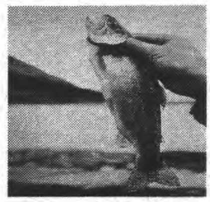
Canada Alberta Northwest Territories

Northern River Basins Study





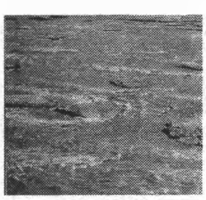


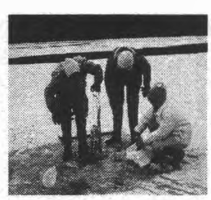



NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 37

PROCEEDINGS OF A WORKSHOP ON WATER QUALITY MODELLING

FOR THE NORTHERN RIVER BASINS STUDY, MARCH 22-23, 1993







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Northern River Basins Study
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by
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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.

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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.

(Dr. F.J. Wrona, Ph.D., Science Director) — 8 June 94 (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;
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(Dr. P. A. Larkin, Ph.D., Chair) — 8 June 94 (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
(Lucille Partington, Co-chair) — June 9, 94 (Date)

______________________ (Date)

PROCEEDINGS OF A WORKSHOP ON WATER QUALITY MODELLING FOR THE NORTHERN RIVER BASINS STUDY, MARCH 22-23, 1993

STUDY PERSPECTIVE

Two of the major objectives of the Northern River Basins Study (NRBS) are to determine the impacts of effluent discharges on the aquatic environment and to develop predictive tools to determine the cumulative effects of such discharges. A particular area of concern related to effluent discharges is the effect of nutrients and oxygen-consuming waste on the aquatic environment. The development of reliable nutrient and dissolved oxygen (DO) models assists in understanding the relationship between nutrients and algal and invertebrate biomass, and between DO in the river water and effluent inputs of nutrients and oxygen-consuming waste. Models are also essential for assessing the consequences of controlling or not controlling effluent inputs.

Related Study Question

5) Are the substances added to the rivers by natural and man-made discharges likely to cause deterioration of the water quality?

7) What concentrations of dissolved oxygen are required seasonally to protect the various life stages of fish, and what factors control dissolved oxygen in the rivers?

13 a) What predictive tools are requred to determine the cumulative effects of man-made discharges on the water and aquatic environment?

14) What long-term monitoring programs and predictive models are required to provide an ongoing assessment of the aquatic environment. These programs must ensure that all stakeholders have the opportunity for input.

This report summarizes discussions and conclusions from a two-day workshop on water quality modelling approaches for the Peace and Athabasca Rivers held March 22 and 23, 1993 at the National Hydrology Research Institute, Saskatoon. The workshop brought together experts in riverine ecology and water quality modelling. Representatives of government, the private sector and academic communities met with the goal of reviewing and assessing available modelling approaches for estimating the impact of oxygen-consuming waste and nutrient loadings on water quality of the Peace and Athabasca river systems.

A general consensus of the workshop participants was that deficiencies exist in current DO and nutrient-related databases for the northern river basins. Specifically, the need for additional information was identified in the following areas: hydraulic coefficients related to reaeration zones; relationships, if any, between headwater DO and winter meteorological conditions; the effect of tributary and groundwater DO on mainstem DO; and the contribution of oxygen-consuming wastes and nutrient-stimulated biofilm growth and subsequent decomposition on under-ice sediment oxygen demand. It was also recommended that the NRBS consider the application of more than one model to improve future DO predictions and that future modelling efforts be pursued by two or more independent teams working in parallel.

The findings of the workshop will be used to identify appropriate models and to direct the collection of information on nutrient and DO-related parameters for the northern rivers.

REPORT SUMMARY

A two-day workshop on water quality modelling in the Peace and Athabasca Rivers was held at Environment Canada's National Hydrology Research Institute in Saskatoon, Saskatchewan on March 22-23, 1993. This workshop was part of the Northern River Basins Study (NRBS) and brought together experts in riverine ecology and water quality modelling from government, industry, and university communities. The goal of the workshop was to review and assess available modelling approaches for estimating the impact of biological oxygen demand (BOD) and nutrient loadings on the water quality of the Peace and Athabasca River systems. Primarily, this workshop dealt with Questions Five and Seven of the Study which, in part, fall under the responsibility of the Nutrients Component Group. These questions deal with the effect of nutrient loading on water quality and with the concentrations of dissolved oxygen (DO) required to protect riverine biota.

The goal of the workshop was achieved by a two-part process: formal presentations by invited speakers, and group discussions on modelling approaches. The series of presentations on available approaches to water quality modelling outlined the structure of model components and reviewed the key rate coefficients necessary for model application. Additionally, these presentations indicated any need for further development to the model structure or better measurement of critical rate coefficients. These presentations were a catalyst for important discussions, particularly on day two when workshop participants engaged in a lively discussion of potential recommendations to the NRBS for future work on water quality modelling.

Chapters 1.0 and 2.0 provide background information for the workshop context. Chapter 1.0 lists the overall objective of the workshop as well as five specific goals: (i) identify NRBS needs in terms of water quality models, (ii) discuss and assess existing water quality models in terms of short- and long-term needs for basin management, (iii) review and assess model structure, examine rate coefficients, and discuss sensitivity analyses, (iv) examine the limitations of available data bases, and (v) identify areas and issues requiring further research. Chapter 2.0 provides a broad overview of NRBS objectives and summarizes the specific needs from, or input to, water quality models as identified by several of the NRBS working groups (i.e., Hydrology, Nutrient Impacts, Contaminants, and Other River Uses). In addition, representatives from the pulp and paper industry provided a summary of their needs for water quality modelling in terms of future planning and operation.

Chapter 3.0 provides a brief overview of the hydrology and development in the basin in order to illustrate the template underlying the water quality monitoring program. The review also summarizes the water quality modelling efforts undertaken within the basin and concludes with several specific issues that must be addressed by NRBS modelling strategies.

Chapter 4.0 presents an examination of four water quality models, namely DOSTOC, NUSTOC, WASP4, and DSSAMt, as well as methods for pattern recognition, in an attempt to identify their potential use as management tools for the NRBS and to establish key limitations to different modelling approaches. Each presentation provides a review of the specific model structure and assesses the strengths and weaknesses of that particular modelling approach. Chapter 5.0 discusses alternative modelling approaches to those discussed in Chapter 4.0. Specifically, this chapter stresses the importance of accurately capturing the ecological processes in water quality models. Currently, these ecological processes are absent or poorly represented in the models proposed for use in NRBS.

Chapter 6.0 provides a summary of the recommendations proposed for water quality modelling in the NRBS by both the workshop participants and external consultants. A general consensus of the workshop was that deficiencies exist in the database. In particular, participants identified the need for additional information on hydraulic coefficients related to reaeration zones; relationships, if any, between headwater DO and winter meteorological conditions; the effect of tributary and groundwater DO on mainstem DO; and the effect, under ice cover, of effluent BOD and detrital material accumulation on SOD. Presently, the relative importance of primary producers in the river as net contributors or users of DO, or as net contributors to increased SOD under ice, is unknown. It was noted that questions on the importance of primary producers to the mass balance of DO in the river cannot be considered in isolation of nutrient impacts.

Because of current limitations and deficiencies in both the database and basic understanding of processes affecting riverine DO, participants felt that changes in existing model structure were not warranted at present. The group was divided as to whether model predictions would be improved by moving from the use of steady-state to dynamic models. It is clear, however, that NRBS should consider the application of more than one model to improve future DO predictions. Finally, given the subjectivity that comes into play when modelling complex systems with parameter-rich models, it was suggested that future modelling efforts be pursued by two or more independent teams working in parallel.

Data on nutrient concentration in the river are very limited and the expansion of this database is considered to be an important product of the NRBS. Participants also felt it was important to generate mass balance equations for TN and TP, as this would allow improved application of predictive water quality models such as NUSTOC. As more data become available, empirical relationships between TP and algal biomass could be attempted. Finally, careful consideration should be given to measuring key components of TN and TP that may be more readily available to the biota (e.g., TDN and TDP).

The workshop succeeded in its primary goals of identifying the gaps in data and knowledge of key processes affecting nutrient and DO concentration. Furthermore, a consensus was reached on the type of models that will be useful for the NRBS given the limited information available for these river systems and our poor understanding of processes controlling water quality in them. This report provides the NRBS with valuable information for use in developing water quality models and coordinating long-term monitoring requirements for the Peace and Athabasca River Basins.

ACKNOWLEDGMENTS

The workshop was conducted and funded under the auspices of the Northern River Basins Study (NRBS). We are grateful to the National Hydrology Research Institute (NHRI) for providing a locale and facilities for this symposium. Prior to the workshop, Dr. Gordon Walder contributed important insight into water quality modelling for the NRBS. Staff at NHRI were particularly helpful during all phases of this project. Colleen Pollock arranged logistical support during the workshop; she and Alec Dale helped compile material for earlier drafts of the proceedings. Dr. Leah Watson provided excellent editorial support and Phil Gregory supervised graphics production. Finally, we acknowledge the efforts of workshop participants whose input and interest provided the stimulus for initiating the workshop concept.

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CHAPTER 1.0

INTRODUCTION TO WATER QUALITY MODELLING FOR THE NRBS

1.0 INTRODUCTION TO WATER QUALITY MODELLING FOR THE NRBS (Dr. J. Culp, NHRI)

1.1 Background and Scope of Workshop

Water quality models are important tools for estimating the impact of nutrient and biochemical oxygen demand (BOD) loadings to large river basins. Often, these models represent the best information available to decision makers and increase the manager's understanding of the effects of existing and potential loadings. Because of the potential utility of these models in designing water quality management strategies for large rivers, a two-day workshop on water quality modelling in the Peace and Athabasca Rivers was held at Environment Canada's National Hydrology Research Institute in Saskatoon, Saskatchewan on March 22-23, 1993.

This workshop was part of the Northern River Basins Study (NRBS) and brought together experts in riverine ecology and water quality modelling from government, industry, and university communities. The focus of this think tank discussion was to review and assess available modelling approaches for estimating the impact of BOD and nutrient loadings on the water quality of the Peace and Athabasca River systems. Contaminant transformation and fate processes were not considered. Primarily, this workshop dealt with Questions Five and Seven of the Study, which fall under the responsibility of the Nutrients Component Group. Specifically, these questions have been defined by the NRBS as:

Question 5: *Are the substances added to the rivers by natural and man-made discharges likely to cause deterioration of the water quality* [i.e., the link between nutrient loading and water quality]*?* One of the primary goals of this workshop was to discuss water quality simulation models as tools for determining the receiving water's ability to assimilate nutrient-rich effluent. In addition, the participants were asked to discuss the potential of these models to predict the cumulative effect of multiple effluent discharges on river water quality and on the abundance and composition of the benthic flora and fauna.

Question 7: *What concentrations of dissolved oxygen (DO) are required seasonally to protect the various life stages of fish, and what factors control DO in the rivers?* An important aspect of this workshop was the discussion of DO simulation models which attempt to determine the receiving water's ability to assimilate oxygen-demanding wastes. These models have the potential for application as tools to predict the cumulative effects of multiple discharges on the receiving water's oxygen content.

The workshop format was a blend of prepared presentations followed by open forums to discuss key issues. Through the course of these presentations and discussions, each NRBS working group specified their needs from, or input to, water quality models. Several available approaches to water quality models were reviewed with the view that a suite of modelling tools may be needed to meet both the short- and long-term goals for NRBS water quality modelling. Thus, the workshop participants attempted to discuss the various models and approaches as tools designed for specific tasks rather than exclusive alternatives.

1.2 Workshop Primary Objective and Goals

Overall Objective

To discuss and assess possible modelling approaches that could be used for water quality planning in the NRBS (nutrient and BOD loadings only).

Workshop Goals

1. Identify NRBS needs in terms of water quality models (define the modelling requirements).

2. Discuss and assess existing water quality models in terms of short- and long-term needs for basin management.

3. Review and assess model structure, examine rate coefficients, and discuss sensitivity analysis.

4. Examine the limitations of available data bases.

5. Identify areas and issues requiring further research.

CHAPTER 2.0

NRBS NEEDS FOR WATER QUALITY MODELLING

2.0 NRBS NEEDS FOR WATER QUALITY MODELLING

2.1 What is the Northern River Basins Study? (Dr. Fred Wrona, Science Director, NRBS)

The Northern River Basin Study is a four and one-half year, $11.3 million project aimed at gathering comprehensive information on water quality; fish and fish habitat; riparian vegetation and wildlife; hydrology and hydraulics; and the use of aquatic resources. This information will form a database that will be used to develop a capability to predict and assess the cumulative effects of development on the water and aquatic environment of the Peace, Athabasca, and Slave Rivers within Alberta and the Northwest Territories (Fig. 2.1).

The Athabasca River originates in the Rocky Mountains and flows northeast across Alberta to Lake Athabasca, discharging in the lake's southwest corner. Currently, there are four pulp mills operating on the Athabasca main stem. Another pulp mill operates on the Lesser Slave River, a tributary of the Athabasca (Fig. 2.2). In addition, the effluents from one tar sand operation and six municipalities discharge to the Athabasca River. The Peace River originates in northeastern British Columbia and flows northeast across B.C and Alberta, discharging into Lake Athabasca to form the Peace-Athabasca Delta. Currently, there are six pulp mills operating and four sites of sewage discharge along the Peace River and its tributaries. The Slave River runs from Lake Athabasca in Northern Alberta to the Great Slave Lake in the Northwest Territories, which drains via the Mackenzie River to the Arctic Ocean.
The Study has three broad objectives:

- ***To provide a scientifically sound information base for planning and management of the water and aquatic environment of the study area so as to enable its long-term protection, improvement, and wise-use.***

- ***To collect and interpret data and to develop appropriate models related to hydrology and hydraulics, water quality, fish and fish habitat, riparian vegetation and wildlife, and the use of aquatic resources in order to predict and assess cumulative effects of development.***

- ***To ensure that technical studies undertaken in the basin are conducted in an open and cooperative manner and their purpose, progress and results are reported regularly to the public.***

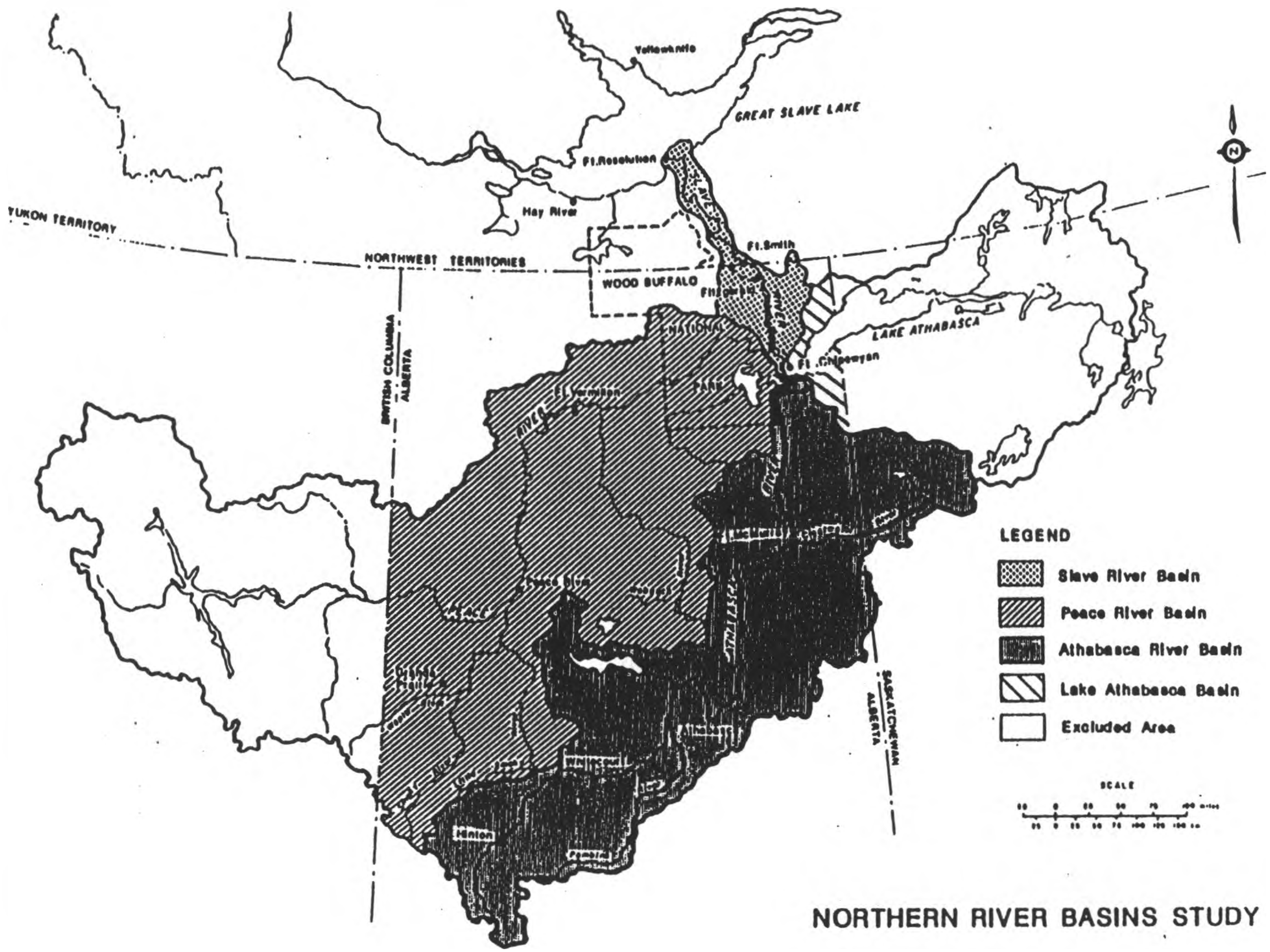
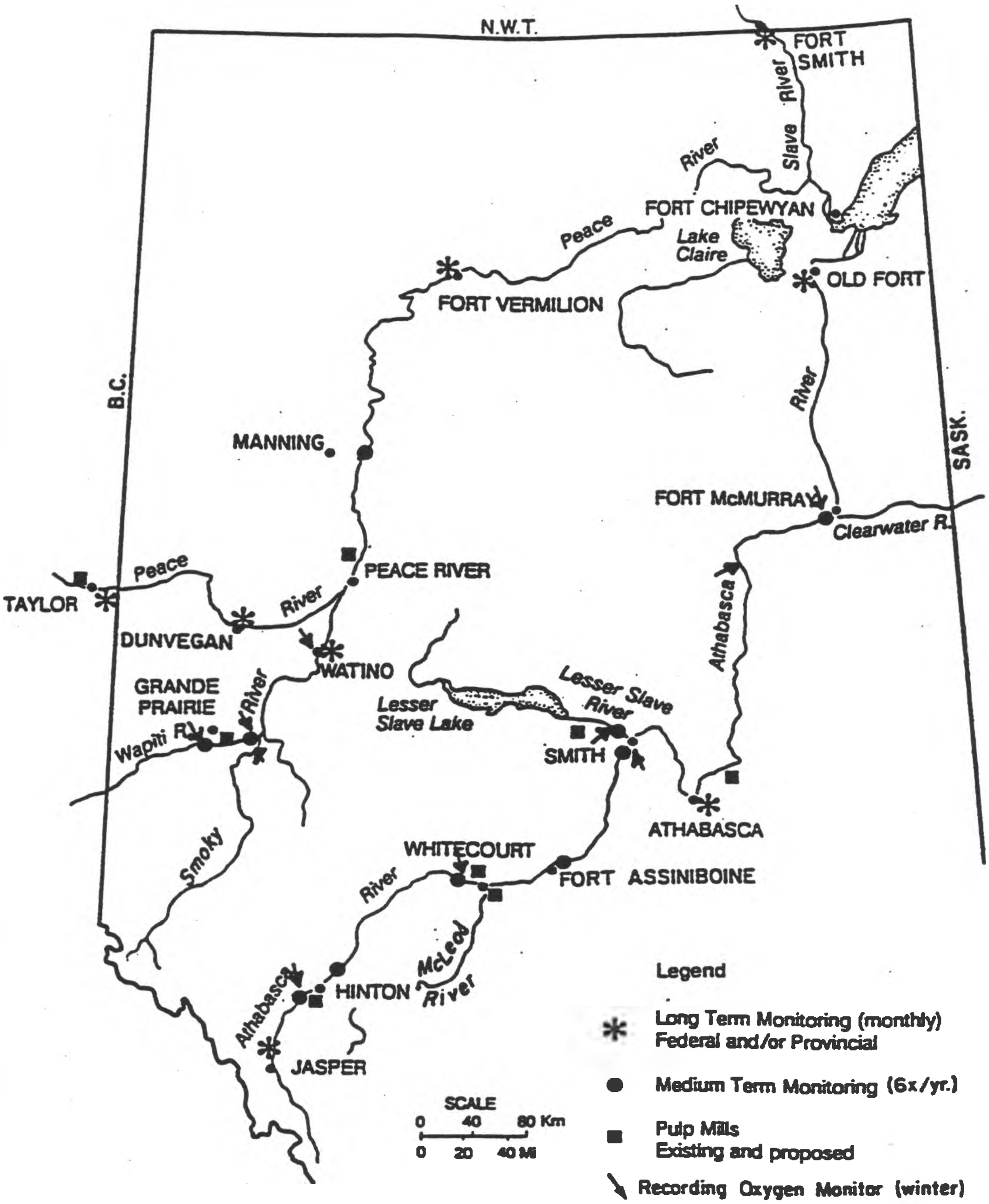


Figure 2.1 Map of the Northern River Basins Study Area Showing the Drainage Area of the Athabasca, Peace, and Slave Rivers.

Figure 2.2 Map of Northern Alberta Indicating the Network of Water Quality Monitoring Sites and the Locations of Pulp Mills on the Peace and Athabasca Rivers.



These objectives dictate an integrated, multi-disciplinary approach (Fig. 2.3). The Study Board drives the Study and is responsible for its overall direction and goals. The Board is comprised of 25 appointed individuals representing federal, provincial, and territorial governments; local municipalities; industry, agricultural, academic, health, and environmental groups; and aboriginal leaders. The Board has identified sixteen scientific and non-scientific questions to serve as guidelines to help the Study meet its objectives. Furthermore, the Study Board meets on a regular basis to ensure that Study objectives are being met. The Board also reviews programs and approves annual budgets and work plans. In addition, a Science Advisory Committee provides scientific and technical guidance to the Board and the Science Director.

To address the 16 questions identified by the Study Board, eight technical working groups were established to plan, implement, and interpret scientific studies. These working or component groups are as follows (leaders in parentheses):

- Hydrology/Hydraulics and Sediment Transport
  (Dr. T. Prowse, National Hydrology Research Institute)

- Nutrient Impacts and DO
  (Dr. P. Chambers, National Hydrology Research Institute)

- Contaminants
  (Dr. B. Brownlee and Dr. J. Carey, National Water Research Institute)

- Food Chain
  (Dr. R. Hesslein, Freshwater Institute)

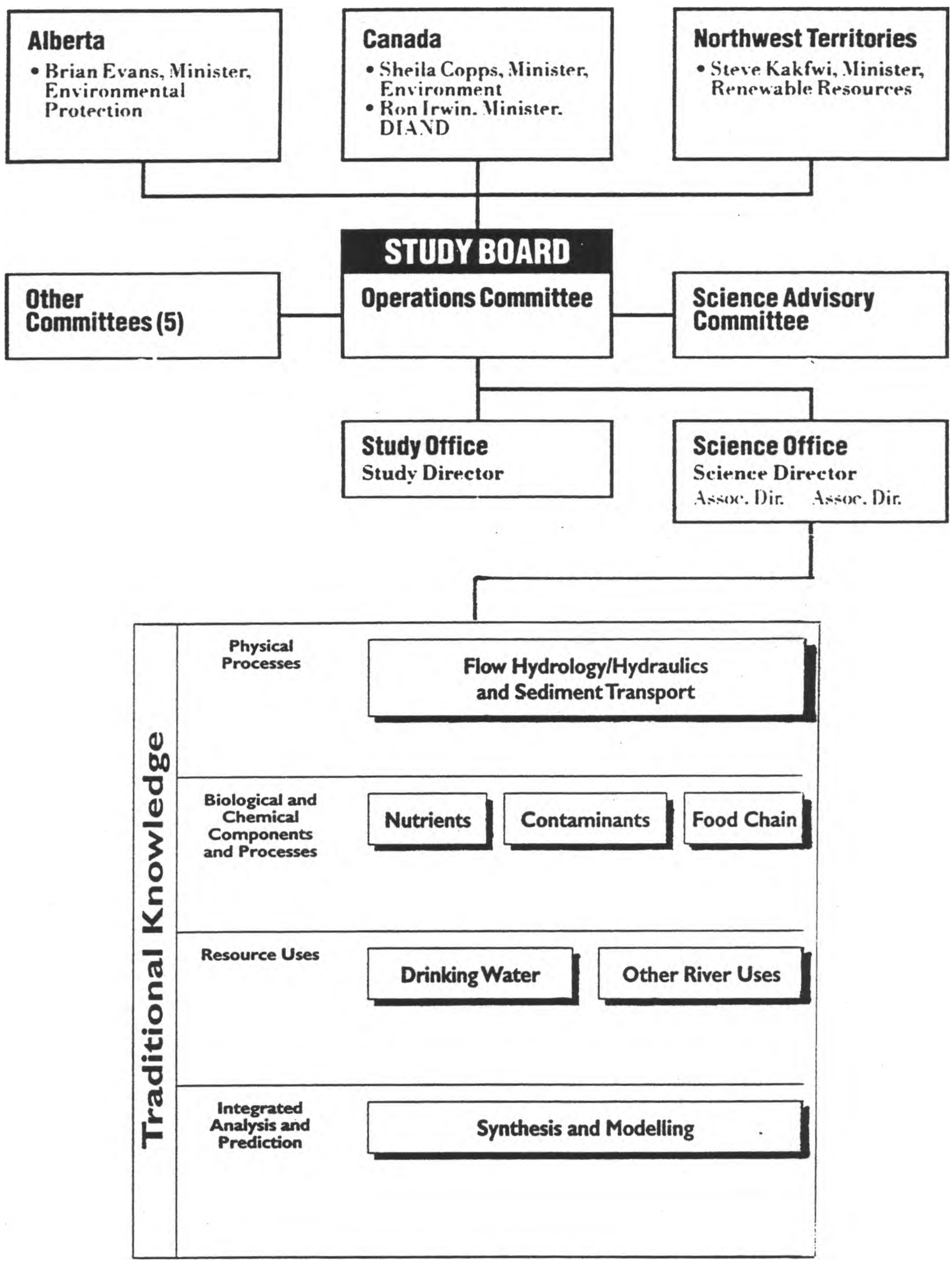
- Drinking Water
  (Dr. D. Smith, University of Alberta)

- Other River Uses
  (Dr. B. MacLock, Alberta Environmental Protection)

- Traditional Knowledge
  (Mr. S. Flett, Alberta Environment)

- Synthesis and Modelling
  (Dr. F. Wrona, National Hydrology Research Institute)

Figure 2.3 Flow Chart Illustrating the Organizational Structure of the Northern River Basins Study, and the Eight Study Components.



2.2 Water Quality Modelling Issues of NRBS

Overview (Dr. F. Wrona)

The primary goal of NRBS is to assess and predict the cumulative effects of development along the Peace, Athabasca, and Slave Rivers within Alberta and the Northwest Territories. In other words, we need (i) to establish the impacts of point source (pulp mill and sewage treatment plant effluents) and non-point source discharges to these rivers, (ii) to develop models to predict the impact of point and non-point source nutrient and BOD loads on instream chemistry and biota and, (iii) given specific loading scenarios, to predict downstream levels of specific water quality variables such as nutrients, DO, and algal biomass in order to help managers set future regulations and develop policy.

2.2.1 Nutrient Impacts and Dissolved Oxygen Component (Dr. P. Chambers, NHRI)

What do we need to predict and why?

1. Instream oxygen concentrations in order to preserve fish because they represent a basis upon which to assess ecosystem health

2. Instream nutrient (nitrogen and phosphorus) concentrations in order to assess trophy and, hence, aquatic food web productivity

3. Benthic invertebrate community abundance and productivity because they represent an important source of food for fish

What time of year is modelling required?

1. DO in the winter (January, February, and March) beneath ice cover due to the lack of reaeration

2. Nutrients in the winter when the flows are lowest and in the autumn when benthic communities are most productive

3. Benthic communities in the winter when flows are lowest (communities can attain high biomasses in open-water leads) and in the autumn when benthic communities are most productive

Which river reaches require modelling?

Monitoring of impacts of effluent loading on river quality shows that impacts are greatest in the Athabasca and Wapiti-Smoky Rivers. In contrast, nutrient loading from the Peace River sewage treatment plant and the Peace River Correctional Institute appears to have little impact on water quality of the Peace River; moreover, water quality simulations for Peace River indicate that nutrients behave conservatively (i.e., downstream concentrations are largely determined by hydraulics). Therefore, modelling efforts should be focused on the Athabasca and Wapiti-Smoky Rivers, rather than the much larger Peace River.

What are the possible limitations to our ability to make these predictions?

We need additional monitoring, including measurements from more sites, sampling during the less well-studied periods (e.g., summer or fall), and collection of additional parameters such as benthic algal abundance. We also need to determine whether or not better measures of rate coefficients are needed and if significant ecological processes have been omitted from the models.

Other issues to be considered

It is important that the variability associated with the model simulations be established. Mean conditions may be less important than the extremes in terms of ecosystem health. Finally, we need to validate previously-calibrated models with an independent data set.

2.2.2 Hydrology/Hydraulics and Sediment Transport Component (Dr. T. Prowse, NHRI)

Are hydrology data limiting the predictability of water quality models?

In other words, are better measurements of flow and river morphometry required? There are two areas that may require better measures: (i) Although open water leads are very important for reaeration of the river during winter, our current understanding of this process makes it difficult to predict the location and size of these open leads. Obviously, this is a critical factor to consider in the development of DO models, and (ii) we need to improve our ability to predict and forecast minimum flows under ice cover. This is particulary critical in the fall when ice build-up can greatly reduce river discharge.

Mapping of Hydraulic Habitat

To assist in the site selection for monitoring programs, a macro-template of the Athabasca River is being produced. This project focuses on identifying depositional and erosional areas of the river and may provide key information for model calibration.

2.2.3 Other River Uses Component
(Dr. A. Trimbee, Alberta Environmental Protection)

What are instream flow needs?

Instream flow needs (IFN) are defined as the quantity of water and water quality conditions needed: (i) to meet the demands for instream, non-consumptive uses of water, and (ii) to protect both river ecology and riparian environments.

Different types of instream flow needs

1. Environmental Protection: The goal of environmental protection is to achieve maintenance of ecological integrity; that is, to support the community of native species, to maintain the basic structure and function of the ecosystem, and to sustain these conditions over the long term.

2. Uses by Humans: This encompasses needs for recreational uses; requirements for navigation, aesthetics, and tourism; needs for waste assimilation of both point and non-point-sources; and needs for fishery management objectives (i.e., sport, commercial, and subsistence fisheries).

Water quality parameters of primary concern

Water quality parameters of concern are those that may be affected by stream flow or point and non-point loadings, and are important for establishing environmental conditions that maintain ecological integrity (exclusive of toxic chemicals and metals). They include DO, temperature, pH, nitrate, nitrite, ammonia, phosphorus, and coliform and pathogenic bacteria. Of primary interest for the Other River Uses group are DO and nutrients as they affect biological productivity of the river.

List of locations and situations of interest

1. Water quality conditions are poorly understood in environments such as: (i) fish spawning habitats (including interstitial water), and (ii) other critical or important

habitats for fish and other biota (e.g., interstitial water, side channels, snyes, pools, backwaters, shoals, tributary confluences, and stream margin areas). Our present knowledge of water quality relates to mid-channel conditions or average water quality across a channel. Clearly, this incomplete knowledge base does not allow a full and robust evaluation of potential effects on fish or other aquatic life.

2. DO under ice cover may set the limits of available habitat for fish in winter. However, our data base and understanding of the ecological effects of under ice DO concentrations are extremely limited.

3. The amplitude of fluctuations in DO can be increased by periodic or irregular effluent discharges. Whether these fluctuations in DO concentration have a negative effect on ecological integrity probably varies diurnally and seasonally.

