alberta canada

ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM

Mixing Characteristics of the Athabasca River Below Fort McMurray-Winter Conditions

Project WS 3.3

April 1979

Sponsored jointly by

Alberta ENVIRONMENT

Environment Canada Environnement Canada

15th Floor, Oxbridge Place
9820 - 106 Street
Edmonton, Alberta, Canada
T5K 2J6

ALBERTA OIL SANDS ENVIRONMENTAL RESEARCH PROGRAM
RESEARCH REPORTS

These research reports describe the results of investigations funded under the Alberta Oil Sands Environmental Research Program, which was established by agreement between the Governments of Alberta and Canada in February 1975 (amended September 1977). This 10-year program is designed to direct and co-ordinate research projects concerned with the environmental effects of development of the Athabasca Oil Sands in Alberta.

A list of research reports published to date is included at the end of this report.

Enquiries pertaining to the Canada-Alberta Agreement or other reports in the series should be directed to:

Alberta Oil Sands Environmental Research Program
15th Floor, Oxbridge Place
9820 - 106 Street
Edmonton, Alberta
T5K 2J6
(403) 427-3943

Mixing Characteristics of the Athabasca
River Below Fort McMurray-Winter Conditions

Project WS 3.3

AOSERP Report 40

This report may be cited as:

Beltaos, S. 1979. Mixing characteristics of the Athabasca River below Fort McMurray-Winter conditions. Prep. for the Alberta Oil Sands Environmental Research Program by Transportation and Surface Water Engineering Division, Alberta Research Council. AOSERP Report 40. 110 pp.

The Hon. John W. (Jack) Cookson
Minister of the Environment
222 Legislative Building
Edmonton, Alberta

and

The Hon. John Fraser
Minister of the Environment
Environment Canada
Ottawa, Ontario

Sirs:

Enclosed is the report "Mixing Characteristics of the Athabasca River Below Fort McMurray-Winter Conditions".

This report was prepared for the Alberta Oil Sands Environmental Research Program, through its Hydrology Technical Research Committee (now the Water System), under the Canada-Alberta Agreement of February 1975 (amended September 1977).

Respectfully,

W. Solodzuk, P.Eng.
Chairman, Steering Committee, AOSERP
Deputy Minister, Alberta Environment

A.H. Macpherson, Ph.D.
Member, Steering Committee, AOSERP
Regional Director-General
Environment Canada
Western and Northern Region

MIXING CHARACTERISTICS OF THE ATHABASCA RIVER BELOW FORT McMURRAY - WINTER CONDITIONS

DESCRIPTIVE SUMMARY

BACKGROUND

Effluent plumes are caused in the Athabasca River near current oil sands developments by discharge of industrial process water, mine depressurization water, and sewage. To properly manage the quality of the Athabasca River one must address not only determining the quantity of effluent but also the timing of such releases. A knowledge of plume behaviour would aid in making such decisions.

This project was developed in mid-1977 with the goal of assessing the ability of the Athabasca River in the AOSERP study area to mix effluent streams under ice conditions. Specific objectives set out were:

1. Develop a procedure and utilize it to determine the mixing characteristics of a selected study reach of the Athabasca River in the AOSERP study area over a range of winter flow conditions for effluents when differential density is not a factor;
2. Estimate the mixing characteristics of all sections of the Athabasca River in the AOSERP study area, including time-of-travel, longitudinal mixing, and transverse mixing under a representative range of winter flow conditions; and
3. Develop a preliminary procedure and use it to determine the mixing characteristics of a selected reach of the Athabasca River under winter flow conditions when effluent density and temperature are factors.

Initially the project was numbered HY 1.4.3. The number was changed to WS 3.3 when the WS numbering series was implemented.

ASSESSMENT

This project has been completed and the winter mixing processes in the Athabasca River have been suitably elucidated in terms of AOSERP objectives. The report has been reviewed by various government and university scientists in Alberta and it has been favorably received. However, the conclusions of the report do not necessarily reflect the views of Alberta Environment, Environment Canada, or the Oil Sands Environmental Study Group and the mention of trade names for commercial products does not constitute an endorsement or recommendation for use. The Alberta Oil Sands Environmental Research Program is pleased with the efforts put forth by the researchers in this project and accepts their report, "Mixing Characteristics of the Athabasca River Below Fort McMurray - Winter Conditions", as an important and valid document. The researchers are thanked for their contribution.

