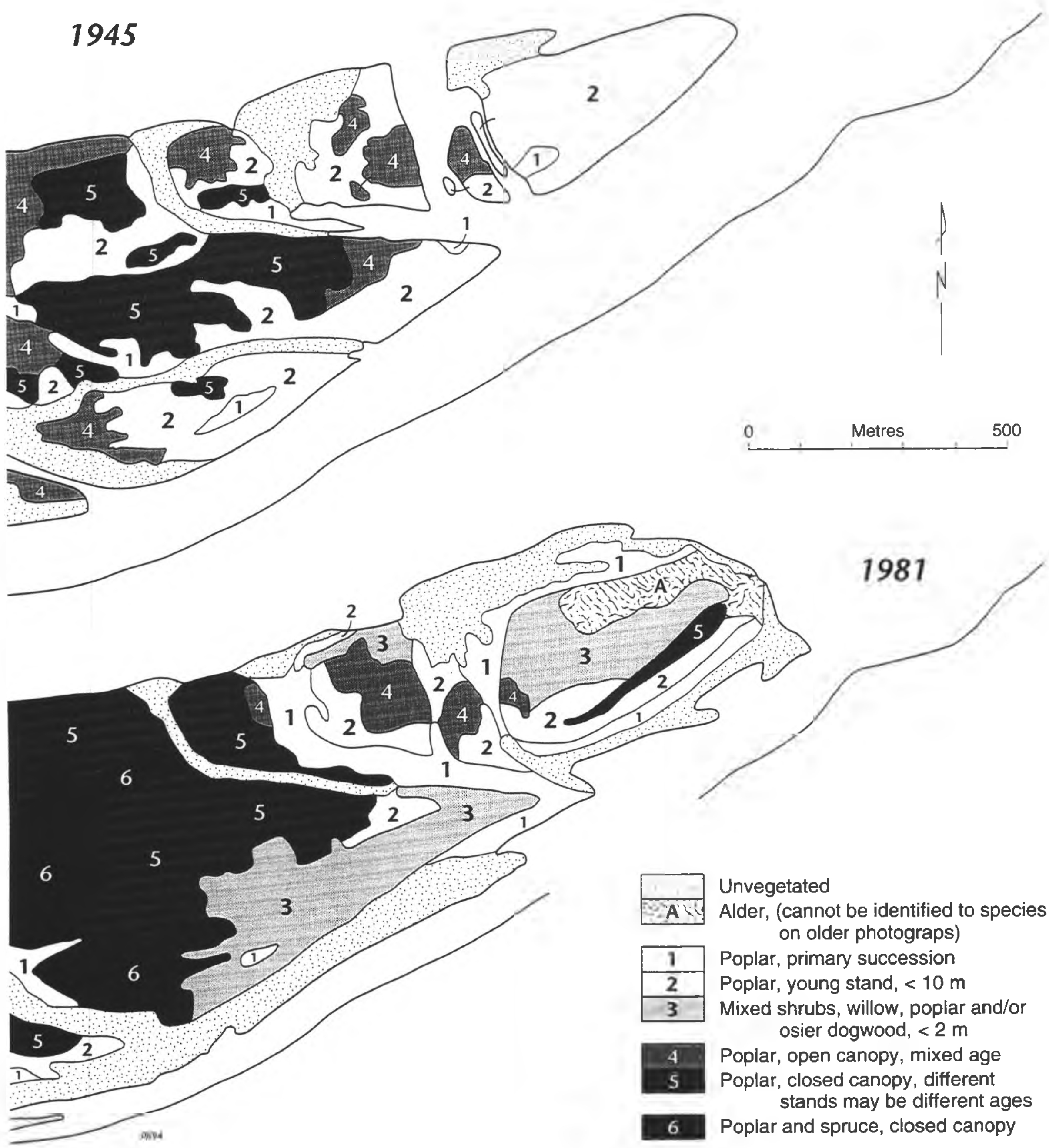

Figure 7: Comparison of riparian vegetation in 1945 and 1981, channel island near Moberly River, British Columbia.

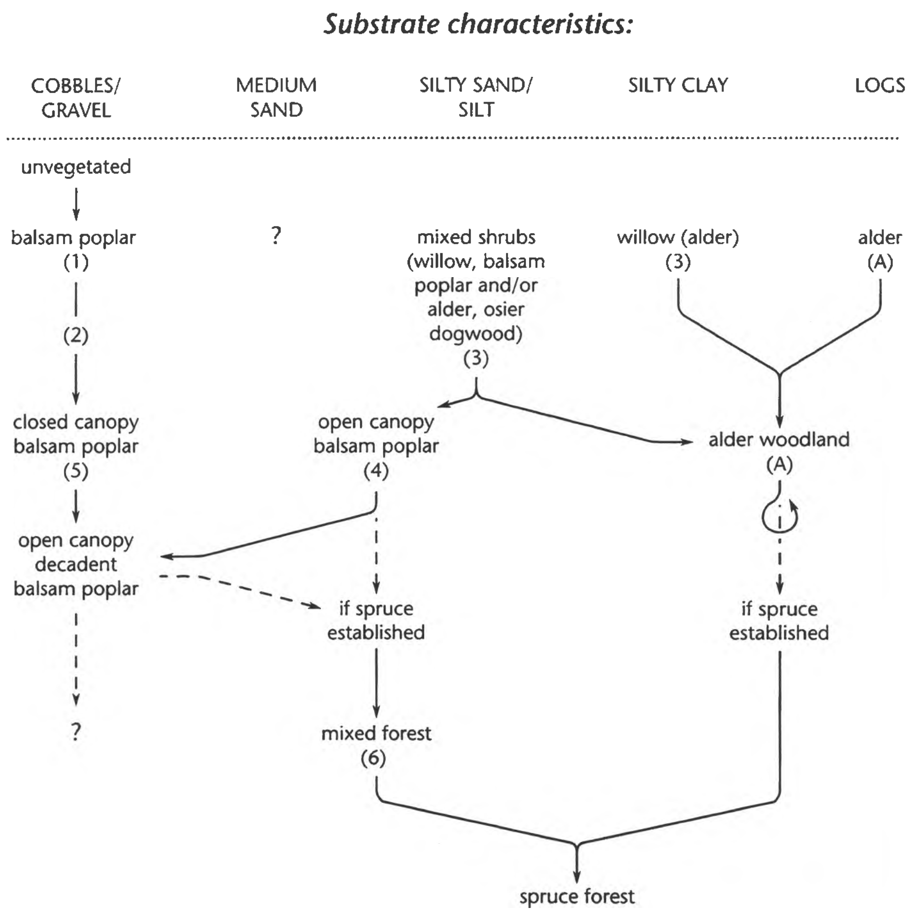

Figure 8: Model of riparian vegetation succession. The solid lines indicate the direction of succession on different substrates. The dashed lines indicate different paths that may be followed depending on the availability of spruce seed. Numbers in parentheses refer to communities delimited on the maps in figure 7. The alder community cannot be identified on the 1945 photographs.

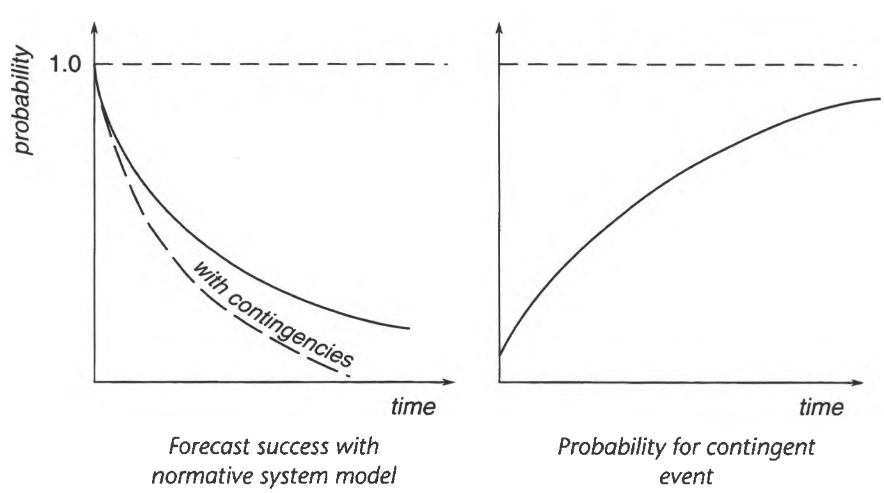

Figure 9: Forecast success as a function of time.

transects on foot of many of the riparian areas. Location of permanent plots for detailed study was arbitrary, constrained by the need to represent each cover type, by accessibility and by the need to ensure long term security of the sites. Nine vegetation types were studied in permanent plots. A duplicate set of sites was set up and recorded. One transect was taken into a back swamp. Table 4 lists the data recorded at each site.

Table 3. Vegetation of the Peace riparian zone between Moberly and Beatton Rivers.(Numbers in brackets refer to communities delimited on the maps in Figure 8.)

SHRUB COMMUNITIES
Primary succession of Populus balsamifera (2)
Young poplar, under 10 m. (3)
Young willow (Salix spp.), under 2 m. (4)
Mixed shrubs, willow, poplar, &/or osier dogwood (Cornus stolonifera), &/or silverberry (Elaeaganus commutata) (4)

WOODLAND COMMUNITIES
Alder (Alnus incana) 2-10 m.

FOREST COMMUNITIES, DECIDUOUS
Poplar, open canopy, young stands (5)
Poplar, closed canopy, different units may be different ages (6)
Mature poplar in open stands, varying heights within stands, shrubs beneath (no sample plots, presumed to be disturbed)
Decadent poplar (7)

FOREST COMMUNITIES, MIXED
Poplar and White spruce (Picea glauca) (8)
White spruce and poplar, the spruce overtopping the poplar (8)

FOREST COMMUNITIES, CONIFEROUS
White spruce (9)

Table 4. Vegetation plot* data.

Species list** arranged by height/strata:
Trees, main canopy and understorey
High shrubs (2-10m)
Medium shrubs (1-2m)
Low shrubs (30cm-1m)
Herb layer, including shrubs >30cm
Mosses and lichens
Plant cover for each species in each strata, recorded on a 6 point scale.
Total number of trees per plot, living and snags.
Height and DBH of selected trees in each plot.
Soil depth, nature of litter, texture and substrate.
Two ground photographs taken into the plot.

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* The specific location of the plots are given in the vegetation report included in Church and Rood (1982).

** An herbarium of the species collected has been made and species determinations have been authenticated at the UBC Herbarium.

Predicted Changes in Vegetation

The model of succession appears to be validated by post-diction but there is no certainty that future imposed flows will maintain either the total volume or regime that is necessary to maintain the existing succession or to allow the initiation of primary successional stages that have previously existed.

Preliminary examination suggests that the rate of successional change as well as the direction of change may be less predictable in the future. Observations that lead to these conclusions include the following.

i) Shrub communities in certain locations are remarkably persistent. Field examination at several sites show that shrubs have been "scythed off" about a metre above the surface. Both willows and poplars sprout from the broken, inverted v-shaped stems, producing a dense, and painful, thicket of shrubs. The frequency of the "mowing" appears to prevent the establishment of tall trees and the assumed succession to a poplar forest. The cause of this repeated disturbance is assumed to be ice riding up into these sites at the break-up, presumably behind temporary ice dams.

ii) The persistence of poplar forests appears to be related to the absence of a spruce seed source. The commonest "invasion" route for the spruce is along the banks of the river on trails created by animals. These paths are often lined with young spruce, though no seed source is anywhere near. Many of the larger animals shelter under the mature spruce trees and the cones become caught on their fur or hair and fall off at a later time when the animal is brushing against plants on a narrow path.

iii) The expected result of the back channels filling in and becoming dry enough for the spread of willow communities is becoming apparent. The transect is particularly useful to monitor this change. However the rate at which such primary succession takes over these abandoned side channels seems to vary depending on the regularity with which the channel is filled from the downstream end by water ponded behind ice jams. Annual flooding may impede the primary succession.

iv) The rapidity with which the mature poplar stands have become decadent and started to fall was rather surprising. Rood's (1990) review of the literature on downstream effects of flow regulation on cottonwoods further south suggests that this effect may be due to a reduced incidence of flooding leading to site impoverishment. Examination of the mortality rates and the soil characteristics of mature stands of similar age on the Pine, and other non-regulated tributaries, should indicate whether flow regulation will lead to more rapid mortality of the cottonwood stands.

v) The species composition of the shrub layer under a closed tree canopy appears to be affected by the occurrence of plant disease. The osier dogwood (Cornus stolonifera) suffered major defoliation after 1981. Forested plots in which the shrub layer was dominated by the dogwood in 1981 now have shrub layers dominated by rose (Rosa spp.) or salmonberry (Rubus spectabilis). This type of species change may be unrelated to river morphology and it may have no significant effect on the dominant tree species, but it may have habitat implications.

Conclusions

The predictions that can be made about morphological and ecological change along the river amount, at this stage, to projections based upon our understanding of how fluvial systems similar to Peace River typically respond to regime changes. The predictions are based upon a normative model of system response. Forecast success in such circumstances becomes poorer and poorer as the time scale lengthens because the effects of imperfect forecasts accumulate (Figure 9). Deterioration in forecast success is especially notable for biological systems since significant contingent events -- events determined by developments outside the immediate system, or ones with specific antecedents not foreseeable -- will eventually affect the course of development of the system. For example, the developing river morphology may be influenced by major landslides, or by new engineering developments. The riparian ecosystem may be impacted by fire, by disease, or by unanticipated changes in water control. In the case of the riparian system, there are normal, internal factors that are impossible to predict with certainty. The path of succession may depend upon the vagaries of seed dispersal, or upon the way in which seasonal weather influences seedling viability. Most simply put, the history of the system determines its further development.

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Implications of Upstream Impoundment on the Natural Ecology and Environment of the Slave River Delta, Northwest Territories **

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Introduction

In Canada deltas constitute a very small percentage of the total land area north of the southern limit of discontinuous permafrost (as defined by Brown 1960). By comparison with other landforms in this region the biological and economic significance of deltas is disproportionately high. Because of the very high botanical productivity of nutrient-rich emergent macrophytes and the large diversity of plant species, these wetlands are important feeding, staging, and breeding habitat for large numbers of waterfowl, muskrat, and other wildlife. Studies of the economic importance of the Peace-Athabasca, Mackenzie, and Slave River deltas indicate significant use and heavy dependence on these landforms by local native populations (Peace-Athabasca Delta Project Group 1972, Berger 1977, Bodden 1981).

The impetus for studying the geomorphological process and biological productivity of deltaic environments in Canada has largely been instigated by past or proposed alterations of natural river regimes by hydroelectric power developments (Reinelt et al. 1971, Day 1971, Fraser 1972, Taylor et al. 1972, Glooschenko 1972, Richardson 1972, Armstrong 1973, Gill 1973, Kellerhals and Gill 1973, Kerr 1973, Gill and Cooke 1974, Maddock 1976, English 1979). Development of northern rivers will, to varying degrees, alter their natural flow regimes and consequently disrupt the natural environment of their deltas.

This paper will discuss the major processes governing the progradation of the Slave River Delta into Great Slave Lake (fig. 1), the relationship between landforms and plant assemblages on the delta, and potential environmental and ecological effects of a proposed upstream impoundment of the Slave River.

** This paper is reprinted from:

Northern Ecology and Resource Management, edited by
Rod Olson, Frank Geddes, and Ross Hastings
University of Alberta Press, Edmonton, 1984: pages 311-339.

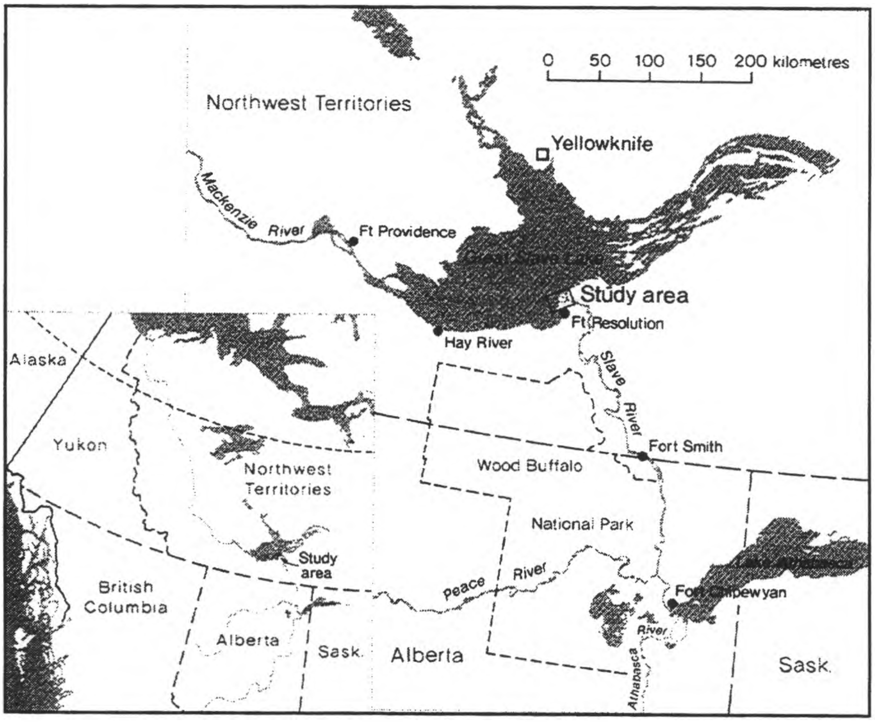

Fig. 1. Location of Slave River Delta, Northwest Territories.

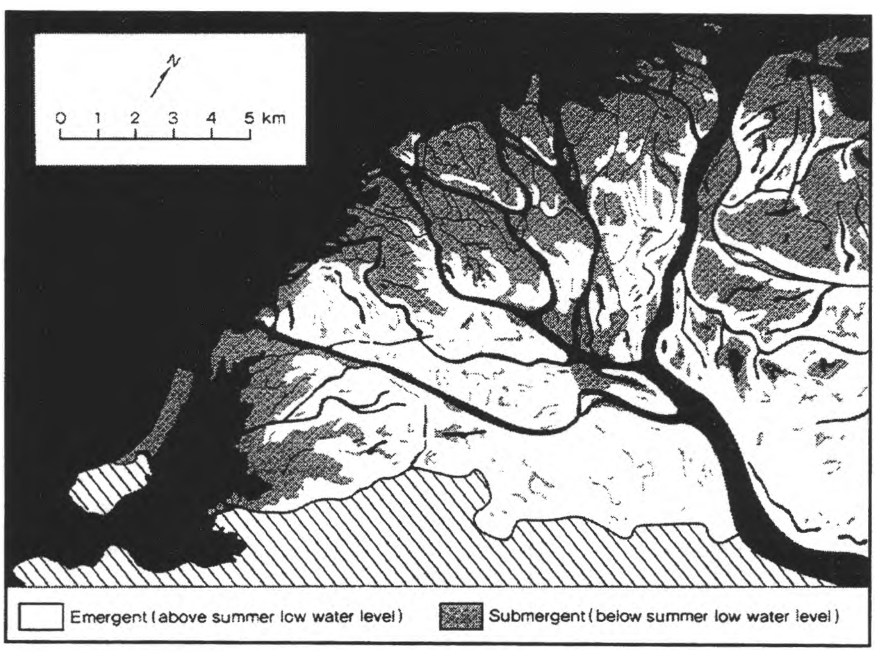

Fig. 2. Submergent and emergent areas - Slave River Delta, Northwest Territories.

Origins of the Slave River Delta

Fifteen thousand years before the present (BP) the Keewatin ice sheet extended into the southwestern corner of the present-day Northwest Territories. Tongues of the main glacier extended up the Peace and Athabasca valleys and westward into the Selwyn Mountains. Glacial retreat began in this region approximately 10,000 years BP (Bryson et al. 1969, Prest 1969), resulting in the formation of glacial Lake McConnell. Drainage of Lake McConnell through the present-day Churchill River system into Hudson Bay was impeded by isostatic rebound. Northward drainage down the Mackenzie Valley began after the Selwyn ice tongue retreated (Cameron 1922). Lowering of the glacial lake water levels resulted in the differentiation of this large body of water into two separate lakes: present-day Great Slave Lake and Lake Athabasca. Alluvial material carried by the Peace and Athabasca rivers entered the southern arm of Great Slave Lake via the Slave River, and formation of the Slave Delta began. As lake levels dropped, the southern arm of Great Slave Lake slowly filled in with alluvium to its present position, where the active delta still progrades into the lake.