4. IFN for waste assimilation should be established. For example, nutrient and BOD loadings from industrial and municipal sources are recognized as critical issues. Non-point sources, such as groundwater inflow during the winter, may need to be considered. Essentially, minimum flow requirements must be established so that loadings are assimilated adequately to maintain environmental conditions suitable for fish and other aquatic life. In addition, for the purposes of evaluating alternative water management strategies, the ability to quantify the minimum flows needed for waste assimilation under various loading scenarios is desirable.

5. What are the implications of the frequency and magnitude of exceeding water quality criteria? To fully assess the environmental implications of changes in water quality, evaluations of various management alternatives in the context of both magnitude and frequency of occurrence of adverse or stressful conditions, historical conditions, and natural conditions are necessary.

2.2.4 Contaminants Component (Dr. B. Brownlee, NWRI)

The Nutrient Impacts Group, through the study of nutrient-contaminant interactions, could provide information to the Contaminants Group on contaminant uptake/biodegradation in the biofilm, particularly with regard to: (i) the effect of flow on biofilm development and contaminant diffusion into the biofilm, and (ii) the effect of nutrients on biofilm thickness.

Field studies on chlorophenol disappearance rates in a small, southern Ontario river suggest that disappearance was largely due to degradation within the biofilm and that the rate was controlled by diffusion of chlorophenols across the water-biofilm interface (Carey et al. 1984). An analytical model describing this process was developed by Lau (1990). The effect of flow rate on biofilm accumulation has been studied in small flumes (Lau and Liu 1993). To address this issue, experiments using artificial streams are under consideration as an approach for studying the effects of flow on biofilm development and contaminant uptake/degradation.

We need the ability to predict diffusion rates of contaminants into the biofilm and degradation rates by biofilm. In other words, the biofilm must be treated as one compartment with two processes: (i) the uptake of contaminants by biofilm, and (ii) the degradation of contaminants by biofilm.

2.2.5 Pulp and Paper Industry Concerns (Dr. B. Steinback, Alberta Newsprint Company and Alberta Forest Products Association)

Information that the pulp and paper industry requires from this workshop

1. An understanding of the current status of knowledge regarding model development, particularly DO, and, to some extent, nutrient modelling on the Athabasca River.
2. What activities is the NRBS undertaking to improve our modelling capability?
3. What areas or issues need further work?

Industry requires answers to some of these questions very soon in order to determine if changes in operating practices are necessary. If answers are not forthcoming from NRBS within six to nine months, industry will consider funding parallel studies to find the tools needed to operate mills with respect to BOD loading.

Aspects of modelling most critical to the pulp and paper industry for planning and operations

1. Determination of the location and magnitude of DO sags in the river.
2. Understanding the relationship between effluent BOD and DO concentrations beneath the ice in order to evaluate contingency plans (i.e., What remediation efforts could be implemented? When and where would these efforts be appropriate?)
3. Risk assessment and probabilistic predictions are needed for use in setting performance standards.

Action needed

1. Dissolved Oxygen Stochastic Model (DOSTOC) needs to be recalibrated with 1990 to 1993 data to assess whether significant processes have been omitted from

the model? (e.g., microbial activity).

2. It is important to assess whether a dynamic model would better serve our management needs.

Nutrient questions

1. What does the NRBS plan with respect to studies on nutrients?

2. Are non-point inputs being captured by existing monitoring programs? For example, do we have estimates for loadings from agricultural tributaries or phosphorus-rich lakes? Do algal blooms act as important seasonal inputs to river productivity?

CHAPTER 3.0

WATER QUALITY MONITORING AND MODELLING ON THE PEACE-ATHABASCA RIVER: A REVIEW

3.0 WATER QUALITY MONITORING AND MODELLING ON THE PEACE-ATHABASCA RIVER: A REVIEW (Dr. P. Chambers, NHRI)

3.1 Introduction

Water quality modelling is required by the NRBS to predict the impacts of further development in the basin, as well as to forecast potential alterations to water chemistry and aquatic biota that may result from changes in loadings from existing effluent discharges. On the basis of predicted scenarios, it is desirable that we be able to set management policies for the river and its basin so as to preserve a desired set of environmental conditions. This review provides a brief overview of the hydrology and development in the basin to illustrate the template underlying the water quality monitoring program. The review also summarizes the water quality modelling efforts undertaken within the basin and concludes with several specific issues that must be addressed by NRBS modelling strategies.

3.2 Hydrology of the Peace-Athabasca Rivers

The Athabasca River, its major tributaries, and the Wapiti-Smoky River (in the Peace River Basin) are not regulated. These systems are all characterized by three distinct hydrologic periods which, in turn, relate directly to water quality: (i) the winter period of ice cover characterized by low turbidity and low DO concentrations, (ii) the period of rising hydrograph in spring and early summer characterized by high turbidity, and (iii) the period of falling hydrograph in the autumn when water clarity increases substantially (Fig. 3.1). This seasonal characterization serves as a template for chemical and biotic conditions in the Athabasca and Wapiti-Smoky Rivers. In the Peace River, however, seasonal differences in flows are dampened due to regulation by the Bennett Dam on Williston Lake.

3.3 Development in the Peace-Athabasca Basin

As of September 1993, three chemi-thermomechanical pulp (CTMP) and four kraft pulp mills operate in the Northern Rivers Basin (Fig. 2.2, Table 3.1). With the exception of Weldwood of Canada and Weyerhauser Canada Ltd. (formerly Procter & Gamble Cellulose Ltd.) which commenced operation in 1957 and 1973, respectively, all mills have come on-line since 1988. In addition to pulp-mill activity, there are ten municipalities and one oil-sands project within Alberta that continuously discharge to the Peace-Athabasca Rivers (Table 3.2). Other activities in the Alberta portion of the basin include four active coal mines, at least 53 gas plants, another oil-sands project, and 12 gravel-washing enterprises; all have little or no discharge to rivers in the basin.

Figure 3.1 Mean Daily Discharge for the Athabasca River at Athabasca, the Smoky River at Watino, and the Peace River at Peace River (Environment Canada 1990).

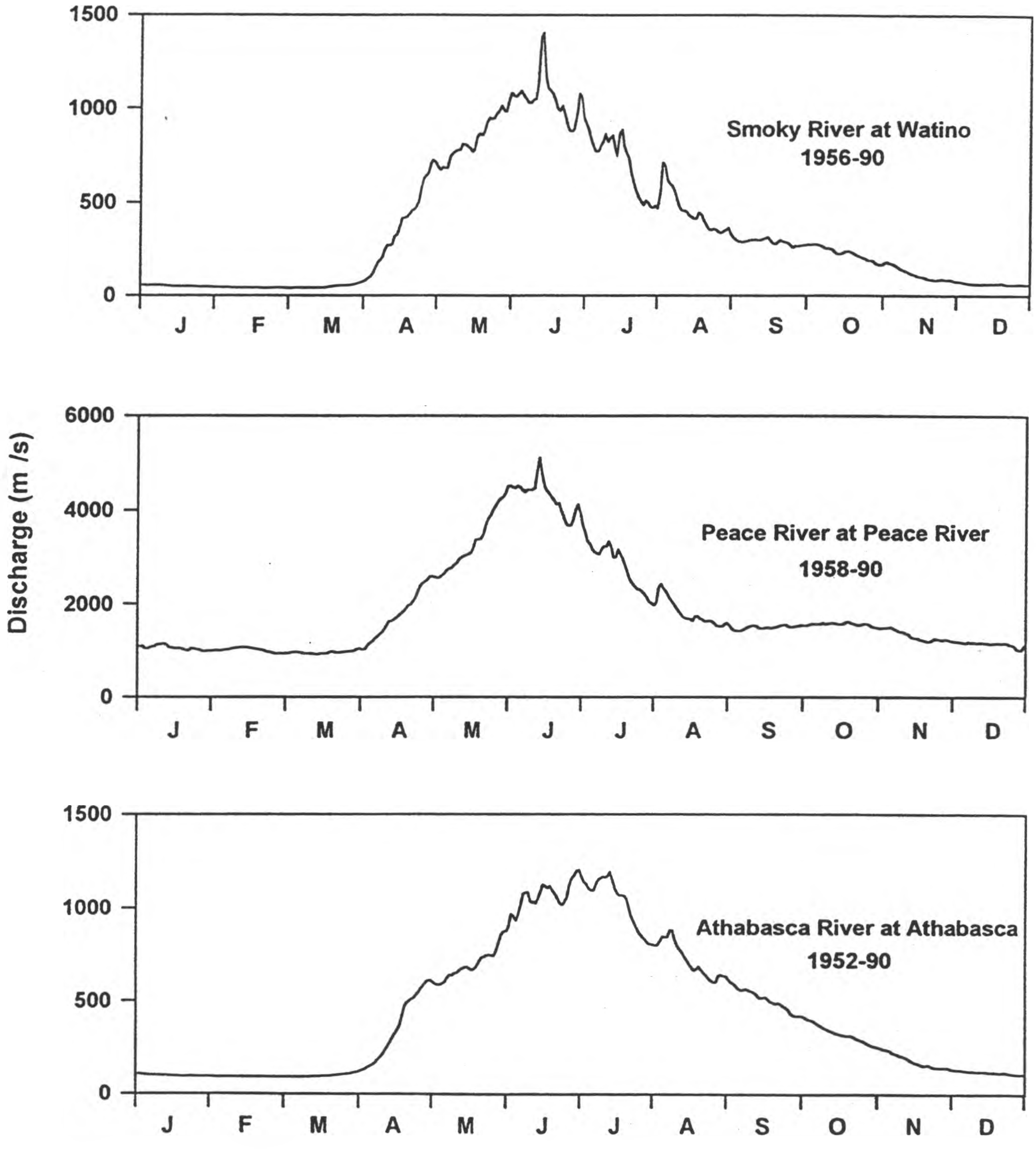


Table 3.1 **Pulp and Paper Mills on the Peace-Athabasca Rivers, Their Production and Operating Characteristics. (ADt/d = air dried tonnes per day; BOD_5 = Five-Day Biochemical Oxygen Demand; TP = Total Phosphorus; TN = Total Nitrogen; ASB = Aerated Stabilization Basin; AST = Activated Sludge Treatment). (Note: Hinton municipal sewage (population 9046 in 1991) is combined and discharged with the Weldwood effluent)**

Location (Receiving Water)	Company	Mill Type	Start Up	Effluent Treatment	1991 Production (ADt/d)	1991 Discharge (m^3/d)	1991 BOD_5 (mg/L)	1991 TP (mg/L)	1991 TN (mg/L)
Hinton (Athabasca)	Weldwood of Canada Ltd.	Kraft Pulp	1957 Expansion 1990	ASB	1,033	111,965	23.8	0.89	5.15
Whitecourt (Athabasca)	Alberta Newsprint Co. Ltd.	CTMP & Paper	August 1990	Extended Aeration AST	519	15,612	10.1	7.01	4.16
Whitecourt (Athabasca)	Millar Western Pulp Ltd.	CTMP	August 1988	Extended Aeration AST	611	12,699	89.1	1.84	8.45
Slave Lake (Lesser Slave)	Slave Lake Pulp Corp.	CTMP	Late 1990	AST	232	3,904	250.3	10.08	
Athabasca (Athabasca)	Alberta-Pacific Forest Industries Inc.	Kraft Pulp	September 1993	Extended Aeration AST					
Peace River (Peace)	Daishowa Canada Co. Ltd. - Peace River Pulp Division	Kraft Pulp	July 1990	ASB	794	63,308		1.70	4.46
Grande Prairie (Wapiti)	Weyerhauser Canada Ltd.	Kraft Pulp	1973	ASB	861	60,495		1.10	10.05

Table 3.2 **Continuously Discharging Effluents from Municipalities on the Peace-Athabasca Rivers. (BOD_5 = Five Day Biochemical Oxygen Demand; TP = Total Phosphorus; TN = Total Nitrogen.) (Note: Hinton municipal effluent discharged with Weldwood of Canada Ltd. effluent.) (Data from 1990-1992 Alberta Environment winter synoptic surveys unless otherwise noted.)**

Source	Treatment	Receiving Water	Discharge (m^3/d)	BOD_5 (mg/L)	TP (mg/L)	TN (mg/L)
Jasper[1]	Aerated Lagoon	Athabasca River	5,700			
Whitecourt	Mechanical	McLeod River	3,456	20.7	2.89	12.65
Slave Lake	Aerated Lagoon	Lesser Slave Lake	2,534		3.56	26.20
Athabasca	Aerated Lagoon	Athabasca River	893		5.72	31.64
Fort McMurray	Aerated Lagoon	Athabasca River	12,874	15	2.6	27.95
Grande Cache[1]	Mechanical/Extended Aerobic	Smoky River	1,946			
Grande Prairie[2]	Mechanical/Rotary Biological Contactor	Wapiti River	17,712	4.9	4.5	14.67
Manning[1]	Mechanical/Aerobic Lagoon	Notikewin River	561			
Peace River[2]	Anaerobic Lagoon	Peace River	3,370		4.7	24.76
Peace River[1] Correctional Institute	Oxidation Ditch	Peace River	225			

[1]after Tones (in press)
[2]Alberta Environment winter synoptic survey 1989-1991

3.4 Water Quality and Monitoring Programs

The Peace and Athabasca Rivers have been monitored monthly by Alberta Environment and Environment Canada for nutrients and DO (as well as other parameters) at a small number of fixed sites for at least three decades (Table 3.3). In 1988-89, Alberta Environment implemented an integrated, basin-wide monitoring program that included an additional seven sites on the Athabasca River and three sites on the Wapiti-Smoky-Peace River system (Fig. 2.2). For the past four years, DO has also been monitored continuously at five sites on the Athabasca River and three sites on the Wapiti-Smoky River during the low-flow, ice-cover period. An annual winter (January-February) water quality survey has been conducted since 1989 on the Athabasca River from upstream of Hinton to Lake Athabasca. The survey progresses downstream at the river's time of travel and includes about 70 sampling sites on the mainstream, at tributary mouths, and from effluent discharges. In addition to government monitoring programmes, water quality data are also collected as part of baseline and post-operation surveys for all new and expanding developments on the river. Industries and municipalities are required to monitor effluent as required by their Licences to Operate.

Monitoring programs have shown that during the low-flow conditions of winter loadings from pulp and paper mills had adverse effects on concentrations of DO and phosphorus in the Athabasca and Wapiti-Smoky Rivers (Noton and Shaw 1989; Noton 1992). The effects of municipal sewage effluents were generally insignificant with the exception of the towns of Grande Prairie and Fort McMurray, which discharge loads similar to the pulp mills (Table 3.2). Analysis of the most recent (Winter 1992) data for the Athabasca River showed three peaks in total phosphorus (TP) concentrations: 20 km downstream of Hinton (42 µg/L), downstream of Whitecourt (34 µg/L), and downstream of the Clearwater River (49 µg/L) (Fig. 3.2). These locations correspond with the highest point-source loads for TP (i.e., municipal and mill effluent at Hinton and Whitecourt, and municipal and tributary inflow (Clearwater River) downstream of Fort McMurray). By comparison, total Kjeldahl nitrogen (TKN) concentrations increased 20 km downstream of Hinton (from 90 to 210 µg/L) and Whitecourt (160 µg/L), but thereafter showed no relationship to point-source inflows (Fig. 3.3). DO concentrations in the Athabasca River decreased steadily from 12.5 mg/L upstream of Hinton to 9.5 mg/L upstream of Grand Rapids, a distance of 817 km (Fig. 3.4). Downstream of the rapids, DO concentrations returned to near-saturation values and thereafter decreased to 10.8 mg/L over a distance of 394 km (Fig. 3.4). The major BOD_5 point-source loads were from the combined mill+town effluent at Hinton, the Lesser Slave River (tributary+mill load), and the Clearwater River.

Table 3.3 ***In Situ* Monitoring of Dissolved Oxygen (DO) and Nutrients (Nitrogen and Phosphorus) Concentrations in the Peace-Athabasca Rivers.**

Monitoring Frequency	Parameter	Athabasca River	Peace River
Long-term Monthly Monitoring	Nutrients	Jasper Townsite Athabasca Townsite Old Fort Townsite	Slave R. at AB/NWT border Peace R. at BC/AB border Peace R. at Fort Vermilion Smoky R. at Watino
Bi-monthly (Since 1989)	Nutrients	u/s Hinton d/s Hinton u/s Whitecourt Fort Assiniboine u/s Smith Lesser Slave River at mouth u/s Fort McMurray	Wapiti R. at Hwy 40 Wapiti R. at mouth Peace R. east of Manning
Winter Synoptic Surveys	Nutrients & DO	Hinton to Lake Athabasca (1988 to 1993)	Wapiti-Smoky Rivers to Little Smoky River (1989 and 1990)
Continuous (Winter)	DO	u/s Hinton u/s Whitecourt u/s Smith u/s Grand Rapids u/s Fort McMurray	Wapiti R. u/s & d/s Grande Prairie Smoky R. u/s of Wapiti R. Smoky R. u/s Watino

Figure 3.2 **Total Phosphorus (TP) Loads from Point Sources and Tributaries, and River Concentrations for the Athabasca River (Winter Synoptic Survey 1992).**

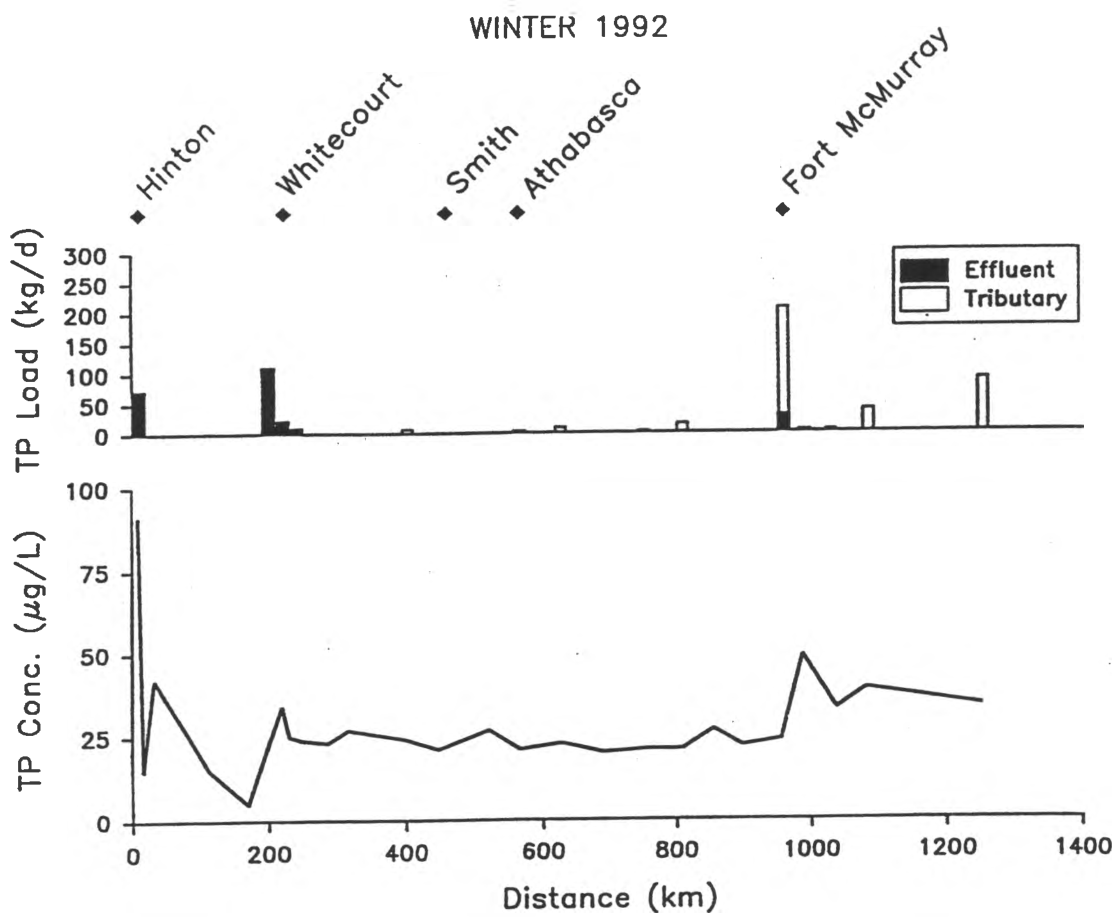


Figure 3.3 **Total Kjeldahl Nitrogen (TKN) Loads from Point Sources and Tributaries, and River Concentrations for the Athabasca River (Winter Synoptic Survey 1992).**

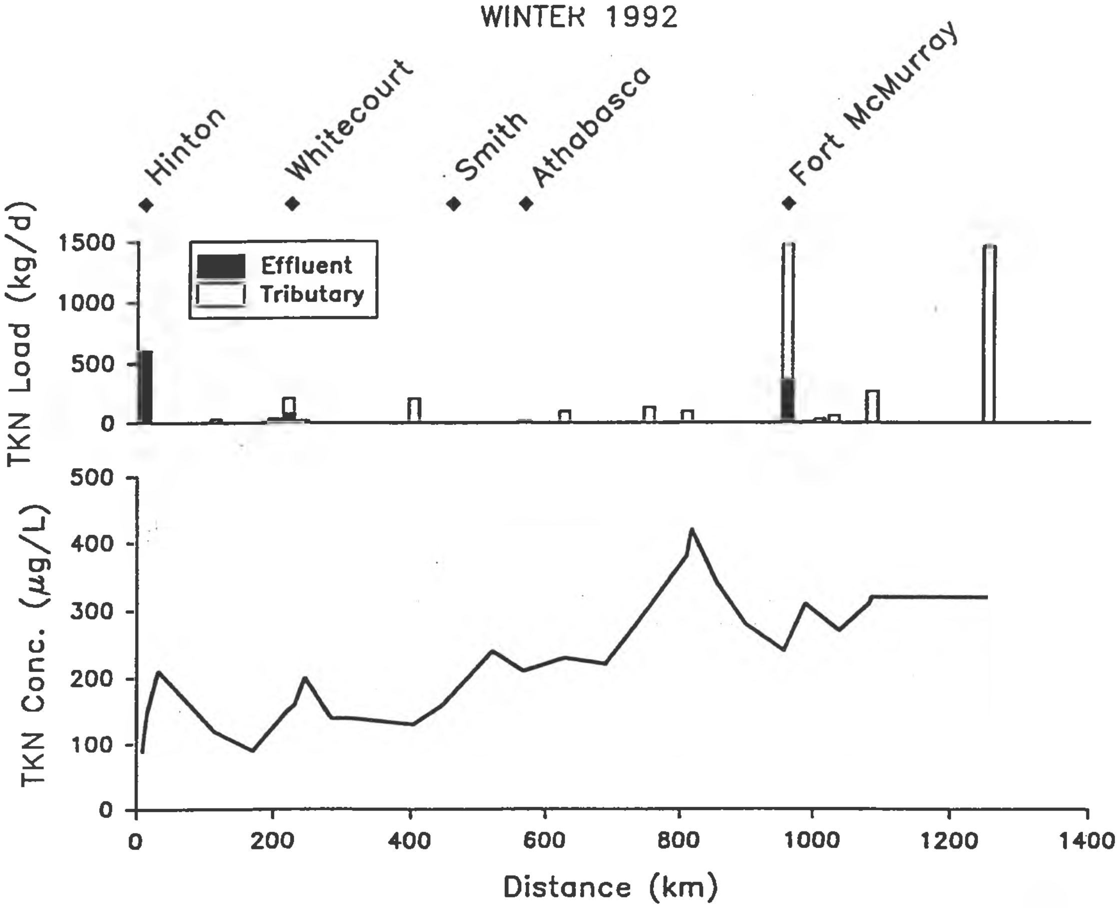
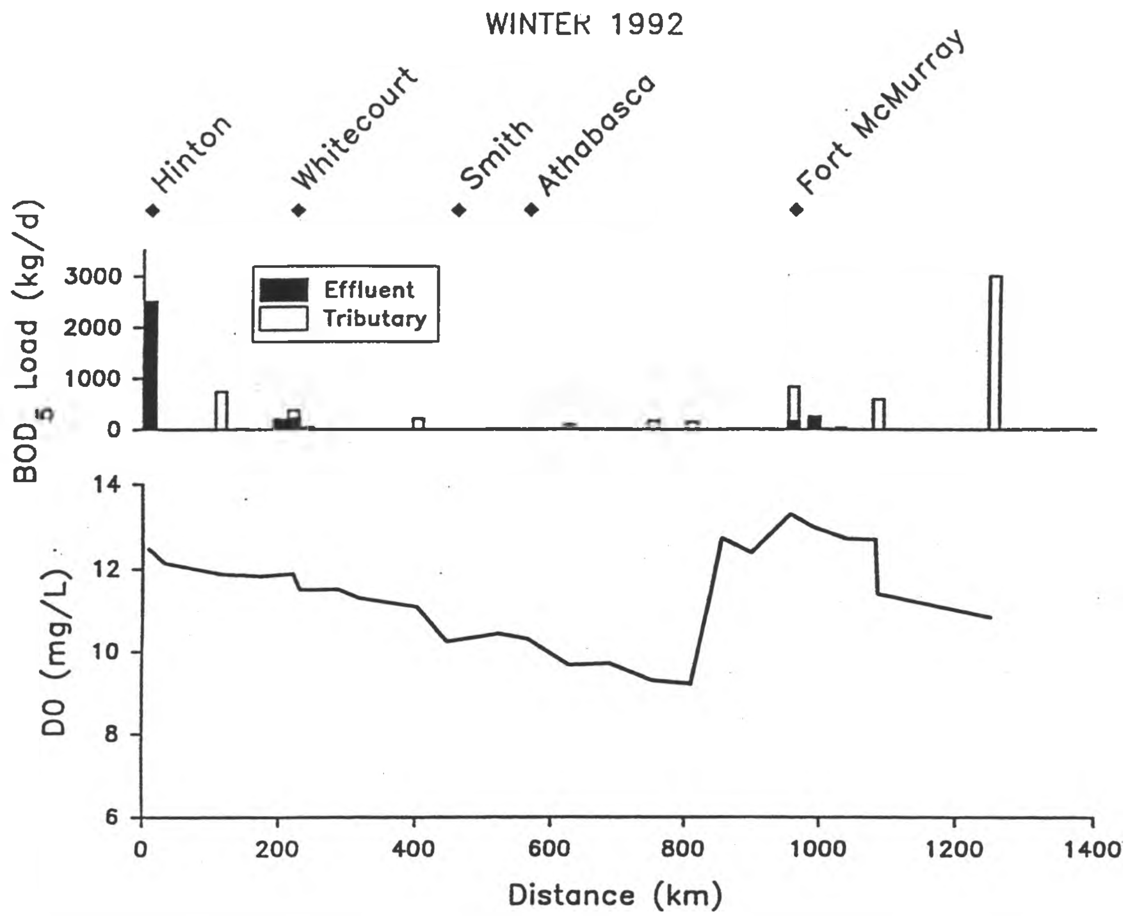


Figure 3.4 **Biochemical Oxygen Demand (BOD_5) Loads from Point Sources and Tributaries, and River Dissolved Oxygen (DO) Concentrations for the Athabasca River (Winter Synoptic Survey 1992).**



The most recent, winter, water-quality data (1987-1991) for the Peace River system show a 2-3 mg/L decline in DO in the Wapiti River from Hwy #40 to the mouth and a similar decline in the Smoky River from upstream of the confluence with the Wapiti to Watino (Noton 1992). TP concentrations in the Wapiti-Smoky River system increased from background values of 5-10 µg/L upstream of Grande Prairie to 80-230 µg/L for a distance of 25 km downstream. Concentrations returned to background after convergence with the Smoky River. Similarly, TKN concentrations increased from approximately 25 µg/L upstream to 60-160 µg/L downstream of Grande Prairie and approached background values after joining with the Smoky River. There is little detectable effect on loadings from the Peace River Correctional Institute and sewage treatment plant on TP and DO concentrations in the Peace River (Macdonald and Taylor 1990).

3.5 Historical Review of Water Quality Modelling for the Peace-Athabasca Rivers

3.5.1 Athabasca River

All water quality modelling efforts to date have focused on the under-ice period. In addition to water quality monitoring, a variety of studies have been undertaken in support of water quality modelling: (i) time of travel studies on the Athabasca River (upper half in Winter 1989 (Andres et al. 1989) and lower half in Winter 1992 (Van der Vinne and Andres 1993)) and Wapiti/Smoky River (Winter 1990); (ii) *in situ* measurements of sediment oxygen demand on the Athabasca River (Winter 1989, 1990, 1992 and 1993; Casey and Noton 1989; Casey 1990; Monenco Inc. 1992; HBT AGRA Ltd. 1993a, b); and (iii) measurements of atmospheric reaeration and aerial photography to quantify open-water areas on the Athabasca River (Winter 1989; Macdonald et al. 1989). The values for rate coefficients and constants applicable to nutrient and DO models for the Peace, Athabasca and Slave River basins have also been compiled (Tables 3.4, 3.5, and 3.6; Shaw and Macdonald 1993).

Water quality modelling of the Athabasca River began in the early 1980s (Table 3.7). In 1984, Water Quality for River and Reservoir Systems (WQRRS) was implemented for the Athabasca River from Hinton to Lake Athabasca (Charles Howard and Associates Ltd. 1984). Calibration was difficult or impossible due to limited hydraulic, non-point source, water-quality data and instream-water-quality data. Flows under ice cover could not be simulated. In 1988 trial runs of the Dissolved Oxygen Stochastic Model (DOSTOC) were undertaken for the Athabasca River using data collected during the 1987 and 1988 winters (Hamilton et al. 1988). Information gaps were identified, and the winter synoptic surveys of 1988 and 1989 were designed to address these gaps.

Table 3.4 Rate Coefficients and Constants Applicable to Nutrient Models for the Peace, Athabasca, and Slave River Basins (Shaw and Macdonald 1993). (Theta defined in Section 4.2.1)

SOURCE	MINERALIZATION				NITRIFICATION		PARTICULATE SETTLING
	PHOSPHORUS		NITROGEN				
	RATE (per day)	THETA	RATE (per day)	THETA	RATE (per day)	THETA	RATE (per day)
GENERAL							
Bowie et al. (1985) - Surface Water	0.001-0.8	1.00-1.14	0.001-0.4	1.00-1.02	0.0-9.0	1.00-1.09	
Bowie et al. (1985) - Large Rivers					0.1-0.3		
REGIONAL - MODEL CALIBRATION VALUES							
Hamilton et al. (1989) - Bow River	0.02		0.02		0.02	1.02	0
HydroQual and Gore and Storrie (1989) - North Saskatchewan River			0.03	1.08	0.5	1.08	0
Macdonald (1989) - Highwood River	0.02		0.02		0.6	1.075	0
EMA (1992b) - Crawling Valley Reservoir	0.25		0.25		0.2		
EMA (1992b) - Syncrude test pits	0.025	1.08	0.025	1.08	0.025	1.08	
NORTHERN RIVERS - MODEL CALIBRATION VALUES							
MacDonald and Radermacher (1989) - Athabasca River			0.03	1.08	0.19	1.08	

Blanks - process not simulated or measured

Table 3.5 Rate Coefficients and Constants Applicable to Algal Growth Models for the Peace, Athabasca, and Slave River Basins (Shaw and Macdonald 1993). (N = Nitrogen; P = Phosphorus; C = Carbon; O = Oxygen) (Theta defined in Section 4.2.1).