S.B. Smith, Ph.D
Program Director
Alberta Oil Sands Environmental
Research Program

R.T. Seidner, Ph.D
Research Manager
Water System

MIXING CHARACTERISTICS OF THE ATHABASCA RIVER BELOW FORT McMURRAY - WINTER CONDITIONS

by

S. BELTAOS

Transportation and Surface Water Engineering Division
Alberta Research Council

Prepared for

ALBERTA OIL SANDS
ENVIRONMENTAL RESEARCH PROGRAM
as Alberta Research Council Contribution Series 943

Project WS 3.3

April 1979

TABLE OF CONTENTS

TABLE OF CONTENTS (CONCLUDED)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (CONCLUDED)

ABSTRACT

This report presents the results of a comprehensive assessment of mixing characteristics of the Athabasca River below Fort McMurray under ice-covered flow conditions. A brief review of mixing processes in natural streams is followed by a description of two tracer tests conducted in February 1978 to provide the necessary field documentation of the Athabasca River. The results of these tests are analysed using recent theoretical models available in the literature. An average value for the transverse mixing coefficient is determined from the results of the first test which was a steady state test. This coefficient compares favourably with that found from a preliminary test in 1974 under similar flow conditions. The results of the second test, which involved central injection of a slug, are compared with a one-dimensional model developed earlier by the author. This model is shown to give fair predictions beyond 20 km from the injection site. It is suggested that this limiting distance be increased to about 80 km when side injection of a slug is considered. To model the results of the slug test within the first 20 km from injection, a numerical algorithm is utilized together with the mixing coefficient found from the first test and shown to give fair predictions. The effects of bars and islands on applications of this algorithm appear to be of localized nature. It is suggested that such effects be ignored unless pertinent hydrometric data are available in considerable detail. Practical applications of the present findings are illustrated by working out two hypothetical examples. Finally, some recommendations are made for future research required to completely define the mixing characteristics of the Athabasca River and Delta system.

ACKNOWLEDGEMENTS

The work reported herein has been funded jointly by Alberta Research Council and Alberta Oil Sands Environmental Research Program (AOSERP), a joint Alberta-Canada research program established to fund, direct, and co-ordinate environmental research in the Athabasca Oil Sands area of northeastern Alberta. At the same time, this work is a part of a continuing research program to study the mixing characteristics of rivers in Alberta. This program is carried out by the Transportation and Surface Water Engineering Division of Alberta Research Council, in co-operation with Alberta Environment under the auspices of the Alberta Co-operative Research Program in Transportation and Surface Water Engineering.

The Division is grateful to Jim Anderson, Scott Flett, Sonny Flett, J. Moore, and L. Campbell of the Alberta Environment Branch at Fort Chipewyan, for their substantial assistance with site reconnaissance and sampling at the delta. The same holds for Corp. Bill Kendell and Const. Krill of the Fort Chipewyan RCMP office. The Parks Department at Fort Chipewyan provided their bombardier for one day.

The loan of several automatic samplers and a fluorometer by A. Masuda, P. Grant, and H. Hamilton of Water Quality Control Branch, Alberta Environment is greatly appreciated. Early discussions with R. Froelich, formerly of AOSERP, were helpful in planning the field operations.

The field work described herein and much of the associated data processing were carried out with the help of M. Anderson, W. Lipsett, C. Ray, T. Ridgway, and J. Thompson of this Division. Mr. Lipsett also reviewed the manuscript. All programming for computer applications has been carried out by V. Arora. The manuscript was typed by Mrs. O. Smith.

1. INTRODUCTION

The heavy industrial development associated with the Athabasca Oil Sands has been the cause of substantial concern over associated environmental impact. One of the main areas of concern is the Athabasca River ecosystem (see also Figure 1).