The Active Delta

The active delta of the Slave River is approximately 300 km^2, which is roughly 3% of the area of deltaic deposits occupying the old southern arm of Great Slave Lake. The semi-aquatic nature of the active delta is illustrated in fig 2. Fifty-one percent of the delta is submergent, either at or below the summer low-water level of Great Slave Lake. The remaining 49% is emergent, above the summer low-water level.

Botanically and geomorphologically the Slave River Delta can be divided into three distinct areas: the outer delta, the mid-delta, and the apex (fig. 3). Further, the outer delta consists of three zones: the submarine delta, and the exposed and protected areas of the subaerial delta. The geomorphological and botanical differences between the three areas relate primarily to their relative elevations above either the lake or river summer low-water levels and thus to the frequency of spring flooding. The subaerial levees in the outer delta rarely exceed 0.5 m above river/lake summer low-water levels (fig. 4). Generally the vegetation in the outer delta consists of semi-aquatic emergent plants and *Salix spp*. (fig. 5). In the mid-delta, levees range between 1.0 m and 2.0 m above summer low-river levels. Plant assemblages in this portion of the delta are diverse, ranging from *Equisetum* to *Populus* assemblages. The *Alnus-Salix* assemblage is by far the most representative assemblage in the mid-delta (fig. 6). Levees along active distributaries in the apex project 2.0 m to 3.0 m above summer low-river levels. The *Picea* assemblage dominates the apex (fig. 7).

Ninety-five percent of the landform types comprising the outer delta are submergent. As a consequence of annual spring flooding, nutrient-rich sediment is deposited on the large expanses of *Equisetum* assemblages occupying the interlevee depressions in the outer delta. The annual influx of sediment is essential for the maintenance of high productivity in these assemblages. *Equisetum fluviatile*, the dominant plant on the outer delta, actively accumulates potassium and sodium from the sediments and water column (Shepherd and Bowling 1973). In turn, *E. fluviatile* is an important source of sodium for

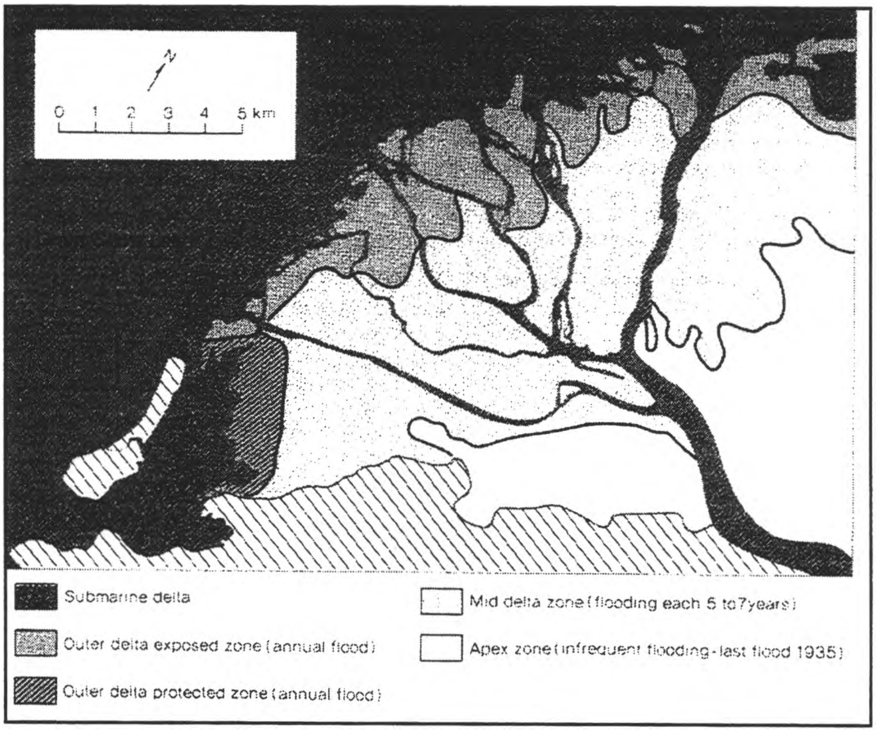

Fig. 3. Flood frequency zones of the Slave River Delta, Northwest Territories.

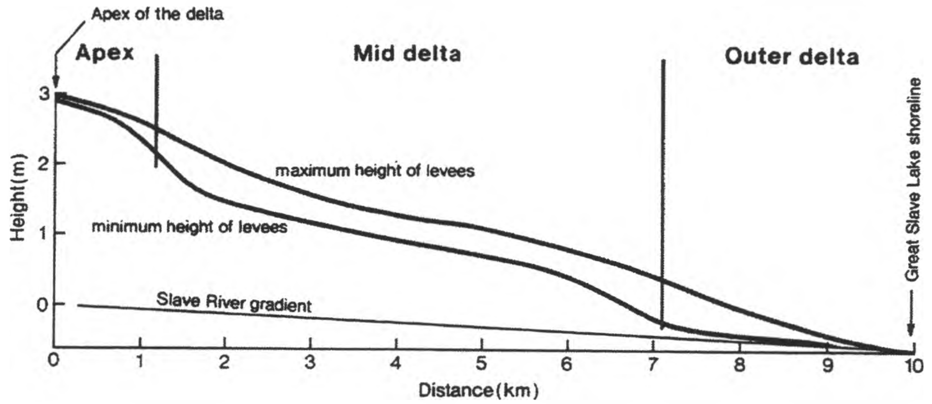

Fig. 4. Levee elevation on the three flood frequency zones of the Slave River Delta, Northwest Territories.

Fig. 5. *Equisetum* assemblage in interlevee depression of a cleavage bar island.

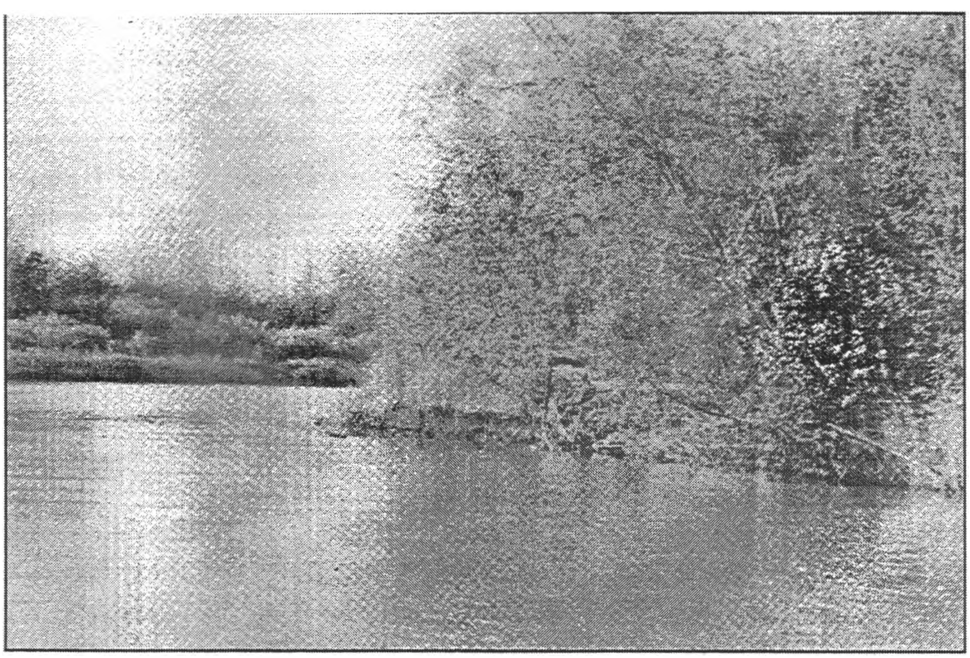

Fig. 6. An *Alnus-Salix* assemblage inhabiting a cut-bank levee.

herbivorous animals (Hutchinson 1975) such as the large and economically important muskrat population that inhabits the Slave Delta (Geddes 1981).

The mid-delta area is transitional between the water-dominated landscape of the outer delta and the elevated, relatively dry apex area. Twenty-five percent of the mid-delta is aquatic. Approximately 50% of the aquatic area is comprised of former channels now elevated above the summer low water levels by sedimentation during occasional spring flooding. The remaining portion of the aquatic area of the mid-delta consists of channels that remain partially open to the river's seasonal fluctuations. Soil profile records and verbal accounts from local residents indicate that flooding of the mid-delta occurs every 5 to 7 years. The relatively poor bryophyte development in the mid-delta zone attests to the occurrence of occasional flooding. Gill (1978) reports that areas in the Mackenzie Delta that experience sediment-rich floods support few bryophytes.

The apex is the oldest portion of the active Slave Delta. Increment boring of mature *Picea glauca* indicates that the Picea assemblage invaded these landforms approximately 250 years BP. The aquatlc areas, comprising 6% of the apex zone, are elevated above the water level of the surrounding distributaries by as much as 2.5 m. Their water supply is mainly snowmelt runoff; occasionally it is river water, when ice damming in the distributing channels instigates unusually high flood levels.

Processes

Essential to an understanding of the processes responsible for the maintenance of high biological productivity on a delta is an understanding of the intersection of a river and the large body of less-turbulent water into which it drains. The formation of the submarine sedimentary platform upon which the emergent landforms of the delta are constructed is a product of the degree of density differential between the river and the body of water into which it is draining.

According to Thakur and Mackay (1973) arcuate deltas, such as that of the Slave River, are formed when the densities of the river and the body of water into which it is flowing are equal. The buildup of the submarine platform upon which the cleavage and wave-built bars will eventually form occurs primarily at or near the mouths of the largest distributary channels, which transport the bulk of suspended sediment and bedload. The primary factor modifying and eroding the shallow submarine platform on the Slave Delta is wave action during the ice-free months. A counterclockwise current in the western arm of Great Slave Lake generated primarily by the Slave River discharge and secondarily by the prevailing northwesterly winds is responsible for removing quantities of sediment from the distributary mouths and transporting the sediment into the lake (fig 8)

The direction of the Slave River Delta's growth and the rate with which it progrades into Great Slave Lake are partly due to the reduction of the river's energy as it diverges from one channel into several. Such energy loss directly affects the ability of the river to transport bedload and suspended sediment. Hence, the deposition of sediment and formation of river bars occur near the diverging point of the main river channel. On the delta, sandbar formation due to energy reduction occurs at the confluence of the

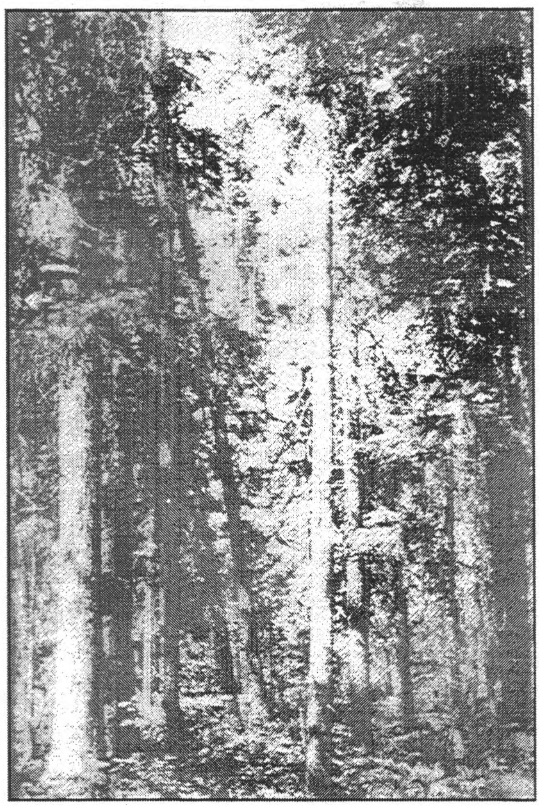

Fig. 7. *Picea* assemblage in apex zone.

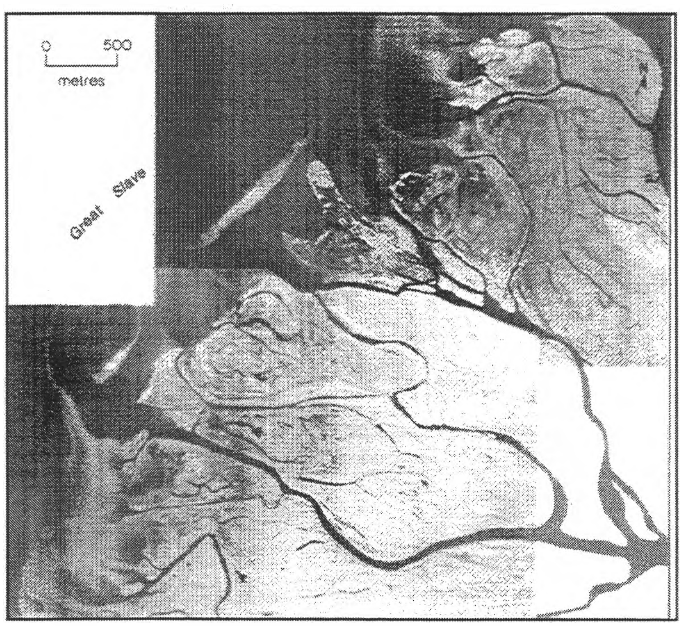

Fig. 8. Sediment discharge from Slave River Delta, Northwest Territories. The thermal imagery flown 7 September 1977 illustrates the flow of the discharging sediment. The discharge from Resdelta Channel (a) creates a current sufficiently strong to draw the discharging water from the other channels in the south along the outer perimeter of the delta. Courtesy of the Canadian Wildlife Service.

main distributaries. Significant growth of these river bars will likely occur when ice damming inhibits flow down major distributaries during the spring melt. Sand bar formation at this critical juncture in the river plays an important role in reducing discharge in some distributaries, concomitantly increasing it in others. The direction and pattern of the growth of the submarine platform, and therefore the subaerial delta, is determined by the dispersion of river energy at the distributary concourse. Deltaic growth will occur mainly at the mouths of channels where deposition of sediment exceeds the erosive capacity of the lake.

Cleavage Bar Development

The major geomorphic process operating on the outer delta is cleavage bar development. As the delta expands into the lake, cleavage bars are formed at the mouths of active distributaries. Coarse fractions of the suspended sediment and bedload are deposited along submarine levees that run parallel to the concourse of the discharging channel. Dahlskog et al. (1972) state that where lake action dominates over river discharge, the development of bars will dominate along one side of the channel mouth. Although wave action is an important force in the geomorphological development o~ the Slave River Delta, the discharge through Resdelta channel (the main distributary) offsets the effects of wave action. The lake current (fig. 8) created by the discharge of Slave River into Great Slave Lake creates a counterclockwise vortex within the western arm of the lake and is a factor in the development of submarine and subaerial landforms on the outer delta.

Fig. 9 illustrates the genesis of a cleavage bar at the mouth of a discharging channel. The submerged levee is forming in a V-shape; hence the term cleavage. The buildup of the submerged levee is largely due to the deposition of bedload during the spring flood (Dahlskog et al. 1972). When the levee builds up to a sufficient elevation, driftwood lodges on it (fig. 10) and stabilization occurs, followed by an invasion of pioneer species of emergent vegetation such as *Equisetum fluviatile*. The upstream portion of the bar matures first, and *Salix* spp. invade the cleavage bar levee, further stabilizing it. Continued development of this deposit into an enclosed cleavage bar island may be aided by the construction of a wave-built shoal along the open end of the V-shaped cleavage bar, as shown in fig. 9.

In some cases protection from the erosive action of the lake is provided by the construction of one or more levees, which may partially (fig. 11) or completely (fig. 12) seal off the open end of the cleavage bar. By using treering analysis, the duration of cleavage bar island development from the submarine levee stage was estimated for an island in the outer delta (fig. 12). The elevated upstream portion of the island was supporting Salix spp. in 1922. The two diverging arms of the cleavage bar were invaded by Salix sp. 10 years later. The levees bordering Great Slave Lake began supporting *Salix* spp. in 1963. The centres of these landforms--the interlevee depressions--support very productive stands of *Equisetum fluviatile*.

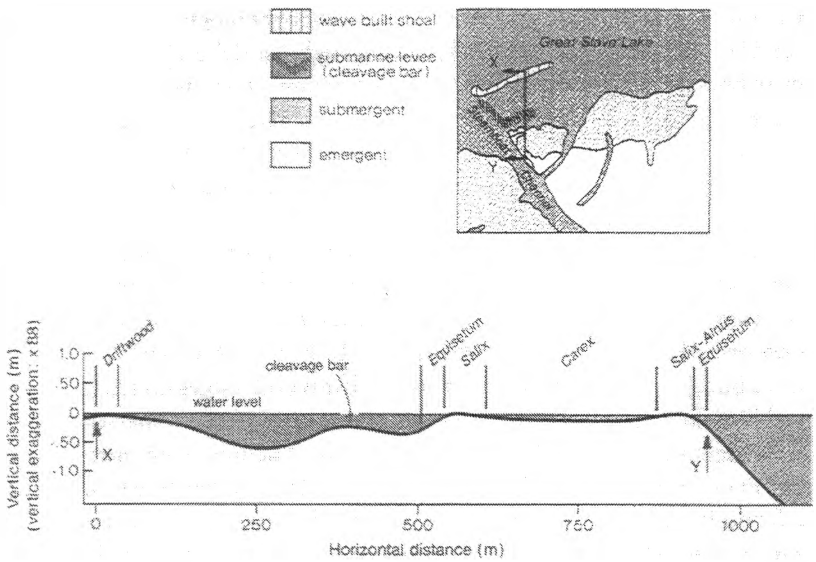

Fig. 9. Transect 14, illustrating plant assemblages and submarine cleavage bar genesis at the mouth of Steamboat Channel (sampled and surveyed 18 July 1977).

Fig. 10. Driftwood accumulation along the outer levees of the cleavage bar islands protects the developing islands from wave action. The levees are further stabilized by pioneer species of *Salix interiot* and *Equisetum fluviatile* (right centre of photo).

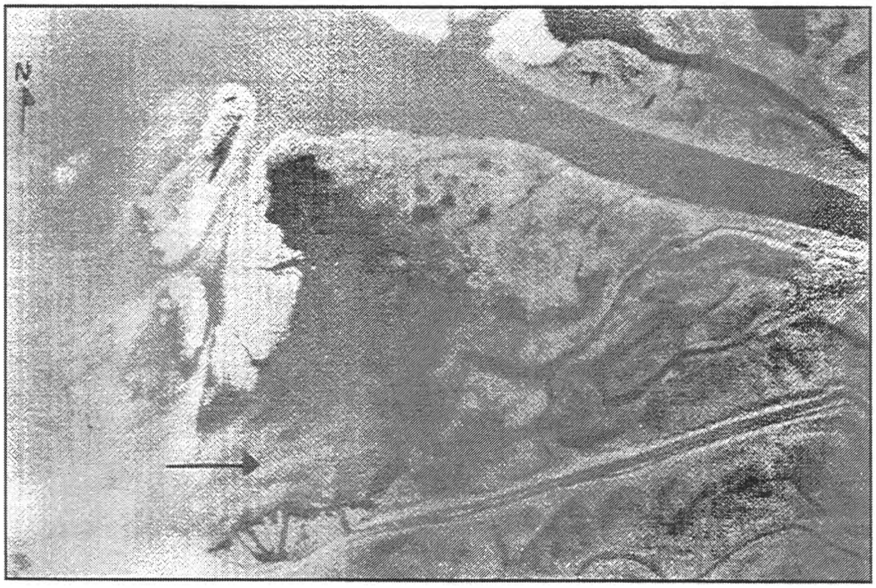

Fig. 11. Panchromatic aerial photograph of a cleavage bar island on the outer delta. This island is still partially open at the lake side (arrow), but submarine levees that are forming from each of the open ends will soon build up and close the cleavage. Courtesy of the Canadian Wildlife Service.