SOURCE	BENTHIC GROWTH		RESPIRATION		CELL STOICHIOMETRY			
	RATE (per day)	THETA	RATE (per day)	THETA	N:C	P:C	O:C	C:Dry Weight
GENERAL								
Bowie et al. (1985) - Diatoms	0.55-5.0	1.01-1.2	0.03-0.59	1.01-1.2	0.067-0.21	0.003-0.14	1.6-2.66	19-53
REGIONAL - MODEL CALIBRATION VALUES								
Hamilton et al. (1989) - Bow River	1.6-2.0		0.8		0.02	0.03	1.6	0.4
HydroQuai and Gore and Storrie (1989) - North Saskatchewan River	0.41	1.066	0.15	1.065	0.10	0.01	1.6	
Macdonald (1989) - Highwood River	0.48		0.15		0.20	0.03		0.4
EMA (1992b) - Crawling Valley Reservoir	2.5		0.08		0.010	0.018		0.49
EMA (1992b) - Syncrude test pits	3.0*	1.05	0.30	1.025	0.025	0.02	2.0	
NORTHERN RIVERS - MODEL CALIBRATION VALUES								
MacDonald and Radermacher (1989) - Athabasca River								
Macdonald and Taylor (1990) - Wapiti-Smoky Rivers					0.1	0.01		

Blanks - process not simulated or measured

* Phytoplankton

Table 3.6 Rate Coefficients and Constants Applicable to Dissolved Oxygen Models for the Peace, Athabasca, and Slave River Basins. (BOD_u = Ultimate Biological Oxygen Demand; SOD = Sediment Oxygen Demand; $CBOD_5$ = Five Day Carbonaceous Biological Oxygen Demand) (Theta defined in Section 4.2.1)

Source	$CBOD_5$ Decay		Maximum Photosynthesis		Respiration		SOD		Winter Reaeration		BOD_u: BOD_5
	Rate (per day)	Theta	Rate (per day)	Theta	Rate ($g0^2/m^2/d$)	Theta	Rate ($g0^2/m^2/d$)	Theta	Rate (per day)	Theta	
General											
Bowie et al. (1985)	0.004-4.24	1.02-1.15	4-40		0-36		0.004-44	1.02-1.13			1-30
Regional - Model Calibration Values											
Hamilton et al. (1989) - Bow River	0.2	1.075									
HydroQual and Gore and Storrie (1989) - North Saskatchewan River	0.12-0.42	1.075	0.49-1.75	1.065	0.16-.06	1.065	0.16-.06	1.065			2.0
Macdonald (1989) - Highwood River	0.6	1.075							0.065	1.075	
EMA (1992b) - Crawling Valley Res.	0.2						3				
EMA (1992b) - Syncrude test pits	0.4	1.047					0.25	1.08			
Northern Rivers - Model Calibration Values											
Macdonald and Radermacher (1989) - Athabasca River	0.18	1.08					0.01-9.0****		0.1-1.81		2.0,5.5*
Macdonald and Taylor (1990) - Wapiti-Smoky River	0.02,0.035***	1.08					0.38		0		2-6.6**
Casey and Noton (1989) - Athabasca River							0.001-0.515				
Casey (1990) - Athabasca River							0.00-0.59				
Monenco (1992) - Athabasca River							-0.002-0.38				
Casey (1990) - Wapiti River u/s P&G							-0.03--0.01				
Casey (1990) - Wapiti River d/s P&G							0.18-0.42				
Casey (1990) - Smoky River							0.02-0.7				

* 2.0 - fast BOD; 5.5 - slow BOD
** 5.0 - mill effluent; 6.4 - headwater tributaries; 2.0 - other effluents
*** 0.02 - background; 0.035 - effluents
**** site-specific for each reach

Table 3.7 **Summary of Water Quality Modelling Efforts on the Athabasca River. (Note: WQRRS = Water Quality for River and Reservoir Systems Model; DO = Dissolved Oxygen; P = Phosphorus; N = Nitrogen; DOSTOC = Dissolved Oxygen Stochastic Model; NUSTOC = Nutrient Stochastic Model).**

Model	Year	Parameters	Reach	Comments
WQRRS[1]	1984	DO, P, N	Hinton-L. Athabasca	Calibration difficult or impossible due to limited hydraulics, non-point source quality and instream water quality data. Flows under ice cover could not be simulated.
DOSTOC[2]	1987\88	DO	Hinton-Athabasca	Limited data. Identified information gaps for 1988 and 1989 field programs
DOSTOC[3] NUSTOC[4]	1992	DO	Hinton-L. Athabasca	Used data from 1988 and 1989 winter surveys. Model calibration.
DOSTOC[5]	1992	DO	Hinton-L. Athabasca	Verification of 1989 models using data collected in 1990. Good match between predicted and observed.
DOSTOC[6]	1993	DO	Hinton-L. Athabasca	Verification of 1989 models using data collected in 1992 and 1993

[1]Charles Howard & Associates 1984

[2]Hamilton et al. 1988

[3]Macdonald and Hamilton 1989

[4]Taylor et al. 1990

[5]Macdonald and Radermacher 1992

[6]Macdonald and Radermacher 1993

In April 1988, a water quality modelling workshop was called by Alberta Environment to recommend the modelling approach to be used for water quality planning in the Athabasca River Basin (Linton and Hamilton 1988). The following recommendations were formulated: (i) implementation of a suite of water quality models for specific parameters or specific river reaches (e.g., DOSTOC and Nutrient Stochastic Model (NUSTOC) for DO and nutrients, respectively, in mixed reaches; MULTI in mixing zones, etc.), (ii) field studies required to calibrate the water quality models (ranked by priority), and (iii) development of the capability within Alberta Environment to analyze model output and prepare presentations for managers and the public.

In 1989, DOSTOC was calibrated using DO data collected during the 1988 and 1989 winter synoptic surveys (Macdonald and Hamilton 1989). TP and total nitrogen (TN) were also modelled, albeit less intensively, with NUSTOC (Taylor et al. 1990) The calibrated model was verified in 1992 using data collected during the 1990 winter synoptic survey (Macdonald and Radermacher 1992). The best test of a model calibration is to run field data that are significantly different from the calibrated conditions and then to compare the model output to the observed data. Conditions in 1990 differed considerably from 1988 and 1989 conditions: (i) temperatures were warmer; therefore, there was less ice cover in 1990 than in the previous two winters; (ii) flows were higher in 1990; and (iii) the effluent treatment system of the Millar Western mill at Whitecourt was operating with greater efficiency in 1990. As a result, the minimum DO concentration recorded in the Athabasca River upstream of Grand Rapids was > 8 mg/L in 1990 as compared with approximately 6.5 mg/L in 1989. DOSTOC was run, as before, with only the revised river hydrology and 1990 headwater, tributary, and effluent loadings introduced. There was a good match between predicted and observed DO concentrations along the entire length of the river.

Verification of previously-calibrated DOSTOC models is currently underway using winter 1991 and 1992 data (Macdonald and Radermacher 1993). Model predictions approximated the longitudinal decline in DO within 0.5 mg/L on average, but over or under predicted concentrations in specific reaches by up to 1.0 mg/L (Figs. 3.5 and 3.6). Predicted DO concentrations were typically lower than observed concentrations in the Hinton to Whitecourt reach and greater than observed concentrations in the Smith to Grand Rapids reach. A sensitivity analysis was conducted for the Athabasca River 1989 calibration by increasing or decreasing input variables by 20% and recording the changes in the DO concentrations at downstream locations. For four of five sites between Hinton and Grand Rapids, headwater DO loading was consistently the most sensitive input variable for prediction of river DO; for example, a 20% change in headwater DO load resulted in an average 17% change in river DO (Macdonald and Radermacher 1993). SOD, ice-cover reaeration, tributary DO concentrations, combined mill BOD/SOD, and velocity were consistently the next most sensitive variables with the least important variables being mill DO, and other effluent DO and BOD.

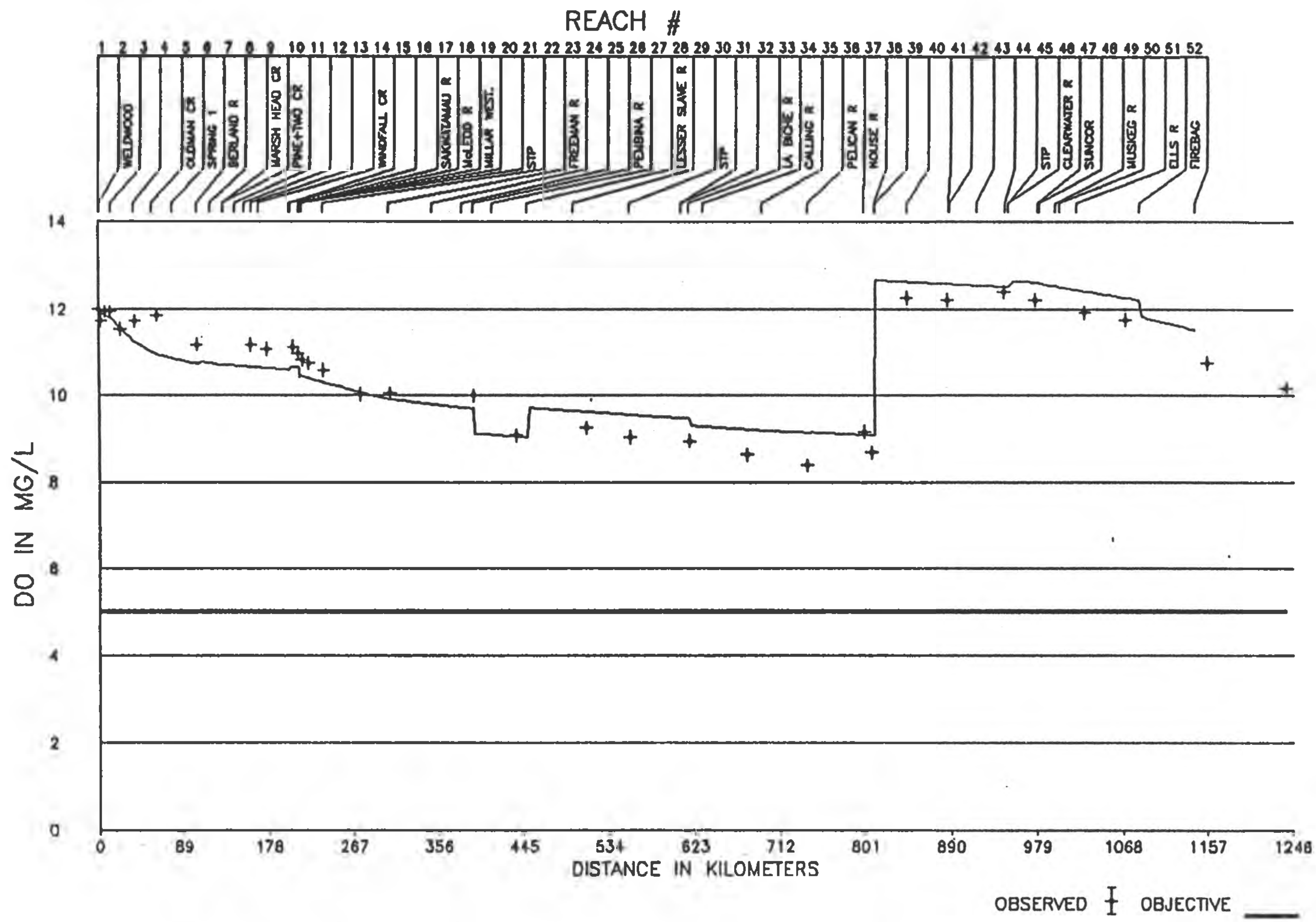


Figure 3.5 Dissolved Oxygen Concentrations along the Length of the Athabasca River (February-March 1991) as well as Concentrations Predicted by the Dissolved Oxygen Stochastic Model DOSTOC (Macdonald and Radermacher 1993).

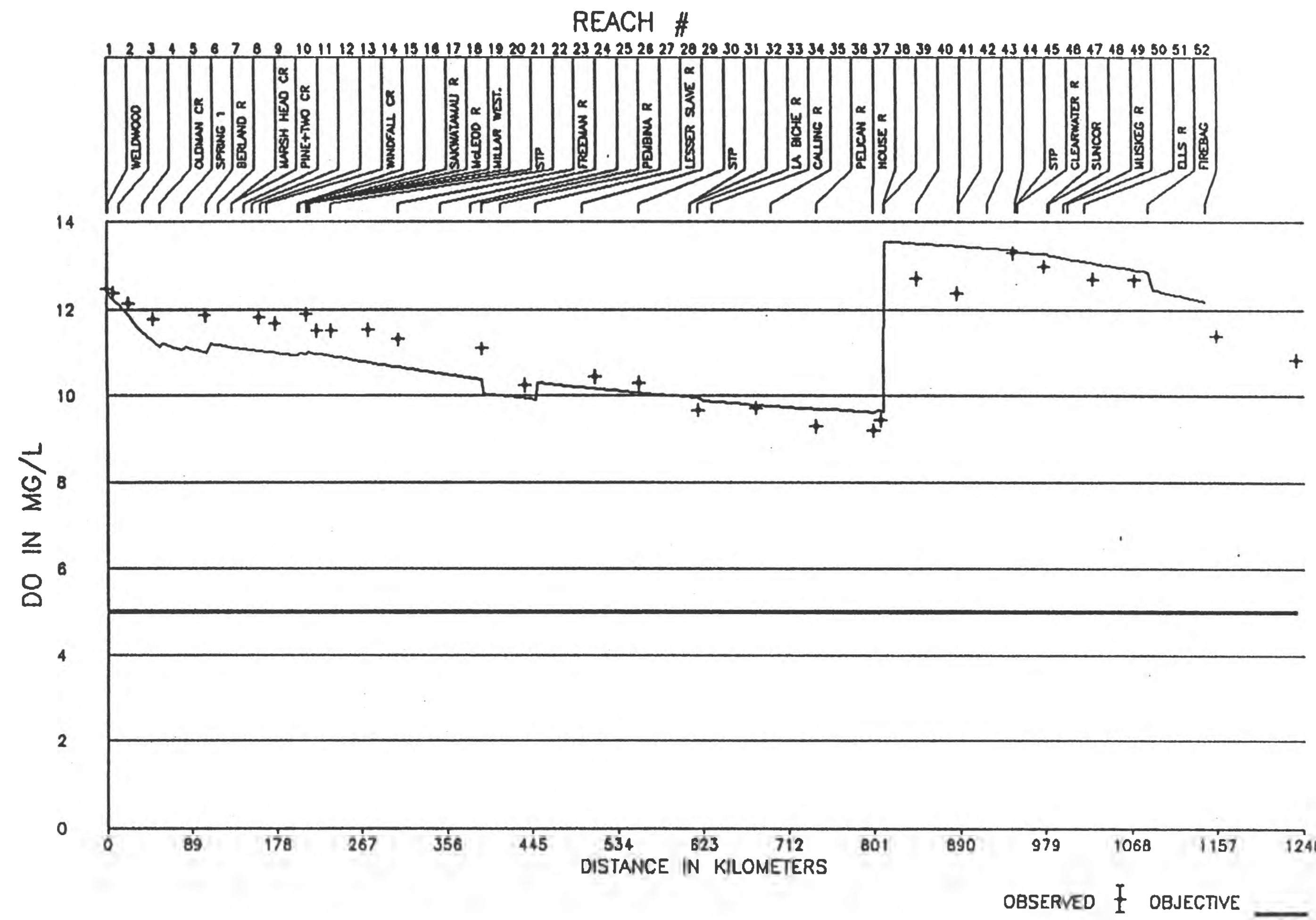


Figure 3.6 Dissolved Oxygen Concentrations along the Length of the Athabasca River (February-March 1992) as well as Concentrations Predicted by the Dissolved Oxygen Stochastic Model DOSTOC (Macdonald and Radermacher 1993).

3.5.2 Peace River System

Water quality modelling on the Peace River began in the late 1980s (Table 3.8). Using field data from March and October 1989, and February 1990 (Wapiti-Smoky Rivers), and October 1988 and March 1989 (Peace River), DOSTOC was run for the Wapiti/Smoky River and WASP4 was run on the Peace River (Macdonald and Taylor 1990). The latter is a large, wide river; therefore, the assumption in DOSTOC of instantaneous lateral mixing of effluent would be unreasonable. Models were calibrated for DO, TP, and TN; there was no verification. In the case of the Peace River, nutrient simulations were run assuming no in-stream processing. In the reach 450 km downstream of Peace River, the model was successful at predicting TP. This suggests that flow is the major factor determining TP concentrations in the Peace River.

Verification of the DOSTOC model calibrated in 1990 for the Wapiti-Smoky Rivers is currently in progress using winter 1991 and 1992 data (Macdonald and Radermacher 1993). Model predictions approximated the longitudinal decline in DO; however, in both 1991 and 1992, predicted DO concentrations were consistently less (by approx. 0.5 to 1 mg/L) than observed concentrations. This may be due to reaeration in the open water not adequately represented by rates in the model. This is particularly true of 1992, when flows in the river were more characteristic of spring than winter conditions.

3.6 Issues to Address at this Workshop

1. Why was DOSTOC (calibrated with 1988 and 1989 data) able to successfully predict winter 1990 DO concentrations but was less successful at predicting 1991 and 1992 concentrations? Do we need to undertake additional or more sophisticated monitoring? Do we need better measures of rate coefficients? Are there ecological processes that have been omitted from the models?

2. Given that nutrient concentrations in the Peace River appear to be predictable on the basis of hydraulics (and not in-stream processing), should we undertake any further modelling efforts on the Peace River?

3. What is the variability associated with the model simulations? In terms of setting policy and ecosystem health, mean conditions may be less important than the extremes.

Table 3.8 **Summary of Water Quality Modelling Efforts on the Peace River. (Note: WASP4 = Water Quality Analysis Simulation Program; DO = Dissolved Oxygen; P = Phosphorus; N = Nitrogen; DOSTOC = Dissolved Oxygen Stochastic Model)**

Model	Year	Parameters	Reach	Comments
WASP4[1]	1990	DO, P, N	Peace River Town of Peace River to Peace Point	Model calibration using data from WASP4 as DOSTOC assumption of instantaneous lateral mixing not valid
DOSTOC[1]	1990	DO	Wapiti-Smoky Rivers	Model calibration using data from March and October 1989 and February 1990 surveys

[1]Macdonald and Taylor 1990

CHAPTER 4.0

WATER QUALITY MODELLING APPROACHES

4.0 WATER QUALITY MODELLING APPROACHES

Overview

The purpose of this portion of the workshop was to examine models commonly used for rivers including WASP4, DOSTOC, NUSTOC, and DSSAMt in an attempt to identify their potential use as management tools for the NRBS, as well as establishing key limitations to the different modelling approaches. This information was primarily, but not exclusively, aimed at assisting the Nutrient Impacts and DO Working Group to establish a strategy for undertaking studies of water quality modelling for the NRBS. The questions identified as central to designing this strategy are as follows:

- What types of models have merit in terms of predicting and/or providing a mechanistic understanding of the impacts of effluent loading on DO and nutrient concentrations in northern rivers?
- What further development is needed to improve the ability of existing models to predict effluent loading impacts to these river basins? Are new models needed?
- Which physical, chemical, and ecological processes of these river basin ecosystems need to be understood better in order to further develop existing or new models?
- To what extent do existing data bases limit the application of water quality models in these river basins?
- How can predictions from these water quality models be incorporated into other components of the NRBS?

The structure of the oral and written reports on the various models centres upon introduction and discussion of specific model structure followed by an assessment of the strength and weakness of the particular modelling approach. Suggestions for further development of models are included where appropriate.

4.1 Stochastic Water Quality Models: DOSTOC and NUSTOC (Dr. P.A. Zielinski, Ontario Hydro)

4.1.1 Introduction

Most of the recent efforts in the area of water quality modelling have focused on the development of mathematical models simulating physical, chemical, and biological processes occurring in river waters through systems of ordinary or partial differential equations. These equations can be considered as deterministic if they provide a single response for each set of input variables such as flows, loadings, model parameters, initial conditions, etc. For many years, deterministic models have been regarded as sufficient tools to reflect the reality of analyzed processes, especially when the magnitude of uncertainty was relatively small. However, deterministic models fail to recognize the model output variability caused by non-deterministic (stochastic) sources. Therefore, although the deterministic approach has been successful in increasing the understanding of how relevant variables change and interact, it has created an unrealistic sense of reliability concerning model results. The main sources of uncertainty in water quality modelling can be associated with (i) relationships among the variables determining the behaviour of the system (often called uncertainty about model structure), and (ii) values of the parameters appearing in the identified structure of the model.

Many researchers now agree on the limitations of deterministic models and are developing models capable of considering process uncertainties. The last decade witnessed development of many water quality models attempting to include uncertainty aspects in the modelling process. Most of these models are based on various forms of Monte Carlo techniques, and this approach is still widely used by water quality modellers (Brown and Barnell 1987; Canale and Effler 1989; Dewey 1984). It should be pointed out that all Monte Carlo applications are based on special assumptions about system uncertainty. The differential equations describing the system are solved first using deterministic methods and then these deterministic solutions are "randomized" via Monte Carlo simulations. Consequently, instead of modelling stochastic systems (mathematically described by stochastic differential equations), these applications offer stochastic analysis of their deterministic solutions which obviously are different from truly stochastic ones (Soong 1973).

This report presents an overview of two stochastic models DOSTOC and NUSTOC developed in 1987 for the Planning Division of Alberta Environment. Both models are one-dimensional and steady-state. All equations describing selected processes are first-order stochastic differential equations with stochastic parameters and random initial conditions.

The DOSTOC model determines first and second order moment of:

- Ultimate carbonaceous biochemical oxygen demand (BOD)
- Dissolved oxygen (DO)
- Nitrogen oxygen demand (NOD).

The NUSTOC model determines the same characteristics for:

- Organic nitrogen
- Ammonia

- Nitrate
- Dissolved phosphorus
- Particulate phosphorus
- Suspended solids.

4.1.2 Stochastic Dissolved Oxygen Model

Background Information

DOSTOC is a steady-state, one-dimensional model based on the system of ordinary differential equations developed by Streeter and Phelps. Their original equations have been modified to include the sources and sinks of oxygen in river processes. As a result, the interactions between oxygen demanding substances, ultimate carbonaceous BOD and NOD, with the sources of oxygen in the river can be described by the following differential equations:

$$\frac{dX(t)}{dt}=-(k_1+k_3)X(t)+S_{BOD} \tag{4.1}$$

$$\frac{dY(t)}{dt}=k_2[D_s-Y(t)]-k_1X(t)-k_4Z(t)-R+P(t)+S_{DO} \tag{4.2}$$

$$\frac{dZ(t)}{dt}=-k_4Z(t)+S_{NOD} \tag{4.3}$$

where:

t is travel time, in days
$X(t),Y(t),Z(t)$ are BOD, DO and NOD concentrations (mg/L), respectively.
D_s is saturation concentration of oxygen, in mg/L
R is loss rate due to respiration, in mg/L/day
$P(t)$ is diurnally varying photosynthetic component, in mg/L/day
S_{BOD}, S_{DO}, S_{NOD} are diffuse (non-point) source loads of BOD, DO and NOD, respectively.
k_1 is BOD decay rate, per day
k_2 is reaeration rate, per day
k_3 is sedimentation and adsorption loss rate for BOD, per day
k_4 is NOD decay rate, per day

In the stochastic version of the above equations, all rate constants, as well as respiration, photosynthesis, and diffuse source loadings, are regarded as stochastic processes. The initial conditions upstream in the river and tributaries and the concentrations of BOD, DO, and NOD in the effluents from sewage treatment plants and industrial users are regarded as random variables. Also, all three equations have an additional stochastic term accounting for randomness resulting from uncertainty about model structure. Stochastic characteristics of these three processes are determined by solving analytically the moment equations associated with the differential equations above. These equations are first reformulated as stochastic Ito differential equations by adding terms for the random variability in the reaction rate coefficients and other parameters. This is done by adding white noise Gaussian processes to each of the random quantities appearing in the equations and also to each of the equations. The noise term added to the parameters represents the natural random fluctuations plus the errors in measurements. The noise terms added to the equations represent random fluctuations in the inputs and modelled processes itself. The solutions of the modified equations, that is the moments of the first (mean values) and the second (variances and covariances) order, are determined as a final result. Full explanations of the method and the derivation of the moment equations can be found in HydroQual and Gore and Storrie (1989); and Zielinski (1988). As an example, the mean and the variance of BOD concentrations for a single river reach are calculated from the following formulas:

First Moment (Mean)

$$E(X)=(X_0-B_1)e^{-(k_1+k_3)t}+B_1 \tag{4.4}$$

where:

X_o is the initial BOD concentration

$$B_1={}^{S_{BOD}}/_{(k_1+k_3)} \tag{4.5}$$

Second Moment

$$E(X^2)=A_2(e^{-(k_1+k_3)t}-e^{(D_1+D_3-k_1-k_3)t})+(X_0^2+B_2)e^{(D_1+D_3-k_1-k_3)t}-B_2 \tag{4.6}$$

where:

$$A_2 = \frac{2(X_0 - B_1)S_{BOD}}{(k_1 + k_3 - D_1 - D_3)} \tag{4.7}$$

$$B_2 = \frac{S_{BOD}^2 + D_7(k_1 + k_3)}{(D_1 + D_3)(k_1 + k_3) - (k_1 + k_3)^2} \tag{4.8}$$

D_1, D_3, D_7 are noise components for the parameters k_1,k_3 and the entire equation, respectively.

Moment (Variance)

$$V(X) = E(X^2) - [E(X)]^2 \tag{4.9}$$

Although the expressions for covariances and the moments for DO are much more complex, these are still closed form solutions, and the values of these statistical characteristics can be easily calculated for any given value of travel time t.

Simplifying Assumptions

The following assumptions were made when formulating governing equations:

1. Longitudinal dispersion is neglected.
2. Velocity is uniform for each river reach.
3. Mean values of rate constants and other parameters are uniform for each river reach.
4. Mixing is instantaneous and complete.
5. DO saturation is temperature dependent only.

4.1.3 Stochastic Nutrients Model (NUSTOC)

Background Information

NUSTOC is another stochastic steady-state and one-dimensional model which predicts organic and inorganic nitrogen as well as dissolved and particulate phosphorus concentrations in river waters. The nitrogen cycle simulation (Fig. 4.1) includes decay of organic nitrogen to ammonia with subsequent nitrification of ammonia to nitrate. The phosphorus cycle simulation (Fig. 4.2) designed specifically for turbid prairie rivers allows for conversion of dissolved to particulate phosphorus. Both the nitrogen and phosphorus components include biological uptake via primary producers (aquatic macrophytes and algae). The above described processes are governed by the following six differential equations:

$$\frac{dX_1(t)}{dt} = -\beta_3 X_1 - \delta_4 X_1 + R_N \tag{4.10}$$

$$\frac{dX_2(t)}{dt} = \beta_3 X_1 - \beta_1 X_2 + B_N - FA_N \tag{4.11}$$

$$\frac{dX_3(t)}{dt} = \beta_1 X_2 - (1-F)A_N \tag{4.12}$$

$$\frac{dY_1(t)}{dt} = -\delta_5 Y_1 + (1-S_P)Y_2 \tag{4.13}$$

$$\frac{dY_2(t)}{dt} = -(1-S_P)Y_2 + B_P - A_P \tag{4.14}$$

$$\frac{dZ(t)}{dt} = -\delta_6 Z + S_Z \tag{4.15}$$

where:

t is travel time, in days
X_1, X_2, X_3 are organic nitrogen, ammonia and nitrate concentrations,

respectively, all in mg/L

Y_1 and Y_2 are particulate and dissolved phosphorus concentrations, both in mg/L
Z is suspended solids concentration, in mg/L
β_1 is ammonia oxidation rate, per day
β_3 is organic nitrogen to ammonia hydrolysis rate, per day
β_N is benthos source rate for ammonia, in mg N/L/day
δ_4 is organic nitrogen settling rate, per day
$R_N = R\alpha_1 A$ is organic nitrogen production due to respiration, in mg/L/day
R is respiration rate of primary producers, per day
α_1 is fraction of plant and algal biomass as nitrogen, in mg N/mg A
A is biomass concentration as carbon dry weight, in mg A/L
F is fraction of algal uptake as ammonia
$A_N = A\alpha_1\mu$ is uptake of inorganic nitrogen due to the algal growth, in mg N/day
μ is growth rate of primary producers, per day
B_P is benthos source for dissolved phosphorus, in mg P/L/day
δ_5 is particulate phosphorus settling rate, per day
$A_P = A\alpha_2\mu$ is algal uptake of dissolved phosphorus, in mg/L/day
α_2 is phosphorus content of algae, in mg P/mg A
$S_P = (1+10^{-6}K_P Z)^{-1}$ is fraction of dissolved phosphorus not adsorbed to particulates
K_P is linear partition coefficient, per kg
δ_6 is suspended solids settling rate, per day
S_Z is diffuse source of suspended solids, in mg/L/day.

The equations were subsequently reformulated as Ito stochastic differential equations by adding terms to account for the variability and uncertainty in rate constants, loadings, initial conditions, and as before, in the model structure itself. As for DOSTOC, the same statistical characteristics (mean values, variances, and covariances) are determined.

Specific Assumptions

The model has been designed specifically for the stretch of the North Saskatchewan River downstream of Edmonton. During the design process a number of assumptions were made to accommodate it. The major ones are:

1. Dissolved phosphorus concentrations are primarily regulated through uptake by benthic algae and phytoplankton and adsorption to suspended solids.
2. The partition coefficient between particulate and dissolved phosphorus is assumed to be linear.
3. Settling is the primary mechanism for removal of particulate phosphorus from the water column.

Figure 4.1 Flow Diagram Illustrating the Nitrogen Cycle Simulation of NUSTOC

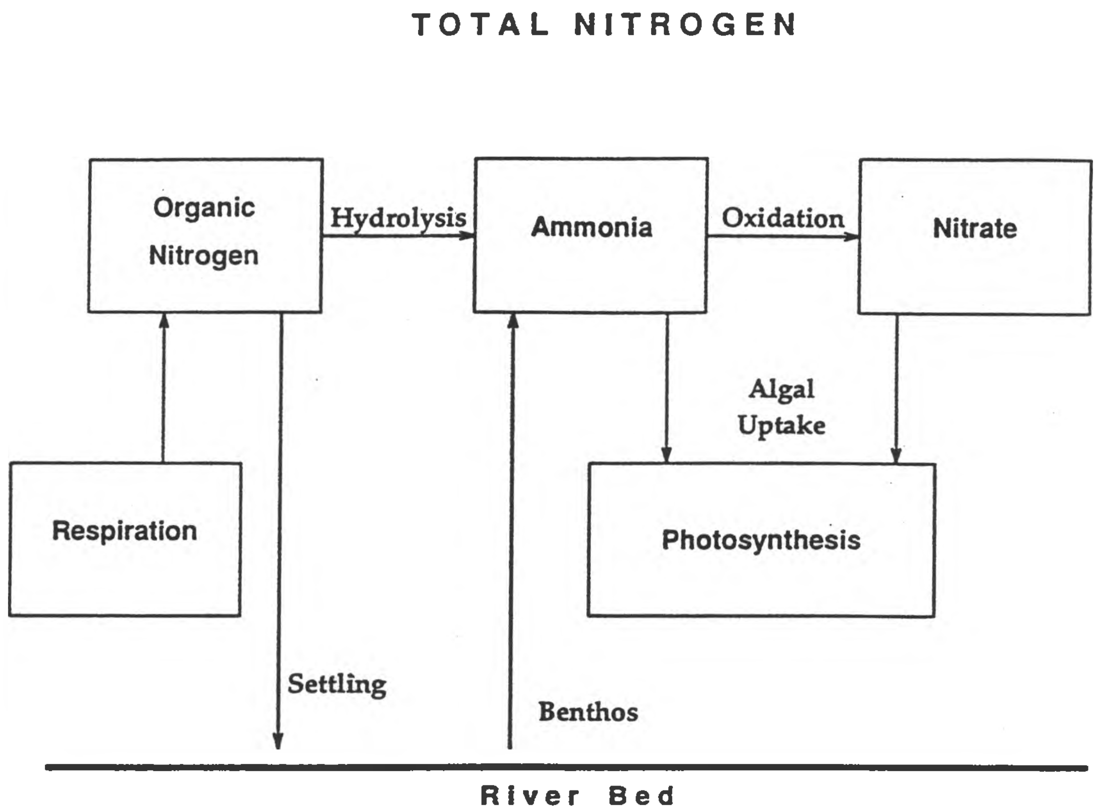
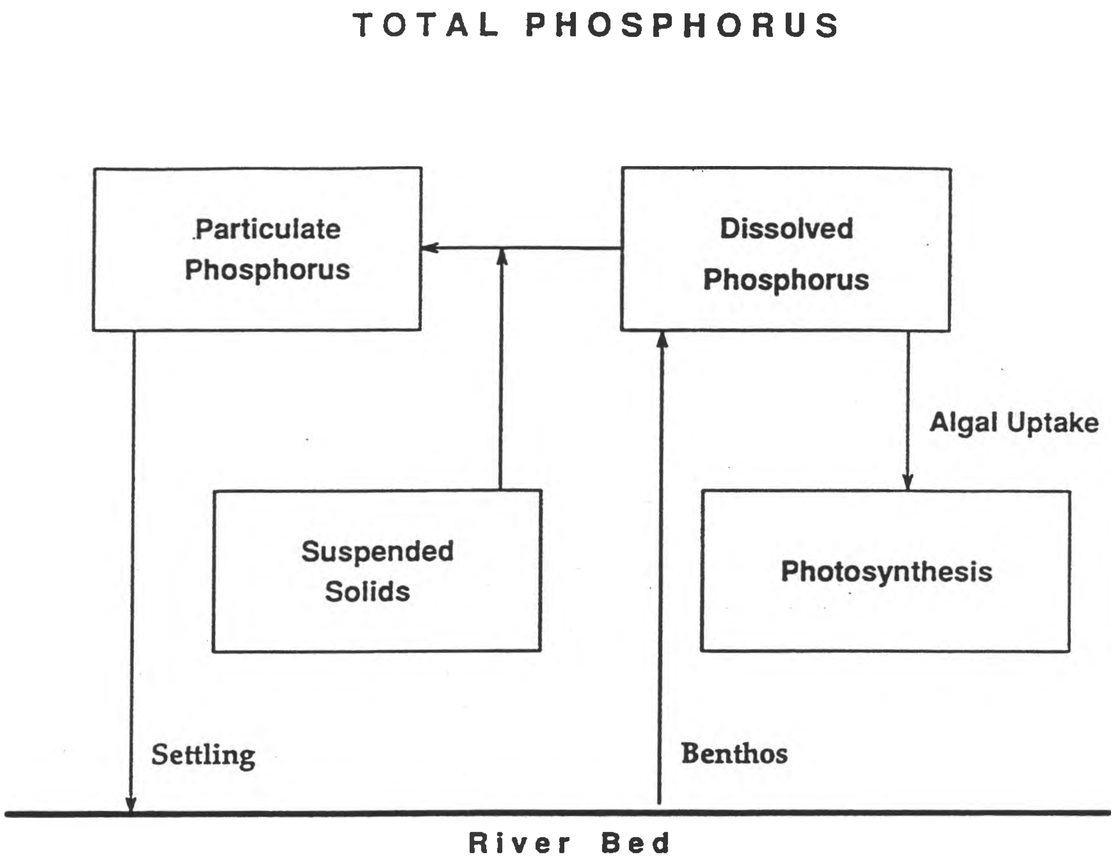


Figure 4.2 Flow Diagram Illustrating the Phosphorus Cycle Simulation of NUSTOC



4. Decay of organic phosphorus to inorganic phosphate is not included.
5. Desorption of particulate phosphorus to dissolved phosphorus is neglected.
6. Conversion of organic nitrogen to ammonia and nitrification of ammonia to nitrate can be described by the first order decay equations.
7. Nitrite is rapidly converted to nitrate and is not simulated.
8. Anaerobic denitrification of nitrate to ammonia is not simulated.
9. Organic nitrogen can be lost from the water column due to settling.
10. Photosynthesis and respiration rates are dependent upon algae/plant biomass and growth rate.
11. Algal preference for uptake of ammonia or nitrate can be selected.