A major problem in extracting oil using existing mining and treatment technology is the disposal of the so-called tailings. Under the present Provincial environmental control regulations, such effluents have to be totally contained on the lease of the mining company. This requires considerable expenditure and, at the same time, the resulting tailings ponds constitute an environmental hazard in themselves. Therefore the answers to the following questions would be of considerable interest to both environmental protection authorities and oil sands industry:

1. What would be the magnitude of impact resulting from accidental releases of tailings into the Athabasca River?
2. Are there conditions under which controlled tailings releases into the Athabasca River would be environmentally tolerable? If so, what are these conditions?

The practical implications and benefits to be derived from investigating these problems have been discussed in detail by Gerard (1977).

For study purposes, that part of the Athabasca River system which is subject to oil sands surface mining development

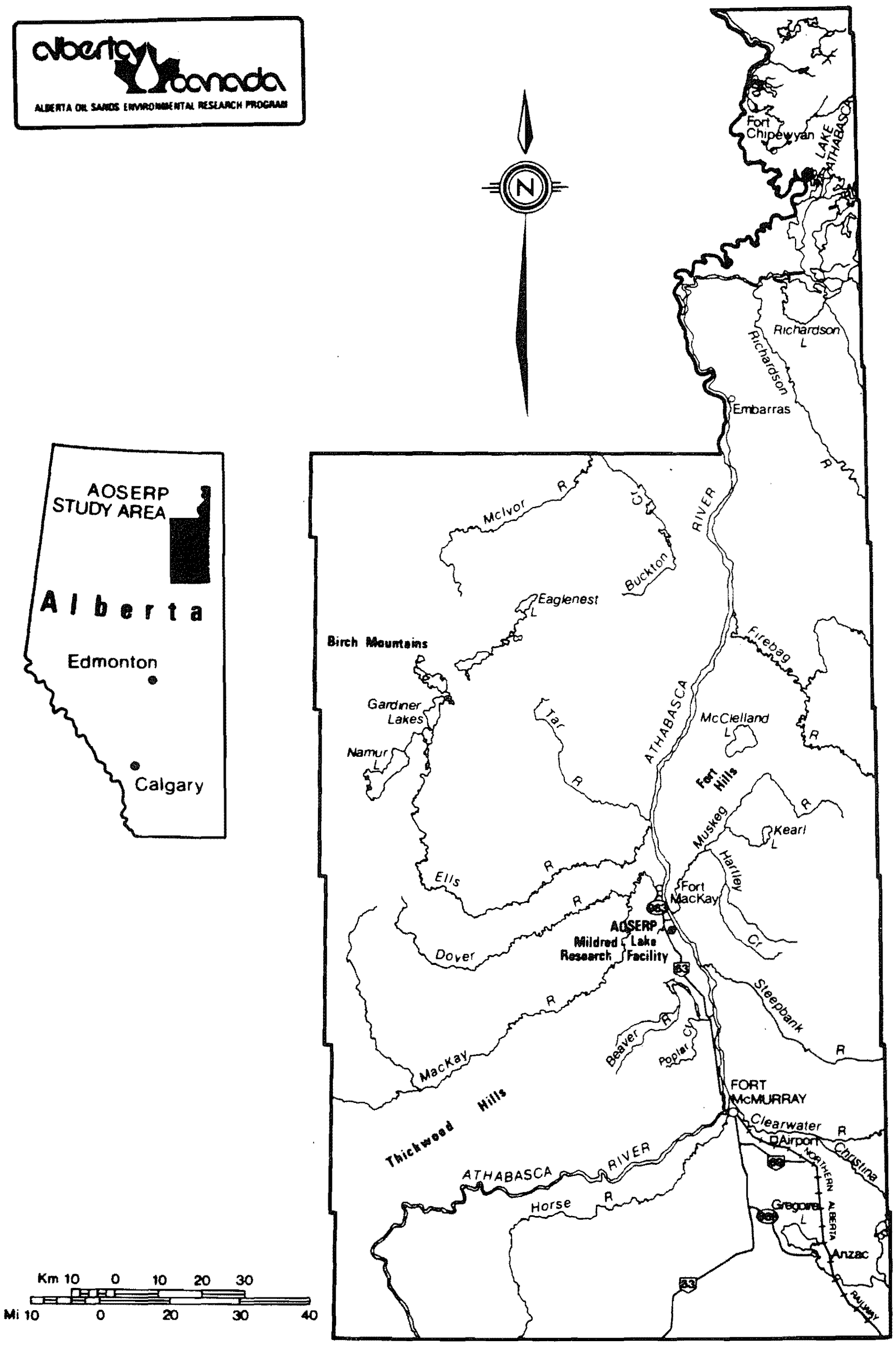

Figure 1. Alberta Oil Sands Environmental Research Program study area.

impact, may be subdivided into two distinct areas: the well-defined river channel between Fort McMurray and Embarras River, and the multiple-channel, Peace-Athabasca delta system. The former area is the subject of the present study.

To answer the preceding questions, it is essential to have a means for estimating the rates of movement and spread of contaminants in natural streams. There are two types of processes which determine the mixing patterns of contaminants released into a stream: those arising from the very nature of streamflow itself and which operate regardless of the nature of the contaminant, and those arising from the nature of the contaminant. The former processes, herein called "river-specific", include diffusion due to random molecular and turbulent motions within a fluid, and dispersion arising from non-uniformities in transverse (time-averaged) velocity distributions. Processes attributable to the nature of the contaminant, herein termed "substance-specific", are caused by such effects as buoyancy, chemical reactions, decay, absorption, etc. Basically, substance-specific processes are due to differences between physical and chemical properties of the contaminant and corresponding properties of water.