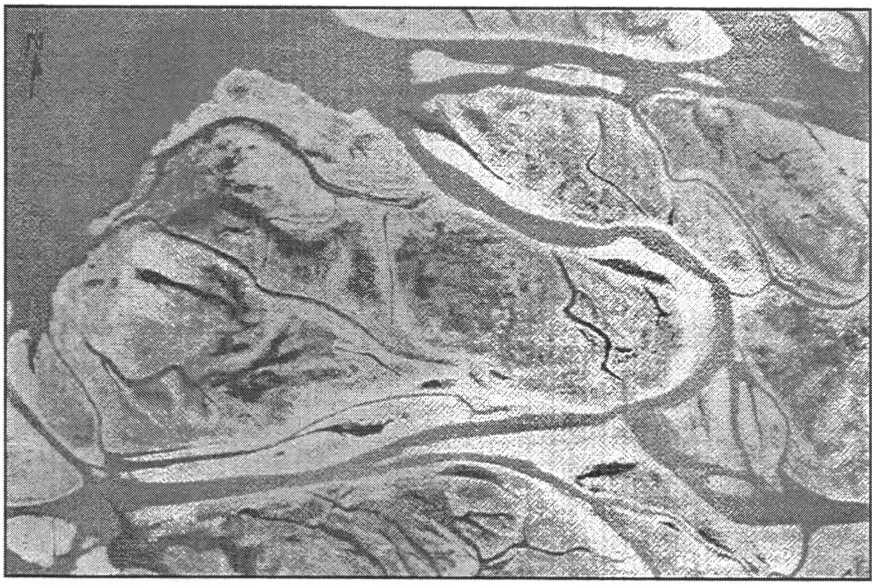

Fig. 12. Cleavage bar island formations, Slave River Delta. This complex of cleavage bar islands is in the final stage of being closed off from the lake. Levees along the outer portions of the island are inhabited by the *Salix-Equisetum* assemblage, while interlevee depressions are occupied by an *Equisetum* assemblage. Courtesy of Canadian Wildlife Service.

Botanical Development

When classifying shoreline vegetation in the Great Slave Lake-Lake Athabasca region, Raup (1975) concluded that the concept of plant assemblages was more practical than that of plant communities. Plant communities have a similar floristic composition among sample plots, which does not occur in these northern wetlands. Instead there is a wide variation in species composition among sample plots, which necessitates a term such as assemblage because it "carries few implications of relationships that are non-existent or unknown" (Raup 1975). This variation among sample plots or assemblages was attributed to ecotypic variations within populations, which in turn have been historically conditioned to the frequent flooding that occurs in these wetland areas (Raup 1975: 138).

Twelve plant assemblages have been identified on the Slave Delta (English 1979); in this chapter the nine most significant assemblages will be discussed. In those assemblages occupying landforms frequently inundated during the spring flood, succession is governed largely by environmental factors such as the elevation of the substrate above or below summer low-water levels. Allogenic succession occurs on the outer delta and on 30% of the mid-delta. The assemblages concerned are *Equisetum*, *Carex*, *Salix-Equisetum*, and *Salix*. Species composition within the assemblages suggests that Raup's previously stated observations apply to those portions of the delta under the influence of allogenic succession. On the outer and mid-delta the wide variation of species composition within a single plant assemblage is most evident in the herb layer and to a lesser extent in the low shrub layer. The frequent flooding in large areas of the delta means that the landforms have a shorter period of stability than the life span of most of the perennial plants that make up the deltaic vegetation. Thus, plant succession within the affected landforms appears fragmented.

A factor that appears to be partially responsible for the fragmented distribution of subdominant plants in the outer delta is the disruption of rooting systems by the annual formation of ice in the sediment. Where the sediment is saturated or is in shallow water (less than 25.0 cm) the temperature gradient from the sediment to the air is sufficient to freeze the sediment to a depth that includes all of the rooting systems of most plant species. The sediment freezes in a stratigraphic pattern: alternating layers of sediment and pure ice. The thickness of the individual ice and sediment layers range between 0.5 cm and 2.0 cm. Observations indicate that in those areas where the sediments are frozen, they remain so after the ice on the standing water over the sediment has thawed. The nature of the sediment-ice stratigraphy indicated that the melting of the ice layers may be delayed in the spring, thus inhibiting the development of emergent vegetation. Further, existing rooting systems may be damaged by the ice formation. These factors contribute to the fragmented distribution of subdominant plants on the outer delta.

Equisetum Assemblage

The *Equisetum* assemblage occupies the interlevee depressions of cleavage bar islands in the outer delta and the abandoned elevated channels and narrow stretches on point bars and sand bars along distributary channels in the mid-delta.

Species composition differences exist between those assemblages found in the interlevee depressions and those on the abandoned channels. Except for a reduced occurrence of aquatic plants the species composition of *Equisetum* assemblages growing on the submerged portions of sandbars resembled that found in the outer delta. *Equisetum fluviatile*, with a cover of 95%, dominates both of these habitats. This species is prominent along the littoral boundary of point bars, usually occupying a narrow strip no wider than 2.0 m. On both point bars and sandbars the environmental gradient from the littorial zone (aquatic) to the terrestrial zone (dry) is sharp, and the transition from *Equisetum* to *Salix-Equisetum* to *Salix-Alnus* occurs over a very short distance. The close proximity of the structurally taller *Salix* spp. in the *Salix-Equisetum* assemblage affects the species composition of the *Equisetum* assemblage. The shade cast by the willow results in the exclusion of shade-intolerant *Equisetum fluviatile* and the successful growth of shade-tolerant *E. palustre* in the semi-aquatic zone closest to the *Salix* assemblage. This species gradient also occurs on sand bars and some abandoned channels.

Because of annual flooding in the outer delta the species successfully occupying the *Equisetum* assemblages are either aquatic (for example, *Rorippa islandica, Lemna minor, Hippuris vulgaris, Utricularia vulgaris*) or have an adventitious rooting system (for example, *Equisetum fluviatile*, *Salix* interior). The species composition of the *Equisetum* assemblages on the elevated, abandoned channels in the mid-delta reflect an environment not exposed to annual flooding and sedimentation. *Carex rostrata* cover is more significant in these assemblages along the abandoned channels than on the outer delta. Thus it appears that the *Equisetum* assemblages will succeed to either the *Equisetum-Carex* or *Carex* assemblage. On the outer delta and point bar and sandbar sites on the mid-delta, succession of the *Equisetum* assemblage is directly related to the depth of water. Continued deposition of sediment on the cleavage bar formations, point bars, or sandbar sites will elevate the *Equisetum* beds such that *Salix spp.* can invade. With time these assemblages will succeed to the *Salix-Equisetum* assemblage. In the calm, clear water of the interlevee depressions on the outer delta, *Salix glauca*, *S. interior*, and *S. arbusculoides* grow in up to 35.0 cm of water. Although their cover is less than 5%, in water depths of less than 20.0 cm their vigour is good. The semi-aquatic nature of these *Salix* spp. may be attributable to respiratory transport of gases by aerenchyma cells on the stems (Hutchinson 1975). Similar aquatic invasion of *Equisetum* assemblages by *Salix spp.* does not occur along the active channels where suspended sediment concentrations are high. Possible reasons for this include reduced sunlight because of high turbidity and an unstable, shifting sediment bed in which the willow root.

Succession of the *Equisetum* assemblage on the outer delta and active channels of the mid-delta is different from that observed in the *Equisetum* assemblages along the abandoned channels. The reason for this successional divergence appears to be partly a function of nutrient supply and demand and the availability of direct sunlight within the different environments.

Due to the absence of tall shrubs or trees the interlevee depressions are open to incoming solar radiation. By contrast the abandoned channels are comparatively narrow (5.0 to 25.0 m wide), and the levees usually support *Alnus-Salix* or *Alnus* assemblages, with shrubs over 4.0 m high. As such, direct sunlight on the surface of the channel is reduced, especially along the shallower channel sides. Of the ten abandoned channels investigated, only two have *Salix sp.* present in the channel shallows; their areal coverage is less than 3% and their vigour is poor. *Carex rostrata* grow more abundantly and vigorously in this environment than on the outer delta or active channels of the mid-delta. As well, *C. rostrata* is a successful subdominant species in the shallow portions of abandoned channels and receives a significant number of hours of direct sunlight per day. The insignificant growth of *C. rostrata* in the interlevee depressions may be due to a combination of the substrate's pH and the calcium demand on this species. The reason for this is as follows. The aquatic nature of the interlevee depressions appears not to be a restricting factor, at least in the shallower perimeter of the landform. Hutchinson (1975) reports that *C. rostrata* may be as aquatic as *Equisetum fluviatile*, the dominant plant in the interlevee depressions. The substrate of the interlevee depressions is composed largely of decaying *E. fluviatile* and sediment. Because *E. fluviatile* actively accumulates potassium and sodium and not calcium or magnesium (Shepherd and Bowling 1973), the amount of Ca in the substrate will be low. Samples taken from several interlevee depressions had Ca concentrations ranging from 2.0 to 20.0 ppm and a pH ranging from 8.0 to 8.3. At these pH levels, *C. rostrata* requires Ca concentrations of 35.0 to 50.0 ppm to support vigorous growth (Lohammar 1938, reported in Hutchinson 1975). Generally speaking, the higher the pH, the higher the Ca demand of *C. rostrata.* The low Ca concentration in the substrate of the interlevee depressions appears to be one reason for the absence of *C. rostrata.* The *C. rostrata* in the abandoned channels of the mid-delta must obtain Ca from the alder and willow leaves that accumulate in the channels each fall. In some of the abandoned channels the standing water, derived from snowmelt runoff, rainfall, and occasional flooding is brown in colour. This indicates the addition of organic acids from decaying vegetation. In some *Equisetum* assemblages this addition may lower the pH sufficiently to reduce the Ca requirements of *C. rostrata*, allowing for vigorous growth in these habitats.

Carex Assemblage

The *Carex* assemblage is relatively unimportant on the Slave Delta. The largest associations are found in the protected zone of the outer delta, on a small bird's foot delta. Smaller associations are found in thin strips along the littoral zones of most channels within 0.5 km of Great Slave Lake, in small associations on the distal portion of the exposed outer delta (it is a pioneer species on some small shoals elevated above water level), and along some of the elevated abandoned channels in the mid-delta and apex zones. The occurrence of this assemblage does not appear to be governed by any specific set of environmental factors, as it occurs in a variety of habitats subject to a wide range of environmental conditions.

Carex aquatilis is the dominant species in the assemblages of the outer delta, while *C. rostrata* dominates the *Carex* assemblages in the older portions of the delta. *Equisetum fluviatile* and *Typha latifolia* occur in most *Carex* assemblages; the latter species is present only in those associations that have direct contact with the river or lake.

In the *Carex* assemblages in the outer, low-lying delta, *Salix interior, S. lasiandra,* and *S. arbusculoides* are present in significant numbers and have excellent vigour, indicating a successional trend towards a *Salix* assemblage. The *Carex* assemblages found on the mid-delta and apex do not appear to succeed any other assemblage. *Salix spp.* found in these locations are low in numbers and show no signs of reproducing.

Salix-Equisetum Assemblage

The *Salix-Equisetum* assemblage occurs in a wide range of habitats. Along the outer delta this assemblage occupies cleavage bar levees and the shallow perimeters of interlevee depressions. In the mid-delta, portions of interlevee depressions of older cleavage bar formations have been elevated through sedimentation and provide habitat conducive to the establishment and success of the *Salix-Equisetum* assemblage.

This assemblage is transitional between the *Equisetum* and *Salix* assemblages. As the willow canopy becomes more dense, the shade-intolerant, subdominant *Equisetum fluviatile* will die out. On the littoral portions of levees on the outer delta, *E. palustre* may replace *E. fluviatile* as the subdominant herb, as the former species is more shade tolerant. With further sedimentation and elevation of the levees to at least 0.3 m above summer low-water levels, *E. arvense* replaces *E. palustre*. However, in these situations, *E. arvense* always has poor vigour.

The successional trend in the maturing interlevee depressions appears to be somewhat different. The dominant shrub, *Salix arbusculoides*, grows in small clumps thus enabling *Equisetum fluviatile* and other herbs to grow in the open spaces. The topography of the maturing interlevee depressions is varied, ranging from swales to sloughs. The vegetation reflects landform patterns, with *Salix arbusculoides* occupying the swales and *Equisetum fluviatile*, *Calamgrostis canadensis, Potentilla palustris*, and *Glyceria maxima grandis* inhabiting the level, saturated plain of the depression in a pattern that is best described as fragmented. The sloughs are shallow and occupied by *Equisetum fluviatile* and a few aquatic species such as *Utricularia vulgaris* and *Lemna minor*. Although there are no *Alnus tenuifolia* present in the sampled plots, the species is beginning to invade the perimeters of these elevated interlevee depressions, where soil moisture conditions are dryer and warmer. Successional direction on this landform depends on the frequency of flooding. Flooding in this portion of the delta, the mid-delta, is infrequent. The likely progression of plant assemblages occupying this landform is from a *Salix-Equisetum* to *Salix* to a prolonged occurrence of *Alnus-Salix*. Infrequent flooding of this landform will probably result in a prolonged dominance of the *Salix-Equisetum* or *Salix* assemblage. The saturated condition of the sediment in the maturing interlevee depressions is maintained by the high water table, snowmelt runoff, and rainfall. Without frequent flooding and the accompanying sedimentation that increases the elevation of this landform, succession to the *Alnus-Salix* assemblage will not occur. Lowering of the water table either naturally, or as a result of manipulation of the Slave River's natural flow regime by man, could result in the invasion of these maturing interlevee depressions by *Alnus tenuifolia.*

Salix Assemblage

The *Salix* assemblage is found along elevated levees in the distal portions of the delta. In the mid-delta, *Salix* assemblages occupy elevated interlevee depressions and elevated portions of point bars and sand bars. The *Salix* assemblage habitats are considerably dryer than the *Equisetum*, *Carex*, or

Salix-Equisetum habitats. The sampled sites in the *Salix* stands have 35% soil-moisture content by weight, compared with saturation conditions or standing water found in the other assemblages.

Salix interior and *S. arbusculoides* dominate the *Salix* assemblages in the frequently flooded areas of the delta, while *S. planifolia* is dominant in the more elevated, less frequently flooded assemblages. *Alnus tenuifolia* was recorded in small numbers but with vigorous growth in all sampled plots, indicating a successional trend from *Salix* to *Salix-Alnus* assemblage. Gill (1975a) reports a similar successional sequence in the Mackenzie Delta. Small numbers of healthy *Populus tremuloides* occur in some of the sampled plots in the mid-delta, indicating that the successional sequence of *Salix* to *Salix-Alnus* may be short-lived. Cordes and Strong (1976) report that the *Salix* community in the Peace-Athabasca Delta usually succeeds to a *Populus* community.

Autogenic Succession

The assemblages discussed in this section occupy mainly the older delta landforms: the apex zone and the islands of the mid-delta. The successional sequence of the plant assemblages inhabiting the older, more elevated landforms of the delta is: *Alnus-Salix*, *Alnus*, *Populus*, decadent *Populus*, and *Picea*. *Picea* is the climax stage of plant assemblage succession on the rarely flooded portions of the delta. Autogenic succession occurs in these assemblages because of the reduced frequency of spring flooding. It is mainly influenced by vegetation structure and composition, rather than by physical factors. With increasing elevation above river level resulting in a reduced frequency of spring flooding, autogenic succession becomes more pronounced.

Alnus-Salix Assemblage

Along the outer delta, *Alnus-Salix* assemblages are found only on the most elevated upstream portions of cleavage bar islands. This assemblage is widespread in the mid-delta, commonly occupying the backslopes of active levees. Levees along abandoned channels, abandoned point bars, backswamps behind cut-bank levees, and upstream portions of islands are among the varied habitat that the *Alnus-Salix* assemblages occupy in the mid-delta.

Although the sample plots are located on diverse habitats, they have a similar species composition. Even the herb layer shows a degree of uniformity that is not present in earlier successional stages. This is directly related to the decreasing influence of the river regime on this assemblage. *Alnus tenuifolia*, with a cover of 75%, is the dominant tall shrub, while *Cornus stolonifera*, with a cover of 45%, is dominant in the low-shrub layer. The herb layer is largely composed of *Equisetum arvense*, which has an average cover of 45%.

Succession from the *Alnus-Salix* assemblage appears to be directed along two paths: toward either a *Populus* assemblage or an *Alnus* assemblage. In *Alnus-Salix* assemblage plots adjacent to either *Populus* or decadent *Populus* assemblages, successional direction is toward a *Populus* assemblage. Where the

Alnus-Salix assemblage plots are not adjacent to the *Populus* or decadent *Populus* assemblages, the *Alnus-Salix* assemblage will succeed to an *Alnus* assemblage.

Alnus Assemblage

Most *Alnus* assemblages are found on levees along abandoned channels and on large expanses in the interior of the more-elevated portions of middelta islands.

The dominant plant species in the shrub, low-shrub, and herb layers is identical to that found in the *Alnus-Salix* assemblage. The only difference is the absence of *Salix* spp. and the increased significance of *Alnus tenuifolia* (from 75 to 85%). Environmentally the two assemblages are similar in elevation above river level, soil moisture, and temperature. The observed differences are soil composition, exposure to wind, litter fall, tallshrub competition, and total organic carbon content of the soil. The *Alnus-Salix* assemblage occupies more exposed sites, where litter accumulating on the ground surface may be subject to removal by strong onshore winds from Great Slave Lake. *Alnus* sites are sheltered from the wind. Thus the removal process is not as efficient. Soil profiles in the *Alnus* sites have an average litter depth of 2.0 cm, while the litter layer in the *Alnus-Salix* assemblage sites averages 0.5 cm.

The sandy loam soil of the *Alnus* stands has a total organic carbon content almost four times as great (4.8%) as the *Alnus-Salix* sites (1.3%).

Samples of *Alnus tenuifolia* from the *Alnus* and *Alnus-Salix* assemblages were compared to determine whether the assemblage differences or similarities (see above) were reflected in the growth rate of this shrub. It was hypothesized that if the assemblage differences were significant, the growth rates would be statistically dissimilar. Alternatively, if the similarities were significant, the growth rates would be statistically similar.

The *Alnus* from both assemblages are of a similar age. The *Alnus tenuifolia* in the *Alnus* assemblage have a mean age of 21.91 years ($s = 6.27, n=20$); those in the *Alnus-Salix* assemblage have a mean age of 21.57 years ($s = 4.69$, $n = 20$). A student-t test (Freund 1972) performed on these two samples demonstrated no significant difference at the 99% confidence interval. Although statistically the sample can be considered to be part of the same age class, there are significant differences in growth rates between the two samples. For this comparison, shrub height and DBH (diameter at breast height) were used as indicators of growth and the student-t test performed accordingly. The heights of *A. tenuifolia* in the *Alnus* assemblage average 6.33 m ($s=1.16, n=20$), while those in the Alnus-Salix stands have a mean height of 4.11 m ($s = 0.58$, $n = 20$). DBH measurements in the Alnus stands average 6.85 cm ($s = 1.54$, $n = 20$), while those in the *Alnus-Salix* assemblage have a mean value of 4.62 cm ($s = 0.74$, $n = 20$). It seems significant that the standard deviations for height and DBH in the *Alnus-Salix* are half those of the *Alnus* assemblage. This may reflect unconformities in the environment of the *Alnus* assemblages and environmental similarities among *Alnus-Salix* assemblages. Because the growth rates are significantly dissimilar (student-t, 99%), it seems probable that the environmental and ecological differences between the assemblages, namely soil composition--both particle size and chemistry (due to the litter accumulation differences), are the factors primarily responsible for the increased growth rates in the *Alnus* assemblage. Other physical factors examined were eliminated as possible contributors to differential growth rates. There was no measured difference in soil moisture, soil temperature, or wind exposure between the *Alnus* and *Alnus-Salix* assemblage plots.

Successional direction is only obvious in a small percentage of the *Alnus* plots. Only the plots occupying the most-elevated sites appear to be succeeding toward a *Populus* assemblage. Successional trends within the *Alnus* assemblage occupying low-lying sites is not apparent. With increased elevation of the sites by sedimentation during occasional flooding, soil conditions may permit the invasion of *Populus balsamifera.*

Populus Assemblage

With few exceptions, the *Populus* assemblage occupies the mesic environment of elevated levees, particularly cut-bank levees. Some *Populus* stands also occur on older levees along ponded sloughs.