4.1.4 Main Features of DOSTOC and NUSTOC

Strength of the Modelling Approach

- The governing equations are solved analytically with closed form solutions.
- Uncertainty aspects are considered directly in the governing equations.
- All random quantities (with the exception of initial conditions) are regarded as stochastic processes rather than random variables.
- Both models can be run as deterministic.
- Modular structure of the computer code assures high flexibility with respect to possible changes in the governing equations.

Weaknesses of the Model

- All dynamical phenomena are neglected.
- All random disturbances have to be Gaussian.
- User interface and graphics are in need of upgrading.

4.1.5 Model Structure

Both models have essentially the same structure. Segments of the computer code responsible for data input and preliminary screening, configuration of the river network and data file editor are independent of the remaining part of the code carrying out the simulation. The structure is illustrated in Figures 4.3 and 4.4.

4.1.6 Discussion

1. Both DOSTOC and NUSTOC use Gaussian white noise to model stochastic fluctuations of model parameters and inputs. Initial conditions in both models are

regarded as random variables with unspecified distributions and known first and second moments. The method applied to solve the resulting stochastic differential equations is based on the moment equations of equivalent stochastic Ito differential equations which can use only white noise as a source of random disturbance. The other option available is to pass the white noise process by an appropriate filter which would result in a coloured instead of white noise.

However, there is a sound justification in using the white noise process. According to the central limit theorem, a large number of various factors affecting the values of the parameters justifies the use of a Gaussian process as an approximate of random fluctuations.

2. Expected values obtained from the Ito equations are different from expectations obtained from the Stratonovich equations because the ways of evaluating the integrand in the stochastic integrals are different. Both solutions are still not very far apart from each other.

3. Both models can be run as purely deterministic if necessary. To do that, the user has to set all noise parameters to zero and proceed as in the stochastic case.

4. Small or very small uncertainty does not affect the way the model is run. Noise parameters can vary from zero to any physically realistic numbers. Since the solutions are determined as closed form functions of travel time, unusually small values of noise parameters do not cause any numerical problems. On the other hand, large values can cause stability problems in the moment equations. However, this is related to the model's structure (equations) and not to the numerical implementation of the models.

5. The difference between two approaches (random variables versus stochastic processes) in incorporating uncertainty in water quality modelling is fundamental. Mathematical detail explaining this statement can be found in Soong (1973) and Zielinski (1991). In practical terms the random variable approach (which assumes that all random parameters and inputs can be modelled as random variables) implicitly assumes that uncertainty is real in estimating the values of the parameters, and once the parameter is correctly determined it remains constant. In other words, it assumes that the parameters have unknown but constant values along the river reach. This goes against common experience which indicates that all physical rates vary randomly about their means as functions of travel time (or distance) along the river reach. This behaviour can be modelled only if the stochastic processes approach is applied. Clearly, this interpretation of random variability is much more justifiable from the physical standpoint.

Figure 4.3 General Block Structure of the DOSTOC AND NUSTOC Water Quality Simulation Models

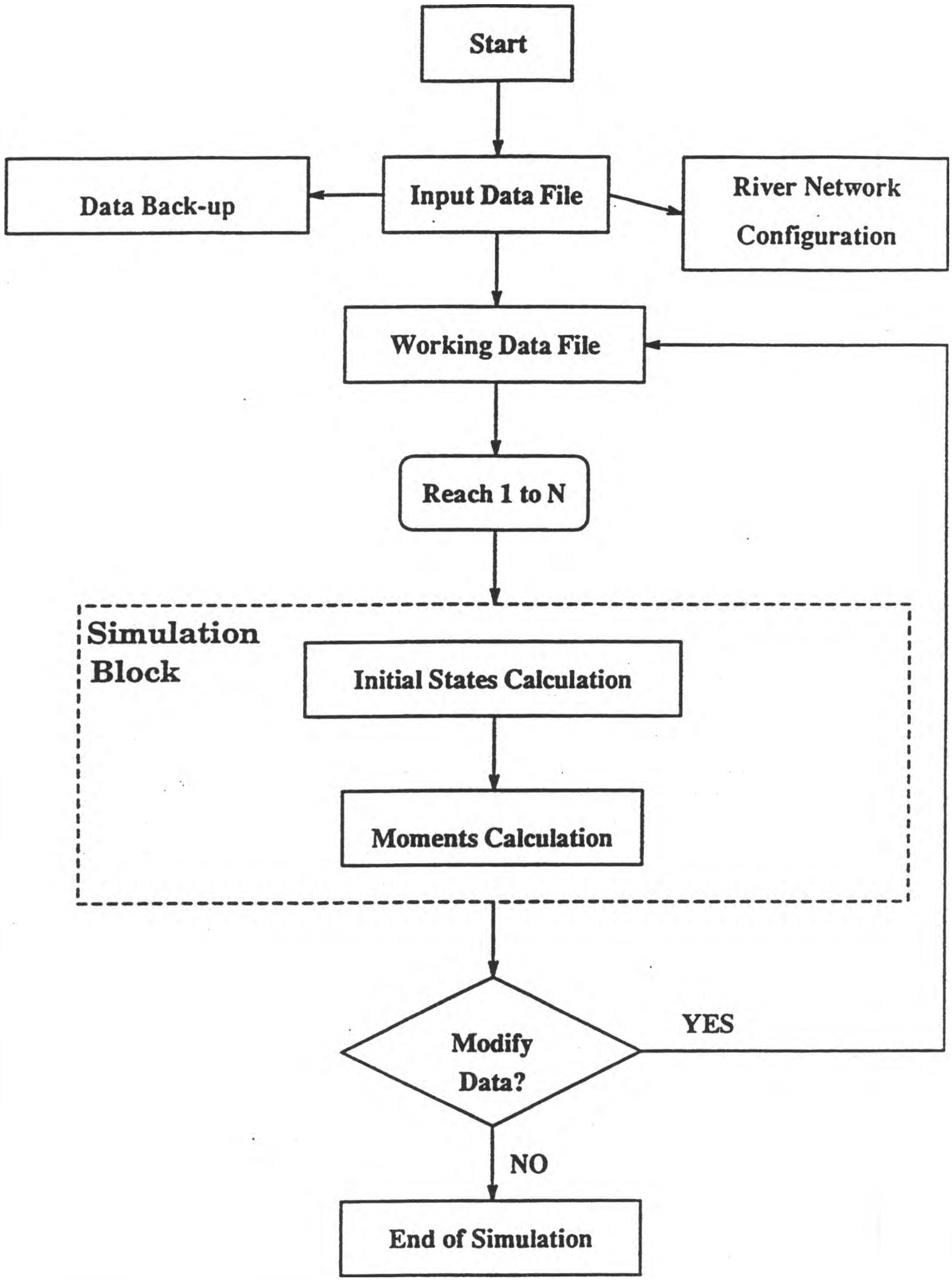
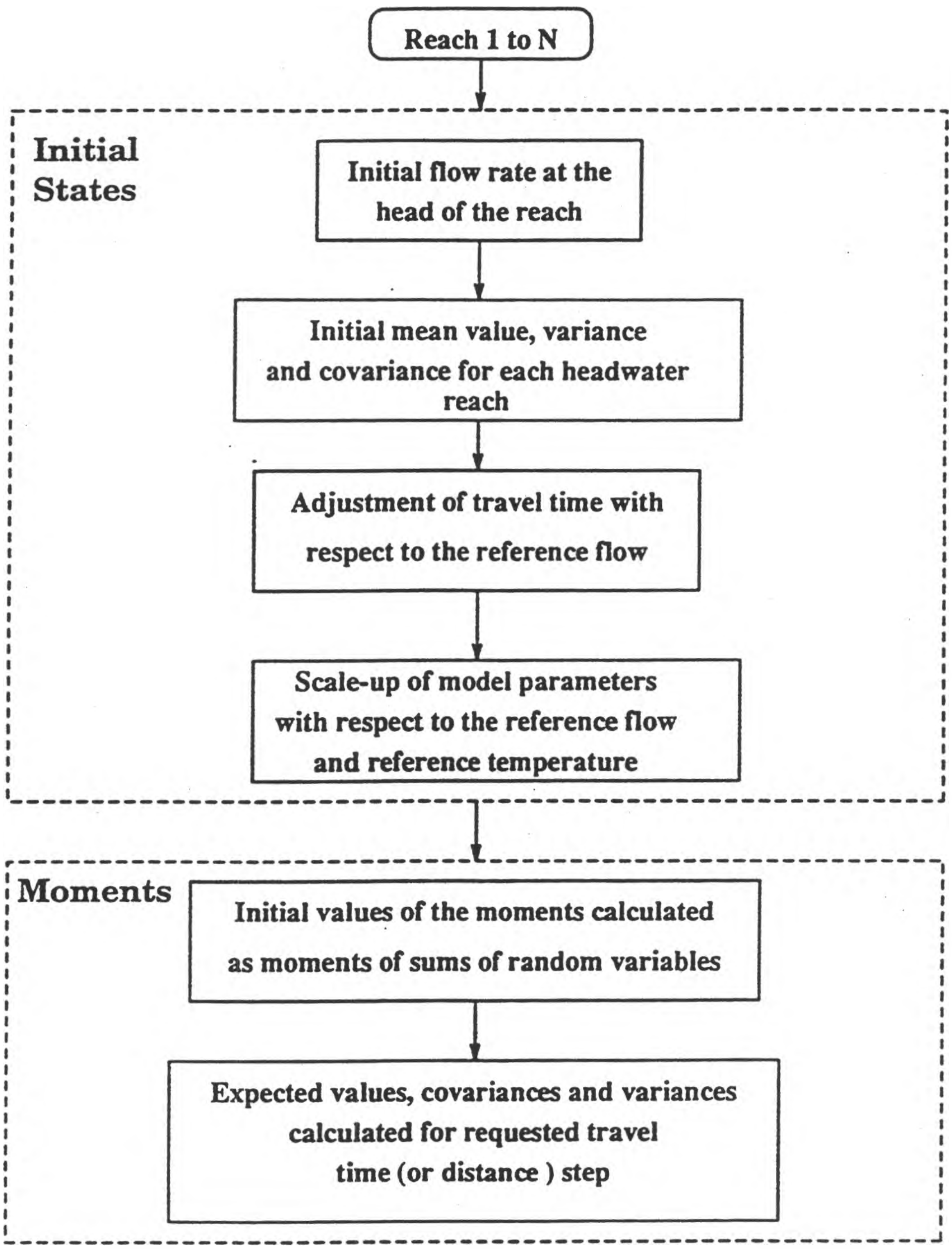


Figure 4.4 Simulation Block Structure of the NUSTOC and DOSTOC Water Quality Models



For practical purposes the difference in estimating the moments using these two approaches can be substantial. Some hypothetical examples showing the magnitude of possible differences are discussed in Zielinski (1991).

4.2 Water Quality Analysis Simulation Program (WASP4) (Mr. G. Macdonald and Dr. R. Shaw, EMA/Golder Associates)

4.2.1 Introduction

The Water Quality Analysis Simulation Program (WASP) was developed in 1981 for the U.S. Environmental Protection Agency (Di Toro et al. 1981). The USEPA Center for Exposure Modelling in Athens, GA has continued to develop and improve the original version. The most recent version (WASP 4.32) was released in 1992. WASP has been widely used throughout North America to predict water quality responses to natural and man-made pollution. WASP has been previously used in Alberta to study:

- Nutrients and DO dynamics in both the Peace and Athabasca Rivers (Macdonald and Taylor 1990; Macdonald and Radermacher 1992).
- Organic contamination from pulp mills in the Peace and Athabasca Rivers (Macdonald and Taylor 1990; Macdonald and Radermacher 1992).
- River water quality resulting from other industrial wastewater discharge (Macdonald and Radermacher 1990).
- Salt and nutrient levels in Buffalo Lake following diversion (Environmental Management Associates 1991, 1992d).
- Organic contamination from an abandoned creosote site (Environmental Management Associates in prep.)
- Stormwater management options for urban runoff from Calgary and a landfill in Edmonton (JNMackenzie Engineering Ltd. (1992); Environmental Management Associates 1992a).
- Siting oilsands facilities in the North Saskatchewan and Athabasca River Basin (Goudey et al. 1990; Taylor et al. 1990).
- Evaluating the feasibility of capping oilsands waste with water (Environmental Management Associates 1992c).

WASP is a generalized framework for modelling water quality in surface waters (Ambrose et al. 1991). The flexibility afforded by WASP is unique among water quality models—it permits the structure of one-, two- and three-dimensional models; allows the specification of time-variable exchange coefficients, advective flows, waste loads and water quality boundaries; and permits tailored structuring of its kinetic processes.

A body of water is represented in WASP as a series of computational elements (segments). Environmental properties and chemical concentrations are modelled as spatially constant within segments. Four different segment types may be simulated—surface water, subsurface water, surface benthic, and subsurface benthic.

The basic principle governing transport of water and material among different segments is conservation of mass. Water volumes and water quality constituent masses are tracked and accounted for over time and space using a series of mass-balancing equations. Six mechanisms may be used to describe mass transport; advection and dispersion in the water column; advection and dispersion in the porewater; settling, resuspension and sedimentation of up to three classes of solids, plus evaporation and precipitation.

WASP includes two kinetic sub-models to simulate two of the major classes of water quality problems: toxic pollution, and eutrophication (Fig. 4.5). The linkage of these sub-models to the WASP transport model gives TOXI and EUTRO, respectively. In addition to TOXI and EUTRO, a tracer sub-model, which is simply one of the kinetic sub-models run without kinetic interactions, is included to simulate conservative substances (Fig. 4.5).

WASP (version 4.32) is written in FORTRAN 77 and is best implemented on IBM PC 486 compatible systems using the Salford FTN77/486 computer and the 32-bit DBOS DOS extender.

4.2.2 Eutrophication Sub-model

The eutrophication model, EUTRO, simulates the transport and transformation of up to eight state variables in the water column and sediment bed, including DO, carbonaceous biochemical oxygen demand (CBOD), algal carbon (and chlorophyll-a), ammonia, nitrate, organic nitrogen, inorganic phosphorus, and organic phosphorus. These variables constitute four interacting systems (algal dynamics, phosphorus cycle, nitrogen cycle, and DO cycle) which are linked by a complex set of reactions and pathways (Fig. 4.6). Because decomposition of organic material in benthic segments can have profound effects on concentrations of oxygen and nutrients in the overlying water, EUTRO includes the option of using a calculated framework that incorporates sediment kinetics and sediment-water interactions. The kinetic reactions and interactions included in EUTRO are described below, based largely on information included in Bowie et al. (1985) and Ambrose et al. (1991).

Algal Biomass

Algal biomass is tracked in EUTRO as phytoplankton carbon. It increases as a result of growth and decreases as a result of respiration, death, and settling. Algal growth rate is a function of the important environmental variables temperature, nutrients, and light (Fig. 4.7).

Temperature has direct physiological effects on algal growth and is simulated with an exponential temperature function based on optimal growth at 20°C (derived from van't Hoff-Arrhenius equation):

$$r_{\max}(T) = r_{\max}(20^{\circ}C)\theta^{(T-20)} \tag{4.16}$$

where:

$r_{\max}(T)$ is the temperature-corrected growth rate at ambient water temperature T (°C), $r_{max}(20°C)$ is the optimal growth rate at 20°C, and θ is the temperature correction factor. This function is used throughout EUTRO to adjust rate coefficients for the effect of temperature.

Nutrient limitation in EUTRO is based on a fixed stoichiometry model that incorporates conventional Monod or Michaelis-Menton kinetics. That is, the nutrient concentrations of the algal cells remain constant (i.e., fixed stoichiometry), and growth rates are determined by the external concentrations of available nutrients. At adequate nutrient levels it is assumed that the algal populations grow at the saturated rate for the ambient light and temperature conditions. At low nutrient levels, however, the growth rate becomes linearly proportional to nutrient levels. The Michaelis constant is that value in which the growth rate is half the saturated growth rate. Because there are two nutrients available for uptake (dissolved inorganic nitrogen and dissolved inorganic phosphorus), a separate growth limitation factor is computed for both nutrients, and the minimum value is chosen to reduce saturated growth rate. (An option to use the multiplicative formulation for nutrient limitation is also available.)

EUTRO provides two alternative formulations for calculating light limitation, methods developed by Di Toro et al. (1971) and Smith (1980). Smith's modelling framework is an extension of that of Di Toro et al. (1971) and accounts for both (i) the attenuation of light with depth and the effect of algae on light attenuation, and (ii) the effect of the resulting light levels on algal growth and photosynthesis. Smith's model also replaces an unknown parameter, (saturating light intensity of algae) that must be determined via calibration, with a term involving parameters that are well documented in the literature. In addition, a variable carbon to chlorophyll ratio is incorporated into his model. This variable ratio is based on the assumption that algal populations maximize growth rates for ambient light and temperature conditions.

Figure 4.5 Schematic Representation of WASP4 Modules

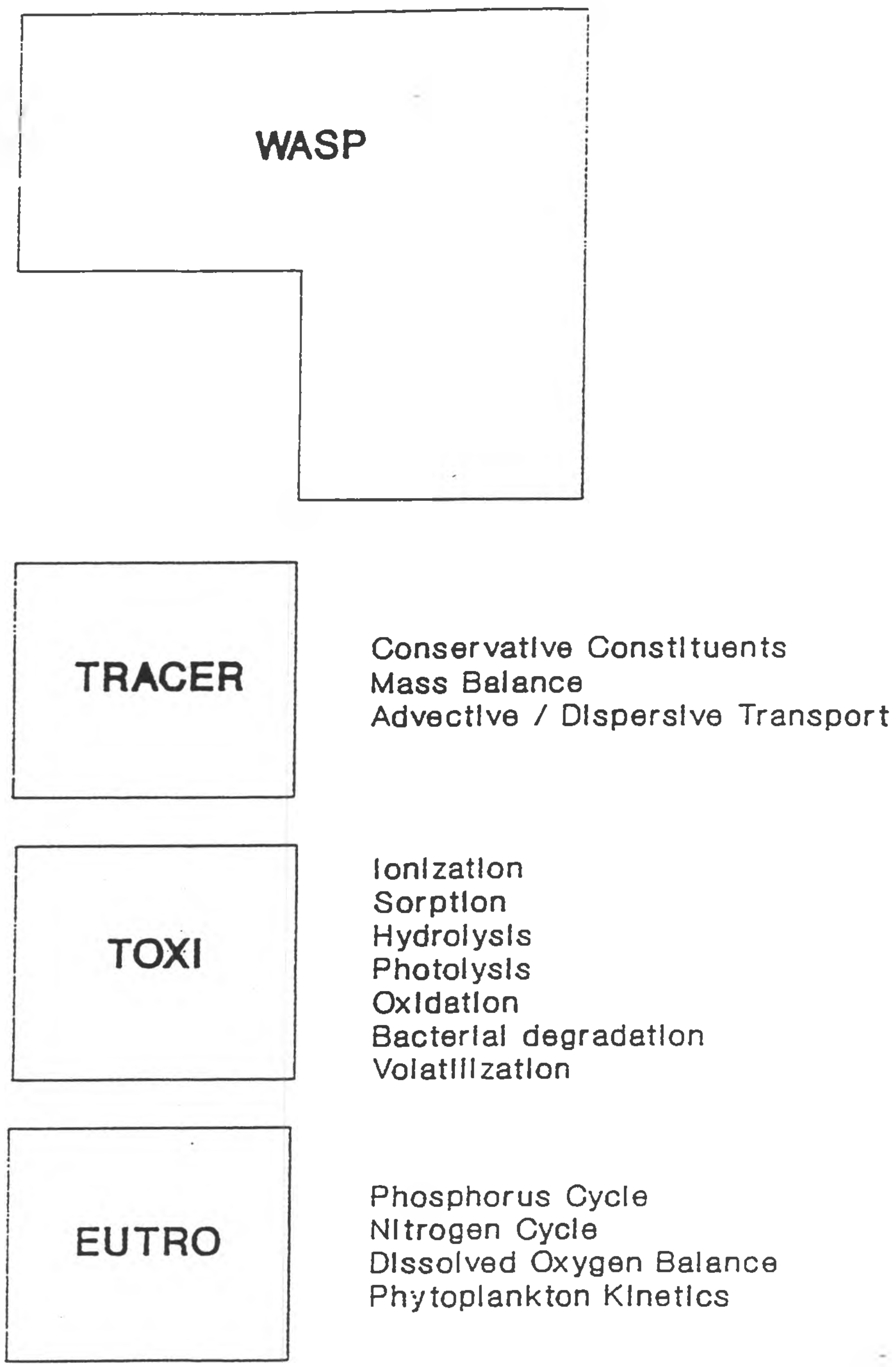


Figure 4.6 **Eutrophication Model (EUTRO4) State Variable Interactions Within the Water Column**

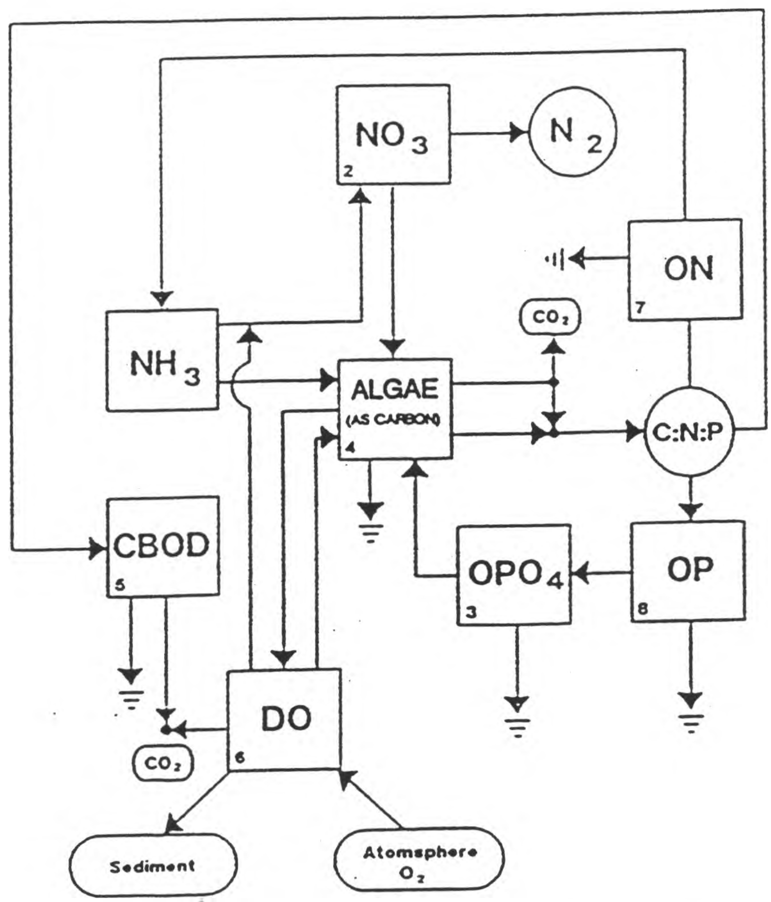
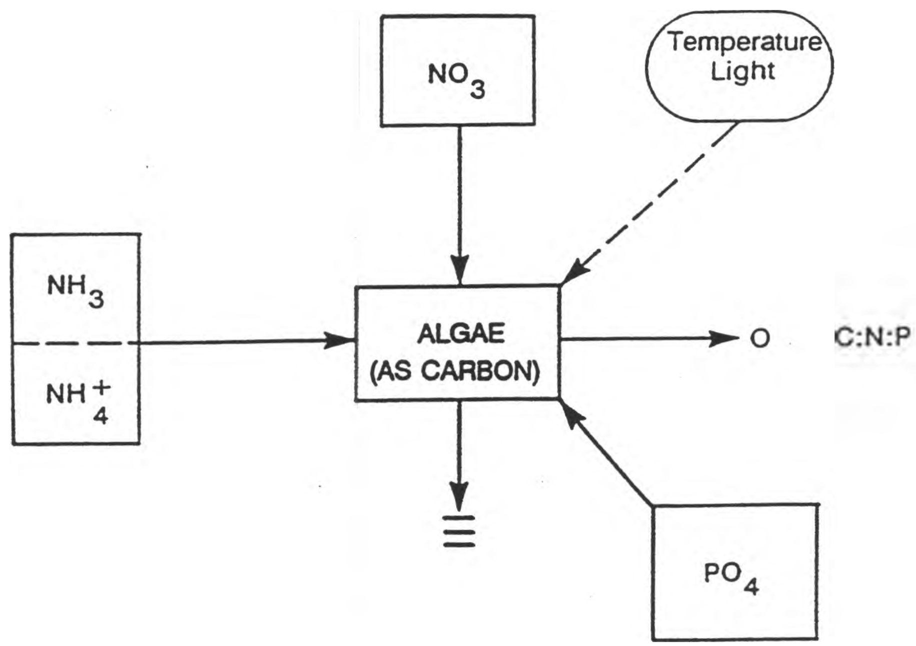


Figure 4.7 Algal Kinetics Component of the Eutro Model



Algal levels in surface waters decrease as a result of respiration, death, and settling. Respiration is the rate at which the phytoplankton oxidize their carbon to carbon dioxide per unit weight of phytoplankton organic carbon. The respiration rate is temperature dependent, as shown in Equation (4.16). Algal mortality results from parasitization, grazing, and toxicity. These processes are not simulated dynamically. Instead, they are described by functions that may vary spatially and temporally.

Phosphorus Cycle

Three phosphorus pools are included in simulations of phosphorus dynamics: algal, organic, and inorganic (Fig. 4.8). The organic and inorganic phosphorus pools include both dissolved and particulate fractions.

Algal growth removes dissolved inorganic phosphorus (orthophosphate) from the water column. Cellular phosphorus is recycled back into the water column as dissolved inorganic and organic phosphorus as a result of both algal death and respiration. Settling removes cellular phosphorus from the water column.

Organic phosphorus includes that phosphorus bound up in organic detritus. Within both the water column and sediment, organic phosphorus increases as a result of algal respiration (water column only) and algal degradation, and it decreases as a result of mineralization to dissolved inorganic phosphorus. Particulate organic phosphorus may also be lost to or gained from the sediment via sedimentation or resuspension, respectively.

As noted above, dissolved inorganic phosphorus is added to the water column by algal respiration, death, and organic phosphorus mineralization. There is also a sorption-desorption interaction between dissolved inorganic phosphorus and suspended particulate material in the water column. The subsequent settling of sorbed inorganic phosphorus can act as a significant loss mechanism of phosphorus from the water column and a source of phosphorus to the sediments.

EUTRO does not include suspended solids as a state variable so adsorption-desorption kinetics are not included. Instead, the dissolved and particulate phosphorus phases are assigned a fixed fraction of the inorganic phosphorus pool. This assumption is based on the fact that (i) rates of sorption reactions are in the order of minutes, i.e., sorption can be considered instantaneous relative to algal and biological kinetics, and (ii) there is sufficient sediment relative to dissolved P so that the adsorbing capacity of the sediment will not be reached.

Nitrogen Cycle

Four nitrogen pools are modelled: algal, organic, ammonia, and nitrate (Fig. 4.9).

Algae utilize inorganic nitrogen from the water column and return a fraction of cellular nitrogen in the form of ammonia during respiration and death. Both ammonia and nitrate are available for algal uptake. However, for physiological reasons the preferred form is ammonia nitrogen, i.e., less energy is required to incorporate ammonia compared to nitrate into proteins. Thus, an ammonia preference term is included in EUTRO. The preference term is most sensitive at low levels of inorganic N. At high ammonia levels relative to nitrate, little nitrate is taken up. The preference for ammonia decreases as the ratio of ammonia to nitrate decreases.

Organic N includes all non-living organic N and that fraction of organic N recycled during algal respiration and death. Organic N levels decrease as a result of mineralization to ammonia. Particulate organic N may also be lost to or gained from the bottom sediments by settling and resuspension, respectively.

Ammonia nitrogen is added to the water column by algal respiration and death and by organic N mineralization; it is added to porewater by algal decay and mineralization. In addition to algal respiration, ammonia N is lost from the water column by the process of nitrification. Nitrate nitrogen is added to the water column by nitrification and removed by algal growth and denitrification (under anoxic conditions). In the sediments, nitrate is removed only by denitrification. Denitrification is included in EUTRO only as a sink of nitrate.