Populus balsamifera, the dominant species in this assemblage, is an important species on other northern deltas. *Populus* communities occupy the high, well-drained levees of the Saskatchewan Delta (Dirschl 1970), the Peace-Athabasca Delta (Dirschl et al. 1974), and the Colville Delta in Alaska (Bliss and Cantlon 1957). In the Mackenzie Delta, well-developed *Populus* stands occur only on coarse point-bar deposits (Gill 1972, 1975a).

In this assemblage the tree layer is composed solely of *Populus balsamifera*, with an average cover abundance of 85%. The tall- and low-shrub layers are dominated by *Alnus tenuifolia* and *Cornus stolonifera* respectively. The average cover for each is 12%.

The *Populus* assemblages sampled in the mid-delta zone do not appear to be succeeding to the *Picea* assemblage as they are on the apex zone. The primary reason for this is the inability of white spruce to produce adventitious rooting during the first few years of its life (Gill 1971). Therefore in an area such as the mid-delta, which experiences frequent flooding (every 5 to 7 years), the white spruce cannot successfully germinate, and succession to a *Picea* assemblage will not occur. Consequently succession from the *Populus* assemblage on the mid-delta is directed toward a decadent *Populus* assemblage.

Decadent Populus Assemblage

This assemblage usually occupies levees along channels that have long been cut off from active distributaries in the mid-delta. The decadent *Populus* assemblage is the edaphic climax forest of the mid-delta.

The decadent *Populus* assemblage on the Slave Delta differs slightly from those reported by Gill (1971) on the Mackenzie Delta. The *Populus* stands in the Mackenzie Delta become "decadent" when flooded during lateral migration of point bars and occupation in meander depressions. Those stands on the Slave Delta would more correctly be termed stagnant or subclimax (Kershaw 1973), as the natural succession has been terminated by frequent flooding, not by geomorphic change. The term "decadent" has been used for the Slave Delta because the stands are visibly deteriorating.

Picea Assemblage

The distribution and ecology of *Picea glauca* forests in northern alluvial habitats is well documented (Jeffrey 1961, Dirschl 1972, Dirschl et al. 1974, Gill 1975a, Cordes and Strong 1976).

Picea glauca clearly dominates the *Picea* assemblages, with an average cover of 95%. In decreasing order of significance the shrub layer consists of *Rosa acicularis*, *Alnus tenuifolia*, *Cornus stolonifera,* and *Vebernum edule*. *Equisetum arvense* dominates the herb layer, with *Pyrola secunda secunda* and *Linnaea borealis* as major subdominant species.

Since flooding is rare on the expanses of *Picea* forest in the apex zone, the bryophyte layer has become extremely well developed. *Hylocomnium splendens* and *Aulacomnium palustre* co-dominate in this layer. The very efficient insulating capacity of the thick (up to 0.4 m) moss carpet in this assemblage results in the soil temperatures being maintained below 0 C below the active layer. The seasonal active layer in the permafrost is a function of bryophyte thickness and proximity to the stems of *Picea glauca* (Gill 1975b). Similar observations were made on the Slave River Delta; the active layer under a bryophyte cover of 6.0 cm (n = 25) averaged 45.0 cm (s=7.0 cm), while the active layer beneath a moss layer of 16.0 cm (n=25) averaged 29.0 cm (s=8.0 cm).

Potential Environmental and Ecological Impacts of River Impoundment on the Slave Delta

Generally speaking the disruption of a river system, which causes changes both in its normal discharge and in the concentration of suspended sediment and bedload, will alter the biophysical regime of downstream wetlands. This is because the wetland vegetation series are a direct response to the frequent inundation by floodwaters and the deposition of sediment. The degree of downstream impact is a function of reservoir size, the filling schedule of the reservoir, and the hydroelectric-plant operating strategy. The short-term effects are a result of the length of time it takes to fill the reservoir and the season(s) in which this is done. The long-term effects may be initiated by the reservoir filling schedule, but will largely be a product of the retention of river sediment in the reservoir and the degree to which the natural discharge pattern of the river has been altered.

Short-Term Implications

Calculation of reservoir volume was accomplished using a head of 209.1 m asl. This was derived from a report that examined various versions of hydroelectric dams that could be built on the Slave River

(Montreal Engineering 1978). The version used in the volume calculation is the most economical of those proposed in terms of power production per dollar invested. Fig. 13 illustrates the number of days required to fill the reservoir, given different conditions of closure (100%, 75% 50%, 25%). Calculations are made on a monthly basis: the volume of water contributed to the reservoir (calculated as 7.308756 x $10^9 m^3$) in each month as product of that month's mean discharge (n = 23 years). Employing these calculations it is possible to foresee and discuss some of the downstream environmental and ecological implications during the initial impoundment period. Fig. 14 summarizes some of these implications in a subjective manner.

A complete closure of the river during the spring period would be most disruptive to the downstream delta. The spring flood and the sediment load it carries, if not stopped completely, would at least be significantly reduced. As the spring flood is the primary initiator of ice breakup in the deltaic distributaries, the date of breakup would be delayed. This delay would affect the microclimate of the delta and therefore the phenology of its vegetation. This reduction of the length of the growing season would be most pronounced in the outer delta. The productivity of the *Equisetum* marshes occupying the interlevee depressions would decline significantly in the ensuing summer, as the annual deposit of sediment, from which these emergent plants absorb nutrients, would not occur.

By employing an equation formulated to predict Great Slave Lake water levels from the discharge of the Slave River:

$$y = .82 + .79 \times 10^{-4} x$$

where y = Great Slave Lake water level (m)
x = discharge (m^3 sec^{-1})

(English 1979), the effect of reduced river discharge on the level of Great Slave Lake can be predicted given the hydroelectric-plant operating strategy. For example, if the river discharge is completely shut off for 13.5 days in June (fig. 13) and allowed to discharge at the calculated mean monthly rate of 6234.8 m^3 sec^{-1} for the remainder of the month, the level of Great Slave Lake would be reduced 0.18 m below the August 1977 summer low water level.

Impacts on the delta resulting from the initial impoundment period may have significant short-term effects. The seriousness of these impacts, as illustrated in fig. 14, Will largely be a function of both the season during which the initial filling of the impoundment takes place and the volume of water allowed past the impoundment during this period.

Long-Term Environmental and Ecological Implications

Regulation by the dam will curtail the natural extremes of discharge in the Slave River. The ecology of the delta has evolved around these extremes.

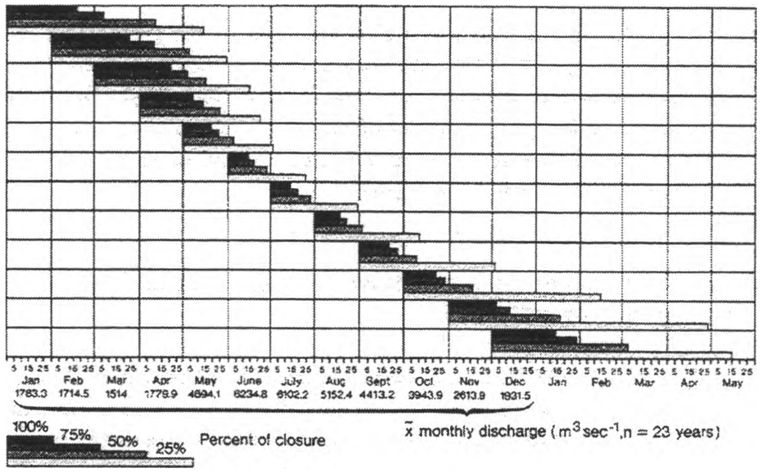

Fig. 13. Initial impoundment period required to fill the Slave River reservoir (with head 209.1 m asl) given certain conditions of closure beginning at the first of each month.

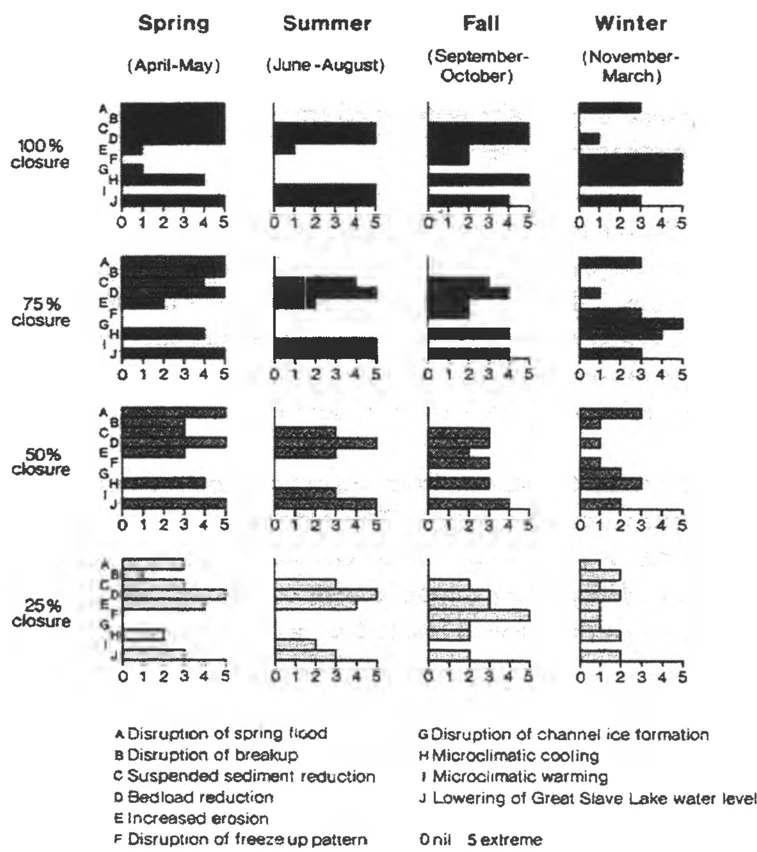

Fig. 14. Initial impoundment period and possible environmental consequences on the Slave River Delta, Northwest Territories.

The spring flood will become a product of the hydroelectric-plant operating strategy. The depletion of water in the reservoir due to winter energy demand will result in a portion of the spring flood being used to refill the reservoir. The reduction of high spring discharge levels will end the annual flooding that a large portion of the outer delta experiences. The intermittent flooding of the mid-delta and the rare floods inundating the apex will no longer occur.

One of the most important and immediate effects of river impoundment will be the loss of bedload and the coarse fraction of the suspended sediment that is trapped or settles out in the reservoir. The deposition of sediment in hydroelectric reservoirs can range from 95 to 100% of the available load (Day 1971). The sediments currently deposited on the Slave Delta range mostly between 2.00 ∅ and 4.25 ∅ (fine sands to coarse silts). Fine silts and clay represent less than 4 % of the deposited sediment. This means that the larger sediment fractions, which are responsible for the continued progradation and aggradation of the delta, will be retained in the reservoir. The formation of the submarine sedimentary platform, submarine levees, wavebuilt shoals, and other subaerial landforms depends upon the continued supply of this sediment load; its loss would largely curtail the growth of the delta.

The increased erosive capacity of the water discharged from the dam would enable the Slave River to regain some sediment between the dam and the delta. However, the amount would be much less than the average daily sediment transport of approximately 60,000 tonnes currently transported by the Slave River above the proposed dam site at Fort Fitzgerald (Water Survey of Canada 1977).

Maddock (1976) states that elimination of the spring flood decreases the width and increases the slope of a floodplain channel, thus providing ideal conditions for the invasion of riparian vegetation along the littoral zone of the old channel. On the other hand, he states that under some conditions the elimination of sediment transported downstream promotes bank erosion, thereby increasing the width of the channel and reducing its slope. Rains (1978) adds that the channel slope immediately below the dam would be reduced. As the load contributed from this source increases downstream from the dam the erosional effects would become less significant. The zone of relatively minor erosion would include the delta area until a post-dam equilibrium is reached. The rather low frequency of flooding that a large portion of the delta currently experiences suggests that after the impoundment of the Slave River, a general widening of the channels and reduction in slope would occur. This may result in a greater erosion of levees and the elimination of much emergent littoral vegetation. Sand bar and point bar development will be retarded as the bedload is greatly reduced.

Sprague (1972) and Gill (1973, 1974) documented the warming effect of spring breakup on the bioclimate of the Mackenzie Delta. Reduction of the spring flood levels and sediment loss would delay breakup in the Slave Delta, prolonging the length of winter conditions and effectively reducing productivity.

The lowering of water levels and reduction of sediment deposition in the interlevee depressions would allow vegetation of later successional stages to invade and displace the highly productive emergent plants. Salix spp. would rapidly invade these marshes and displace the now-dominant, shade-intolerant *Equisetum fluviatile*. The existing successional sequence indicates that *E. palustre* would replace *E. fluviatile*. *E. palustre* would not maintain the large herbivore population currently supported by *E. fluviatile* because the former plant manufacturers two poisonous alkaloids, palustrin and palustridin, both of which would discourage consumption of the plant (Hutchinson 1975).

The elimination of flooding will allow white spruce to successfully germinate on the mid-delta, and eventually, portions of the outer delta. Invasion of bryophyte species such as *Hylocomnium splendens* will occur, and soil temperatures will drop. Organic decomposition in the soil will be reduced, the pH of the soil will become slightly acidic, and the active layer of the permafrost will restrict root growth. After a period of time, the middelta will resemble the present vegetation composition of the apex zone. The large-scale reduction of plant production and species change in the outer delta will have severe economic repercussions on the village of Fort Resolution, due to a reduction in economically important wildlife populations.

Acknowledgments

Special thanks are due to Ross Hastings for his outstanding contribution to the fieldwork. Jim English and Ross Hastings edited and made useful comments on this manuscript. H. Beaulieu, K. Bodden, and S. Schiff helped with the fieldwork. R. Hastings and K. England identified the vascular plants and bryophytes.

A special note of acknowledgment is due to the late Don Gill, whose tutelage and encouragement significantly aided all stages of this research. Financial assistance was provided by the Boreal Institute for Northern Studies at the University of Alberta, through a grant-in-aid for research to the author; the Inland Waters Directorate of Environment Canada, through a special projects grant to Don Gill; and the National Research Council of Canada, through a research grant (number 8700), also awarded to Don Gill.

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A Model for Managing
Emergent Wetland Vegetation:
Indicator Species and the Maximization of Diversity

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Abstract

The intermediate diversity model is described and its potential for facilitating wetland management is discussed. The model, introduced by Grime (1973a, 1979), describes changes in diversity and composition of herbaceous vegetation along gradients of stress, disturbance, and standing crop. The model predicts the following:

1. Maximum species diversity will occur in herbaceous communities with intermediate amounts of standing crop.
2. Competitive dominants will be most abundant where standing crop is high. Competitive dominants are tall, fast growing plants and are indicative of fertile, undisturbed locations.
3. Stress-tolerators will be most abundant where standing crop is low. Stress-tolerators are small, slow growing plants with compact growth forms. These species, which include isoetids, are indicative of infertility.

The applicability of these predictions to emergent wetland vegetation is tested and validated using data from 36 different eastern Canadian wetlands. Maximum diversity is found to occur at 20 - 25 gm / .25 m^2, where vegetation is approximately .2 - .3 m high. Because the intermediate diversity model has been validated for emergent wetland vegetation, the model can be used in wetland management. For example,

1. Rare species can be expected more frequently in low standing crop sites than in high. At high standing crop, there is a convergence towards the same, few, competitive dominants, while at low standing crop, there is a divergence in species composition.
2. At sites with low standing crop, eutrophication will increase species diversity but may decrease the numbers of rarities. At sites with intermediate standing crop, eutrophication will cause species diversity to decline.
3. Stabilizing water levels will suppress disturbance events required by certain species, altering species composition.

The intermediate diversity model can facilitate the management of emergent wetlands by

1. identifying the hydrologic regime needed to maintain the existing vegetation,
2. predicting how a community might be altered if environmental factors are changed, and
3. by allowing specific desired characteristics of the wetland to be emphasized.

Introduction

With increased recognition of the importance and vulnerability of wetland habitat (Sustaining Wetlands Forum 1990), there is an increasing need for wetland management tools. Models have long been one such tool, with the most useful models being those that combine description with an understanding of process.

The intermediate diversity model (Grime 1973a, 1979) combines the description of herbaceous vegetation with the processes of competition and stress and/or disturbance tolerance. The model highlights species diversity and suggests how certain species can be used as indicators of underlying environmental gradients. The intermediate diversity model (1) facilitates habitat description by emphasizing important environmental gradients, (2) characterizes the herbaceous vegetation with respect to the underlying environmental gradients, and (3) makes predictions regarding species' distributions and species diversity.

The Intermediate Diversity Model

The intermediate diversity model was first proposed by Grime (1973a, 1979) to explain changes in species diversity within herbaceous plant communities. He proposed that three gradients were important in predicting patterns of diversity: gradients of stress, disturbance, and standing crop (Figure 1). Stresses he defined as factors which limit the rate of biomass production. Disturbances he defined as factors which cause its partial or total destruction. Since both stresses and disturbances act to decrease total biomass, these two gradients are inverse to a gradient of standing crop (Figure 1). In herbaceous communities, standing crop is indicative of primary productivity and is closely correlated with various measures of fertility (Wisheu et al. 1991).

Just as stresses and disturbances can limit the production of standing crop, so too, can intense stresses or disturbances limit the number of species able to exist in an area. Where standing crop is low, species diversity is also low because only a few species are particularly suited to the extreme conditions (i.e., stress or disturbance tolerators, Figure 1). In contrast, where environmental conditions are benign, standing crop is high, but species diversity is again low because a few tall, fast growing, dominant plant species are able to outcompete smaller, slower growing subordinants (Figure 1). Maximum species diversity should therefore occur at intermediate levels of standing crop where moderate stresses and

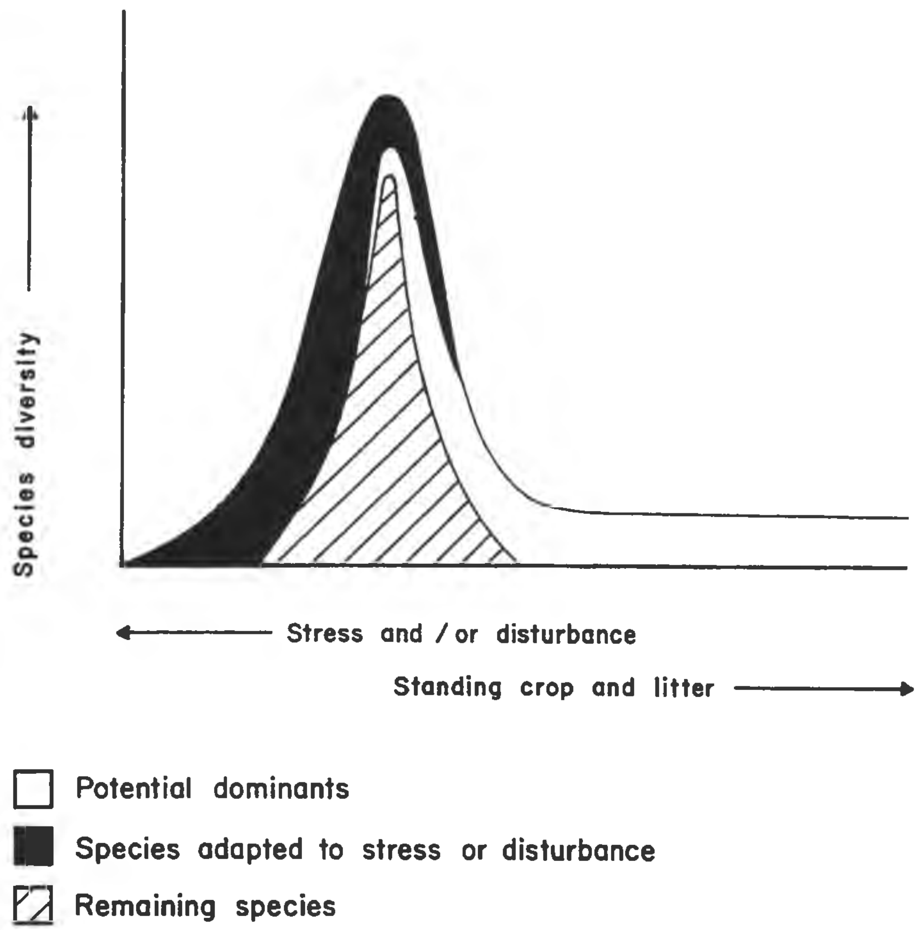

Figure 1. The intermediate diversity model. After Grime 1973a, 1979.

moderate disturbances reduce the competitive ability of the few dominants and allow the greatest number of species to co-occur.

The intermediate diversity model was initially developed to explain changes in species diversity in Great Britain's chalk grasslands (Al-Mufti et al. 1977, Grime 1979, Willems 1980) but the model has since been tested in a variety of different herbaceous habitat types (e.g. pine-wiregrass savannas, Walker and Peet 1983; grasslands, road verges, reed swamps, fens, Vermeer and Berendse 1983; fens, Wheeler and Giller 1982; South African fynbos vegetation, Bond 1983). The following is a report on the applicability of the model to emergent wetland vegetation.

Applicability of Model to Wetlands

Data Collection

To test the applicability of the intermediate diversity model to wetlands, species diversity and standing crop data were collected from a range of different wetland types found throughout eastern Canada (Figure 2). The wetlands that were sampled included productive, high biomass cattail or reed stands, intermediate biomass carex or forb dominated meadows, and low biomass sites experiencing either stresses or disturbances. The most common disturbances to the wetlands were ice scour, wave wash, and frequent flooding. These factors act as disturbances in destroying and removing plant tissue, and act as stresses in removing litter and small nutritive particles. Infertility was the most common stress factor in the wetlands although some sites suffered lowered light levels during prolonged floods or after mud deposition. In all, 36 different wetlands were sampled, representing a variety of habitat types.

At each wetland site, .25 m^2 quadrats were positioned below the shrub zone and above aquatic macrophytes, within the zone of emergent vegetation. All rooted, vascular plant species within each quadrat were identified and counted, then the quadrat was harvested of all above-ground living and dead attached vascular plant material. The plant material was then dried at 60° C for at least 24 hours in a forced-air convection oven, and weighed to the nearest .01 g. In total, 628 quadrats were sampled.

All quadrats were sampled between July 23 and October 1, intermittently from 1983 to 1992, as part of six separate studies described elsewhere (Day et al. 1988, Gaudet 1993, Lee 1993, Moore and Keddy 1989a, 1989b, Wisheu and Keddy 1989a). Although the sampling methodology had been standardized for all six studies, the number of quadrats collected per wetland site did vary. Anywhere from 4 to 74 quadrats were collected per site, depending upon the size of the wetland and the purpose of the original study.

Predicting Diversity

To test whether species diversity changed along the wetland standing crop gradient as predicted by the intermediate diversity model, species counts from the 628 sampled quadrats were plotted against their corresponding values of standing crop (Figure 3). There were from 1 to 24 species per quadrat, with from .4 to 1,219 g / .25 m^2. As predicted by the model, species diversity was greatest at intermediate levels of biomass. Maximum diversity occurred at 20 - 25 gm /.25 m^2 standing crop, as described by a quadratic regression equation $\log(y + 1) = .47 + .82 \log(x + 1) - .3 \log(x + 1)^2$ ($p = .001$, $r^2 = .31$). Note that values were logged to reduce heteroscedasticity and that a value of 1 was added to prevent the function from becoming undefined at zero. The standing crop value corresponding to maximum diversity is equivalent to vegetation approximately .2 to .3 dm in height.

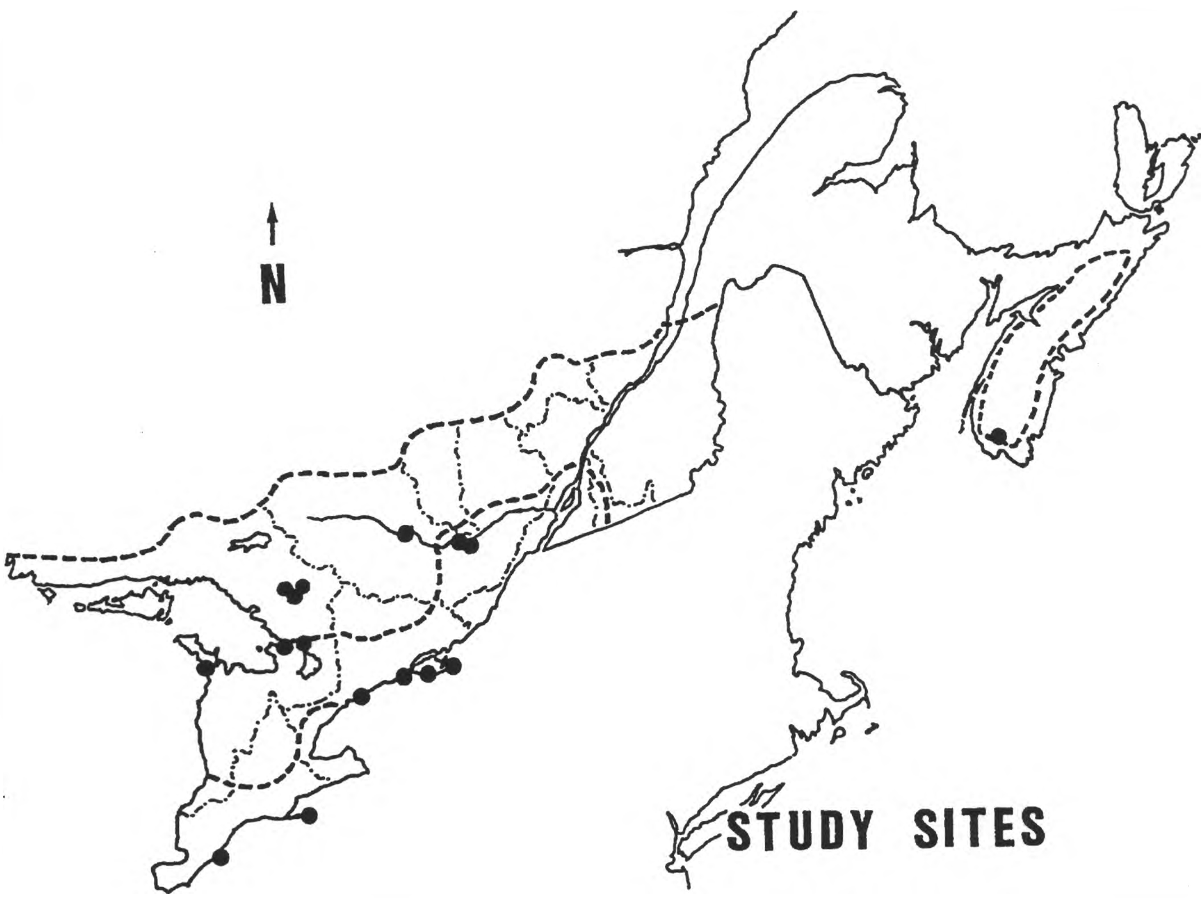

Figure 2. Locations of data collection within Ontario, Quebec, and Nova Scotia.

Distribution of Indicator Species

The pattern of maximum species diversity at intermediate levels of standing crop is consistent with the proposition that extreme stresses and disturbances limit the numbers of species at low levels of standing crop while competitive dominants limit diversity where standing crop is high. An abundance of competitive dominants at high standing crop and an abundance of stress tolerant species at low standing crop would therefore be indicative of the underlying environmental conditions and consistent with the proposed mechanism of the model.

Competitive dominants

Competition is defined by Grime (1973b) as the tendency of neighbouring plants to utilize the same particle or volume of resource. Competitive dominants are therefore those plants with combinations of traits that facilitate the preemption of resources; height, lateral spread, rapid growth rate etc. Since these plant traits act in combination and are of a relative nature, the designation of species as competitive dominants can be subjective.

To avoid subjective designations, competitive dominants were identified on the basis of an objective, systematic screening experiment which ranked 44 different wetland species with respect to their abilities to avoid suppression by neighbours (Gaudet and Keddy 1988). Four species which ranked among the top five were *Lythrum salicaria*, *Bidens cernua*, *Phalaris arundinacea*, and *Typha latifolia*. These same four species fit Grime's (1979) description of a competitive dominant in that all are tall, fast growing, canopy forming plants. Their distribution along a standing crop gradient illustrates how competitive dominants are absent at low standing crop and most abundant when standing crop is high (Figure 4).

Stress-tolerant isoetids

Isoetids are a group of taxonomically unrelated species that share common growth forms and characteristics. They all have very short stems and rosettes of short stiff leaves (Hutchinson 1975, Boston and Adams 1987). They are slow growing species, often evergreen, and are characteristic of inorganic, nutrient-poor substrates (Boston 1986). Since isoetids are considered stress-tolerators (Boston 1986), a predominance of isoetids in regions with low standing crop would therefore be indicative of environmental stress and consistent with the intermediate diversity model.

Ten species which occurred within the quadrats described earlier have been identified by Boston and Adams (1987) as isoetids; *Elatine minima*, *Eleocharis acicularis*, *Eriocaulon septangulare*, *Gratiola aurea*, *Isoetes echinospora*, *I. macrospora*, *Juncus pelocarpus*, *Lobelia dortmanna*, *Myriophyllum tenellum*, and *Sagittaria graminea*. When the distribution of isoetid species is plotted along the standing crop gradient, they are seen to be most abundant where standing crop is low. They then decrease in

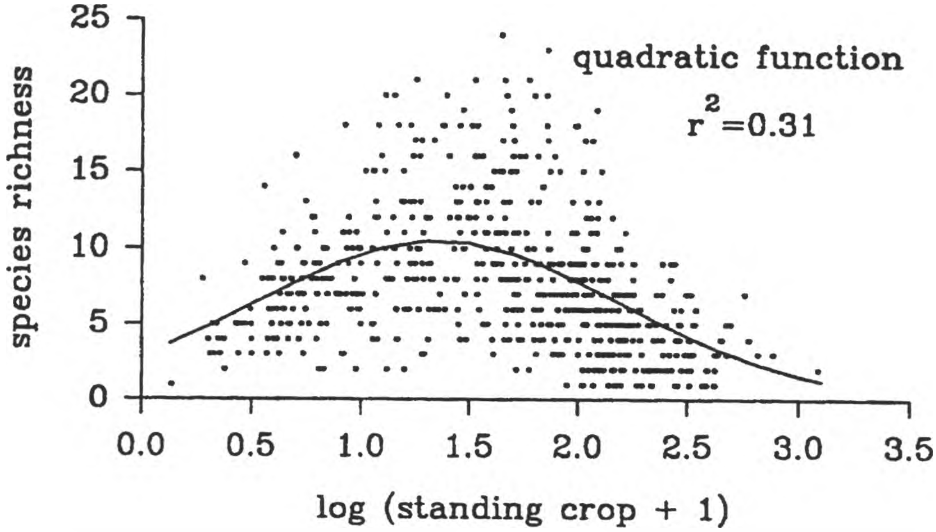

Figure 3. The species richness - standing crop relationship as described by a quadratic regression equation. A community with 1 (or 10 gm standing crop / .25 m^2) contains vegetation less than .1 - .2 dm high, a community with 2 (or 100 gm standing crop / .25 m^2) contains vegetation approximately 1 m high, while a community with 3 (or 1,000 gm /.25 m^2) supports vegetation 2 - 3 m high. Note that although the equation was generated used logged variables, the y axis is unlogged.

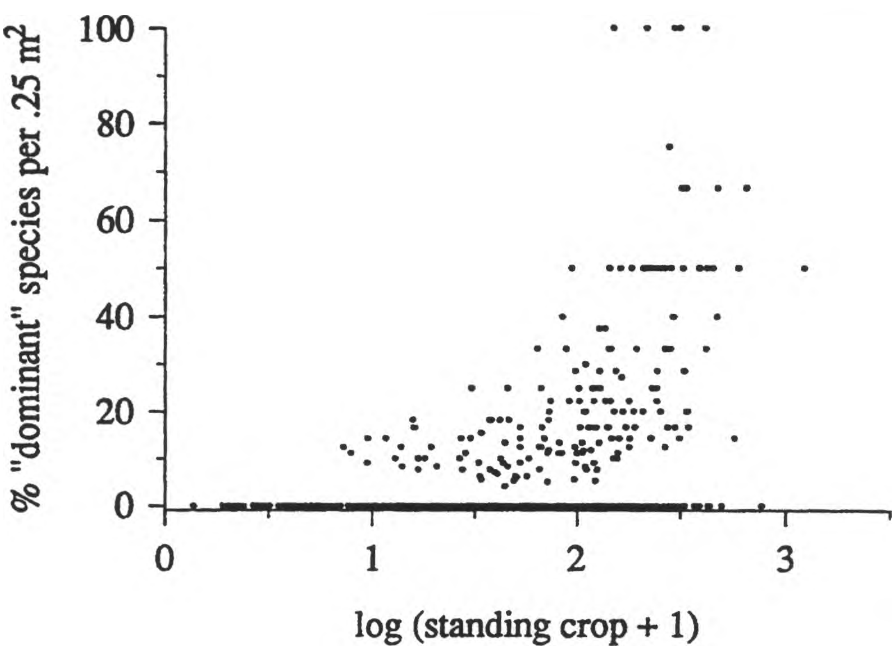

Figure 4. The distribution of competitive dominants along a wetland standing crop gradient.

abundance as standing crop rises, and are absent from high biomass quadrats (Figure 5). These results are consistent with Chambers (1987) and suggest that in regions of low standing crop, species may need to tolerate environmental stresses, which may in turn, limit the number of species that can occur. Either stress tolerant or disturbance tolerant species are predicted to occur in regions of low standing crop (Grime 1977, 1979).

Application of Model to Wetland Management

Distribution of Rarities

When wetlands with high standing crop are compared to each other with respect to their species composition, they are found to be more similar to each other than are equivalent wetlands with low standing crop. There is a convergence in high standing crop wetlands towards the same, few, competitive dominants and a divergence in species composition in low standing crop sites (Moore 1990, see also Hodgson 1987). Wetlands of low standing crop are often the products of unique combinations of stresses and disturbances, and the existing flora can therefore be unique or even rare. For example, the Atlantic coastal plain flora, which is a freshwater flora endemic to the eastern seaboard of North America, occurs only within infertile, low standing crop wetlands (Keddy and Wisheu 1989, Wisheu and Keddy 1989b). As well, at Buffalo Lake, Alberta, rare plants concentrate along wave-disturbed, low standing crop shores (S. Markum, pers. comm.). Can the relationship between standing crop and rarity be used as a management tool?

To test the strength of the standing crop - rarity relationship, species lists from the previously described 628 wetland quadrats were checked using Argus and Pryer (1990). Of the 262 different species that occurred within the 628 quadrats, 11 were either nationally or globally imperiled or rare; *Aristida longespica*, *Coreopsis rosea*, *Panicum rigidulum* var. *pubescens*, *Euthamia galetorum*, *Hydrocotyle umbellata*, *Platanthera flava* var. *flava*, *Rhexia virginica*, *Sabatia kennedyana*, *Scirpus longii*, *Scleria verticillata*, and *Utricularia subulata*. As illustrated in Figure 6, these 11 species were found exclusively in quadrats with less than ~150 gm/.25 m2 (see also Moore et al. 1989).

The association of rare plants with infertile, low standing crop habitats seems to extend well beyond North American wetlands. For example, Ellenberg (1988) found a similar relationship between rare species and infertile conditions for European wetland/moorland, heathland/grassland, woodland/brush, and frequently disturbed habitats (Figure 7). Although exceptions will undoubtedly be found, is does seem that rare wetland plants do occur more frequently in infertile, low standing crop wetlands than in productive, high standing crop sites.

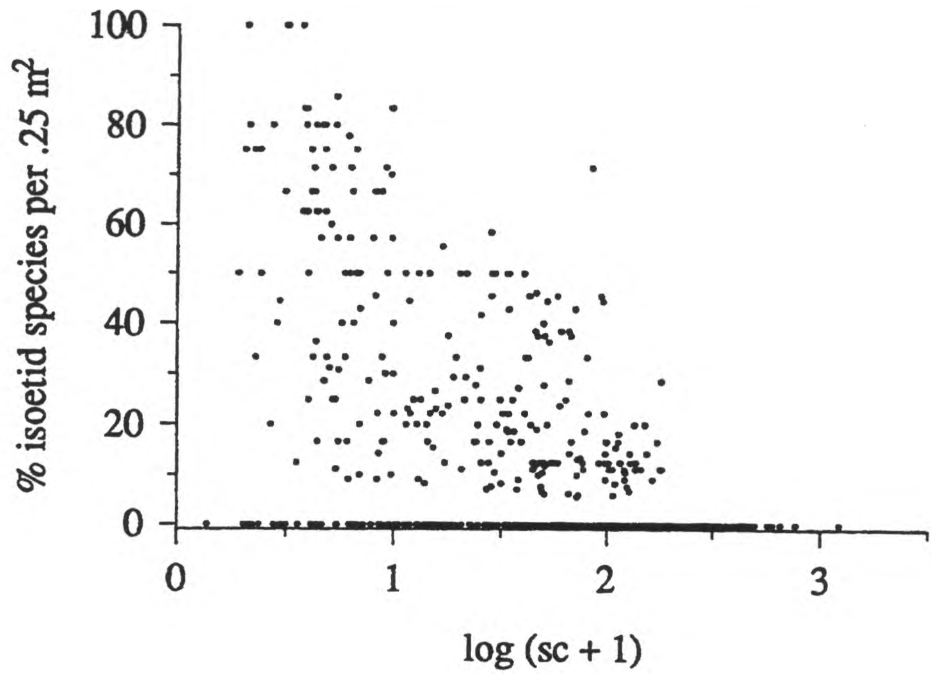

Figure 5. The distribution of isoetids along a wetland standing crop gradient.

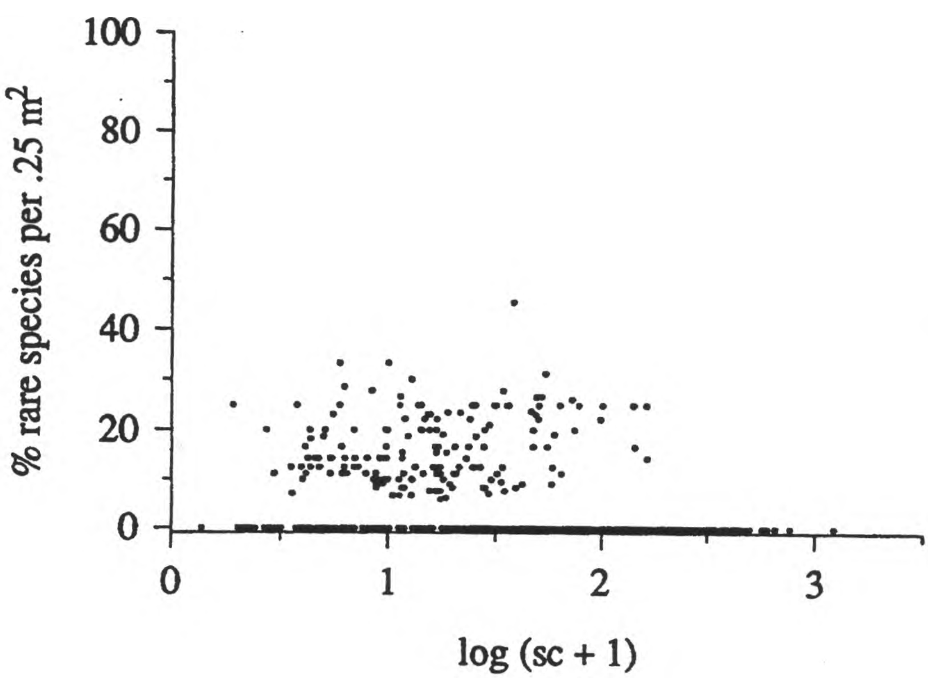

Figure 6. The distribution of rare species along a wetland standing crop gradient.