4.2.3 Dissolved Oxygen Balance

Five state variables are involved directly in the DO balance: algal carbon, ammonia, nitrate, CBOD, and DO (Fig. 4.10). EUTRO includes several different options for modelling DO kinetics. The simplest form involves solving the Streeter-Phelps BOD-DO equations, albeit in slightly modified forms:

$$\frac{dBOD}{dt} = -k_d BOD_{Tot.} - \frac{v}{D} BOD_{Par.} \tag{4.17}$$

Figure 4.8 Phosphorus Kinetics Component of the Eutro Model

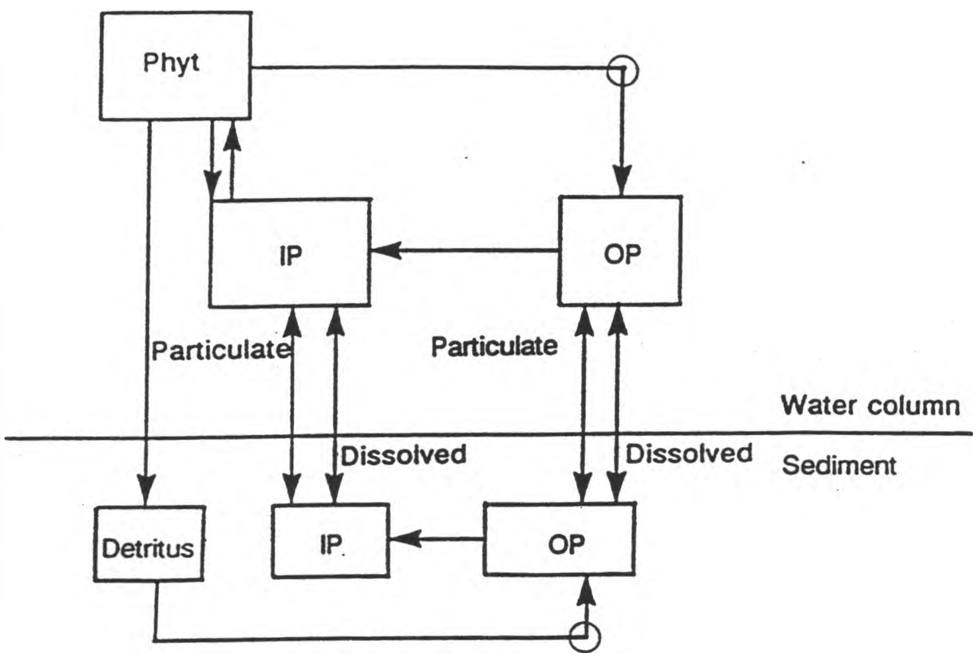
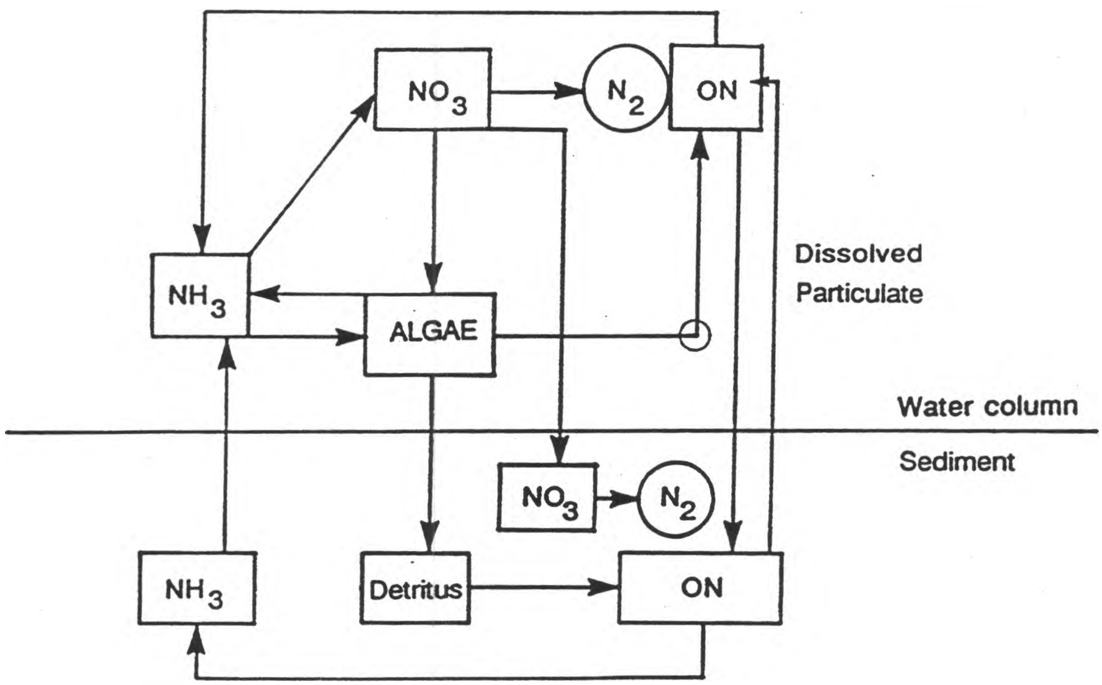


Figure 4.9 Nitrogen Kinetics Component of the Eutro Model



$$\frac{dDO}{dt} = k_2(DO_s - DO) - k_d BOD_{Tot} - \frac{SOD}{D} \tag{4.18}$$

where:

k_d and k_2 are deoxygenation and reaeration rates (per day) respectively, v is particulate settling velocity (m/d), D is depth (m), $BOD_{Par.}$ and BOD_{Tot} (mg/L) are particulate and total BOD respectively, DO_s is saturation dissolved oxygen (mg/L), and SOD is sediment oxygen demand (g/m^2/d). Thus, nutrient kinetics and algal growth are not simulated with this option.

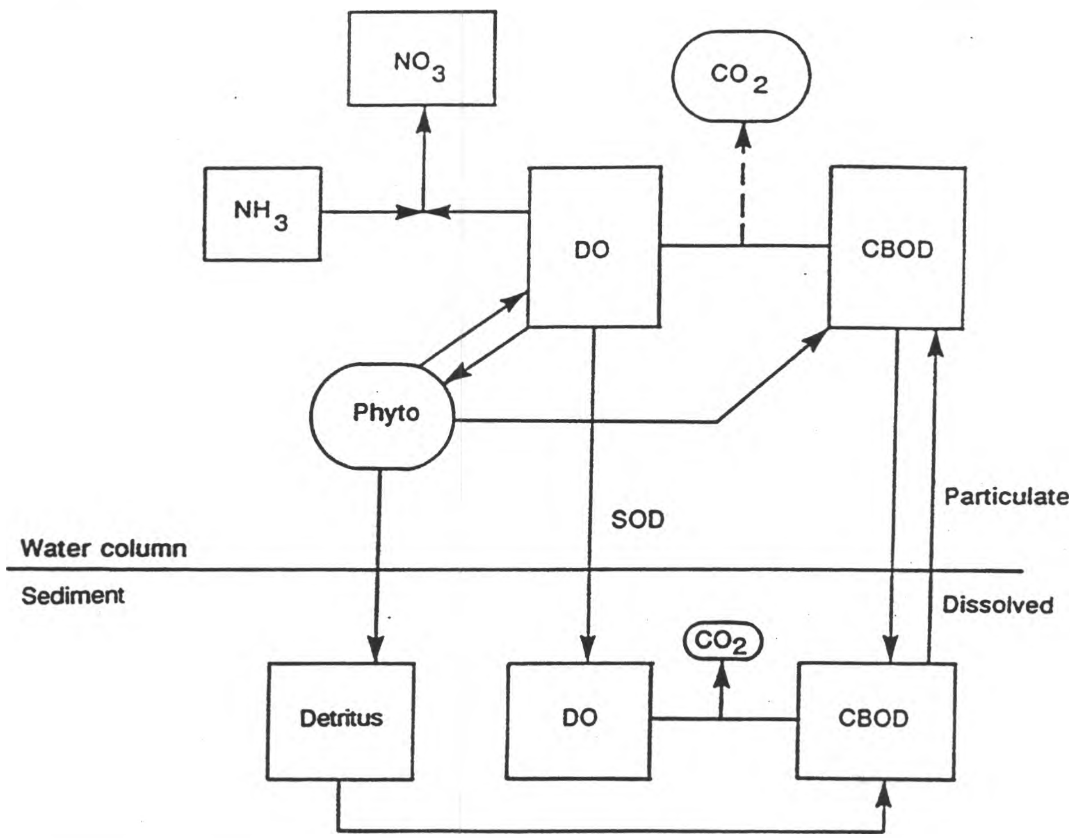
The next level of complexity that may be modelled involves dividing BOD (Equation 2) into carbonaceous and nitrogen fractions thus giving rise to three state variable CBOD, NBOD, plus DO. The NBOD process may also be divided into mineralization and nitrification, and the effects of photosynthesis and respiration from given algal levels included (i.e., full linear DO balance). Increasing levels of complexity result from simulating the growth and death of algae along with its effect on nutrient cycles and DO balance. Finally, in its most complex form, EUTRO allows for inclusion of a full set of benthic interactions. Thus, sediment oxygen demand may be simulated dynamically. This option for simulating DO is described below.

At the air-water interface, atmospheric reaeration replenishes DO in the water column during periods of oxygen deficit and removes DO from the water column during periods of supersaturation. Reaeration rates are a function of water velocity, depth, wind, and temperature and are calculated based on the Cover method.

The only other source of oxygen to the water column is from algal photosynthesis. The rate of oxygen production from photosynthesis is proportional to the growth rate of the algae since cell stoichiometry is fixed. Additionally, oxygen is released into the water column as ammonia levels decline and nitrate is utilized by the algae. During nitrate uptake, nitrate is reduced to ammonia which releases 3.43 mg of oxygen for each mg of phytoplankton carbon produced. Oxygen is diminished in the water column as a result of algal respiration; nitrification; oxidation of CBOD and detrital algae; and sediment oxygen demand (discussed below).

The principle source of CBOD in both the water column and sediments is algal carbon produced as a result of algal death. The loss mechanisms associated with CBOD are oxidation and denitrification, although the latter is only a significant loss mechanism under anoxic conditions, e.g., within sediments.

Figure 4.10 Dissolved Oxygen Cycle Component of the Eutro Model



Within the detrital sediments the reactions that convert algal and refractory carbon to their end products are complex. Initially, algal and refractory carbon are converted to reactive intermediates that participate in further reaction, e.g., volatile acids react to form methane. However, the mechanisms that control these reactions are not well understood so these reactions are not explicitly simulated in EUTRO (or in any other water quality model). Instead, sediment oxygen dynamics are based on DO and CBOD. This simplification ignores the effects of reduced species such as iron, manganese, and sulphide on the overall redox reactions and in the generation of sediment oxygen demand.

The decomposition reactions that drive the sediment mass balance equations are the anaerobic decomposition of detrital algal carbon and the breakdown of benthic organic carbon. Both reactions are sinks of oxygen and will drive its concentrations negative in EUTRO (the user has the option of allowing negative concentrations); the negative concentrations can be considered the oxygen equivalents of the reduced end products produced by the chain of redox reaction in the sediments. A detrital sediment oxygen demand (SOD, g/m^2/d) is then produced by the flux of oxygen into the sediments from the overlying water:

$$SOD = \frac{E_{DIF}}{D}(C_{SED} - C_{SURF}) \tag{4.19}$$

where:

E_{DIF} is the diffusive exchange rate (m^2/day), D is the benthic layer depth (m), and C_{SED} and C_{SURF} are the DO concentrations (mg/L) in the adjoining sediment and surface water segments, respectively.

4.2.4 Application of WASP to Northern Rivers

Several computer modelling and field studies have been completed to assist in the evaluation of DO and nutrient conditions in the northern rivers (Shaw and Macdonald 1993). WASP has previously been applied to the Peace and Athabasca Rivers to simulate nutrient (TN, TP) and DO levels during winters (Macdonald and Taylor 1990; Macdonald and Radermacher 1992). This model has some distinct advantages over the other model, DOSTOC, that has been routinely used for these rivers (Table 4.1). One of the major advantages of WASP is that it can be configured to handle two-dimensional problems. Thus, where river mixing is incomplete, e.g., in Peace River downstream of Smoky River confluence, it can track plume dispersion; DOSTOC, on the other hand, is a one-dimensional model. The flexibility of WASP results in a more complex input deck so it is more time-consuming than simpler models to implement.

Another major advantage of WASP, compared to DOSTOC, is that it is a dynamic model, i.e., it can provide a continuous simulation of water quality conditions for any given time period, e.g., few days to years. Potentially, therefore, it could track the build up of detrital material below pulp mills over the winter and simulate the change in SOD over that period. Implementation of any dynamic model comes at the expense of increased model run times.

There are advantages and disadvantages associated with any model applied to a specific problem. The present version of WASP is no exception and has some limitations with respect to modelling DO conditions in the northern rivers. A potential limiting factor is its lack of benthic algal (and aquatic macrophyte) growth routines (at present it only simulates phytoplankton dynamics). Whether this is a real problem or simply a perceived problem requires resolution of the importance of benthic algae (or aquatic macrophyte) communities to winter DO depletion.

Probably of greater concern than WASP's lack of benthic algal simulation, is that the DO cycle is based on traditional, first-order BOD kinetics (as are virtually all surface water models). It is becoming clear that BOD_5 is a poor indicator of the actual oxygen demand from pulp mill effluents and other state variables may have to be considered if we are to refine DO simulations in these systems. Since decomposition of organic carbon is quite likely the primary cause of SOD in these rivers, it seems reasonable to consider attempting to directly simulate these pathways rather than indirectly utilizing a laboratory-based surrogate like BOD_5. This would require the addition of routines that include other parameters, e.g., carbon (perhaps in several forms, such as particulate, dissolved, labile, and non-labile), chemical oxygen demand (COD), and bacteria.

Finally, the current version of WASP is a deterministic model operating with the underlying assumption that model parameters and processes can be described fully by a unique set of values and that uncertainties in these parameters and processes are small or negligible. In contrast, probabilistic models include errors in model parameters and, thereby, provide error bounds on model predictions. Evaluation of model output error is critical when management decisions are based on model studies. Considering the potential complexity of the model, the only option for estimating output errors would be modification of the program to allow for Monte Carlo simulations. With this approach repeated simulations would be run, each simulation consisting of a unique set of input parameters specified by sampling at random from their assumed probability distribution. Thus, a large number (e.g., 1000) of different output solutions would be obtained, and these could be analyzed statistically to derive confidence intervals to quantify model output uncertainty.

4.2.5 Potential Errors and Sensitive Input Parameters for WASP

As discussed above, all computer models are simplified versions of reality and there are

Table 4.1 The Advantages and Disadvantages of Applying the Eutro sub-model of WASP to the Athabasca and Peace Rivers of the Northern River Basins Study.

Advantages	Disadvantages
- One-, two- or three-dimension application - Routines easily modified or added - Steady-state or dynamic application - Deterministic - Support by USEPA - The model can also be used for simulating contaminant fate and transport in the Northern Rivers Basins Study	- More complex to set up and run compared to simpler models - Relatively time consuming to implement compared to DOSTOC - Increased computational time for dynamic simulations - Output errors not computed - No benthic algal or aquatic macrophyte growth routines - DO cycle based on traditional first order BOD kinetics - Not carbon based, no bacterial growth routines

uncertainties associated with model predictions. We have outlined some of the potential errors associated with the use of WASP for DO and nutrient modelling in the northern rivers. For example, DO cycle is based on BOD kinetics as are virtually all water quality models.

Identification of the sensitive input parameters for WASP is speculative at this time. A sensitivity analysis would have to be undertaken with WASP configured to the northern rivers before one can state with certainty which parameters are the most sensitive. However, experience with other models applied to these rivers and with WASP on other systems suggests that winter DO simulations will be very sensitive to headwater oxygen concentrations and sediment oxygen demand. The reliability of nutrient simulations will likely be a function of the accuracy with which nutrient loads to the rivers are quantified.

4.3 Dynamic Stream Simulation and Assessment Model (DSSAMt)
(Mr. J. T. Brock, Idaho State University *and* Rapid Creek Water Works; and Dr. C. L. Caupp, Frostburg State University)

4.3.1 DSSAMt Overview

DSSAMt was designed to simulate water quality conditions in a river system where polluting substances enter the modelled reach from a variety of sources including tributaries, point-source effluent discharges, point-source runoff of surface waters, non-point runoff, groundwater, and leaching and scouring from the bottom sediments. DSSAMt provides a dynamic representation of diel (24-h) variation in modelled constituent concentrations over the period of simulation. The model simulates competition between two assemblages of benthic algae including nitrogen-fixing algae growing under conditions of low nitrogen. DSSAMt includes a routine involving heat transfer equations for simulation of water temperature based on ambient conditions. River pH is simulated through an evaluation of the carbonate equilibrium based on acidity, alkalinity, and uptake of carbon dioxide. The biomasses of algae are modelled dynamically as a function of nutrients, light, temperature, current velocity, and other environmental variables. The model is based on an assumption of steady flow conditions with exponential relationships used to estimate river hydraulics. The model has been applied to the Truckee River (Nevada) and the Red Deer River (Alberta).

The current version of the model DSSAMt is a hybrid of two previously published stream models (SSAM V and LPSM) and has been enhanced with the addition of a module to simulate water temperature. DSSAMt had its origins in SSAM IV, Stream Simulation and Assessment Model: Version IV (Grenney and Kraszewski 1981) and LPSM, Lotic Periphyton Simulation Model (Runke 1985). SSAM IV is a steady-state model of water quality in stream environments that deals with both hydraulics and water quality, but it treats periphyton and aquatic macrophytes in only a rudimentary fashion. The LPSM model, on the other hand, focuses specifically on the dynamics of the periphyton community. LPSM is dynamic with respect to biological responses to environmental conditions but does not deal with stream chemistry or hydraulics except as input data. For use in modelling water quality in the Truckee River, we grafted the LPSM periphyton algorithm onto a modified version of SSAM IV to create DSSAMt. The current version of DSSAMt includes a heat transfer sub-model giving DSSAMt the capacity, internally, for prediction of water temperature. This enhancement facilitates assessment of lotic-ecosystem response to alternatives involving management of river flow.

DSSAMt is both dynamic and deterministic, capable of simulating diel swings of all the water quality constituents modelled. DSSAMt was developed initially during 1985-1987 to investigate potential biostimulatory effects that various operational scenarios of the Reno-Sparks Wastewater Treatment Facility might have on the Truckee River, Nevada (Brock et al. 1989). DSSAMt initially emphasized simulation of pH, DO, and ammonia nitrogen (both total and un-ionized) because of the relevance of these water quality parameters to fish survival. The early applications of DSSAMt to the Truckee River did not involve river flows other than those observed historically, so observed water temperature conditions were entered as input data and not predicted. An assessment of potential effects of a flood control project on the Truckee River provided us with the opportunity in 1989 to develop a shade and water temperature model (separate from DSSAMt). The model included a detailed assessment of the effects of topographic and riparian shading on water temperature. In 1990 additional development of the river model involved the capacity to specify diel variations of constituents at the upstream boundary and from a point-source loading; and the incorporation of additional constituents (particulate phosphorus, soluble non-reactive phosphorus, particulate organic nitrogen, and soluble organic nitrogen) required for the assessment of total nutrient loadings to the modelled system. Total dissolved solids (TDS) and chloride were added to help track conservative substances.

During 1991-1992 DSSAMt was calibrated to 1989 Truckee River conditions and used to provide the State of Nevada's Bureau of Water Quality Planning with a technical basis for assessing water quality standards and waste-load allocation for point and non-point pollutant sources to the lower Truckee River. The calibrated model was used to evaluate the downstream ecosystem response to a series of nitrogen loadings emanating from municipal and agricultural sources. Our analysis focused on predicting growth and removal of benthic algae under varying nutrient loads and the associated impacts on DO regimes. These simulations provided a basis for revisions to the State of Nevada's water quality standards and the specification of allowable nutrient loadings to the Truckee River.

DSSAMt is currently (1992-1993) being applied to the Red Deer River as part of Alberta Environment's assessment of instream flows needed to protect water quality. For use on the Red Deer River study, DSSAMt was augmented to include simulation of water temperature, light extinction, and decay of faecal coliform bacteria. Through our association on the Red Deer River instream flow study with hydraulic engineers at W-E-R AGRA, Ltd. (Calgary), lateral flow stratifications are being developed within each one-dimensional model segment of DSSAMt. Current development activities include separate biomass terms for benthic organic matter and algal chlorophyll to allow for improved simulation of benthic dynamics associated with flushing flows. The current version of DSSAMt does not include a phytoplankton or aquatic macrophyte component. From a computer coding perspective, additional functional components can be added without difficulty due to the program's modular architecture.

DSSAMt may be applied to a river system with distributed surface inflows and/or outflows, and distributed groundwater inflows and/or outflows. The main program operates three distinct sub-models in sequence: (i) system layout and flow balance, (ii) water temperature simulation and, (iii) simulation of water quality constituents. The first sub-model (Hydraulic) starts with the headwater flow of the mainstream and proceeds downstream conducting a flow balance by adding (or subtracting, as appropriate) distributed surface flow, distributed subsurface flow, point load flows, and diversion flows. The model calculates the average velocity, cross-sectional area, and hydraulic radius at specified points in the stream network and stores these data for later use. The Temperature and Water Quality sub-models also start at the headwater of the stream utilizing hydraulic data stored by the hydraulic sub-model and proceed downstream solving the heat transfer equations and a system of differential equations to predict concentrations of the water quality constituents.

The concentration of the water quality constituents at any point in the river system are the results of two processes:

1. The collection and physical transport of the substances from upstream sources by the flowing water.

2. The biochemical and physical reactions causing changes in concentrations or chemical composition during the time that the substances are being transported.

Each of these processes is simulated by the model. For the first process, the constituents entering the water are mixed with the main stream-flow and transported downstream at the average cross-sectional velocity of the flow. The second process is simulated by biophysical and physical reaction kinetics. The constituents listed in Tables 4.2 and 4.3 are presently included in DSSAMt. Figure 4.11 illustrates the relationships and linkages between these state variables in DSSAMt.

The model calculates diel constituent concentrations for constant flow conditions over a specified time period. Due to the steady-state assumption associated with hydraulics and transport, it is preferable if the selected time period is not less than the travel time of flow through the sub-basin being modelled. We define the term "pass" to represent the length of time (in days) during which flows are held constant. During a single pass of the model it is assumed that river flows do not vary significantly relative to total travel time.

Steady-state models based on a cartesian reference frame (such as DSSAMt) are incapable of modelling the transport and flow dynamics associated with modelled periods characterized by variable flow, such as storm runoff or releases below impoundments used for hydroelectric generation.

A model "simulation" consists of a single model pass or a connected series of model passes. Passes of the river model are connected by using the final values for the first pass as initial conditions for the second pass; the final values for the second pass become initial conditions for the third pass, and so on. Thus, model simulations could vary in length from a single pass to an entire year. The concept of linking multiple passes during a simulation provides a mechanism for predicting biological responses, such as accumulations of benthic algae, which integrate conditions over an entire growing period.

The time span for a simulation of DSSAMt is specified for the application at hand. The program is structured so that time periods can be linked successively, and, at the end of a period, the program writes a set of final values for all constituents and model elements. This output data file for the period can then represent the initial values for a new time period. Accordingly, DSSAMt could be run for a day, a year, or many years of river time, depending on the particular management objective. The time-step for the input of new meteorologic conditions during the model pass is determined by data availability. For the Red Deer River simulations, we made use of meteorologic and solar radiation data that were available hourly. Options are available to account for diel variability (i.e., ten samples per day) in constituent concentration for upstream boundary conditions and for a point load such as a wastewater treatment plant. The Red Deer River water quality model is currently operated at a time-step of every two hours during the ice-free period of April through November. DSSAMt has yet to be applied to river conditions with ice cover.

Table 4.2 Modelled Water Quality Constituents in DSSAMt III as Applied to the Red Deer River

Constituent	Abbreviation
I. Primary Constituents Used in Kinetic Equations	
Water temperature	
Soluble reactive (ortho) phosphorus	SRP
Soluble non-reactive phosphorus	SNRP
Particulate phosphorus	PP
Ammonium-nitrogen	NH_4N
Nitrate-nitrogen	NO_2H
Nitrate-nitrogen	NO_3H
Soluble organic nitrogen	SON
Particulate organic nitrogen	PON
Ultimate biochemical oxygen demand	BODU
Dissolved oxygen	DO or O_2
Benthic algae	ALGAE
Non blue-green algae	ALGAE1
Blue-green algae	ALGAE2
Acidity	ACID
Total alkalinity	ALK
Carbon dioxide	CO_2
Total dissolved solids	TDS
Chloride	CL
Faecal coliform bacteria	F COLI
II. Secondary Constituents Calculated Based on I	
Un-ionized ammonia	UN.NH3N
pH	pH
Total soluble inorganic nitrogen	TSIN
Total nitrogen	TOTAL N
Total phosphorus	TOTAL P

Table 4.3 Modelled Water Quality Processes and Transformations in DSSAMt III as Applied to the Red Deer River

Process	Abbreviation[1]
I. Processes	
Sediment oxygen demand	SOD
Oxygen reaeration	k_2O_2
Carbon dioxide reaeration	k_2CO_2
Nitrification	
Phosphorus/nitrogen recycling	
Nutrient uptake by benthic algae	
Scour of benthic algae at higher velocities	
Benthic algae removal by invertebrates	
Photosynthesis	
Respiration	
Decay of organic nitrogen	
Decay of organic phosphorus	

NOTE: Not all processes have abbreviations

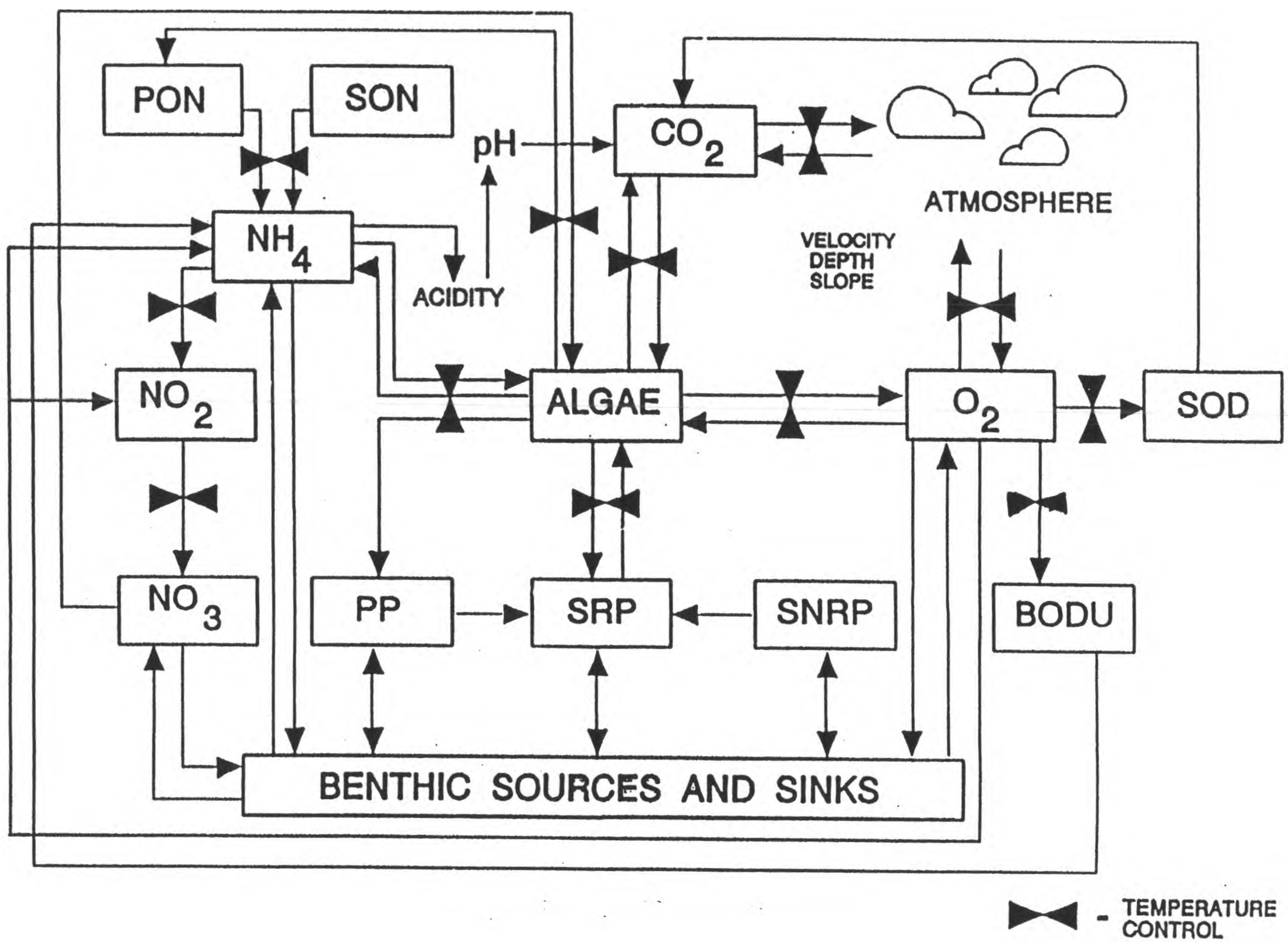


Figure 4.11 Systems Diagram of DSSAMt III

4.3.2 Hydrodynamic Features of DSSAMt

River hydraulics are modelled for the one-dimensional, steady-state condition. Reach average coefficients are used to estimate velocity, depth, cross sectional area, and river width within each reach. Channel hydraulic properties are defined by the relationships of average cross-sectional velocity to flow and hydraulic radius to flow by power equations first suggested by Leopold and Maddock (1953). The power equations take the following form:

$$V = \theta_1 Q^{\theta_2} \quad \textbf{(4.20)}$$

$$W = \theta_3 Q^{\theta_4} \quad \textbf{(4.21)}$$

$$A = Q/V \quad \textbf{(4.22)}$$

$$R = A/W \quad \textbf{(4.23)}$$

where:

V, A, R, and W are average cross-sectional velocity (m/sec), area (m^2), hydraulic radius, and width (m), respectively. For the DSSAMt application to the Red Deer River, the Θ_i coefficients were estimated from log-log plots of measured cross sections combined with cross-sectional flow data obtained from HEC-2 model runs (WER-AGRA Ltd. 1993).

Application of DSSAMt to the Red Deer started with segmenting the river into a series of reaches (shown in Fig. 4.12). Reaches were selected so that the following characteristics were more or less uniform within each reach:

1. Channel hydraulic properties (slope, cross-section, flow-velocity relationship, bed roughness, bed material size, etc.)

2. Channel sinuosity, channel sinuous amplitude, frequency of occurrence of islands, and relative occurrence of riffles and pools.

3. Benthic habitat characteristics with respect to types of primary producers,

presence of large woody debris, and cover for fish.

4. Type of land use and riparian vegetation adjacent to the reach including distributed surface and subsurface flow.

Each reach was segmented into computational elements of variable length—for the Red Deer River we selected a total of 81 elements each 7 km in length. The number of elements within each reach can vary with longer elements in relatively homogeneous reaches, and shorter elements where gradients are observed or expected in functionally important components of the ecosystem.

The capability in DSSAMt to adjust the length of the computational elements provides useful flexibility. As a one dimensional model, constituent concentrations are assumed to be completely mixed laterally and vertically within each element, and only a single point load can enter in an element. The use of short length elements can improve model resolution but at the cost of increased computational time. When the model is used for preliminary screening purposes relatively long elements can be used. If it becomes desirable to assess water quality with finer resolution in specific segments, the model can be reconfigured for those sections using shorter elements for the river segment of interest. For example, if results of initial model simulations indicated a zone of bio-stimulation that impacted DO downstream from a point load high in nutrients, the length of computational element within this zone of interest could be shortened to provide better resolution of the biological community's response to the loading.

DSSAMt is presently configured to the main trunk of a river. Water quality of tributaries is not modelled; they are treated as point sources to the boundary of the modelled reach. If it were desirable to apply DSSAMt to a system that included tributaries, each tributary could be modelled as a separate river and the output saved to be used as the boundary conditions for the main stem of the river system. Alternatively, the DSSAMt computer code could be enhanced to allow simulation of river networks.