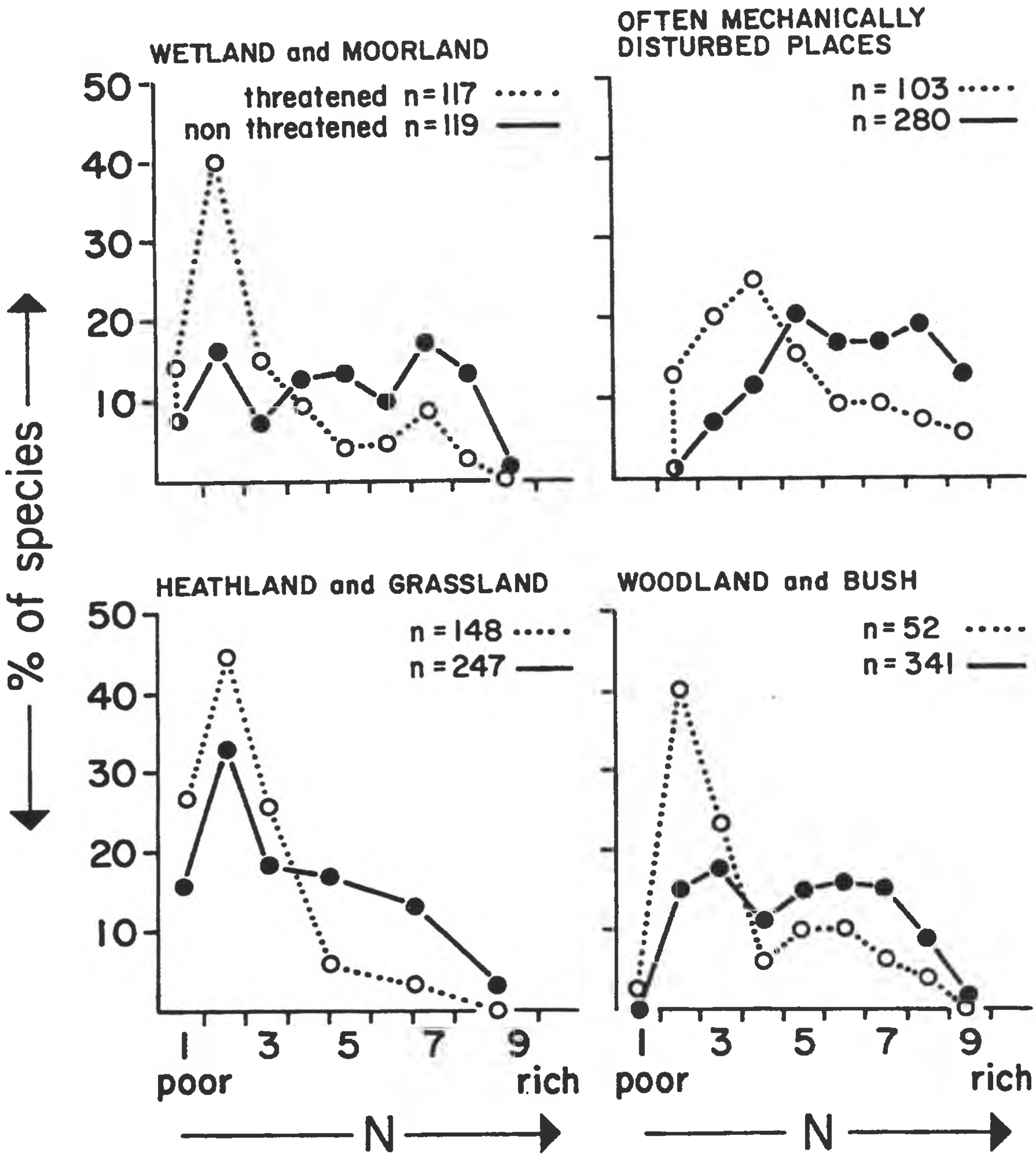

Figure 7. The distribution of central European plant species along a nitrogen gradient. After Ellenberg 1988.

Effects of Eutrophication

The ability to predict the number and types of plant species that will occur after eutrophication is an important tool if wetlands are to be successfully managed. The intermediate diversity model is one tool that can be used to make such predictions (Wisheu et al. 1991).

It is predicted for example, by the intermediate diversity model, that as eutrophication increases standing crop, there will be decreased richness in sites that once supported only moderate amounts of standing crop. Rich assemblages of wetland plants can be converted to near monocultures with eutrophication, a scenario already documented by Jackson, Futyma, and Wilcox (1988). An examination of the paleoecological history of an Indiana pond revealed how nearby development and the resulting increase in dissolved nutrients, organic matter, and particulate material helped convert a diverse flora into a dense stand of *Typha angustifolia*. Experimentation with artificial wetlands has also demonstrated how increased fertility will decrease species richness (Moore and Keddy 1989b, Wisheu et al. 1991).

An alternate scenario that is also predicted by the intermediate diversity model, is that eutrophication will increase species richness where standing crop is low. However, this conversion would be accompanied by decreases in the numbers of rare plants. Such a loss has been documented by Ehrenfeld (1983) when she compared pristine and enriched stream communities in the New Jersey Pine Barrens. Enriched streams had greater numbers of species but rare and endemic species were replaced by widespread and non-native plants.

Stabilization of Water Levels

When water levels are stabilized, two things occur. First, wetland habitat is lost. Without water level fluctuations, shrub invasion can occur and the zone supporting emergent wetland vegetation shrinks in size (Townsend 1984, Keddy and Reznicek 1986, Peace-Athabasca Delta Implementation Committee 1987, Keddy 1991). Second, with water level stabilization, wetland habitat is modified. Floods, wave wash, and ice scour no longer occur and specific components of the existing vegetation can be lost.

Disturbances such as flooding, washing, and scouring, can influence community composition by altering substrate fertility. Floods, ice scour, and wave wash can remove both large fragments of organic material and small nutritive particles. During extended drawdowns, thin layers of organic matter can either oxidize or be blown away. The resulting reduction in fertility can either increase or decrease species richness, depending on the initial conditions.

Stabilizing water levels can also alter community composition directly by reducing the abundances of disturbance tolerant species. Annuals and fast growing ruderals move in after disturbance events and produce copious seed quickly (Grime 1979). Without periodic disturbances, they would be overgrown by competitors. Stabilizing water levels would also eliminate those species which require periodic drawdowns for emergence from the seed bank (van der Valk 1981, Keddy and Reznicek 1982, Smith and Kadlec 1983, Pederson and van der Valk 1984, Gerritsen and Greening 1989, Keddy et al. 1989).

Conclusions

The intermediate diversity model can facilitate the management of emergent wetlands by identifying the hydrologic regime needed to maintain the existing vegetation. For example, large numbers of annual species indicate that periodic drawdowns and/or disturbances are required to allow regeneration from seed. An appropriate hydrologic regime would therefore include water level fluctuations of amplitude sufficient to provide either prolonged exposure or severe disturbance.

With recognition of what structures a community, comes the ability to predict how a community might be altered if environmental factors are changed. For example, decreased flow velocities would increase sedimentation rates which would, in turn, increase substrate fertility. Fast growing ruderals or competitive dominants could then increase in abundance, to the detriment of slower growing species. This shift in community composition would most probably be accompanied by a decrease in species diversity, unless initial fertility was very, very low.

The intermediate diversity model not only facilitates the maintenance of existing vegetation and the prediction of future vegetation types, but the model can also be used to manage for specific desired characteristics. For example, the lush vegetation required for increased water fowl production can be achieved by increasing substrate fertility and /or by reducing disturbances. This management regime would decrease species diversity but would increase the abundance of tall, fast growing competitive dominants.

The maximization of species diversity is an increasingly urgent priority for wetland managers and is a goal facilitated by the intermediate diversity model. As recognized by the model, diverse intermediate standing crop wetlands are a delicate balance of moderate nutrient stress and moderate disturbance and their maintenance requires careful and thoughtful management.

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Instream Flows and Riparian Forests Along Alberta's Southern and Northern Rivers

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Abstract

Instream flow needs (IFN) have been partially determined for riparian (river valley flood plain) cottonwood (*Populus*) forests along southern Alberta rivers. The forests require occasional high flow conditions to promote river meandering and to create and saturate point and lateral bars that are the principal sites for seedling recruitment. Subsequent flow declines must be gradual enough for the seedling roots to maintain contact with the receding water table, and sufficient minimum flows must be provided to prevent drought stress during the hot, dry period of summer.

This IFN model is suitable for riparian woodlands in semi-arid regions but is not directly transferable from southern to northern rivers in Alberta. In both regions, high flows are essential to produce disturbance events and drive geomorphological processes. However, in northern areas, evaporation and transpirational demands are lower due to cooler temperatures and local precipitation is higher, resulting in a substantially different water balance. Northern streams are generally hydrologically 'gaining' streams, in which there is a net inflow from the adjacent groundwater into the stream. In contrast, 'losing' streams often occur in southern Alberta as there is a flow from the stream into the riparian water table during the summer. Due to this fundamental hydrological difference, riparian vegetation along Alberta's northern rivers is less dependent on water from stream flow than along southern rivers and consequently northern riparian woodlands are probably less vulnerable to stream flow modifications than the southern cottonwoods.

A biological indicator of the prevalent hydrological conditions is the distribution of trees. In the semi-arid regions of southern Alberta, native trees are limited to cottonwood groves in riparian zones. In contrast, in northern Alberta, mixedwood forests predominate both adjacent to and away from streams. The habitat value of riparian woodlands is very high in both southern and northern regions but the upland woodlands in northern regions provide alternative forest habitats making the riparian woodlands ecologically less distinctive than the riparian cottonwoods in the treeless grassland regions of southern Alberta. However, riparian woodlands provide extremely rich habitats in both southern and northern regions and further study of the status and processes of northern riparian forests is required.

Introduction

Considerable research has recently been conducted in Alberta investigating the status and processes in riparian forest ecosystems along southern Alberta rivers (Bradley et al., 1991; Rood and Mahoney, 1991). The reliance of riparian vegetation, particularly cottonwoods, on stream flow and the direct and indirect importance of high flow events have been documented. By integrating studies from various river systems, general interpretations of instream flow needs (IFN) of riparian cottonwoods have been proposed (Mahoney and Rood, 1991; Scott et al., 1993; Stromberg and Patten, 1991). These and other studies enable partial analyses and predictions of impacts of stream flow modification due to river damming and flow management.

Due to the demonstrated impacts of stream flow modification on riparian woodlands, analyses of proposed river flow management patterns on riparian vegetation are now required components of environmental impact analyses EIA for river damming or diversion projects. The potential impacts of the Oldman River Dam Project on riparian cottonwoods became a major environmental concern and was a focus of considerable discussion at the Federal Environmental Assessment Review (1992; Mahoney and Rood, 1993). The recent EIA for the proposed Pine Coulee Project for Willow Creek similarly stressed possible impacts on riparian woodlands downstream (Wagner, 1993).

These EIA for southern Alberta streams can provide some guidance for environmental and socioeconomic analyses of proposed projects and management of Alberta's northern rivers. However, fundamental differences exist in the hydrology and ecology of riparian forests along southern versus northern rivers. These differences will demand substantial revision to the models used to analyze impacts of proposed flow scenarios.

Some aspects underlying geomorphological process will be common in northern and southern streams while other aspects will vary. For all streams, high discharges provide velocities and stages that are competent to drive erosional and depositional processes that underlie dynamic stream meandering. These high flow events thus create the point and lateral bars that are prime recruitment sites for willow and cottonwood seedlings (Bradley and Smith, 1986; Stromberg et al., 1991). However, fundamental differences in other characteristics exist in northern versus southern rivers, particularly hydrologic relations between the stream and riparian water table. These differences make instream flow needs models for southern streams less applicable for northern streams.

The present discussion does not attempt to define the models for analyzing impacts of stream flow modification along northern streams. Instead, it introduces some of the possible climatic, hydrological and vegetation differences of northern versus southern streams. In so doing, direction for further study may be gained along with some predictions regarding relative vulnerability of riparian forests along northern versus southern streams.

The present discussion contrasts the status and process in Alberta's 'northern' versus 'southern' rivers. However, it must be recognized that the latitudinal pattern is confounded by numerous factors. The river types are not clearly distinguished since the systems change gradually along a northerly transect.

Hydrological variations throughout the year and across years complicate the distinctions and localized physiographic influences exist, further complicating the broad transitions.

Additionally, elevational patterns and proximity to the Rocky Mountains influence all aspects of the river systems. Particularly in the southern one-third of the Province, an east-to-west pattern exists that shares many similarities with the south-to-north pattern. For example, the transition from Lethbridge west to the Crowsnest Pass shares many similarities with the transition from Lethbridge north to Edmonton. Due to the relatively steep topographic slope and major climatic impact of the mountains, the east to west transition is more abrupt than the south to north transition. In general, both transitions go from warm and dry, to cool and wet and these changes influence the hydrological linkages between the stream and adjacent ground water, the suitability for different riparian tree species, and the vegetation composition in adjacent upland regions. For ease of discussion, 'southern' and 'northern' rivers will be compared in the present paper but it must recognized that this is a deliberately simplistic representation.

Alberta's Climatic and Ecological Regions

Alberta's southern streams are exotic, with stream flow being especially dependent on distant rather than local precipitation. Heaviest precipitation in the Province occurs in the Rocky Mountains adjacent to the southwestern border with British Columbia. Both meltwater from Rocky Mountain snowpack and mountain and foothills rain contribute to flows of the northeastward-draining southern streams.

Two general climatic trends occur in Alberta and these are principal factors influencing the ecophysiology of riparian forests. In a south to north (or east to west) pattern, temperatures generally become cooler and precipitation increases. The summer net moisture index represents the countering effects of evaporative loss, increased by higher temperatures and wind, versus contributions from precipitation. The summer moisture index is lowest for the southeastern region of the Province and increases northward and westward. In the corner of the Province extending south and eastward from about Lethbridge and Brooks, the summer moisture deficit is 40 cm or more (Pettapiece, 1967). This water balance is insufficient to support trees and consequently this region comprises Alberta's mixed and dry mixed grasslands. In these grassland regions, native trees are restricted to riparian areas where the adjacent stream satisfies the trees' moisture demands.

With increasing precipitation and decreasing evaporational demand, the next ecoregion occurs. This extends in a narrow strip to the west of the grasslands and in a broader belt north of the grasslands to about Edmonton and eastward through Lloydminster. Here, summer moisture deficits of 20 to 40 cm are typical and July precipitation is usually substantially greater than that of the drier grasslands to the south. This moisture balance is sufficient to support a mosaic of trembling aspen, *Populus tremuloides*, and rough fescue, *Festuca scabrella*.

Some areas further north are also characterized by summer moisture deficits of 20 to 40 cm, similar to the aspen parkland regions. Consequently, the Peace River valley and Grand Prairie areas support low boreal mixedwood (deciduous and coniferous trees) forests dominated by aspen. White spruce, *Picea* *glauca*, occurs as a climax species here and is a common tree in other boreal forest ecoregions.

Most other northern regions are wetter, with summer moisture deficits from 0 to 20 cm. The boreal forest occupies the northern half of the Province with the mid-boreal mixedwood ecoregion providing the largest component. This and other boreal forest ecoregions support deciduous and mixedwood groves with the balsam poplar, *Populus balsamifera*, becoming an abundant tree. This is noteworthy since the balsam poplar is also the principal riparian pioneer tree and the only cottonwood occurring along central and northern Alberta streams. Thus, in contrast to the southern region of the Province, in northern Alberta: (i) trees are not limited to riparian areas and (ii) the principal riparian tree type, *Populus* is much more widespread.

To some extent, ecological value is proportional to scarcity. With this as a measure, the ecological value of individual riparian cottonwoods (poplars) in southern Alberta would be higher than that of individual riparian poplars in northern Alberta. This must not be interpreted as indicating that northern riparian forests have little value. Instead, this concludes that because balsam poplars and other trees are widespread in northern Alberta, the ecological importance of riparian trees may be lower in northern than southern Alberta since no other native trees occur in large areas of southern Alberta.

Trees of Alberta's Riparian Forests

Riparian Cottonwoods

The principal and often exclusive pioneer trees along Alberta's streams are cottonwoods or poplars (the two common names are often used synonymously), various *Populus* species that are adapted to and dependent upon the dynamic streamside zones. Alberta's riparian woodlands include three cottonwood species and another subspecies. This range of species provides substantial biodiversity in the riparian woodlands of southern Alberta.

The most extensive riparian cottonwood in Alberta is the balsam poplar, *P. balsamifera*. The balsam poplar dominates early seral stages along rivers in central and northern Alberta, and also occurs in the foothills and mountain regions of southern Alberta. Some dispute continues regarding the taxonomic relationships of the balsam poplar and the black cottonwood, with the latter being considered either a subspecies of *P. balsamifera* (subsp. *trichocarpa*) or a separate species, *P. trichocarpa*. With respect to distribution, the balsam poplar is considered the tree type that occurs to the east of the Rocky Mountains, whereas the black cottonwood occurs primarily west of the Rockies but slips into Alberta through mountain passes and occurs in riparian areas in the foothills regions (Hosie, 1979). Regardless of the taxonomic treatment, these two cottonwoods are extremely similar in appearance and habitat.

The prairie, plains, or western cottonwood, *P. deltoides* (sometimes previously referred to as *P. sargentii*), enters Alberta from the east and is the principal species along the South Saskatchewan River. It also occurs along the Red Deer River from Drumheller downstream and along the Oldman River from Lethbridge downstream (Brayshaw, 1965; and personal observation). Canada's only occurrence of the narrowleaf cottonwood, *P. angustifolia*, is in southwestern Alberta, in the Oldman River Basin from about Fort Macleod southward (Brayshaw, 1965; and personal observation). Narrowleaf cottonwood saplings are frequently mistaken for willows and juvenile balsam poplar shoots produce some leaves that appear similar to narrowleaf cottonwood leaves, complicating interpretation.

The riparian cottonwood forests of southern Alberta thus include four tree types, the balsam poplar, black cottonwood, narrowleaf cottonwood and prairie cottonwood, cottonwoods that enter from the north, west, south and east, respectively.

The interpretation of southern Alberta's cottonwoods is substantially complicated by extensive, and globally unique, interspecific hybridization (Brayshaw, 1965; Rood et al., 1986). Where species overlap, some interbreeding occurs, producing hybrid genotypes with leaf shapes intermediate between the parental species. In contrast to earlier interpretations (Brayshaw, 1965), the trembling aspen, *P. tremuloides*, probably does not hybridize with the riparian cottonwoods and thus, the interspecific hybrid near Lethbridge involves three and not four *Populus* species. The extensive interspecific hybridization of cottonwoods contributes further biological diversity to the riparian woodlands in southern Alberta.

In contrast to the trispecific hybrid swarm, only the single species, *P. balsamifera*, occurs along Alberta's central and northern rivers. In these riparian forests, other deciduous and coniferous trees also occur contributing to the forest diversity along those streams.

Riparian Conifers

Few conifers, or deciduous trees other than cottonwoods, occur in the riparian forests in southern Alberta. Thus, cottonwoods serve as almost exclusive trees along southcentral and southeastern Alberta streams. In contrast, the balsam poplars along central and northern streams serve as seral pioneers and other deciduous and coniferous trees also occur in riparian woodlands. This ecological difference is significant with respect to impacts of stream flow management. If dynamic fluvial processes are reduced such as through the attenuation of flood flows, the recruitment of new cottonwoods would be retarded along southern or northern streams. In both southern and northern Alberta, this would reduce the replenishment of cottonwoods and their abundance along streams would decline as established trees aged and died. The consequence of retarded seedling recruitment along southern streams would be the decline of the riparian forests whereas along northern streams, the consequence would probably be a shift in species abundance with the reduction in the pioneering cottonwoods being accompanied by increases in climax species. With respect to the broader landscape, the loss of cottonwoods in the riparian zones along southern streams will result in a landscape void of trees whereas in the central and northern regions, forests including deciduous species would occur even following severe modifications of stream flows. It must be recognized that clonal recruitment offers another form of replenishment for riparian cottonwoods and may partially compensate for reduced seedling recruitment along flow attenuated northern or southern streams (Rood and Bradley, 1993; Rood et al., 1994). However, clonal recruitment does not introduce genetic diversity that is essential for long term adaptation of riparian woodlands.

In foothills regions of southern Alberta and most regions of central and northern Alberta, a number of conifers enter the riparian forests after the pioneering balsam poplars. White spruce is widespread in Alberta (Hosie, 1979) and commonly occurs in riparian zones from Calgary northward and westward. In wetter zones, black spruce, *Picea mariana*, also occurs, as well as certain other conifer species. As already indicated, the conifers generally provide climax species. However, due to disturbance events not only relating to fluvial processes but also due to fire and other impacts, Alberta's central and northern riparian upland and woodlands are generally mixedwood stands, containing both deciduous pioneers and climax conifers. Alberta's deciduous forest groves tend to permit more light penetration than closed conifer stands and this enables more complex understories that provide richer wildlife habitats. Thus, in northern regions, riparian balsam poplars provide very important wildlife habitat but deciduous groves also occur outside of the riparian zones.

Fluvial Characteristics - Gaining and Losing Streams

There are fundamental hydrological differences between southern and northern streams and these are related to the climatic differences previously discussed. Due to the moisture deficit during much of the growing season, southern rivers and particularly, southeastern rivers are hydrologically 'losing' streams, streams with a net flow of water from the stream into the riparian zone. The riparian water table represents a relatively horizontal extension of the stream surface but slopes gradually downward *away from* the losing stream (Rood et al., 1995). In contrast, in most other areas of Alberta, including mountain, central and northern regions, rivers are typically 'gaining' streams. Here, local precipitation contributes to the ground water that flows into the stream, and consequently the riparian water table slopes downwards *towards* the river. The recharge of the riparian water table is thus from different sources in losing versus gaining streams. Along the losing streams of southern Alberta, the riparian water table receives water from the stream whereas along the gaining streams of northern Alberta, the water source for the riparian zone is from groundwater inflowing from adjacent upland regions as well as from local precipitation.

This fundamental hydrological difference in southern versus northern streams has a major impact on the water balance in the riparian zone. The difference also partly determines the sensitivity of the riparian zone to artificial changes, and especially reductions in stream flow (Rood and Mahoney, 1990). In a gaining stream situation, riparian vegetation will still obtain water from the groundwater source, even is stream flow is severely limited. Conversely, along losing streams, reductions in stream flow will result in the corresponding decline of the riparian water table, creating drought stress on riparian vegetation.

It is probable that the principal causes of the abrupt decline of riparian cottonwoods along southern Alberta streams has been the reduction of water availability in the riparian zone due to stream flow reductions following damming and diversion offstream for irrigation (Rood and Heinze-Milne, 1989; Rood et al., 1995). This impact would be much less important in a gaining stream situation. It is consequently highly probable that riparian forests along central and northern rivers will be less vulnerable to drought-induced mortality following stream flow modifications than riparian cottonwoods along southern Alberta streams.

Research Needs and Opportunities for Northern Rivers

Considerable research has investigated the status, prospects and processes associated with riparian forests of southern Alberta. Efforts have particularly focussed on the South Saskatchewan River Basin since this region serves as Canada's national center of irrigation agriculture. Most rivers in the Basin are dammed and flow interruption and water diversion offstream are particularly substantial during the hot, dry periods of summer when irrigation demand is maximal but water demand by cottonwoods is also greatest. Extensive studies investigating instream flow needs of riparian woodland have been conducted along the Oldman River and its tributaries, the St. Mary, Belly and Waterton Rivers and the Willow Creek. Studies have also been conducted along the lower reaches of the Bow and Red Deer rivers and some studies have been conducted along the Highwood River and other streams. These studies have generally involved 'losing' streams in semi-arid areas. Vegetation provides an integration of climatic condition and the lack of woody vegetation in the uplands in these semi-arid areas of southern Alberta indicates that the local water balance is insufficient to support trees, except in riparian areas.

Interpretations and models based on southern river systems will not be directly applicable to central and northern streams. As already discussed, two interrelated differences exist. Firstly, the aspen parkland and particularly boreal forest regions are already forested and thus, local precipitation is sufficient to support trees. Secondly, the northern rivers are gaining streams, reducing the reliance of riparian vegetation on stream flow. Thus, there is substantially less importance of instream flows for the provision of water to support the moisture needs of trees in central and northern Alberta.

While the hydrological differences argue for a reduced importance of stream flows for the sustenance of riparian vegetation along northern versus southern rivers, the dynamic stream flows of all of Alberta's rivers are essential to drive the disturbance and geomorphological processes in the riparian zone. Thus, studies of instream flow needs for northern rivers may particularly consider the role of flood flows that are essential to permit the recruitment of balsam poplars. This investigation may be particularly relevant for the Peace River, due to the artificial attenuation of flow patterns resulting from the operation of British Columbia's Bennett Dam. Other studies are also highly deserving to further clarify the ecophysiology and population dynamics of riparian forests along Alberta's northern rivers.

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Approaches to
Assessing and Modelling Wildlife Habitat
in Riparian Areas

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Value of Riparian Areas to Wildlife

In most regions of North America, riparian communities are one of the most important habitats for wildlife; they:

1. provide an important year-round habitat for species such as shrews, small rodents, several small carnivores such as weasels, mink and marten, and some upland gamebirds (More 1978; Green 1979; Eccles *et al.* 1986). They also are important to the active and inactive life history phases of some amphibians;

2. offer a broad diversity of plant foods for herbivores from large species such as moose and black bear, to small species such as shrews, warblers and sparrows. Because of the early green-up of vegetation in most riparian areas, as compared to upland communities, riparian areas often provide critically important food resources for wildlife during late winter and early spring. Indeed, riparian communities along the Athabasca, Slave and Mackenzie river systems appear to provide regionally important late winter to early spring habitat for moose (e.g., LeResche *et al.* 1974; Walton-Rankin 1977; Hauge and Keith 1980; Telfer 1984; Eccles et al. 1986);

3. provide abundant prey for predators such as lynx, wolves, and some mustelids due to the attractiveness of riparian areas to small mammals, birds and some ungulates, (Green 1980; Eccles *et al.* 1986;);

4. offer excellent hiding cover for moose and deer, particularly during early spring when young are born (see below) (Telfer 1984). Communities such as balsam poplar forests, mature willow and alder shrub thickets, and sandbar willow thickets are of particularly high value;

5. provide important thermal cover (e.g., dense shrub thickets and mature coniferous forest) that is critical to the overwinter survival of some wildlife such as moose and deer (Eccles *et al.* 1986). Importantly, thermal cover often occurs in proximity to high quality browse resources;

6. support one of the most diverse, if not the most diverse breeding bird assemblages of any habitat type in Alberta (e.g., Francis and Lumbis 1979). This is thought to be the result of the complex vertical and horizontal vegetation structure, as well as the diversity of plant and insect foods which are available to breeding birds;

7. provide a broad range of nesting sites for passerine birds, waterfowl, and waterbirds. For example, old balsam poplar snags often provide nest sites for cavity nesting species such as chickadees, wood ducks or buffleheads; and,

8. provide important calving sites for moose. Forested islands in large rivers have been shown to provide the cow with a protected area away from predators, as well as ready access to browse, early green-up vegetation and water (Decker and Mackenzie 1980; Eccles *et al.* 1986).

A number of factors contribute to the high value of riparian habitats to wildlife. Perhaps the most important aspect of riparian and deltaic communities is the dynamic successional state created by changing water levels and shifting channels and waterbodies. Within the Peace-Athabasca delta, for example, it is possible within a narrow corridor to find a broad diversity of communities along a successional continuum from newly-established sandbar willow communities to old growth white spruce forest. As a result of these changes, and the range of topographic and hydrologic conditions, riparian areas usually provide a high interspersion of vegetation communities. This, in turn, often provides a species with all or many of its habitat needs within a relatively small area.

The same hydrological forces also contribute to productive growing conditions through the deposition of new soil materials, provision of nutrients, and easy access to water. In more northerly areas, permafrost may also be limited in riparian areas.

As noted above in regards to breeding bird assemblages, riparian systems often provide a tremendous range of vegetation structural diversity in both the vertical and horizontal planes. Within a balsam poplar forest along the Slave River, for example, there is commonly a well-defined tall tree canopy, a tall shrub canopy, a low shrub canopy and groundcover layer within the vertical plane (Eccles *et al.* 1986). In contrast, along a horizontal plane, one can find a repeated succession of well drained and flooded sites of various elevations supporting areas dominated by sedges, water-tolerant grasses, sandbar willow, willow and alder thickets, balsam poplar, and even trembling aspen and white spruce.

And lastly, because riparian communities most commonly have long, linear shapes that abut a variety of upland vegetation communities, the transitions zones between these habitats provide a high degree of habitat interspersion and habitat edge. Both of these factors are important in determining the types, diversity and abundance of wildlife that will use these habitats.

Wildlife Habitat Modelling

Approaches to Habitat Modelling

During the past two decades, a wide variety of approaches have been developed to estimate the presence, distribution, and/or abundance of a wildlife species or group of wildlife species, using information on actual or possible habitat conditions (Morrison *et al.* 1992). These approaches, referred to as wildlife habitat modelling or predictive modelling, are all based on the principle that the physical and biological attributes of an area determine its ability to support a specific species or group of species. Some approaches have attempted to predict the numbers of animals that can be supported by a particular landscape. The other approach is to comparatively evaluate the biophysical attributes of a landscape relative to the optimal habitat conditions for a species. The latter approach, developed by the USFWS in the mid-1970s, and referred to as Habitat Evaluation Procedures or HEP, was intended primarily for assessing the impacts of various developments or environmental perturbations on wildlife.

The HEP procedure is based on the assumption that certain measurable variables within any habitat type (e.g., percent tree or shrub canopy closure, age and composition of forest stand) are strongly correlated to the habitat's suitability to support a given wildlife species (i.e., carrying capacity). The appropriateness of such an approach for assessing the impacts of certain development or management activities on wildlife can be summarized as follows:

> "Numbers of species and numbers of individuals often may change for unpredictable reasons but habitat potential remains unchanged. Because of its relative stability, it is this habitat potential which should be documented by the wildlife manager interested in ecologically valid impact assessment"
>
> (U.S. Fish and Wildlife Service 1980).

Population-Based and Habitat-Based Assessments

Two types of information on wildlife -- population-based or habitat-based data -- are suitable for impact assessments. While both data bases can be used to assess biological conditions before, during and after a given environmental change, the degree to which each should be used is dependent on several factors, including:

1. the size of the study area;
2. the nature of the expected impact (i.e., short or long-term); and
3. the species of wildlife involved.

Population-Based Approaches

Population-based approaches are designed to provide an indication of species abundance, animal densities or absolute numbers within a given land unit, generally an arbitrarily defined study area or particular habitat type. An impact assessment based on such data compares baseline abundance levels with corresponding values after a given change in ecological conditions. For such an approach to be valid, several conditions should be satisfied:

1. Abundance estimates must be accurate and precise to ensure that changes in animal numbers are adequately detected. Unfortunately, sampling techniques designed to estimate animal abundance are prone to biases and inaccuracies, particularly for animals with clumped distributions, migratory tendencies, and/or poor visibility when surveyed. Invariably, the only means of improving the accuracy and reliability of estimates is to increase sampling intensity, both on an area and frequency basis. Such an option becomes prohibitively and unrealistically expensive for large, heterogeneous study areas.

2. During the life of the study, factors other than the environmental change in question should not be contributing to changes in animal numbers. This condition may be satisfied for studies conducted over a short period of time (i.e., less than several months). However, as study length increases, confounding factors such as predation (including hunting), disease outbreaks, and normal demographic cycles have an increasing potential of contributing significantly to changes in animal abundance. As a result, interpreting the cause of change in animal numbers becomes increasingly complex, requiring control plots for comparative analyses, and/or multivariate statistical techniques.

3. The study should permit the significance of changes in animal numbers to be assessed on a regional scale. Assuming that the first two conditions are satisfied, an impact assessment based on animal numbers is still faced with evaluating the significance of any detected change. Reduced animal numbers within a study area following project development may indicate actual animal loss, with an associated loss of regional productivity, or a simple displacement of animals to habitats outside of the study area, with no loss of net productivity, or both. In any event, each of these scenarios must be assessed on a regional basis. Even animal deaths and resulting loss in productivity may be of negligible significance if regional productivity is altered only slightly. Securing adequate population data on a regional basis is both difficult and expensive, particularly in areas where few previous studies have been conducted.

In summary, population studies for impact assessment are best suited for: (1) small study areas; (2) short term impacts (i.e., where natural population cycles are not likely to confound population changes associated with impacts); and (3) species which can be effectively censused, and for which good quality regional data over an adequate pre-development time period can be readily obtained. Population studies also are appropriate for endangered or rare species whose abundance is limited by factors other than just habitat availability, and/or species which demonstrate a high degree of fidelity to traditional ranges (e.g., bighorn sheep, mountain goats) and, hence, can be easily censused.

Habitat-Based Approaches

Habitat suitability modelling provides a structured approach to the assessment of wildlife-habitat relationships. The application of habitat suitability modelling procedures, such as HEP, allows impacts to be assessed in a semi-quantitative manner consistent with baseline information, thereby providing unbiased comparisons of different areas. In brief:

> "...the method can be used to document the quantity of available habitat for selected wildlife species. The procedures provide information for two general types of wildlife habitat comparisons: (1) the relative value of different areas at the same point in time; and (2) the relative value of the same area at future points in time. By combining the two types of comparisons, the impact of proposed or anticipated land and water use changes on wildlife habitat can be quantified"
> (USFWS 1980a).

Habitat suitability modelling is generally based on a comparison of existing habitat potential with the optimal conditions for sustaining wildlife. Impact assessments which employ habitat suitability techniques are based on comparative, quantitative assessments of the reduction in habitat suitability from baseline values, generally on a species-specific basis. It relies primarily on the quantification of broad habitat types and a knowledge of species/habitat relationships. Documentation and supporting evidence for the selection of habitat variables and the numerical relationship between the habitat parameters and the key species are provided as part of the assessment. Some data on species abundance and distribution are required, but only as a means of determining the habitat preferences of the study species. This approach is ideally suited for: (1) large study areas; (2) long-term impacts; and (3) most species, for which species/habitat relationships can be determined.

Although wildlife populations fluctuate according to environmental conditions (not the least of which is human interference), habitat potential changes at a much slower rate which is guided by natural vegetative succession and various physical attributes of the landscape (e.g., slope, aspect). It is this habitat potential which is of greatest importance to sustain the species' presence within an area. The habitat evaluation procedure relies on the suitability of the habitat to support a species at the present time and/or in the future, whether or not the species is using the habitat to its full potential at the time of assessment.

Limitations of Hep and Other Habitat Suitability Techniques

Habitat evaluation procedures are not intended as a population assessment tool. HEP does not take into account socio-economic or behavioural variables (e.g., the effect of hunting pressures, traditional or learned behavioural adaptations by wildlife) which may be limiting a population below the habitat potential. HEP is best used for omnivores or herbivores due to the lack of measurable field parameters which can be used to estimate habitat suitability for predators.

Schamberger and O'Neil (1984) discuss some of the major limitations of habitat modelling approaches like HEP, which are based on habitat suitability indices (HSI). More specifically they draw attention to the dangers of using untested models and difficulty and expense required to test models. These authors also point out the practicality and advantages of the HSI approach, noting that, "The reliability of these models (HSI models) is not as high as we like, yet alternatives have not been developed which are widely accepted". Schamberger and O'Neil (1984) go on to summarize HSI models in the following paragraph:

> "In summary, HSI models are not research models, carrying capacity models, population predictors, or comprehensive. HSI models are practical, operational planning models, designed to assess impacts of changes; and based on a narrow definition of both habitat and carrying capacity. They also provide a bridge between the fields of planning and science, in that science is used to improve model performance in planning activities."

Realistically, the HEP method is a conservative approach to assessing impacts of habitat loss or change because the model does not generally address environmental and behavioural variables which may be limiting a population below the habitat potential. As a result, the models may overestimate the value of an area for wildlife.

The Hep Methodology

The Habitat Evaluation Procedures (HEP) method was developed by the U.S. Fish and Wildlife Service (USFWS 1980a) as a standardized method of quantifying wildlife habitats for use in impact assessments of proposed water and land resource development projects. The following assumptions are inherent in using HEP:

- It is possible to quantify wildlife habitat.
- There is a direct relationship between habitat and the potential population and this relationship can be expressed as an index (Figure 1).
- Habitat suitability can be predicted.

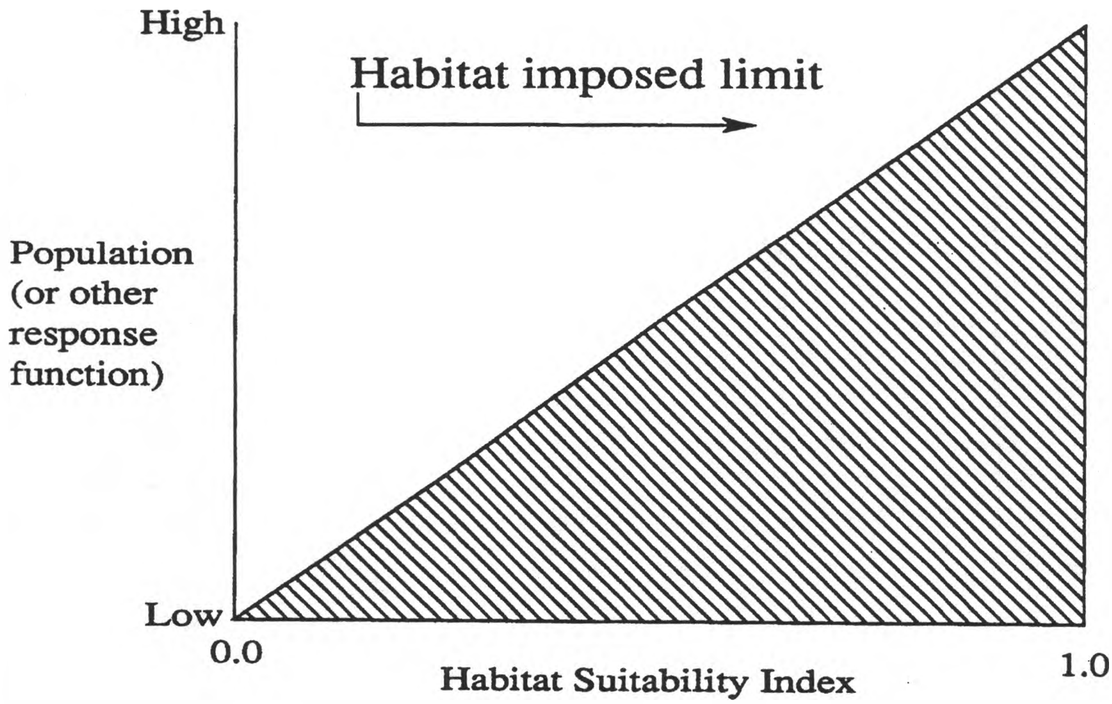

Figure 1. Relationship between the Habitat Suitability Index (HSI) and the potential population or other modelled parameter.

To assess habitat suitability for a given species, variables that are considered to be ecologically significant to a given species must be selected, measured on-site, and their values compared to corresponding values in habitats supporting the wildlife species at or near maximum levels (i.e., an approximation of optimum habitat conditions). The ratio of study area values to optimum values provides one with an assessment of habitat quality.

The modelling procedure requires the completion of seven basic steps, which include:

1. The selection of "evaluation" or study species;

2. The delineation and quantification of relatively homogeneous habitat types within the study area;

3. The determination and selection of measurable variables considered important for rating habitat suitability for each of the evaluation species;

4. The measurement of these selected habitat variables at sampling sites within each of the identified habitat types;

5. The development of habitat suitability index (HSI) models for each key species;

6. Modification and fine-tuning of the habitat suitability index models; and

7. The calculation of total available habitat (Habitat Units [HUs]) within the study area for each of the evaluation species.

Each of these steps is discussed below.

Selection of Evaluation Species

Due to the large number of wildlife species in most study areas, it is not practical to directly address all species when quantifying project impacts. Consequently, key or evaluation species which represent a variety of habitat requirements are selected for study. Selected species for an assessment commonly include two different types of key species:

- "emphasis" (or high profile) species for the area, and
- habitat representatives (i.e., species which represent the habitat requirements of wildlife species utilizing a certain habitat type).

With the increasing recognition and emphasis of recent impact assessments on the documentation and conservation of biodiversity, the latter type of key species have become increasingly important.