The nodal structure used for the Red Deer stimulation is given in Figure 4.13. Each point inflow or diversion is identified as a node. Inflows can be tributaries, industrial point sources, or discharges from municipal wastewater treatment facilities. The discharge (m^3/s) and concentration of all water quality constituents are specified at each node of inflow for every model pass. For point diversions, only outflow volume per unit time needs to be specified. Flow into or out of the element can be zeroed for passes where there is no flow at that node. If two or more point loads or diversions are located within one element, the user can either:

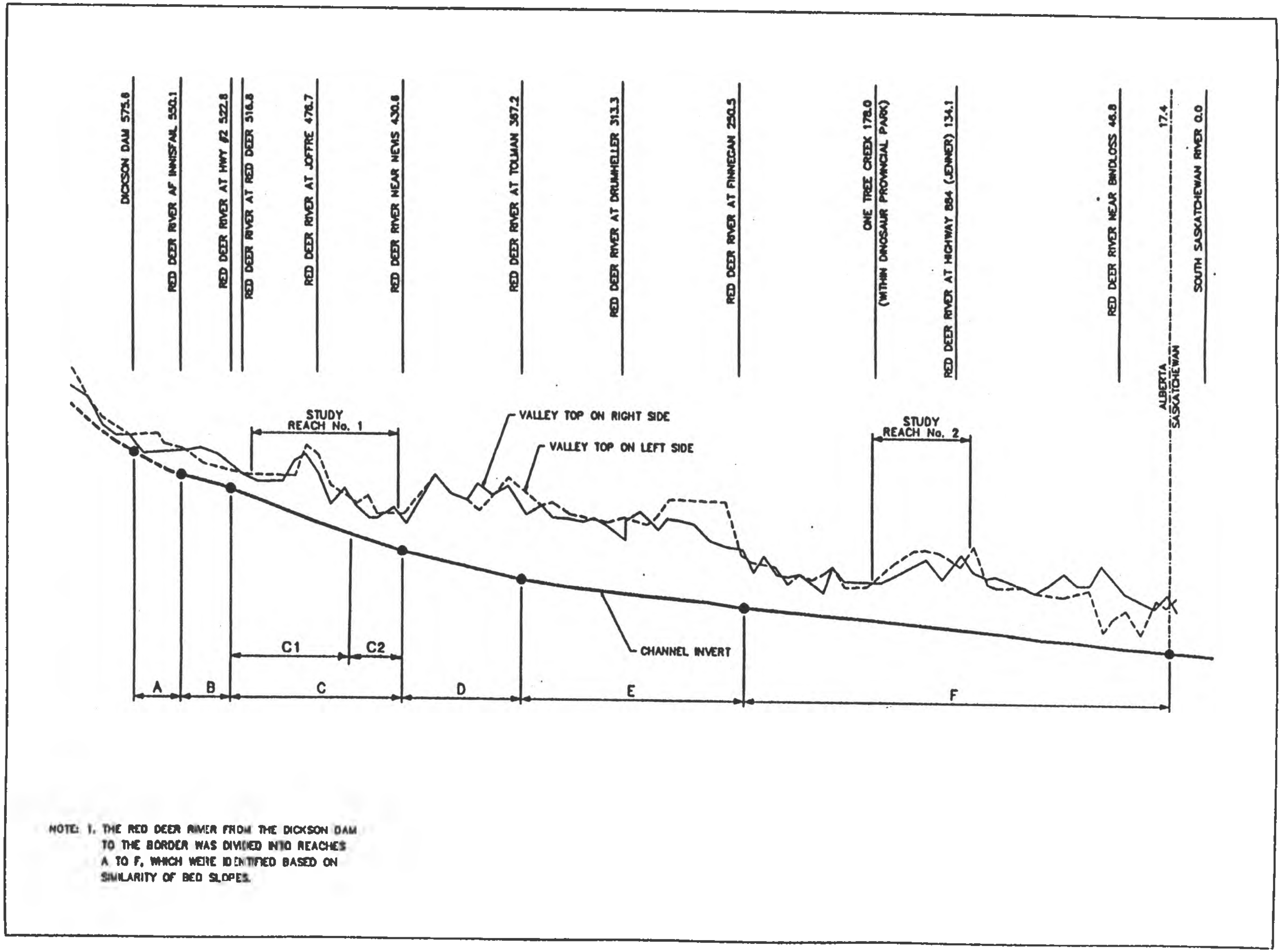


Figure 4.12 Profile View of the Study Reaches on the Red Deer River. Each Reach was Divided into Computational Elements of Variable Length for Application of DSSAMt

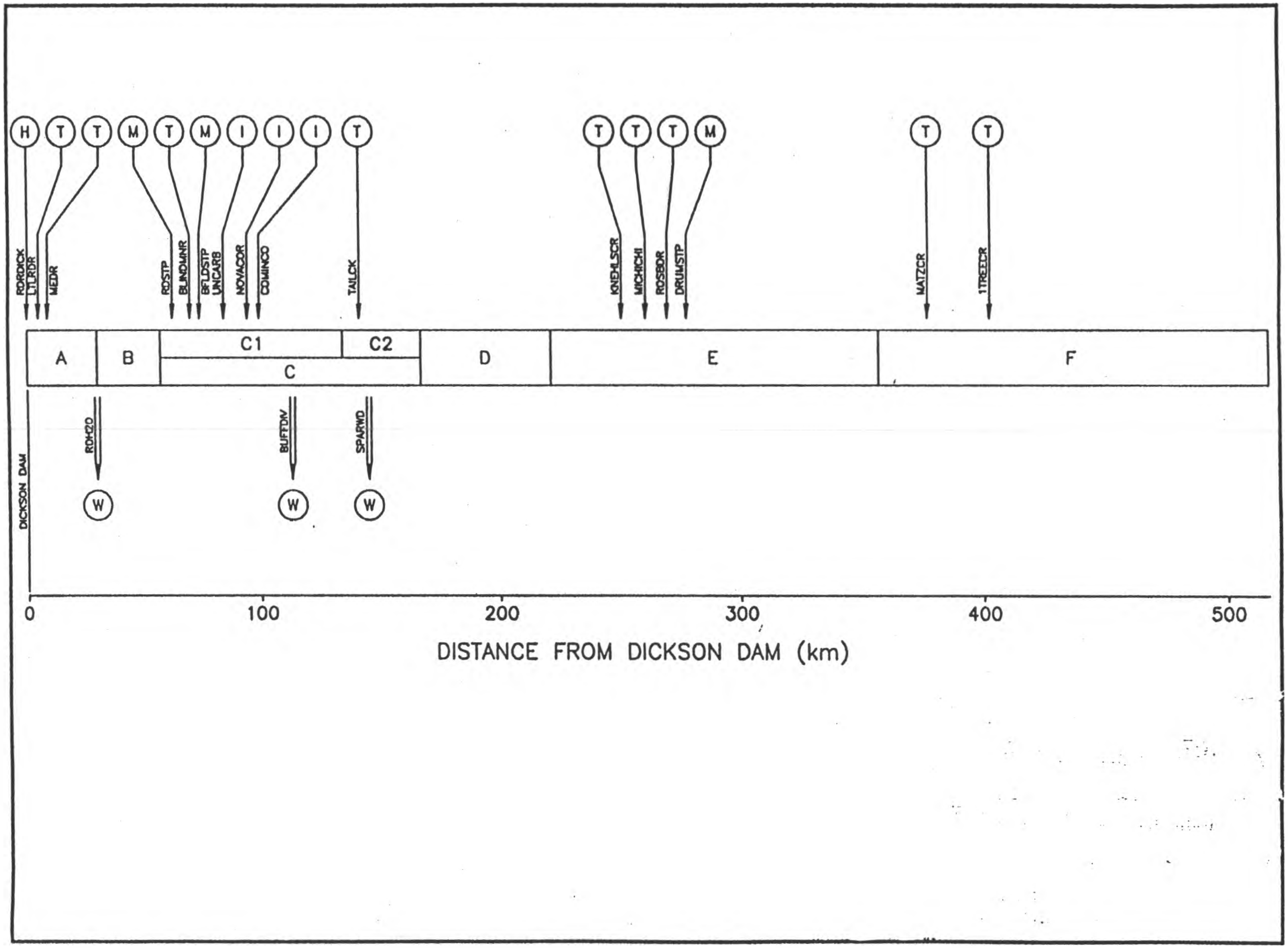


Figure 4.13 Nodal Structure of the DSSAMt Model as Applied to the Red Deer River

1. Calculate a mass balance of the loads and enter the combined flow and concentrations,

2. Adjust the location of a node by moving it up stream or downstream in the model, or

3. Reduce the length of the elements.

Once the point load enters the element, a flow balance is calculated along with a mass balance for the water quality constituents. The total flow within the element is then used to calculate reach mean values for depth, velocity, cross sectional area, and top width.

The steady-state flow assumption used in DSSAMt has the advantage of reducing the input data requirements and simplifying the flow and transport model requirements as well as hydraulic calculations. Flow conditions for each reach are held steady over the specified period of time (pass duration). This assumption tends to be valid for rivers not subjected to significant variation in flow, or where flow variations are within a window of depths and velocity that results in similar growth conditions for the benthic algae. The benthic algae tend to integrate conditions during the pass. If instantaneous discharges within a modelled time period are sufficient for scouring of algae, we typically adjust the pass duration so that it is short enough that the mean discharge for the pass is sufficiently high to scour the algae. For example, for the calibration of DSSAMt to the Red Deer River, three ten-day passes were used for the month of July, allowing the simulation to include the elevated current velocities associated with peak runoff flows observed during the period (see Fig. 4.14). This approach allows the dynamics associated with flushing flows to be addressed within the framework of a steady flow model. In some instances it may become necessary to employ an unsteady flow model to represent adequate scour and movement of benthic organic matter in the sediments. Past studies on bed movement associated with elevated flows have typically emphasized inorganic sediment. There is a clear need for further research on the scour of benthic primary producers and organic sediments that are critical to modelling DO and nutrients in rivers.

Longitudinal variation in depth and velocity within a reach are represented by an adjustment for pools and riffles. Pools are defined as depositional areas where conditions are unsuitable for growth of benthic algae. Riffles are defined as erosional areas where conditions are favourable for the growth of benthic algae. In DSSAMt algal growth rates and biomasses are calculated for the riffle conditions with the simulated biomass for algal assemblages representative of the optimal values found in the riffles. Uptake of nutrients and oxygen are calculated separately for riffle and pool habitat based on their fraction of the total area. For example, if the relative area of riffles in the reach is 35%, then uptake of a nutrient would be 0.35 of the amount based on the biomass in the riffle. Processes associated with sediment oxygen demand are assumed to occur only in pools. The stratification of reaches into riffles and pools allows for differentiation of

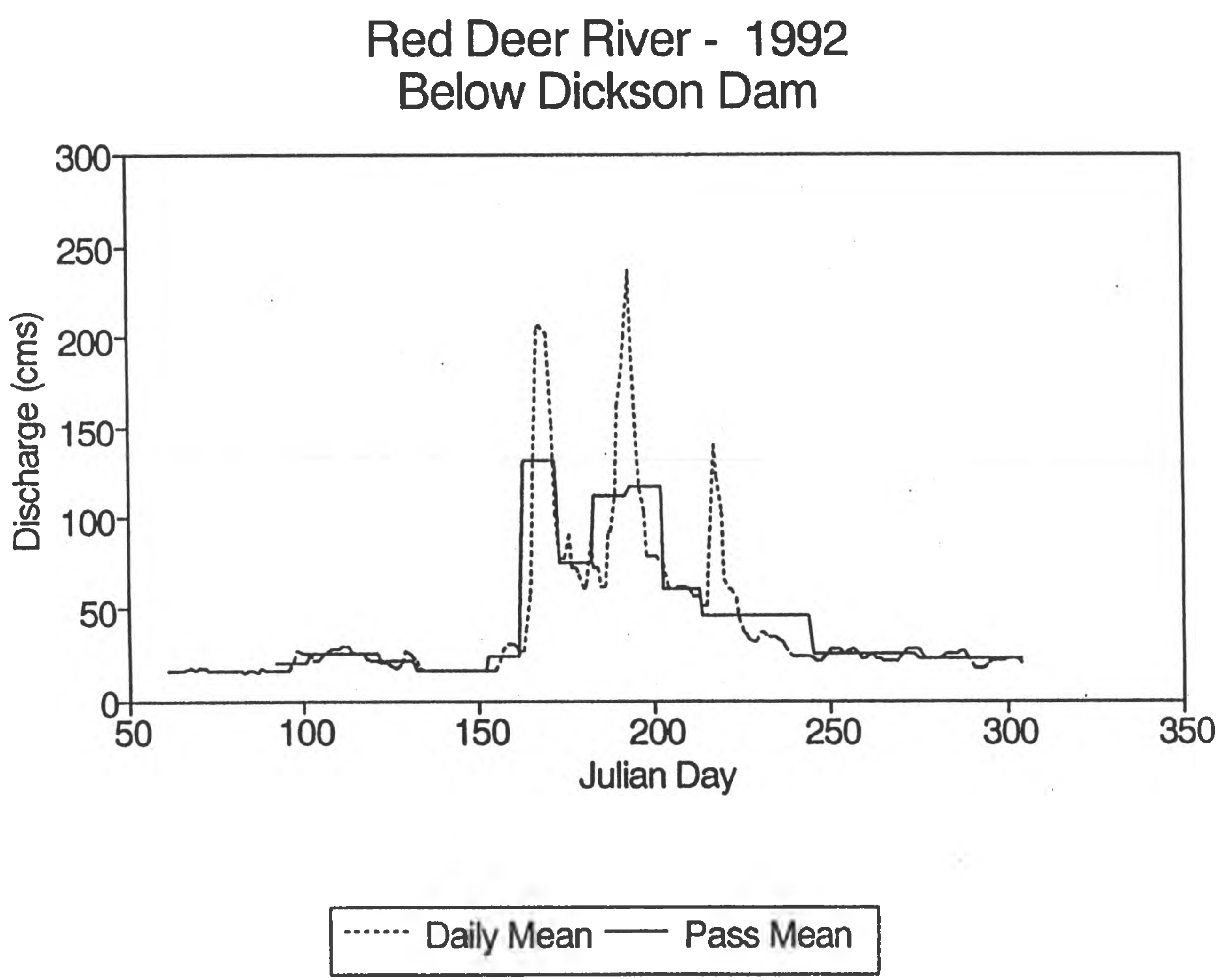


Figure 4.14 Daily Mean Discharge in the Red Deer River Below the Dickson Dam During July 1992 and Discharge Estimates Used in Three Ten-day Passes During the Application of DSSAMt

functionally significant ecosystem processes within the framework of a steady flow model.

In large floodplain rivers, lateral (across the channel) variation in habitat can be greater than longitudinal variation within a reach. For instance, the combined effect of river depth and turbidity conditions often creates a euphotic ("good light") zone along the margins of river banks. In such cases light penetration to the benthos of mid-channel zones is insufficient to support photosynthesis; autotrophic activity thus becomes restricted to a ribbon along the margins of the river and its islands. Adequate simulation of water depth and light penetration become critical to accurate representation of photosynthetic capacity in such rivers. The Truckee River is generally transparent and shallow enough so that a habitat-based adjustment to mean depth and velocity was deemed adequate to characterize the euphotic zone. The Red Deer River has a deeper channel and carries a more turbid load than the Truckee River, and lateral variation becomes greater than longitudinal variation within in each reach. For our initial model simulations, the riffle:pool habitat stratification was used to represent the lateral variation within each reach. The riffle fraction was used to represent the portion of the reach with active benthic algae growth. Hydraulic engineers at W-E-R AGRA Ltd. have developed a methodology for estimating hydraulic coefficients laterally across the river which will allow us to incorporate an algorithm featuring lateral segmentation for inclusion within DSSAMt. The coefficients will be used to calculate the fraction of the reach with velocities greater than the depositional limits as well as the reach's euphotic fraction. This enhancement to DSSAMt promises to improve significantly the model's ability to simulate ecosystem processes realistically in large rivers and to assess their impacts on DO and nutrients.

4.3.3 Benthic Algae Algorithm

DSSAMt simulates the dynamics of the river periphyton by considering, separately, the blue-green and non blue-green algal assemblages. The benthic algae algorithm includes periphyton biomass as a state variable and three multi-variate rate vectors—primary production, algal respiration, and the removal processes that result in export of biomass from the system.

Primary Production

The periphyton models of McIntire (1973) and Runke (1985) provided the basis for DSSAMt's algal growth formulations. Algal growth is predicted by assuming that the community is in a state of balanced growth. Whenever nutrients or other environmental variables are sub-optimal growth becomes limited. A maximum specific growth rate for each assemblage is estimated based on water temperature (Eppley 1972). The maximum rate is subsequently reduced according to the intensity of the suite of environmental "growth" variables to which the periphyton are exposed. The model considers the variables current velocity, photosynthetically active radiation, and the nutrients nitrogen and phosphorus. DSSAMt assumes Liebig's Law of the Minimum which asserts that growth will be determined by whichever of the growth variables is shortest in supply, relative to its optimum level. During a time-step of a DSSAMt simulation, normalized forms of these growth factors are used, along with a term that accounts for spatial limitation, to produce an adjusted rate that is applied to the photosynthesizing biomass.

The formulations used in DSSAMt for periphyton growth resemble those for phytoplankton used in several other river water quality models (e.g., QUAL2E), except for the density dependent term (McIntire's "SPEC" or specific growth rate reduction factor) and the velocity enhancement term. The Monod model for uptake of the nutrients nitrogen and phosphorus is employed with values assumed for the Michaelis-Menten constants which are used to adjust the maximum specific growth rate for the ambient temperature. A light-dependent growth rate reduction factor is estimated based on light transmitted through the water column. Thus far in the development and application of DSSAMt, we have not had the need to treat phytoplankton as a functionally separate assemblage of algae since the rivers to which DSSAMt has been applied have not had significant populations of phytoplankton.

The growth rate for benthic algae for a given time period is a function of temperature, nutrients, light, current velocity, and biomass density. The maximum growth rate at the present temperature is first calculated. The maximum growth rate is then reduced by the limiting factor (either nutrients, current velocity, or light). The maximum growth rate for the given environmental conditions is next modified by the "SPEC" term. The SPEC term represents the growth rate reduction due to crowding. The maximum biomass is a function of numerous factors including type and size of bed material, current velocity, and algal species. The SPEC term is difficult to measure but is very important. After the SPEC density is reached, growth is reduced because there is no suitable substrate to colonize. Once the maximum biomass is reached, further biomass accumulation can occur only after a portion of the existing biomass decays and is removed by current velocity or grazers. The SPEC term is somewhat difficult to grasp conceptually since it represents the complex interaction of several variables; nevertheless, the use of SPEC or some similar formulation is essential to the realistic simulation of function in benthic ecosystems such as the Truckee River.

It is important to develop growth relationships for the river and seasons to be modelled. It is also important to incorporate temperature growth relationships for the region to be modelled. The use of growth temperature relationships developed for warm, southern rivers can underestimate growth during the cooler seasons. Light adaptation in the river should be explored. Use of literature values for the half saturation constant for light often underestimates growth under low light conditions in the fall and winter. Algae can adapt to low light conditions, achieving relatively high growth rates.

Current velocity enhancement is an important factor in rivers and differentiates rivers from lakes. The flowing water brings a constant fresh supply of nutrients past the algae, so growth is possible at lower nutrient levels than in lakes. The flowing water also moves recycled nutrients downstream, unlike in lakes where nutrients are often lost to the sediments as phytoplankton fall to the bottom.

Respiration of Periphyton

The respiration rate of benthic algae is calculated as the sum of a temperature-dependent endogenous respiration term plus photorespiration. The respiration rate is temperature-dependent and is calculated as a fraction of the photosynthetic rate. The respiration rates used in DSSAMt have been determined empirically for natural algal assemblages, although further studies dealing with river periphyton are needed.

Removal of Periphyton

Processes of removal of benthic periphyton in rivers are poorly understood and difficult to quantify. To estimate rates of removal of periphyton from the substratum, DSSAMt includes the following processes: (i) herbivory, (ii) mechanical disturbance by benthic organisms, and (iii) scour by the water current. Rate coefficients for these processes have been estimated using information from literature sources and parameter estimation during model calibration. Predicting the removal dynamics associated with periphyton is complicated by poorly quantified factors including the growth form, age, and condition of the algae, and the disturbance history of the benthos time (characteristics of and time since last disturbance). Removal processes are critical to predicting the biomass and photosynthetic activity of periphyton. In rivers in which benthic processes significantly impact water quality, the degree of success with which removal is simulated may be the limiting factor on the overall performance of models to predict biomass levels and, hence, DO and nutrients. Rate coefficients for scour by water current are especially important in determining the removal of biomass during periods of high flows. Such high flows are often referred to as flushing flows and are important in resetting the biomass to an earlier stage of community development. During extended periods without flushing flows, biomass can accumulate resulting in lower than expected oxygen levels.

Algal biomass and its metabolic processes of production and respiration are linked to pH through the carbonate buffer system; directly to DO through respiratory consumption and photosynthetic production; and to phosphorus and nitrogen through nutrient uptake.

4.3.4 Data Requirements for DSSAMt Water Quality Model

In order to apply DSSAMt to a river system, coefficients and data specific to the river must be collected. These data are then used in the model to calibrate the model coefficients. At a minimum, river specific data for the following must be collected:

Hydraulic coefficients

- Leopold Maddock hydraulic coefficients for each reach.
- Elevation of reach endpoints.
- Percent riffle and percent pool.

Boundary Conditions at Headwater, Point, and Diffuse Inflows

- Constituent concentrations.
- Flow volume of (m^3/s for point, $m^3/s/km$ for diffuse).

Boundary values are required for all primary constituents listed in Table 4.2 except temperature, benthic algae, and acidity. The boundary value for acidity is calculated using boundary value temperature, pH, and alkalinity. Several options exist with respect to water temperature. In the simplest form, water temperature and solar radiation can be entered daily, or every five days. For the first option the user needs to enter the maximum temperature, average temperature, time of maximum temperature, daily solar radiation, and length of photoperiod. For the second option, the user enters the data necessary for the model to calculate water temperature. The following meteorologic data are required:

- Wind velocity.
- Dry- and wet-bulb temperature.
- Barometric pressure.
- Solar radiation (an option exists to calculate solar radiation based on date and location).
- Photosynthetically Active Radiation (PAR) either entered or calculated based on short wave radiation.
- Water temperature data at the headwater and for each tributary.

Simulations with DSSAMt can be carried out with all, or selected rate coefficients set to zero. This can be useful as a check on the flow balance and mixing assumptions. The model can also be run to predict only temperature, or another selected constituent.

4.3.5 Simplifying Assumptions Used in DSSAMt

1. Sediment oxygen demand occurs in pools only.
2. Processes of periphyton production and respiration occur in riffles only.

3. Kinetic and hydraulic coefficients are uniform within pools and riffles for each river reach.
4. Mixing is instantaneous and complete.
5. Longitudinal dispersion is insignificant.
6. Mean flow during a model pass adequately represents relevant conditions related to flow.
7. Import of periphyton biomass from outside the system is negligible.
8. Losses of periphyton from the system can be accounted for by endogenous respiration, invertebrate herbivory, and removal by water flow.
9. The phytoplankton and aquatic macrophyte communities are functionally insignificant to predictions of water quality, or can be adequately represented by the benthic algae algorithm.
10. Constant relationship between short wave radiation and PAR if PAR values are not entered as boundary conditions.

4.3.6 Sensitivity of DSSAMt Predictions for Nutrients and DO

Our experience with DSSAMt applications thus far on the Truckee and Red Deer Rivers indicates that benthic algae and DO predictions have been especially sensitive to the following:

1. Light versus algal growth relationship.
2. Algal growth versus temperature relationship.
3. Respiration versus temperature relationship.
4. Relative extent of geomorphic habitats (riffle and pool).
5. Hydraulic characteristics of the channel (depth and current velocity).
6. Density dependent term (SPEC) for algae.
7. Rate of recycle for nitrogen and phosphorus from dead and respired algae.
8. Solar radiation and light extinction.
9. Temperature.

4.3.7 Strengths and Weaknesses of DSSAMt

The nature of the task at hand determines wether or not a given model attribute is disadvantageous (a weakness) or advantageous (a strength). In the following section we have grouped attributes according to "strengths" and "weaknesses". The reader should focus on the nature of the attribute and how it sets DSSAMt apart from other models, and not whether the characteristic is listed as a strength or weakness. Some attributes are included in both listings to emphasize this point.

Strengths of DSSAMt

1. Benthic growth dynamics linked to a companion temperature model.
2. Multiple assemblages of algae (blue-green and non blue-green) allowing for resource competition.
3. Down-river nutrient recycle (spiralling).
4. Simplified input/output tables and graphics linked to PC-based worksheets.
5. Modular architecture which facilitates modification.
6. Steady-state flow has less complex data input requirements compared to an unsteady flow model.
7. Inclusion of relevant nutrient forms allows estimation of total nutrient loads.
8. Mechanistic—capable of predicting state variable levels based on changing conditions.
9. Carbonate equilibrium and pH included, allowing calculation of simulated degree of ionization of ammonia.
10. Computer run time: approximately one hour per year of simulation on 486-based micro processor PC.
11. Statistical output of water quality constituents with comparison against standards.
12. "Map" reaches for areas of SOD, periphyton production, etc., rather than averaging over reach.

Weaknesses of DSSAMt

1. Steady-state flow not capable of accounting for short-term (hourly-daily) flow variations.
2. No direct calculation of error or uncertainty.

Note: Items 3-11 are suggested areas for further development or emphasis in field studies

3. Typically there is incomplete knowledge from field studies of biomass and rate coefficients (this is true of most water quality models).
4. Better mechanism needed for accumulation of benthic organic material between flushing flows.
5. Chlorophyll and biomass pools, and density-dependent term for benthic algae would benefit from better definition.
6. Scour of algae and benthic organic material associated with elevated flows.
7. Improve empirical basis for enhancement of algal growth associated with current velocity.
8. Luxury uptake by algae especially for phosphorus.
9. Nutrient bio-availability, especially soluble organic nitrogen and soluble non-reactive phosphorus.
10. Mechanistic processes for sediment oxygen demand.
11. Simulation algorithm for aquatic macrophytes and phytoplankton would allow

model to be more generally applied.

12. Better resolution of hydraulic characterization of channel.

4.4 Pattern Recognition Techniques for Water Quality Modelling (Mr. M. Palmer, Beak Consultants)

4.4.1 Introduction

During this workshop some of the available water quality prediction models were discussed in terms of their usefulness to the NRBS. These ranged from the interactive personnel computer versions of DOSTOC and NUSTOC, initially developed for Alberta Environment as planning instruments for the North Saskatchewan River, to DSSAMt and WASP4 which are sophisticated models constructed in a building-block fashion. WASP4 is the most complete model, since many of the independent variables in dominant processes can be incorporated into the predictive equations. However, it is notable that DSSAMt also incorporates much of the complexity captured by WASP4. All of these models are deterministic with the exception of DOSTOC and NUSTOC which may be applied as a stochastic model.

In the past, deterministic models similar to those previously mentioned have been very popular because they predict results knowing the magnitude of the causes. Consequently, these models have been used to assess changes that will occur in receiving water quality if loadings are changed. Any assessment of deterministic models requires a review of the appropriateness of the independent variables and the required number of measurements of these variables. In general, better models are directly related to the number of measurements—the more measurements available, the better our understanding of the system. In the following text, these components of the predictive modelling effort will be discussed.

In prediction, one does the best with the best tools available. The focus is on continually improving observations and models. Historically, when complex results occurred, one looked for complex causes. For example, when there was a random relationship between what goes into the model compared to the output, randomness was built in to the models by adding noise and error. However, instead of seeking one model with a sufficient number of adjustable coefficients that can be manipulated so that the predictions match the measured data, more than one predictive model should be used.

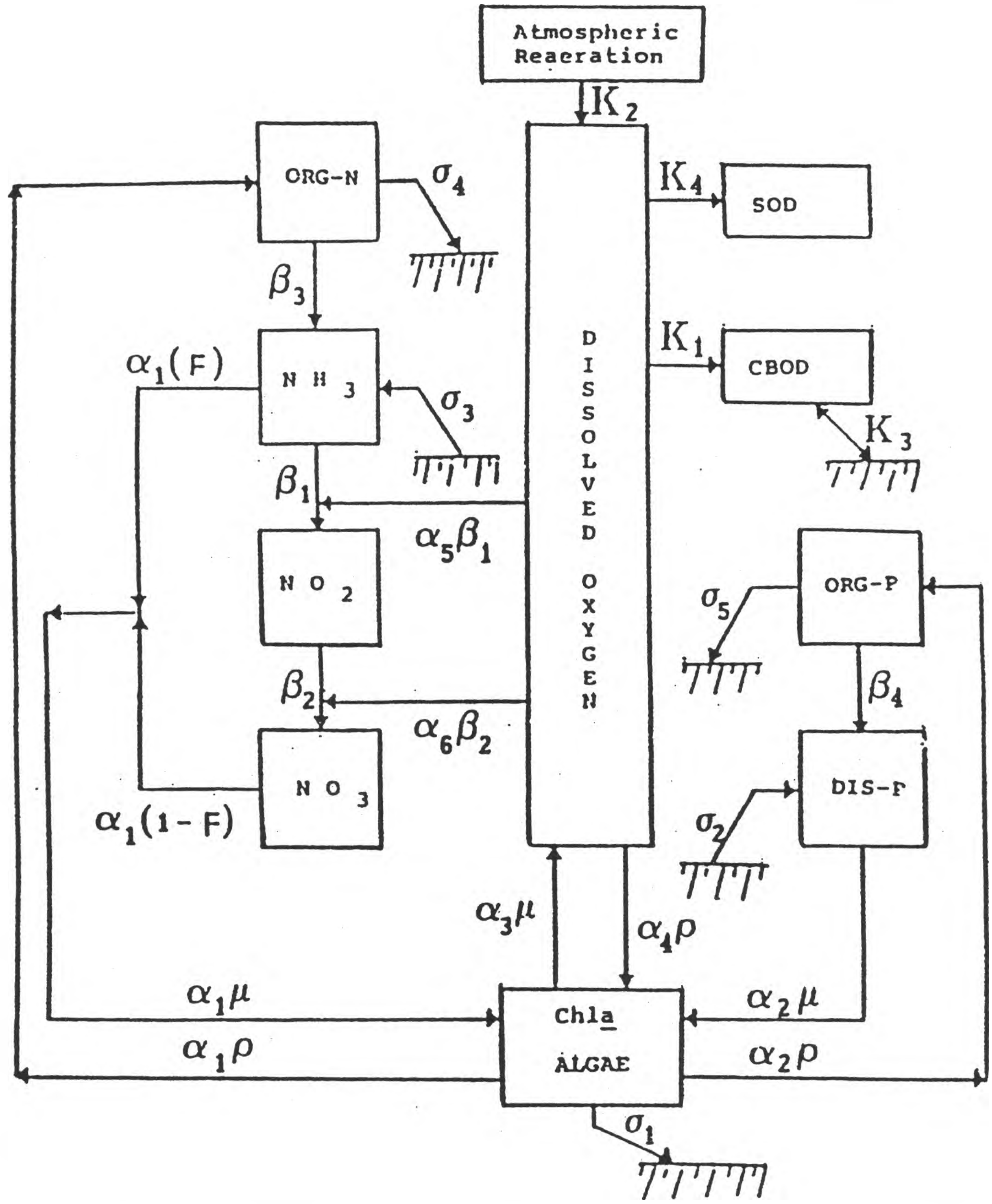
The traditional concept that very small influences can be neglected may not be true because there is convergence, and arbitrarily small influences will not affect the solution. Thus, even in complex models, small differences in the input or initial conditions could quickly become overwhelming differences in the output. Small differences can be particularly important in numerical solutions where chaos conditions can occur. In fact, it has been found that chaos is not necessarily random; rather, it can have an underlying structure. The analysis of this underlying structure is called pattern recognition.

These pattern-recognition approaches are very powerful and are used in weather forecasting which is a combination of pattern recognition and data collected at fixed locations throughout the country. Although large data sets are required, pattern recognition can improve and expand the range of predictability. These predictions do not use deterministic equations. Presently, the mathematical methods for pattern recognition have only been developed for fixed point data sets (Eulerian data sets) and normally use time series data.

Deterministic Models

These models have been discussed in Sections 4.1 to 4.3 and in Zielinski (1988). Although all the important independent variables are included in whatever model is used, there are more independent variables in the WASP4 model sub-component, EUTRO, than in the simplified form of the model used in DOSTOC and NUSTOC. Therefore, before choosing a deterministic model one must first assess which model includes the processes relevant to the river in question. Figure 4.15 from the QUAL2E manual shows the processes and the coefficients generally used in DO models. The biomass processes are generally algae driven and there are no terms for aquatic macrophytes and benthic algae. DSSAMt considers benthic non-blue greens and blue greens, CO_2, and scour. DOSTOC lumps all the biomass into one term. Thus, the different models vary in the way important processes are modelled, suggesting that we ask several important questions about model structure. Is there scientific evidence that the DO and nutrient processes included in the models are appropriate for the Peace and Athabasca Rivers? For example, are the processes included in EUTRO appropriate for these rivers, or do they need to be simplified? Finally, are the simplified processes used in DOSTOC and NUSTOC appropriate for northern rivers? In the case of nutrient modelling, it is important to note that the nutrient dynamics included in deterministic models were developed for freshwater lakes where phytoplankton biomass dominates and phosphorus is assumed to be the controlling nutrient. In contrast, for nutrient poor rivers the control can be either phosphorus or nitrogen (Bothwell 1992). Are there nutrient limits in the Peace and Athabasca Rivers? Clearly, investigative studies like flow-through mesocosm experiments are required to determine the least number of processes needed to improve our modelling capability and, hence, our predictions of river water quality.

Figure 4.15 Processes and Coefficients Generally Associated with Dissolved Oxygen Models and Included in QUAL2E



However, whatever the final model structure becomes, it is important to note that the more processes included in a deterministic model, the more extensive the field monitoring required.

Another point to consider is whether a model has nonlinear terms that will increase the tendency of a system to become chaotic. Deterministic models require time of travel or, additionally, that the river flow dynamics be known. In the WASP4 model, the hydrodynamic model component can be used or substituted by some other more appropriate model. DOSTOC, NUSTOC, and EUTRO models require time of travel as an input. Both the flow dynamics and time of travel have nonlinear terms in the governing equations. Consequently, even if the water quality prediction models are simplified to linear forms, the flow dynamics and time of travel are nonlinear. Obviously, as nonlinear terms in the model increase, the "limits of predictability" will decrease. Therefore, our models should be only as complex as is needed.

Finally, the methods presently available for predicting the time of travel or flow dynamics which are nonlinear (i.e., simplified power functions like the Leopold-Maddock (1958) equations) are not suitable for shallow wide rivers with poor lateral mixing, or for river benches during low river flows, since the above methods require that the effluent be completely mixed with the river water. Because the models are for well-mixed conditions, it is not possible to predict the extent of nutrient enrichment or DO depletion in embayment and backwater areas. Another example of the limitations of existing hydraulic models, is the impact of frazil ice on the flow patterns in the river cross section. The hydraulic models currently used in water quality models should be reviewed to determine their applicability to the Peace and Athabasca Rivers, particularly in terms of the different methods used in the models.

4.4.2 Pattern Recognition Methods and Their Application to the NRBS

Water quality prediction for the NRBS is required in order to evaluate the impact of discharges to the river from effluent sources like pulp mills and municipal sewage treatment plants. At the outset, it must be realized that the discharges from these effluent sources are variable. For example, when the data collected in Ontario from 24 mills (MISA 1993) and 10 sewage treatment plants (MISA 1991) are used as indicators of the performance of these facilities, the following is found:

- Municipal Sewage Treatment Plants—The coefficient of variation for 10 plants using composite samples was, on average, 90% for BOD and 72% for ammonia nitrogen.

- Pulp Mills—The coefficient of variation for 24 mills for composite samples was 23% for BOD, 70% for ammonia nitrogen, and 20% for phosphorus.

Discharges to the Peace and Athabasca Rivers likely will probably have similar variability. These discharges are the inputs to any water quality prediction model. The combination of variable inputs and non-linear prediction models will lead to the development of chaotic outputs when the models are used.

Thus, because of the potential for chaotic outputs from deterministic models, it is difficult to define the "limits of predictability" for a particular model. In an attempt to define the robustness of a given model, sensitivity analyses have been employed in which the independent variables are varied through a range of magnitudes that might be experienced in model applications. These methods have been valuable in identifying the important terms in deterministic models, but they do not establish the "limits of predictability". Historically, one data set has been used to calibrate deterministic models, and another data set for verification, where the verification is a measure of predictability. If model verification fails, the failure may be attributed to (i) the coefficients determined in the calibration process are not valid for the verification, (ii) the equations as formulated for the calibration are not appropriate for the verification, or (iii) the "limits of predictability" have been exceeded. In many instances the "limits of predictability" are evolved through successive application of a model in different settings with site-specific data. For example, a simple method is to make at least two independent predictions. If the two independent predictions do not match, then the limit has been exceeded. When the limits have been exceeded, either the model must be re-initialized and restarted, or other methods should be used.

Pattern recognition methods have been used to predict river flow (Galeati 1990; Kember et al. 1993). In the case of Kember et al. (1993), the use of conventional methods for predicting the river flow, such as the application of a complex flow prediction model, failed. However, by using the "nearest neighbour method" (NNM), it was possible to predict river flow (Fig. 4.16). Using the pattern recognition method, recorded histories of river flow were used to develop a predictive instrument. The prediction method is evolved from the analyses of time histories of river-flow records at a fixed point. Given a portion of the history, it is possible to predict future river flows using the model developed. These methods are based on the quantification of coherent structures in chaotic results or pattern recognition. The success of these methods is not restricted to the prediction of river flow data. Kember and Fowler (1992) and Fowler et al. (1993) have used the methods in the analyses of respiratory and other medical data. The methods have also been used to filter and separate tidal and wind seiche effects on water-level records of an estuary along the eastern seaboard of the U.S.A.. Can pattern recognition methods, like the "nearest neighbourhood method", be used to improve predictions of water quality by, either enhancing the deterministic models, or replacing these deterministic models altogether?

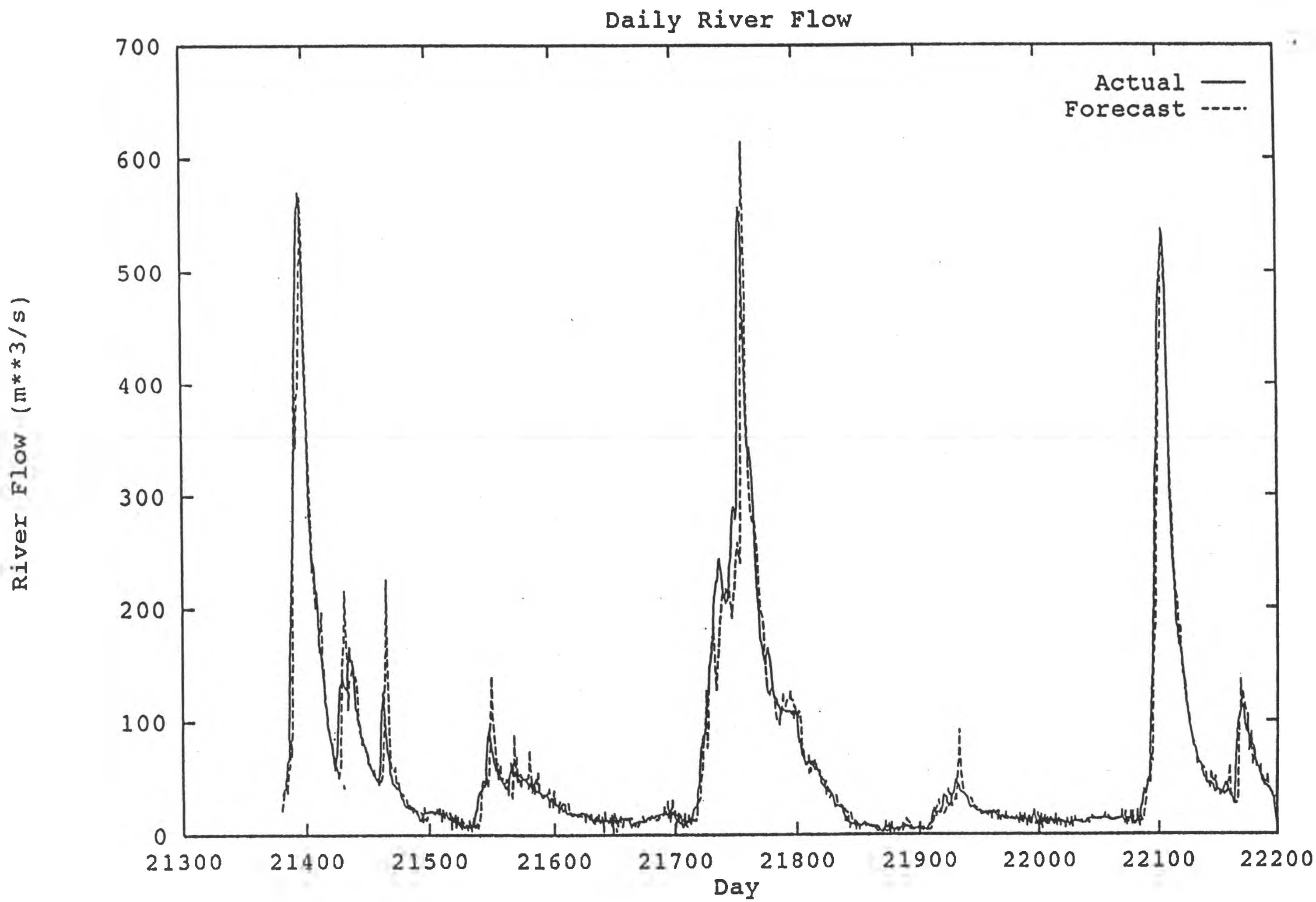


Figure 4.16 Pattern Recognition Methods Used to Predict River Flows

4.4.3 The Application of Pattern Recognition Methods to the Athabasca and Peace Rivers

Pattern recognition analyses can be useful in helping establish patterns of water quality in the Athabasca and Peace Rivers. For example, pattern recognition methods could be used to develop a predictive capability and to identify the periodicities of the processes which determine the DO in the rivers using the existing DO data.

As discussed in this workshop, there are very limited measurements of sediment oxygen demand, reaeration, BOD_u, etc. It was agreed that more measurements were required. Furthermore, since these variables are expected to be spatially variable, it will be difficult to obtain sufficient measurements to represent these processes in the DO process equations for the whole river. The strength of pattern recognition methods is that they operate on the measured results, not on measurements of the factors that cause these results. Thus, pattern recognition methods are not dependent upon the measurements of the processes determining DO and nutrients, the variability of processes in the river, or the methods used to measure the independent variables.

Pattern recognition assumes that there are many factors causing a result, and, while these factors may generate what can be interpreted as chaos, there is a recognizable pattern in the results which can be identified by mathematical techniques. Once this pattern has been quantified, it is possible to develop a predictive instrument for a limited time period starting with a known result. In other words, if the DO history for the last five days was known, pattern recognition techniques could be used to predict the DO for the next five days. Furthermore, the methods can be used to separate and identify various processes that determine the results.

Methods have been developed to analyze time histories of a scaler parameter at one or more fixed locations (e.g., river flows, DO, water level). These methods can be used to identify periodicities and trends between the recording instruments. Analysis of several years of data by the NNM would identify the patterns in the data and the relationships between, for example, the five continuous DO stations on the Athabasca River if these relationships exist. This analysis would identify any periodicities in the records, and, thereby, produce a predictive model which may be very useful for predicting the low DO conditions and the magnitude of these low DO conditions. The predictive model developed could be used to assist in the definition of the "limits of predictability" and to predict beyond the "limits of predictability". Chaos methods have greater "limits of predictability" than deterministic models.

The apparent weakness of pattern recognition methods is that they do not explicitly consider the factors that produce the results. Consequently, it is difficult to determine the impact of any particular independent variable on the result. For example, the relative importance of sediment oxygen demand, one of the factors in the DO prediction equations, cannot be determined using pattern recognition methods. It can be argued that if all the factors could be measured the DO could be precisely predicted by deterministic equations. However, this assumes that the predictive equations are complete. Because of the limitations in the measurements of the variables required for the deterministic equations and the possibility that the equations may not include all the factors in the DO prediction equations, there is a need to use additional, alternative methods.

CHAPTER 5.0

ALTERNATIVE MODELLING APPROACHES: EVIDENCE FROM OTHER AQUATIC SYSTEMS

5.0 ALTERNATIVE MODELLING APPROACHES: EVIDENCE FROM OTHER AQUATIC SYSTEMS (Dr. E. McCauley, University of Calgary)

5.1 Introduction to Problem

Nutrient enrichment may be an important perturbation to the rivers under investigation in the NRBS and could lead to large changes in the composition and structure of riverine biota (i.e., algae to fish). The effects of enrichment on biota have been extensively studied in other aquatic systems, such as lakes, reservoirs, and some streams, and these studies of eutrophication may provide valuable pointers when considering strategic issues in modelling water quality in the NRBS. Note, water quality in its broadest sense is defined to include traditional water chemistry as well as biological responses. The key "strategic" question in modelling water quality is—"what do we include in our model?" That is, what physical, chemical, and biological features should be included to enable us to predict both the short-term dynamics (i.e., within year variability) and long-term changes (i.e., among year trends) in water quality variables such as DO concentration, benthic algal biomass and production, algal composition, etc.? These strategic questions are not simply academic. The ability of a tactical model to predict river water quality will be influenced by both the accuracy of the model structure and the accuracy of parameters. If a key process is omitted from a model, it is highly unlikely that "parameter tuning" will enable the model to recover from the structural failure.

The major lesson to be conveyed from work on modelling water quality in other aquatic systems is that ecological processes (e.g., competition, herbivory, predation, etc.) play a major role in predicting the effects of nutrient enrichment or eutrophication on biota. This observation may sound obvious, but these ecological processes are noticeably absent from many of the models proposed for use in NRBS.

5.2 Importance of Food Chain Structure to Water Quality Predictions

As an illustration of the role of food chain structure in affecting the response of biota to enrichment, the complexity associated with trophic interactions in plankton communities from lakes will be used; however, these major points could be made as easily by considering nutrient-phytoplankton competition (e.g., McCauley et al. 1989; Downing and McCauley 1992).

To illustrate how complexity associated with food chain interactions can strongly influence predicted effects of nutrient enrichment, consider the 2-level and 3-level simple food chains illustrated in Figure 5.1 whose interactions can be described dynamically by the equations in Figures 5.2 and 5.3. Although these examples are from lake ecosystems, the theory is applicable to rivers, as recently demonstrated by Power (1990).

Figure 5.1 **Schematic Representation of Even- and Odd-linked Food Chains**

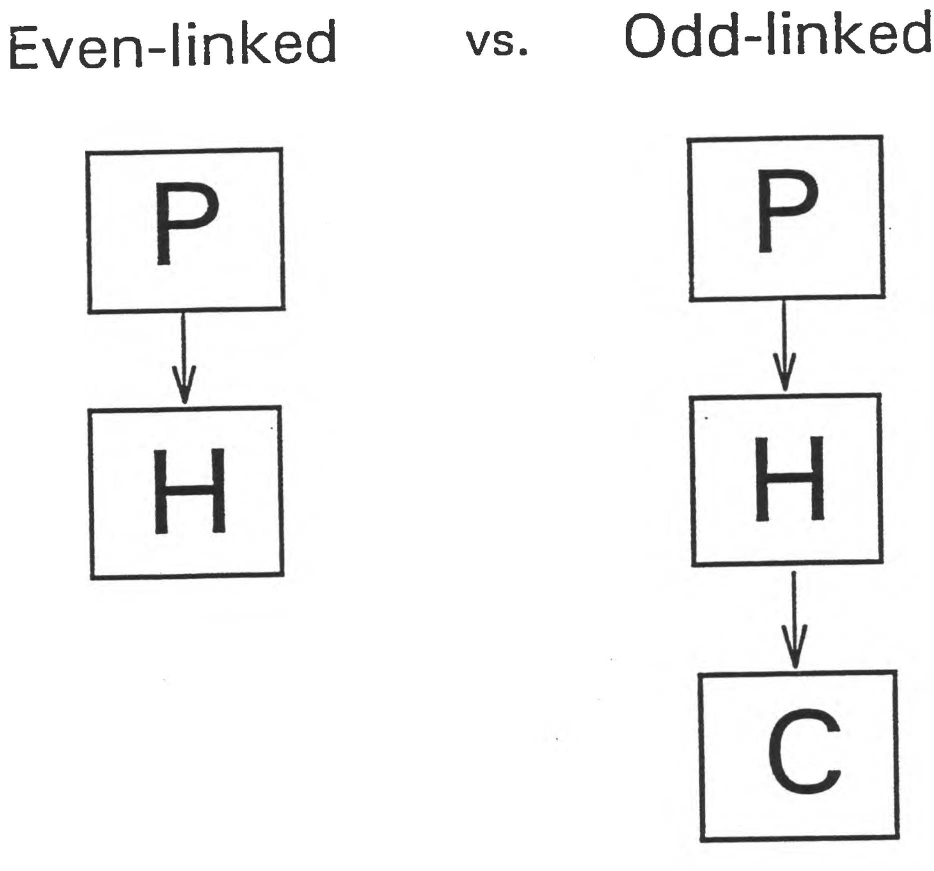
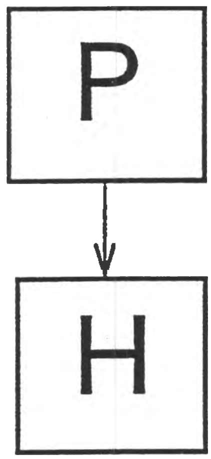


Figure 5.2 Structural Representation of a Two-level Food Chain and the Equations Which Describe the Dynamics of These Food Chain Interactions

Two-level Food Chain



Autotrophs

$$\frac{dP}{dt} = rP\left(1-\frac{P}{K}\right) - \frac{aPH}{1+aT_hP}$$

Herbivores

$$\frac{dH}{dt} = Hb\left(\frac{aP}{1+aT_hP}\right) - mH$$

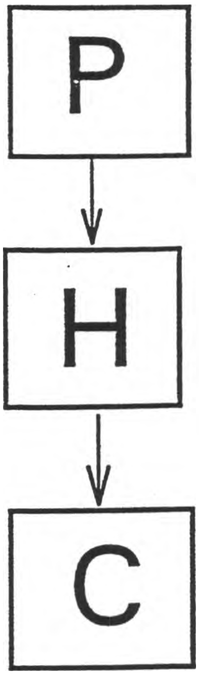
Equilibria:

$$H^* = \frac{r}{a}\left(1-\frac{P}{K}\right)(1+aT_hP)$$

$$P^* = \frac{m}{a(b-mT_h)}$$

Figure 5.3 Structural Representation of a Three-level Food Chain and the Equations Which Describe the Dynamics of These Food Chain Interactions

Three-level Food Chain



Autotrophs

$$\frac{dP}{dt} = rP(1-\frac{P}{K}) - (\frac{aPH}{1+aT_hP})$$

Herbivores

$$\frac{dH}{dt} = b(\frac{aP}{1+aT_hP})H - (\frac{\alpha HC}{1+\alpha\theta H})$$

Carnivores

$$\frac{dC}{dt} = e(\frac{\alpha H}{1+\alpha\theta H})C - dC$$

Equilibria:

$$(1-\frac{P^*}{K})(1+aT_hP^*) = \frac{d}{e\alpha}(\frac{1}{1-\theta d/e})$$

$$H^* = \frac{d}{e\alpha}(\frac{1}{1-\theta d/e})$$

$$C^* = \frac{b}{\alpha}(\frac{aP^*}{1+aT_hP^*})\ (1+\alpha\theta\ [\ \frac{r}{a}\ (1-\frac{P^*}{K})\ (1+aT_hP^*)\ ]\ )$$

If one simply wants to predict the effects of nutrient enrichment on changes in average levels of phytoplankton, these equations can be solved for their equilibria and used to predict how changes in parameters affected by nutrient enrichment, such as algal carrying capacity (K) or algal growth rates (r), change the equilibria (Figs. 5.2 and 5.3).

The predicted effects of enrichment are dramatically different between the two systems. Nutrient enrichment of two-level systems predicts an increase in herbivore biomass accompanied by no change in levels of phytoplankton despite the fact that enrichment affects phytoplankton parameters. In the three-level system, nutrient enrichment leads to an increase in phytoplankton and carnivores, and to no change in herbivore biomass. Water quality is typically assessed by changes in phytoplankton biomass. In two-level systems, no change in water quality would be predicted, whereas in three-level systems, a reduction in water quality would be predicted. Thus, the structure of the food chain has a qualitative effect on water-quality predictions. .

Recent evidence, which contrasts the changes in algal biomass among lakes with nutrient enrichment throughout the world (Fig. 5.4), provides some support for these dramatic food-chain effects. Hansson, Lindell, and Tranvik (1993) found significant differences in the slope of algal-zooplankton relationships in two-level planktonic food chains, compared to general relationships based on three-level food chains (McCauley and Kalff 1981).

In addition to the effects caused by differences in food-web complexity, complexity within a single trophic compartment (e.g., primary producers like phytoplankton) can alter the response of higher trophic levels to enrichment. For example, food chain models generally combine the phytoplankton into a single compartment (Fig. 5.5 A and C) which assumes that algal species are equally susceptible to herbivory. However, it is well known that herbivores feed selectively on phytoplankton, and this selectivity can have a profound effect on predicting changes in water quality with enrichment. If one considers a simple branched food-chain (Fig. 5.5 B and D) that recognizes edible and inedible algae (i.e., algal groups that differ qualitatively in their susceptibility to grazing by herbivores), then the model predicts enrichment should produce an increase in the biomass of inedible algae and no change in the biomass of edible algae. Empirical evidence from lakes supports this prediction. Watson and McCauley (1988) showed that the average biomass of inedible algae increased significantly with TP among lakes, while edible biomass remained relatively constant (Watson, McCauley, and Downing 1992). As predicted by theory, enrichment did not significantly increase the average biomass of edible algae, despite the fact that productivity for the two groups increased in parallel with enrichment (Figs. 5.6).

Thus far, only the effects of enrichment on equilibrium levels of phytoplankton have been considered. Non-linear, ecological interactions dramatically modify predictions concerning the effects of enrichment on temporal dynamics of phytoplankton. If these systems are viewed as "coupled" predator-prey systems (i.e., plant-herbivore systems for

Figure 5.4 **Biomass of Zooplankton vs. Phytoplankton. (fresh weight; μg/L; log transformed) in South Georgian Lakes (n = 19; open symbols; linear regression: $y = 0.31x + 1.63$; $r^2 = 0.52$), and in a Data Set Including European and North American Lakes (n = 17; dark symbols; McCauley and Kalff 1981. Linear regression: $y = 1.39x - 1.40$; $r^2 = 0.74$). The slopes of the regression lines differ from each other (t = 17.64; $p < 0.001$).**

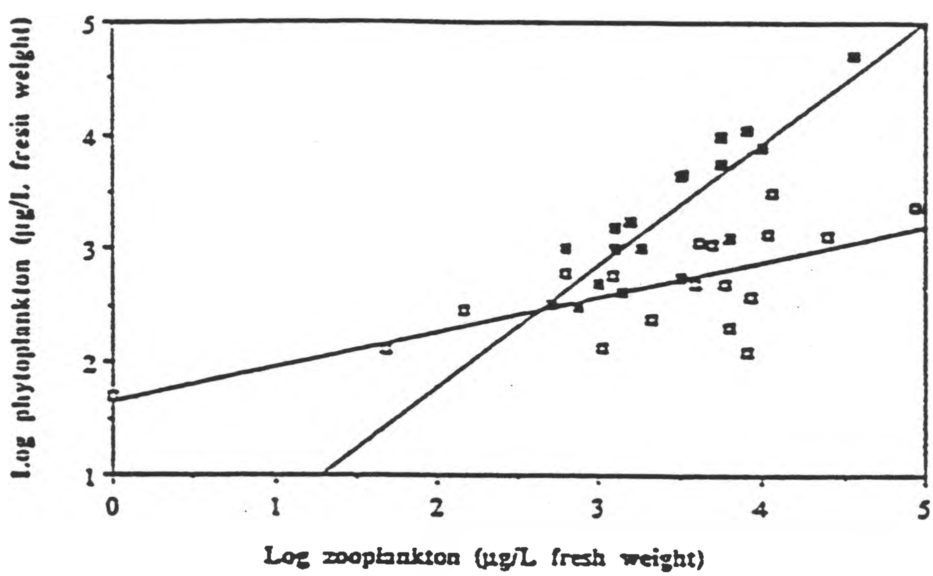


Figure 5.5 Structural Representation of Odd - (A and B) and Even-linked (C and D) Food Chains Composed of Phosphorus (P), All Algal Groups Combined (A), Edible Algae (E), Inedible Algae (I), and Zooplankton (Z).

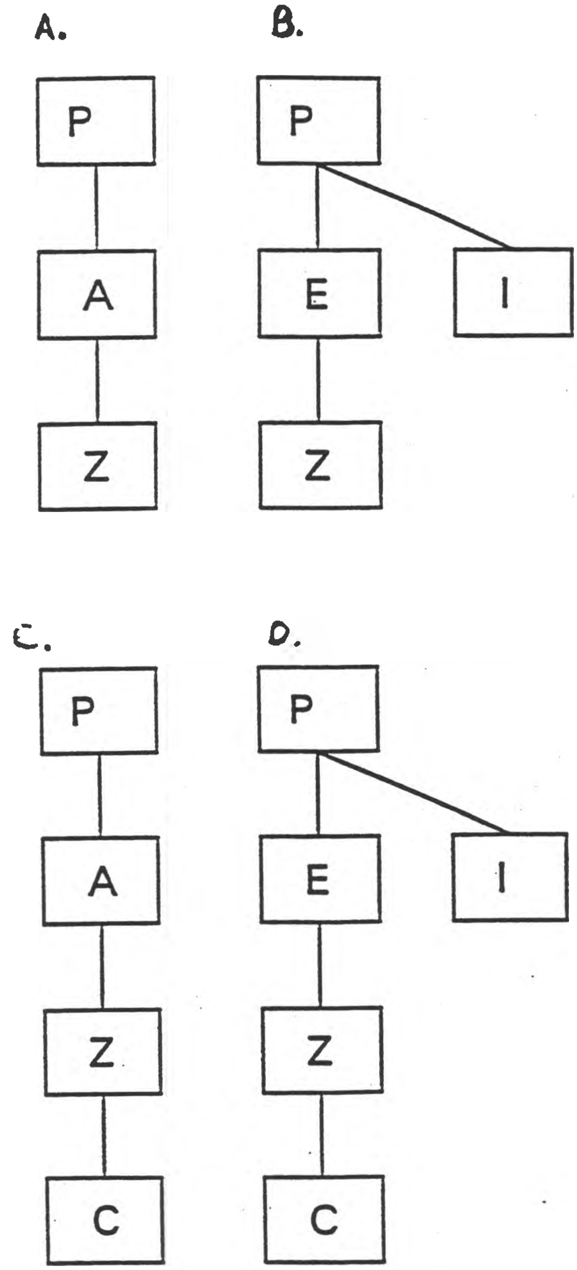
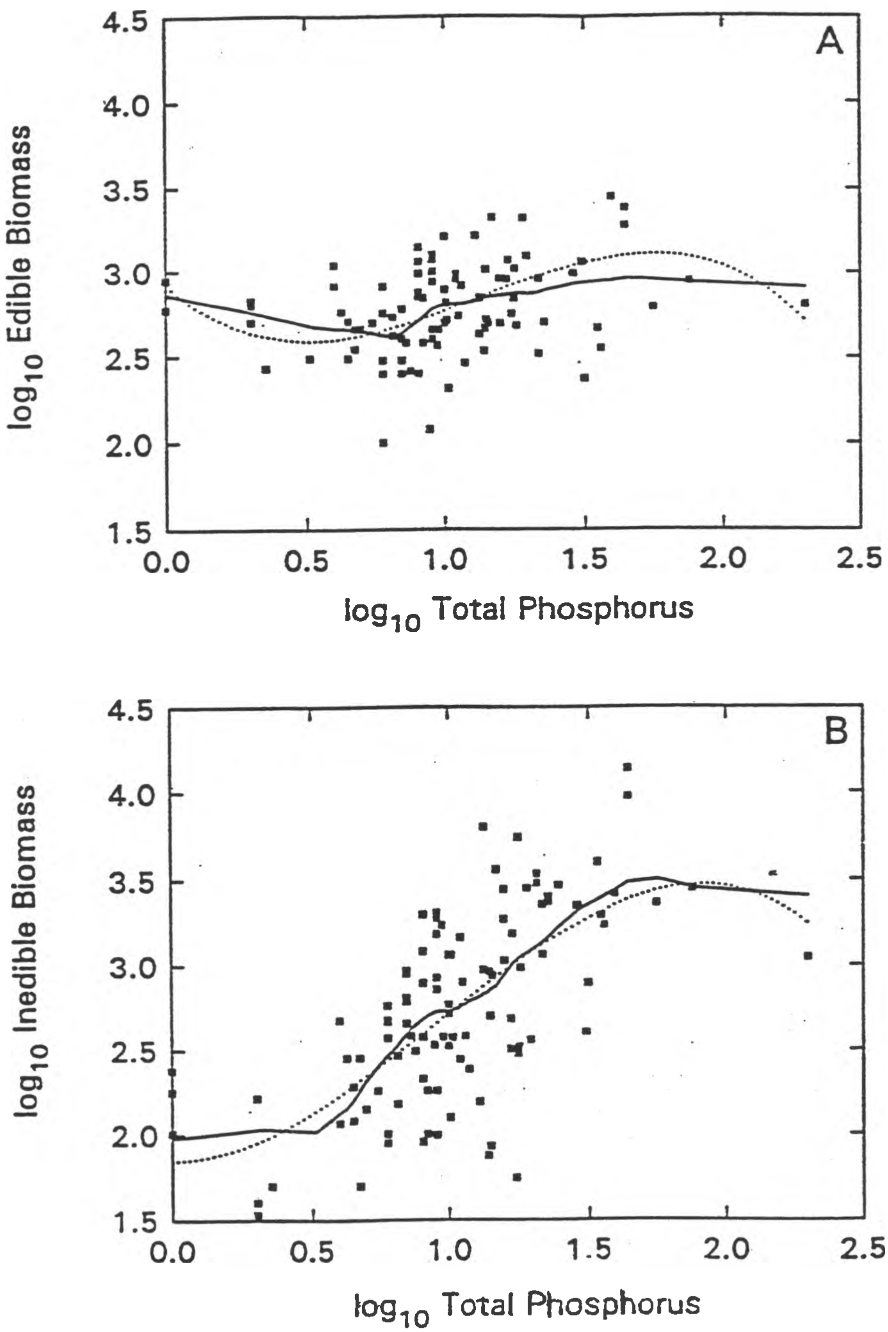


Figure 5.6 **The Relationship Between Log_{10} Total Phosphorus and: (A) Log_{10} Edible Algae Biomass, and (B) Log_{10} Inedible Algal Biomass for Lakes Throughout the World (Modified from Watson and McCauley (1988) and Watson et al. (1992)).**



example), then non-linear relationships in the interactions can play a large role in determining the stability of the interactions, and, thus, how the dynamics respond to changes in enrichment. One well known example is the paradox of enrichment (Rosensweig 1971; McCauley and Murdoch 1990) which arises from a predator-prey interaction in which the predator possesses a type II functional response (i.e., a decelerating increase in feeding rate as prey abundance increases) and in which the prey population has density-dependence. Stability depends on the dynamic tension between stabilizing prey density-dependence and destabilizing features of predator biology (i.e., a type II functional response). When prey density-dependence dominates the interaction (i.e., in nutrient poor environments), the system is stable. When the prey's environment is enriched, leading to an increase in carrying capacity *(r)*, the strength of the prey density-dependence is reduced and the destabilizing aspects of predator foraging dominate with the result that the dynamics become highly unstable leading to large amplitude fluctuations in prey and predator density. This scenario predicts instability with enrichment. Similarly, changing model structure by adding complexity associated with inedible algae can also dramatically affect predictions concerning the effect of enrichment on dynamics (Kretzschmar, Nisbet, and McCauley 1993).

Thus, predicting the effects of enrichment on aquatic biota depends dramatically on model structure, and there is considerable empirical support from other aquatic systems (and indeed other terrestrial systems) for the idea that complexity associated with ecological processes plays a major role in affecting water quality predictions. The key issue is how much biological complexity to include in the model so as to derive accurate predictions of changes in water quality with enrichment, but yet keep it simple enough to provide insight into the mechanisms responsible for changes in water quality.

5.3 Strategic Questions for Water Quality Models in NRBS

Observations from other systems raise significant questions concerning modelling water quality in NRBS:

1. Is the "biology" in these rivers fundamentally different from other freshwater systems? That is, do flow rates, disturbances, or water resident times constrain biology to such an extent in these river systems that the importance of ecological interactions are reduced?

   There are implicit dangers in excluding ecological interactions and minimizing the representation of biology in models of river water quality based on the assumption that biology is constrained by high flow rates, i.e., that potential water quality problems associated with enrichment are "solved" by high flow rates that devastate the biota at particular times of the year. The problem is that if seasons with low-flow rates occur, then biological processes no longer constrained by physical restrictions, may produce dramatic changes in water quality that could not be predicted from water quality models.