The selection of suitable key species for any given study is generally based on the following:

1. Species should be of particular ecological or socio-economic importance;

2. Species should generally (although not always) be herbivores or omnivores rather than carnivores, as the abundance and distributions of most carnivores are influenced to a greater degree by prey availability than by habitat parameters (e.g., wolves);

3. Species should have relatively well understood habitat requirements; and

4. Species should adequately represent the habitat requirements of a variety of other species. For example, the red squirrel can act as a representative species for other animals dependent on the cone crop of mature coniferous forests, such as the northern flying squirrel, as well as being indicative of species such as marten which depend on the red squirrel as a prey base. This attribute of some key species permits assessments of baseline habitat availability or potential environmental impacts for the selected species to be extended to other association members. Such an approach greatly reduces the number of species for which

detailed habitat relationships must be researched, without sacrificing the ecological adequacy of the information being collected.

Delineation and Mapping of the Study Area

A HEP analysis requires the delineation of discrete habitat types for the study area. This step, if properly conducted, divides the study area into homogeneous units, within which biophysical conditions and, hence, habitat suitability remains relatively constant. This permits the assessment of habitat suitability to be extrapolated from sampled to unsampled areas. An assumption must be made that unsampled areas are relatively similar to areas that have been sampled. Sampling must be undertaken in a broad range of conditions within each habitat type, and this assumption must remain constant for all phases of analysis (i.e., baseline, impact, and mitigation).

Biophysical factors considered to directly influence habitat suitability can include vegetation cover type, slope and aspect, and other topographic features. Since vegetation cover type is actually an expression of a variety of biophysical conditions such as soil, aspect and relief, it generally offers the most current and valid prediction of habitat suitability for most wildlife species.

Selection of Habitat Variables

All wildlife species require a combination of particular habitat conditions to ensure that the major life requisites of food and cover are supplied. Factors of importance to an animal may be as specific as the presence or absence of a particular forage species. However, in the majority of cases, habitat suitability can be governed by biological and physical characteristics such as shrub or tree canopy cover, slope, and topographic characteristics.

In recent years, considerable wildlife research has been directed towards evaluating habitat suitability, based on such broad biological and physical characteristics. Any habitat analysis relies, to a large degree, on the large body of literature which has resulted from this research. Information on important habitat factors of each evaluation species is synthesized as an initial step in the development of a habitat suitability ranking system. Variables which best measure the habitat factors in question are then selected. In general, each habitat factor should meet three criteria:

1. the variable is related to the capacity of an area to support the evaluation species;

2. there is a basic understanding of the relationship of the variable to habitat suitability (e.g., what is the best and worst value for the variable and how does the variable interact with other variables); and,

3. the variable is practical to measure, either in the field or from remotely-sensed data sources.

On-Site Measurement of Habitat Variables

Once the habitat variables have been selected, the availability of these variables within the study area must be determined through direct measurement and/or remote sensing. Depending on the variable, this can involve simple to complex field sampling (i.e., the presence or absence of a particular plant species such as a type of boreal lichen, measurement of the density of important browse species, height or age of trees). In contrast, some variables can be adequately measured using remote sensing tools such as Landsat imagery or aerial photographs (e.g., determination of vegetation cover types from satellite imagery). In some assessments, it may be possible to utilize existing mapped information such as forest cover maps to estimate some habitat variables.

Development of Habitat Suitability Index (HSI) Models

The HEP approach is based on the development of a numerical relationship between variable values and habitat suitability for the wildlife species in question. This relationship is generally expressed in the form of a Suitability Index graph (Figure 2).

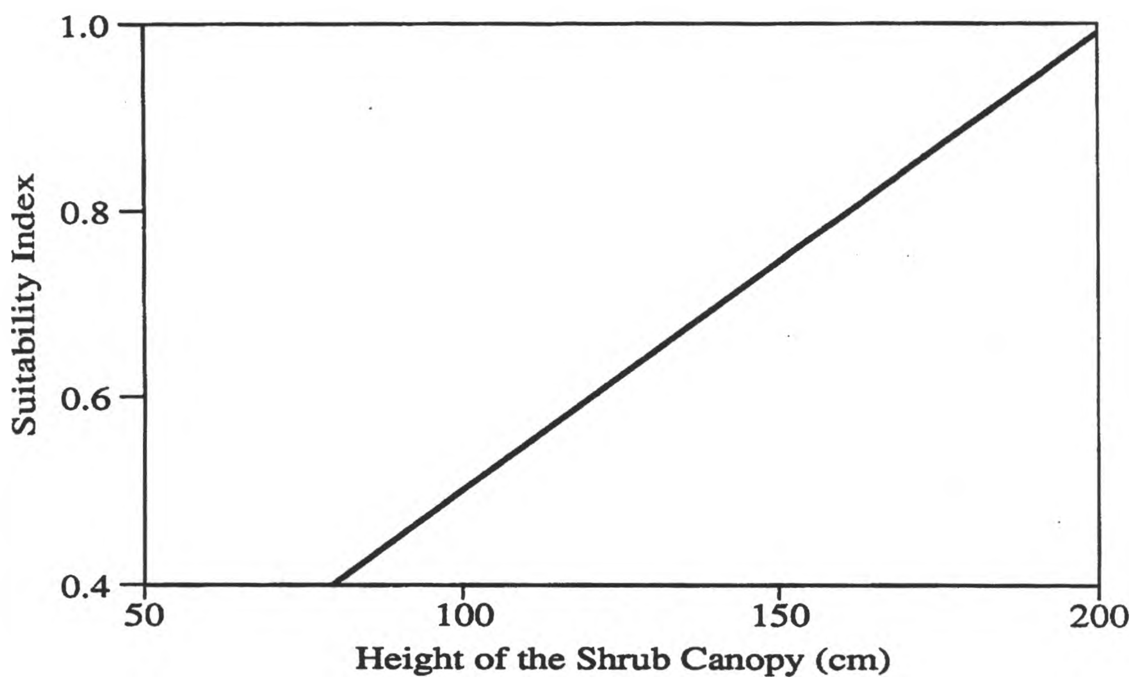

Figure 2. Example of a Habitat Suitability Index (HSI) graph. (based on a model for the Yellow Warbler)

Values are measured for each habitat variable selected for modelling, describing the full range of that variable's values found in the study area, and a suitability index (SI) value ranging from 0.0 to 1.0 is assigned or calculated for each value. Under this format, an SI value of 1.0 would be assigned to the variable value at which habitat conditions are considered optimal for the wildlife species in question. Other measurements of the same variable would be assigned a reduced SI value, based on animal abundance trends observed for different variable values, observations of other researchers working in comparable habitat types (i.e., northern boreal forest), or other relevant information. If the optimum value is not the highest value in the data set, then the values exceeding this number are calculated by one of three formulas which reduce, reverse, or level out, the HSI values.

Once SI relationships and values are developed for each habitat variable that is considered to be important to the species, an overall Habitat Suitability Index (HSI) is calculated for each habitat type, based on an aggregation of the individual SI's (i.e., habitat evaluation [HSI] model).

Fine-tuning of Habitat Evaluation Models

It is generally recognized that the nature in which habitat factors influence habitat suitability for a given wildlife species may change slightly from one geographic area to another. Consequently, habitat models developed largely from research data collected outside of a given study area should be "fine-tuned" to adequately reflect species-habitat relationships within the study area. This is generally accomplished by reviewing available local data on selected population parameters for a variety of evaluation species within the study area.

Calculation of Total Available Habitat Units

The measure of habitat availability in the modelling approach is the Habitat Unit (HU), a measure which reflects both habitat quality and quantity. For any given habitat polygon, habitat availability is calculated for an evaluation species using the following formula:

$$HUs = (HSI \times A)$$

where HSI = habitat suitability index for the polygon
A = area of the polygon

Total habitat availability for a given species within the entire study area is, in turn, calculated as follows:

$$HUs = \sum_{i}^{N} (HSI_i \times A_i)$$

Where HSI_i = the HSI value for habitat type i
A_i = total area of habitat type i within the study area
N = number of habitat types

Use of Hep Models for Instream Flow Needs Assessments

What are some of the potential uses of HEP in relation to future planning and management of in-stream flow needs? Assuming that appropriate data bases can be developed and updated at regular intervals, HEP can be used to:

1. Compare existing differences in habitat values for wildlife among different river reaches. HEP can also be used to assist in the preparation of habitat suitability maps for riparian communities and adjacent upland habitats;

2. Assess the potential impacts of different combinations of land and water management practices on habitat availability for various key wildlife species. These types of assessments would need to be strongly integrated with prediction of vegetation responses to various water regimes and land use practices;

3. Identify preferred sites for habitat compensation if water management and land management practices have or will result in important local or regional losses of wildlife habitat. For example, recent studies of the Peace-Athabasca delta have indicated that altered water regimes have resulted in significant losses of some kinds of riparian and deltaic communities within the Delta (Jacques 1989, 1991). HEP could be used as a tool to identify potential sites for habitat restoration and enhancement; and

4. As part of a habitat restoration or enhancement program, HEP can be used to determine the potential benefits which may be realized as a result of the habitat mitigation projects. HEP provides a means of comparing the effects of potential habitat losses and changes, to the potential benefits of habitat compensation programs.

Special Considerations for Habitat Modelling in Riparian Areas

If HEP or any other habitat-based approach is used to assess the effects of various in-stream flow regimes on wildlife, there are several factors which will require special consideration:

1. First, because of the complexity of many riparian communities and the interspersion of habitats, it is important to consider the size of the individual habitat polygons relative to the home range requirements of the species and the

needs of the key species for thermal and hiding cover and proximity to food resources. For example, moose generally require a contiguous block of coniferous cover at least 350 to 500 m wide to provide high quality thermal cover. Hiding cover should be in the order of 185 to 350 m wide. In addition, areas of browse generally must be within 500 m of hiding cover. These spatial requirements must be considered in selecting an appropriate size and boundaries for the study area;

2. As noted earlier, because riparian communities often have long, linear dimensions, there is a high degree of habitat edge with different communities, particularly upland communities. The proximity of different upland communities to riparian communities will have a strong modifying effect on the value of both the upland and the riparian communities to a key species. For example, a riparian shrub community bounded by a jackpine forest will have a substantially lower value than a similar shrub community bounded by a mixed wood forest;

3. Interpretation of remotely sensed data for riparian areas can be complex, time consuming and expensive. For example, during the Slave River Hydro Mammal Study, it was important to accurately differentiate between alder shrub communities and willow shrub communities. However, the signature of these two habitat types on air photos are similar. Accurate differentiation of these communities would likely require use of seasonal photography (i.e., to differentiate shrubs on the basis of leaf colour during the fall) or spectral data such as Landsat imagery; and

4. Use of habitat models to predict effects of instream flow management on wildlife will be limited by our ability to predict how riparian vegetation communities will respond to varying water regimes. It is therefore important that adequate field studies and remote sensing be completed to be able to predict how riparian vegetation communities will likely respond to altered water management regimes and land use practices.

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5.0 WORKSHOP DISCUSSIONS

After listening to background presentations and contributed papers, workshop participants engaged in a series of discussions. These discussions were structured according to a list of selected topics, each of which was addressed for a predetermined period of time. The following sections summarize the main elements of those discussions.

5.1 FISH AND AQUATIC HABITATS SESSION

5.1.1 Data Organization

Instream flow needs studies typically involve collection of large amounts of data, including information on fish distribution, movements, life history, and habitat utilization as well as hydrology, stream transect and habitat distribution data. There is also generally a need to incorporate historical data into the analysis.

Due to the size of the study area, which is much larger than is commonly considered in IFN studies, the amount of information that must be dealt with will be unusually large. The need for a comprehensive, integrated, and effective data management system was emphasized. The importance of this is due primarily to the need to reference large amounts of a wide variety of data in interpreting results of IFN analyses. Use of a geographic information system (GIS) for this purpose was recommended.

5.1.2 Critical Habitats

Available information on fish resources of the study area, including their distribution, movements, and known spawning areas were reviewed and discussed. In addition to general information on distribution and movements, the following types of information about fish populations are needed to support IFN studies:

1. What life activities are associated with mainstem areas
2. Any barriers or limitations to movement
3. Associations of fish with different habitat types
4. Relative value of different habitat types
5. Areas of critical or potentially limiting habitats
6. Seasonal changes in habitat use

It was generally agreed that information presently available on general fish distribution and major movements in the mainstem was adequate. However, more specific information on associations with different habitat types (e.g., side channels, stream margins, sloughs, backwaters), locations of critical habitats, and activities associated with mainstem areas is needed.

5.1.3 Hydrology and Hydraulics

The presently available hydrologic data was reviewed and discussed. Hydraulic models being developed at the University of Alberta were described.

The need to consider water levels in addition to stream discharge was emphasized. In addition, the importance of localized flow conditions and the effects of ice on local flows was discussed. Scouring by ice may significantly affect fish habitat in some areas from time to time. Formation of frazil ice is an important consideration with respect to winter fish habitat.

Short term flow variability (i.e., daily) due to hydropower operations on the Peace River should be considered in IFN studies. However, this can be difficult to deal with due to the impracticality of simulating with models the daily flow variation under different flow regimes.

The potential for applying a new finite element hydraulic model, recently developed at the University of Alberta, in IFN studies was discussed. This model has a number of advantages over other hydraulic models that have typically been used for IFN studies in the past.

5.1.4 Sediment Transport

The types of post-regulation geomorphological changes likely to occur were reviewed. It was noted that sediment transport is linked primarily to peak flow events and that the timing of regulated peak flows in the Peace River may now be asynchronous with tributary peak flows. The importance of considering the effects of various land use practices on sedimentation was mentioned.

Sediment transport is a major issue in instream flow needs analyses because of the potential effects on fish habitat quality. The potential biological effects of changes in sediment transport were discussed. These include reduction in spawning gravel quality, aggradation and isolation of sloughs and side channels, and effects on benthic invertebrate production.

5.2 RIPARIAN AND DELTA HABITATS SESSION

5.2.1 Channel Morphology and Riparian Vegetation Responses, Ice Effects, and Wildlife Habitat

Responses of river channel morphology and riparian vegetation communities to changes in flow regime can be examined on the Peace River by conducting a historical review of aerial photography. Changes can be measured on photographs from pre-regulation and post-regulation periods and interpreted in the context of the historical stream flow record.

It was emphasized that there is a need to develop a better understanding of how the riparian system behaves in response to various disturbance events. Such events include extreme flow events, ice jam induced floods, ice scouring, landslides, and fire. Riparian vegetation communities are expected to bee less dynamic under condition of annual flow regulation. The immediacy and extent of change is expected to be correlated with flow change.

However, the ability to predict responses is reduced over time. This is due to the fact that disturbance events are important factors in determining the character of riparian communities. Such events cannot be predicted in terms of either occurrence or severity. The difficulty of determining whether observed changes are due to flow regulation or are the result of natural flow variation or natural disturbance events was discussed.

The temporal resolution of discharge and water level data is an important consideration in IFN analyses for riparian communities and assessment of potential effects of flow regime changes. Monthly data are insufficient and weekly data are probably adequate.

Available information about the high profile wildlife species (e.g., moose, deer, waterfowl) and their habitat requirements is quite good. It is probably not necessary to collect additional data on these species to support IFN analyses on the Peace River. However, less is known about small mammals and songbirds. There is virtually no information available about reptiles, amphibians, and terrestrial invertebrates along the Peace River. Aspects of vegetation communities that are important in terms of wildlife habitat include distributional changes in space and time, forest diversity, and age structure of the community.

5.2.2 Descriptive Analyses, Monitoring Programs, and Predictive Tools

The establishment of permanent vegetation plots on the Peace River to serve as study sites for long term monitoring was strongly recommended. These are needed not only to document changes, but to establish the pattern of succession on undisturbed sites and compare it to vegetation succession at sites affected by various disturbance events.

The need to establish a database for long-term storage of monitoring data was identified. Special requirements for a riparian vegetation database include the need to ensure continued accessibility of the data over a period of many decades.

It was suggested that biodiversity could be a target in recommending instream flow requirements. The assumption would be that managing for maximum biodiversity would provide adequate protection of riparian environments.

Modelling of vegetation succession and community responses to disturbance was discussed in some detail. However, there was considerable uncertainty as to what factors might influencing riparian communities in the Northern River Basins most strongly. More research and experimentation is probably needed to adequately support predictive modelling efforts.

There was a general consensus that we are not yet very close to being able to undertake quantitative predictive modelling of responses of riparian communities to changes in river flow regime. This is due to an insufficient understanding of system functions as well as a lack of information on specific process rates. However riparian vegetation response modelling at the conceptual level would be a useful undertaking. It was suggested that a good scientific and intellectual exercise would be to try to set up a conceptual framework for a model early on in the investigations.

6.0 CONCLUSIONS AND RECOMMENDATIONS

After discussion sessions on the selected topics outlined in Section 5.0, workshop participants were asked to consider what conclusions could be reached and what recommendations they would like to make regarding potential IFN investigations in the Northern River Basins. The following material summarizes the discussions on conclusions and recommendations.

The major conclusions of the fisheries and aquatic habitats session of the IFN workshop are as follows:

1. Emphasis and priority in IFN studies should be on the Peace River because of the existing flow regulation on this river.

2. Some additional data on fish resources of the Peace River are needed to support instream flow needs analyses. It was generally agreed that the information presently available on general fish distribution and major movements in the mainstem was adequate. However, more specific information on associations with different habitat types (e.g., side channels, stream margins, sloughs, backwaters), locations of critical habitats, and activities associated with the mainstem is needed.

3. The need for a comprehensive, integrated, and effective data management system was emphasized. The importance of this is due primarily to the need for reference to large amounts of a wide variety of data in interpreting results of IFN analyses. Use of a GIS for this purpose was recommended.

4. There was a general consensus that we should probably not pursue IFN studies based on hydraulic modelling to predict microhabitat characteristics (depth, velocity, substrate), at least at the present time. Reasons for this recommendation are related to logistic problems on large rivers, spatial limitations due to the necessarily short length of modelled segments, and difficulty of obtaining adequate data on the microhabitat preferences of the various fish species and life stages.

5. The preferred approach to aquatic habitat IFN analysis was considered to be one based on mapping of various habitat types (e.g., main channel, side channels, sloughs, backwaters) at different discharges. This approach involves taking aerial photography or videography at several different discharges and at a scale appropriate for identification of important habitat features. Surface areas of the various habitat types are measured on digitized images in order to develop habitat-discharge relationships.

6. Sediment transport is a major issue in terms of IFN and fish habitat, and therefore should be included in IFN analyses and evaluations of the effects of flow regulation.

7. The need to consider ice effects was identified.

The second session of the IFN workshop was focussed on how flow and water levels influence riparian and delta habitats and on methods for addressing the question of IFN for protection of these habitats. This session was held on January 6-7, 1994 in Edmonton. The structure and format was similar to the first session of the workshop.

The major conclusions of the riparian and delta habitats session of the IFN workshop are as follows:

1. There was strong support for a historical review of aerial photography on the Peace River (1949 to 1993) to examine changes in river channel morphology and riparian vegetation communities and to interpret these in the context of the historical stream flow record. (This work was undertaken in NRBS Project 1321-C1).

2. Establishment of permanent riparian vegetation plots on the Peace River to serve as study sites for long-term monitoring was strongly recommended.

3. It was suggested that some studies be undertaken to address the need to better understand the response of the system to critical and unusual events (e.g., extreme flow events, ice jam induced floods, ice scouring, fire) because these events are important factors in determining the character of riparian communities.

4. The need to establish a database for long-term storage of monitoring data was identified. Special requirements for a riparian vegetation database include the need to ensure continued accessibility of the data over a period of many decades. Care needs to be taken to ensure that the computer database does not become inaccessible due to advancing computer hardware and software technology.

5. The temporal resolution of discharge and water level data is an important consideration in IFN analyses for riparian communities and assessment of potential effects of flow regime changes. Monthly data are insufficient and weekly data are probably adequate.

6. It was suggested that biodiversity could be a target in recommending stream flow regimes that will provide protection of riparian environments (i.e., managing for maximum biodiversity).

7. For evaluating the capability of riparian areas to support wildlife, an approach based on habitat suitability analysis was recommended as better than approaches that attempt to model actual wildlife production.

8. There was a general consensus that we are not yet very close to being able to undertake quantitative predictive modelling of the responses of riparian communities to changes in river flow regime. This is due to an insufficient understanding of system functions as well as a lack of specific process coefficients, which cannot be

obtained quickly (i.e., in less than 5 years). However, it was suggested that riparian vegetation response modelling at the conceptual level would be a useful undertaking.

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APPENDIX B - TERMS OF REFERENCE

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