2. How can among year changes in water quality be explained if there are no mechanisms in the models for parameter evolution?

   If long-term changes in parameter values have to be accounted for by parameter tuning, what is actually being predicted? Have the models provided a sufficient understanding of the functioning of the systems to predict expected changes in water quality? Should food chain components be considered in predicting long-term (i.e., among year) changes in water quality? Invertebrate and fish communities have a longer time-scale than algal communities. How can we integrate the biotic response of these groups to enrichment over appropriate space and time scales?

It is unlikely that adequate biological information for the Northern River Basins is available to construct a mechanistic predictive model concerning the effects of nutrient enrichment on water quality. Baseline information on the biota, their phenology, and spatial distributions is lacking, as well as an adequate description of energy flow or rates of biological production. In the absence of these data, it might be appropriate to investigate whether simple empirical models that describe the statistical relationship between response variables (such as algal biomass and/or composition) and independent variables (e.g., total phosphorus, nitrogen, nutrient ratios) could be used to predict the effects of nutrient enrichment. While these empirical models are most highly developed for lakes and reservoirs, recent work (Soballe and Kimmel 1987) shows that the response of algal biomass to enrichment across freshwater systems (i.e., comparisons among lakes, reservoirs, and rivers) may be linked via independent variables describing differences in flow rates or residence time of water in the systems. These are exciting developments.

One important limitation on the development of such empirical models is that their predictive power depends to some extent on the range of independent variables. A major question is whether sufficient empirical models that could be used to predict the effects of enrichment on the biota at different levels of the food chain exist. If they exist, then it would be relatively easy to test the predictive power of these equations in the Northern Rivers Basin. However, if they do not exist, then several problems emerge. Most notably, is there a sufficient range of observed values of nutrients to establish statistical relationships with the biota? In addition, the time-scale in the response of the biota to enrichment must be taken into account. This is not widely recognized, but it is implicitly assumed, in using existing relationships, that they are "robust" with respect to time. The empirical relationships are static, implying that the biota at a given nutrient concentration are in "equilibrium". This may not be the case with systems that are being perturbed by nutrients, especially if the organisms considered have long generation times. This time-scale problem could play a significant role, not only in applying existing empirical models to NRBS, but also in developing new empirical models to predict responses to nutrient enrichment.

CHAPTER 6.0

WATER QUALITY MODELLING RECOMMENDATIONS

6.0 WATER QUALITY MODELLING RECOMMENDATIONS FOR THE NRBS (Compiled and edited by Dr. J. Culp and Dr. P. Chambers, NRHI)

6.1 Introduction

The workshop focus was to review and assess available modelling approaches for estimating the impact of BOD and nutrient loadings on the water quality of the Peace and Athabasca River systems. This goal was achieved by a two-part process that included formal presentations by invited speakers and group discussions on modelling approaches. The presentations on available approaches to water quality modelling outlined the structure of model components and reviewed the key rate coefficients necessary for model application. Additionally, these presentations indicated any need for further development to model structure or better measurement of critical rate coefficients. These presentations were a catalyst for important discussions, particularly on day two when workshop participants engaged in a lively discussion of potential recommendations to the NRBS for future work on water quality modelling. The following sections include a summary of the discussions by workshop participants, as well as specific recommendations submitted by external consultants following the meeting.

6.2 Recommendations by Workshop Participants

Discussions by the workshop participants were divided into two categories: those focusing on dissolved oxygen and those on nutrient modelling. Within each of these categories, participants considered the need for further data acquisition, the suitability of available modelling approaches, refinements of rate coefficients, and any requirements for producing empirical relationships among key variables.

6.2.1 DO Modelling

Data Acquisition

1. Standardize BOD_5 and BOD_u methodology and evaluate discrepancies in methodologies between laboratories.

2. SOD data:

   - Confirm the precision and accuracy of the existing methodology.
   - Increase sampling effort downstream of Smith.
   - Test the effect of variation in velocity and nutrient concentrations on SOD.
   - Characterize depositional areas likely to be the major sources of SOD.
   - Obtain a better understanding of the source of SOD (allocthonous or autocthonous).

- Link SOD and sediment sampling to the hydraulic characteristics of the channel.

3. Obtain better estimates of reaeration and quantify open-water areas.

Modelling Approaches

1. Test the ability of the previously calibrated DOSTOC model to predict 1992, 1992, and 1993 DO conditions.

2. Explore the idea of using other surrogates (such as TOC or DOC) for BOD_5 (BOD_5 has a five-day time delay, but TOC can be measured almost instantaneously).

3. Evaluate the advantages and disadvantages of moving to dynamic, two-dimensional models.

4. Consider having two independent teams work in parallel when it comes to model fitting. Given the subjectivity that comes into play when modelling complex systems with parameter-rich models, this will allow examination of how robust the model fitting actually is.

Refinement of Rate Coefficients

1. Develop an empirical relationship to predict headwater DO concentration from parameters such as discharge, duration of ice cover, and temperature.

2. Test the assumption used in the calibration of DOSTOC for the Peace-Athabasca Rivers that SOD is linearly related to effluent BOD.

Development of Empirical Relations

1. Develop empirical relations for total organic carbon (TOC) and dissolved organic carbon (DOC) versus BOD_u. Evaluate whether TOC or DOC should be used as a surrogate for BOD.

6.2.2 Nutrient Modelling (Instream Nutrient Concentrations and Biotic Abundances)

Data Acquisition

1. Evaluate the impact of seasonal sewage discharge.
2. Evaluate spatial and temporal (diel) variability in river water nutrient concentrations.
3. Evaluate the impact of loadings from non-point sources.
4. Evaluate appropriate methodologies for nutrient analyses to overcome possible interferences between colour and chemistry.
5. Take into account, if necessary, the seasonal changes in the composition of particular communities (e.g., in the case of the biofilm, from algae in the fall, to bacteria or fungi in the winter).

Modelling Approaches

1. Establish a mass balance for nutrients.
2. Test the ability of the previously-calibrated NUSTOC model to predict 1991, 1992, and 1993 nutrient (TP and TN) concentrations.
3. Depending upon outcome of mass balance and verification of NUSTOC, evaluate whether rate coefficients or the model structure need further refining.
4. Evaluate whether standing crop or productivity of biota should be modelled.
5. Consider modelling TDP and TDN concentrations in addition to TN and TP.
6. Assemble and evaluate long-term databases (if available) on biotic abundances and composition upstream and downstream of point-source of nutrient loading.
7. Consider using estimates of fish population biomass (i.e., standing stock, age-structure, etc.) and available energetic models to estimate the necessary invertebrate production levels required to support such a fish stock.

Development of Empirical Relations

1. Develop empirical relationships to predict biotic abundance. Recognize, however, that unless a wide range of levels is found within the northern rivers, the likelihood of successfully developing empirical models based on this data alone is slim, and data from other river systems may need to be included in the model to increase its predictive power. In addition, it should be noted that empirical models assume the response variable (e.g., algal biomass, invertebrate density) is in equilibrium with the level of nutrients. This assumption could be invalid if responses of the biota to changes in nutrient levels vary substantially from one year to the next.

6.3 Recommendations by External Consultants

The following recommendations on water quality modelling for the NRBS were provided after the workshop by external consultants as part of their contracts.

6.3.1 Dr. P.A. Zielinski, Ontario Hydro

There is an emerging need for NRBS to channel present and future efforts into two separate kind of activities: (i) a short-term goal of identifying the reasons behind the inability of DOSTOC to predict DO levels during the 1992/93 winter, and (ii) a long-term goal of selecting and developing a complex model capable of simulating various aspects of basin management.

To achieve the first goal, NRBS may consider two alternatives. The first alternative is to select another one-dimensional, steady-state model, or models, capable of simulating processes which were not included in DOSTOC and which are suspected to be the main reason for the lower than predicted DO levels during the 1992/93 winter. The second alternative is to reformulate DOSTOC and include the missing links in the model. The way DOSTOC was designed makes the implementation of any changes in the modelling equations relatively easy and inexpensive.

The second goal is less clearly defined but is one more indicator that possibly more than one model should be investigated. The criteria for model selection should be based on a compromise between the research and management needs in the basin, and the field data available. It should be kept in mind that the chosen model(s) cannot be "better" than the data base supporting them. If the database is not sufficient to meet model requirements, there is no point in using complex, dynamical, multi-dimensional models because their calibration, even if successful, cannot be justified. Application of the models should lead to a better understanding as to which processes are controlling the behaviour of the entire system and which ones are irrelevant and can be neglected. This, in turn, should lead to establishing much more precise criteria for the models necessary for the basin management, and consequently, to adaptation of existing or development of new models designed according to specific management needs of each basin. The other point to consider with model selection is that most of the models which have the capability for uncertainty analyses are seriously outdated. Applied stochastic methods have been rapidly developing during the past decade and presently there are a variety of mathematical tools available which were nonexistent a few years ago. These new techniques can substantially improve the quality of risk analysis calculations. This aspect of modelling should be considered by NRBS, especially for situations when model results will be applied in basin management decision making.

6.3.2 Mr. G. MacDonald and Dr. R. Shaw, EMA/Golder Associates

There is some concern about the suitability of the existing water quality models, DOSTOC and NUSTOC, that have been applied to the northern rivers. For example, during February 1993, DO concentrations in the Athabasca River dropped to almost 6.5 mg/L, 1 mg/L below that projected by DOSTOC. However, this discrepancy between predicted and observed conditions was not due to problems with model structure or formulation. Rather, it was a result of limitations in the data base (e.g., limited information on hydraulic coefficients for the Grand Rapids and Boiler Rapids areas) or failures in some input assumptions (e.g., that SOD is linearly related to effluent BOD). This illustrates two important aspects of any model study—the goal(s) of the study must be clearly defined and the inherent limitations of computer models must be recognized. For example, one cannot expect simulations to be accurate if conditions in the watershed change from those used to calibrate the computer model.

Low winter DO concentration in the Athabasca River is probably the single most important management issue pertaining to DO or nutrients in northern rivers. Thus, the primary focus of future modelling efforts should be on improving predictions of winter DO concentrations in the Athabasca River. In particular, there are two major goals with respect to winter DO predictions: (i) simulation of short-term DO concentrations based upon existing watershed conditions (e.g., simulate February 1994 DO concentrations based upon information available in December 1993), and (ii) projection of future DO concentrations for long-term basin planning (e.g., how might DO concentrations change as a result of more stringent effluent standards). The existing model for the Athabasca River, DOSTOC, is applicable for long-term basin planning but is less suitable for short-term predictions because it is a steady-state model. Prediction of short-term DO concentrations would likely require a dynamic model: i.e., a model that provides a continuous simulation of water quality conditions for any given time period, for example, for a few days to years. Such a model could potentially track the build up of detrital material below pulp mills over the winter and simulate dynamically the change in SOD over that period. However, at this time it is premature to implement a dynamic model until DOSTOC has been updated, all pertinent data have been reviewed, and management goals have been more clearly defined. As a first step to improve predictions of under-ice DO concentrations, DOSTOC should be updated to more accurately represent existing conditions and to incorporate additional information concerning boundary condition assumptions for the Athabasca River. Presently, a study is under way to test the capability of the previously calibrated DOSTOC model to predict 1991 and 1992 DO conditions in the Athabasca and Wapiti-Smoky Rivers (Macdonald and Radermacher 1993). A sensitivity analysis is also being conducted for the Athabasca River, 1989 calibration. Initial results indicate that (i) headwater DO concentrations are a very sensitive variable with respect to winter DO levels in the lower reaches of the Athabasca River, and (ii) headwater DO levels may be related to meteorological conditions. Thus, it would be valuable to attempt to develop an empirical relationship between headwater DO and meterological conditions, then incorporate this relationship into a model to improve both short- and long-term DO simulations.

Nutrients have also been identified as an area requiring evaluation by NRBS. To date, relatively little effort has been directed towards the evaluation of nutrient dynamics in northern rivers. Thus, one of the first steps should involve deriving mass balances for TP and TN, which requires quantifying TP and TN loads from non-point (e.g., ungauged watersheds) and point sources (effluents and tributaries), plus consideration of in-stream processes (e.g., particulate settling and resuspension). Much of this information is already available; a model such as NUSTOC would be valuable for initially integrating this data. If a reasonable mass balance is attained with NUSTOC, then the use of a more detailed mechanistic model such as WASP might be warranted. For example, this would allow dynamic simulations of nutrients (both in the water column and sediments) within the plume of an effluent, a useful capability if benthic algal or aquatic macrophyte biomass can be related to nutrient levels.

One additional recommendation is that any model applied to northern rivers should have the capability to quantify uncertainty in model output. Computer simulation models are tools designed to represent a simplified version of reality. Water quality models can, in theory, predict water quality conditions for a particular system based on the system's physical properties coupled with chemical and biological processes that are known to occur in surface water environment. However, simplifying assumptions must always be made to construct a model because field situations are much too complex to be simulated exactly. Deterministic models operate with the assumption that model parameters can be described fully by a unique set of values estimated from a limited set of field data. Probabilistic models, on the other hand, include an assessment of the effect of variances in model input parameters on the confidence that can be placed on model predictions. Analysis of this output variability is particularly important in a management context as it helps establish error bounds on the predictions.

6.3.3 Mr. J. T. Brock, Idaho State University and Rapid Creek Water Works; Dr. C. L. Caupp, Frostburg State University

The water quality modelling workshop identified the needs of the NRBS for a predictive model that can be used to estimate DO concentrations in the Peace and Athabasca Rivers. Past modelling efforts have resulted in a simulation model that appears to perform satisfactorily if loading conditions, the nature of the pollutants, and other environmental conditions do not change. However, many of the processes controlling DO in these rivers and their DO kinetics remain poorly understood. The first issue to address is the need for better definition of the processes controlling DO, in particular:

1. The sources of SOD and the processes that modify and transport SOD in the rivers.

2. The processes that control upstream DO concentrations.

3. The processes that control tributary DO.

4. The importance of diel (24-hr) swings in DO.

5. The contribution of nitrogenous oxygen demand to DO consumption.

6. The role of primary producers in contributing or removing oxygen.

7. The relative importance of allocthonous versus autochthonous sources of organic matter to the river ecosystem.

Once the processes controlling under-ice DO are better understood, mechanistic models can be developed or reformulated to address the question of cumulative impacts of development in the basin in the face of changing environments.

The second issue to consider is the need for steady versus unsteady (i.e., dynamic) model(s). It is important to recognize that the failure of a steady-state model to predict water quality adequately is not resolvable by simply implementing a dynamic model. A good understanding of the system is required. The factors to consider when assessing the value of a steady-state versus a dynamic model are as follows:

1. Are unsteady flow variations (daily or hourly) important in determining DO concentrations?

2. Are the measured rates and databases adequate for implementing a dynamic model?

When considering dynamic models, the question of moving from a one-dimensional to a two- or three-dimensional model should also be assessed. A two dimensional modelling approach is needed if variation across the channel is important to biology and water quality.

In conclusion, to improve predictions of water quality, particularly DO conditions in the Peace-Athabasca Rivers, the process controlling DO must be better understood and this information incorporated into the previously-used, one-dimensional methods. After evaluating the ability of the reformulated models to predict water quality, the need to progress to a dynamic or multi-dimensional model should be assessed.

6.3.4 Mr. M. Palmer, Beak Consultants

Model Selection

The NRBS should review the water quality models currently being run and assess their ability to meet both short-term goals (i.e., to predict DO conditions for any given winter) and long-term goals (i.e., to predict future DO conditions in relation to changes in industrial operations, land-use activities, etc.).

As a first step, DOSTOC and NUSTOC should continue to be used with the most up-to-date data. These models are well understood and have been used extensively. A second model such as QUAL2E-UNCAS should also be run in order to compare the "limits of predictability". QUAL2E is available to the public and has been extensively tested, and the mathematics of the model are well known. Both DOSTOC and QUAL2E are setup for variable data inputs. At this stage, there is no indication of a requirement for two-dimensional models, and data are not available for a two-dimensional model. However, if new model(s) need to be selected, several factors should be considered:

1. Use of more than one predictive model so that the "limits of predictability" can be determined.

2. Selection of models capable of considering the high variability of the discharges, coefficients, and input data for the rivers.

3. Obtaining a clear understanding of mathematical functioning of the models because of its importance in the prediction process.

In addition, the NNM should be used to analyze river flow and DO data in order to provide direction to the prediction model application and to extend the "limits of predictability".

With respect to data collection, the network of recording DO meters should be maintained particularly at the known SAG locations. Additional field data collection programs should not be undertaken until after DOSTOC and NUSTOC have been run with the latest data, and data are available from the NRBS artificial stream experiments. The results of these studies will provide direction for the collection of additional field data. These studies should also identify the need for additional measurements of reaeration, sediment oxygen demand, attached algae, etc. In addition, the validity of extrapolating site-specific measurements (e.g., re-aeration or SOD rates) to river reaches extending for 10s of kilometres requires consideration.

Methods also should be developed to allow coefficients determined at one river flow to be used at another. These methods must be suitable for small flows in wide shallow rivers with and without ice.

6.4 Summary of Workshop Recommendations (Dr. J. Culp and Dr. P. Chambers, NHRI)

6.4.1 DO Database and Modelling

A general consensus of the workshop was that deficiencies exist in the database. In particular, participants identified the need for additional information on hydraulic coefficients related to reaeration zones (e.g., Grand Rapids) and for improved empirical relationships between headwater DO and winter meteorological conditions. Many of the processes that may control DO in these rivers are poorly understood. At present, it is uncertain how SOD is affected by effluent BOD within a longitudinal reach of the river, or by the accumulation of detrital material during the period of winter ice cover. Furthermore, the effect of tributary and groundwater DO on mainstem DO needs to be determined. Finally, the role of primary producers as contributors or users of DO is not known for these rivers. Note, however, that questions about the importance of primary producers to the mass balance of DO in the river cannot be considered in isolation of nutrient impacts since nutrient enrichment can lead to increased primary production. Presently, the relative importance of primary production in the river as a contributor to increased SOD under ice is unknown. Similarly, the role of SOD in decreasing DO in the water column is poorly understood.

Because of the current limitations and deficiencies in both the database and the basic understanding of processes that affect riverine DO, participants felt that change to existing model structure was not warranted. The group was divided as to whether model predictions would be improved by moving from the use of steady-state to dynamic models. It is clear, however, that NRBS should consider the application of more than one model to improve future DO predictions. Finally, given the subjectivity that occurs when modelling complex systems with parameter-rich models, it was suggested that future modelling efforts be pursued by two or more independent teams working in parallel.

6.4.2 Nutrient Database and Modelling

Data on nutrient concentrations in the rivers are very limited, and the expansion of this database would be an important product of the NRBS. Participants also felt it was important to generate mass balance equations for TN and TP, as this would allow improved application of predictive water quality models such as NUSTOC. As more data becomes available, empirical relationships between TP and algal biomass could be attempted. Finally, careful consideration should be given to measuring key components of TN and TP that may be more readily available to the biota (e.g., TDN and TDP).

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APPENDIX A

GLOSSARY OF TERMS

APPENDIX A Glossary of Terms

Ammonia, Nitrite, Nitrate - these forms of inorganic nitrogen constitute the stepwise transformation from ammonia to nitrate.

Benthic Algae - attached algae associated with the substratum of lakes and rivers. Chlorophyll *a* or dry mass are typically used as measures of biomass. Benthic algae can be modelled as a single assemblage or can be partitioned into two or more functionally distinct subgroups, such as green and blue-green algae.

Benthic Herbivory - removal of benthic plant material through consumption by animals.

Benthos - organisms which live on the river bottom including invertebrates, algae, and macrophytes.

Biochemical Oxygen Demand (BOD) - utilization of dissolved oxygen by aquatic microbes to metabolize organic matter, oxidize reduced nitrogen, and oxidize reduced mineral species such as ferrous iron.

Boundary Conditions - Boundary conditions refer to the flows and their water quality constituents entering the system from headwaters, point loads and dispersed source Boundary conditions can also refer to exogenous parameters affecting the system (e.g., sunlight, wind velocity, etc.)

Carbonaceous Biochemical Oxygen Demand (CBOD) - utilization of dissolved oxygen by aquatic microbes to metabolize organic matter.

Denitification - reduction of nitrate to N_2 under anaerobic conditions.

Deterministic - cause-effect relationships are modelled but do not include uncertainty.

Dissolved Oxygen (DO) - dissolved oxygen concentration estimated as a balance between surface reaeration and metabolic exchanges (photosynthesis, respiration and other processes such as the oxidation of ammonia to nitrate) in the water column and benthos.

Empirical - based on non-interacting theoretical water quality processes; rate coefficients are isolated from other processes in system.

Five-Day BOD (BOD_5) - measure of the amount of oxygen consumed in laboratory tests on a water sample over a five-day period, usually at 20°C.

Ice - effects of ice are commonly analyzed by reducing reaeration rates. Ice as a process is only added for models which simulate effects of ice on hydraulic process.

Light Extinction - the availability of photosynthetically active radiation is estimated based on an extinction coefficient taking into account depth and turbidity.

Macrophytes - aquatic macrophytes can take various forms including rooted emergent or submersed angiosperms, non-rooted floating macrophytes and attached epiphytic algae. While the macrophyton can be functionally important in some aquatic systems, this component is rarely included in water quality models.

Mechanistic - based on theoretical relationships and interactions amongst various water quality processes.

Mineralization - breakdown of organic matter to inorganic forms, e.g., organic phosphorus to orthophosphate.

Nitrification - transformation of reduced forms of nitrogen (ammonia) to more oxidized forms (nitrate).

pH, Alkalinity - the pH is estimated based on a solution of the carbonate equilibrium. Alkalinity may be modelled as a conservative substance with no source or sink terms.

Phosphorus - the phosphorus (P) cycle is handled with varying levels of resolution, including soluble inorganic P, soluble organic P, particulate P and soluble non-reactive P.

Phytoplankton - suspended algae in the open water of lakes and rivers. Chlorophyll *a* or dry mass are typically used as measures of phytoplanktonic biomass. Algae can be modelled as a single assemblage or can be partitioned into two or more functionally distinct subgroups, such as green and blue-green algae.

Sediment Dynamics - sedimentation and erosion of particulate material. Sediment is treated as a conservative constituent that can settle and erode from the benthos. Adsorption and desorption of dissolved substances with sediments may also be included along with exchanges between pore water and the water column.

Sediment Oxygen Demand (SOD) - all processes related to bottom sediments that require or produce oxygen, e.g., respiration by benthic organisms, degradation of organic material.

State variables - variables for which a model simulates transport and transformation reactions to project concentrations.

Stochastic - incorporates inherent uncertainty of the model or process by an estimation of central tendency and some measure of variability.

TDS/Conductivity - total dissolved solids modelled as a single conservative substance with no source or sink terms. Conductivity typically estimated using empirically-derived relationships based on TDS.

Theta (θ) - temperature correction coefficient for biological rates.

Ultimate BOD (BOD_u) - measure of the amount of oxygen consumed in laboratory tests on a water sample over a long period of time (>120 days), usually at 20°C.

Uptake - accumulation of inorganic nutrients (C,N,P) by plants during photosynthetic growth.

Zooplankton - the animal component of the plankton, included in some water quality models (mostly lake) due to its impact on phytoplankton, or as food source for fish.

APPENDIX B

SCHEDULE OF WATER QUALITY WORKSHOP

APPENDIX B **Schedule of Water Quality Workshop Held on March 22-23, 1993 at the National Hydrology Research Institute, Saskatoon, Saskatchewan.**

DAY 1 - Monday, March 22

MORNING SESSION CONCEPT:
Identify NRBS needs in terms of water quality models

8:30 *Introductory Remarks*
(Dr. J. Culp, NHRI)

- Conceptual framework, goals and schedule for workshop

9:00 *Needs of NRBS: Overview*
(Dr. F. Wrona, NRBS Director)

- Impact of pulp mill and sewage treatment plant effluents; Non-point sources
- Given specific loading scenarios, the model(s) must predict downstream levels of specific water quality variables like nutrient, DO, algal biomass, etc. in order to help managers set future regulations and develop policy

9:30 *Open Forum: Needs and concerns of NRBS working groups*

- Specific needs from water quality models for working groups to meet their objectives
- Concerns with and input to present models (parameters, coefficients, model structure, etc.)
- Contaminants, Hydrology, Industry, Nutrients, Other Uses and Traditional Knowledge will be represented

10:00 COFFEE

10:30 *Open forum: Needs and concerns of NRBS working groups*

- Continuation of discussion

11:00 *What modelling approaches have been used in the Peace/Athabasca to date?*
(Dr. P. Chambers, NHRI)

- Modelling work on the Peace/Athabasca
- Model application, results and successes, data availability, rate coefficient review

11:45 LUNCH

AFTERNOON SESSION CONCEPT:

We will consider the structure of a suite of modelling tools that may be needed to meet both short- and long-term goals for NRBS water quality modelling. We need to view models as tools built for specific tasks, rather than exclusive alternatives.

1:00 *Introductory Remarks*
(Dr. J. Culp, NHRI)

- Review of the morning's discussions and concept for afternoon session
- Questions for discussion during workshop:

(1) What types of models have merit in terms of predicting and/or understanding nutrient and BOD loading impacts?

(2) What further development is needed to improve existing models? Are new model structures needed?

(3) Which physical, chemical and ecological processes need to be understood?

(4) To what extent do existing data bases limit the application of water quality models?

(5) How can predictions from these nutrient loading models be incorporated into other components of the NRBS?

1:15 *Available Approaches 1: WASP*
(Mr. G. Macdonald and Dr. R. Shaw, EMA/Golder)

- Flow diagram and explanation of model components
- Review of coefficients, error associated with terms, sensitivity analysis for terms, etc.

2:00 *Available Approaches 2: DOSTOC/NUSTOC*
(Dr. A. Zielinski, Ontario Hydro)

(Review models as above)

2:45 **COFFEE**

3:15 *Available Approaches 3: DSSAMt3*
(Dr. C. Caupp, Frostburg State University and Mr. J. Brock, Idaho State University)

(Review model as above)

4:00 *Available Approaches 4: Pattern Recognition*
(Mr. M. Palmer, Beak)

(Review model as above)

4:45 **ADJOURN**

DAY 2 - Tuesday, March 23

MORNING SESSION CONCEPT:
What can we learn by examining alternative modelling approaches?

8:30 *Introductory Remarks*
(Dr. J. Culp, NHRI)

- Overview of today's schedule and concept for morning session

8:45 *Discussion of Modelling Approaches (Part 1): Experiences gained from modelling other ecological systems*
(Dr. E. McCauley, University of Calgary)

- Potential synergistic interactions between alternative modelling approaches (i.e., between tactical and empirical models)
- Linkage among freshwater ecosystems: similarities, dissimilarities, boundary problems, etc.
- Importance of non-linearities in biological processes and ecological interactions: What do we include in our models? How can we decide what to include, especially once a large initial investment is made in model development? How "transportable" are tactical models of water quality?
- Problems associated with evaluating impacts from point sources: spatial heterogeneity, local effects, predicting in the region of point sources.

10:00 **COFFEE**

10:30 *Discussion of alternative modelling approaches (Part 2): Questions arising from workshop*
(Group discussion lead by Dr. E. McCauley, Dr. P. Chambers and Dr. J. Culp)

- Discussion of questions outlined on Day 1
- Merits of available approaches and strategic modification of existing models
- Should the flow diagrams of our models change?
- Incorporation of critical ecological processes (e.g., Red Deer River)

11:45 LUNCH

AFTERNOON SESSION CONCEPT:
Continuation of discussion on alternative modelling approaches

1:00 ***Discussion of modelling approaches (Continuation of Part 2)***

- Overview of morning discussion
- Discussion of five questions outlined in Day 1
- How will geographical area and basin type modify our approach?
- Considerations for future modelling approaches during the NRBS
- Factors to consider in the design of monitoring programs (e.g., Red Deer River)
- Modelling DO under ice (e.g., Athabasca River)

2:45 COFFEE

3:15 ***Wrap-up discussion of modelling approaches***

- Where do we go from here?

4:45 ADJOURN

APPENDIX C

ATTENDEES OF THE NORTHERN RIVER BASIN STUDY WORKSHOP ON WATER QUALITY MODELLING.

APPENDIX C List of Attendees of the Northern River Basin Study Workshop on Water Quality Modelling.

List of Attendees	Affiliation	Phone #	Fax #
Max Bothwell	*NHRI	306-975-5768	306-975-5143
Brian Brownlee	**NWRI	416-336-4706	416-336-4972
Jim Brock	Rapid Creek Waterworks	208-322-8950	208-376-9557
Kevin Cash	NHRI	306-975-4010	306-975-5143
Craig Caupp	Frostburg State University	301-689-4755	301-689-4737
Patricia Chambers	NHRI	306-975-5592	306-975-5143
Joseph Culp	NHRI	306-975-5742	306-975-5143
Donna Dustin	NHRI	306-975-5774	306-975-5143
Judy Evans	University of Alberta	403-492-5497	403-492-8160
Mary Ferguson	NHRI	306-975-6057	306-975-5143
Nancy Glozier	NHRI	306-975-6057	306-975-5143
Dave Hutchinson	Alberta Pacific	403-525-8000	403-525-8095
Kevin Himbeault	NHRI	306-975-5774	306-975-5143
Lam Lau	NWRI	416-336-4919	416-336-4989
Laudy Lickacz	Weldwood of Canada	403-865-8505	403-865-8550
Allan Locke	Alta. Environ. Protection	403-427-6734	403-422-4560
Rick Lowell	NHRI	306-975-6303	306-975-5143
Gord Macdonald	EMA/Golder Associates	403-299-5616	403-299-5606
Ed McCauley	University of Calgary	403-220-5583	403-289-9311
Tom Olson	Alta. Environ. Protection	403-427-9506	403-422-9560
Merv Palmer	Beak Consultants	604-278-7714	604-278-7741
Cheryl Podemski	NHRI	306-975-4655	306-975-5143
Colleen Pollock	NHRI	306-975-5759	306-975-5143
Terry Prowse	NHRI	306-975-5757	306-975-5143
Garry Scrimgeor	NHRI	306-975-5909	306-975-5143
Jackie Shaw	EMA/Golder Associates	403-297-8270	403-297-8232
Randy Shaw	Alta. Environ. Protection	403-299-5637	403-299-5637
Brian Steinback	Alberta Newsprint	403-778-7000	403-778-7072
Pat Tones	Sentar Consultants	306-665-7655	306-665-3312
Annette Trimbee	Alta. Environ. Protection	403-427-2375	403-422-4190
Gee Tsang	NHRI	306-975-5760	306-975-5143
Marley Waiser	NHRI	306-975-5762	306-975-5143
Greg Wagner	NRBS Office	403-427-1742	403-422-3055
Ken Weagle	WER-Agra	403-291-1195	403-250-7165
Dennis Westhoff	WER-Agra	403-291-1195	403-250-7165
Fred Wrona	NHRI	306-975-6099	306-975-5143
Andy Zielinski	Ontario Hydro	416-207-5497	416-231-4513

*National Hydrology Research Institute **National Water Research Institute

APPENDIX D

TERMS OF REFFERENCE

NORTHERN RIVER BASINS STUDY

SCHEDULE A - TERMS OF REFERENCE

Project - Water Quality Modelling Workshop

Requirements

1. The workshop will identify the water quality modelling requirements of NRBS and, for each NRBS working group, specify their needs from or input to water quality models. Techniques that have been used on the Peace and Athabasca rivers will be examined and other available modelling approaches will be explored. Participants will include experts from government, industry and university communities. A final report of the workshop's findings will be produced.

Reporting Requirements

1. A two-day workshop will be organized to examine approaches to model water quality in the Peace-Athabasca System. A final report of the workshop proceedings will be prepared.

2. Ten copies of the draft report are to be submitted to the Project Manager (Greg Wagner) by March 31, 1993.

3. Three weeks after receipt of reivew comments, the Contractor is to submit ten cerlox bound copies and two camera-ready originals of the final report to the Project Manger. An electronic copy of the report, in WordPerfect 5.1 format, is to be submitted to the Project Manager along with the final report. The final report is to contain a table of contents, list of figures (if appropriate), list of tables (if appropriate), acknowledgements, executive summary and an appendix containing the Terms of Reference for this contract.