A complete assessment of mixing characteristics of various contaminants requires knowledge pertaining to both river-specific and substance-specific processes. Though the former are independent of contaminant properties and can thus be studied using "neutral" tracers[1], the latter must be identified and quantified for each particular substance. Very often, substance-specific processes involve net losses so that study of the mixing processes for neutral substances can be considered to provide upper bounds of concentration. There are circumstances, however, under which the above statement will not be valid. For example, chemical reaction of other substances present in the fluid may result in net gain; density differences between the mixing substance and the fluid may, under certain conditions (Turner 1973), produce density currents that suppress mixing.

1.1 BRIEF REVIEW OF RIVER SPECIFIC MIXING PROCESSES

The state of the art concerning the mixing of neutral tracers in natural streams has been reviewed by the writer recently (Beltaos 1978a and 1978b). For convenience, a brief summary is presented in this section. It will be assumed that river flow is steady, as is usually the case in practice.

The problem to be answered can be formally stated as follows: Given details of injection of a neutral tracer into a stream as well as the stream hydraulic characteristics, predict the tracer concentration at any time after, and at any location downstream of, injection.

---

[1] That is, substances with properties very closely approximating those of water and thus being subject to river specific processes only.

Due to the complexity of this problem, mixing calculations are generally carried out in terms of depth averaged concentrations assuming that satisfactory vertical mixing has been established. This condition is satisfied beyond a certain distance from the injection site, this distance being in the order of one hundred river depths. This assumption enables suppression of the vertical co-ordinate and thus renders the problem two-dimensional (Beltaos 1978a).

Mixing processes can be distinguished into two categories, based on their dependence on time:

1. Transient mixing. The concentration changes with time at any one location in the channel. Transient mixing occurs when the rate of injection changes with time. The simplest case of a time-dependent injection rate is a very brief injection of a certain mass of tracer. This type of injection can, for practical purposes, be considered instantaneous and is known as a slug injection. Because mixing processes adhere to the principle of linear superposition, the concentration distribution arising from a slug injection in a stream forms the basis for deducing concentration distributions caused by more complex injection procedures.

With reference to Figure 2, the variation of concentration with time at a point with co-ordinates x, y, z[1], due to a slug injection at x = 0, t = 0 (t being time from injection), is as shown in Figure 3a. Tracer begins to arrive at the point (x, y, z)

---

[1] All symbols are defined where they first appear in the text; a list of symbols is given in Appendix 8.1.

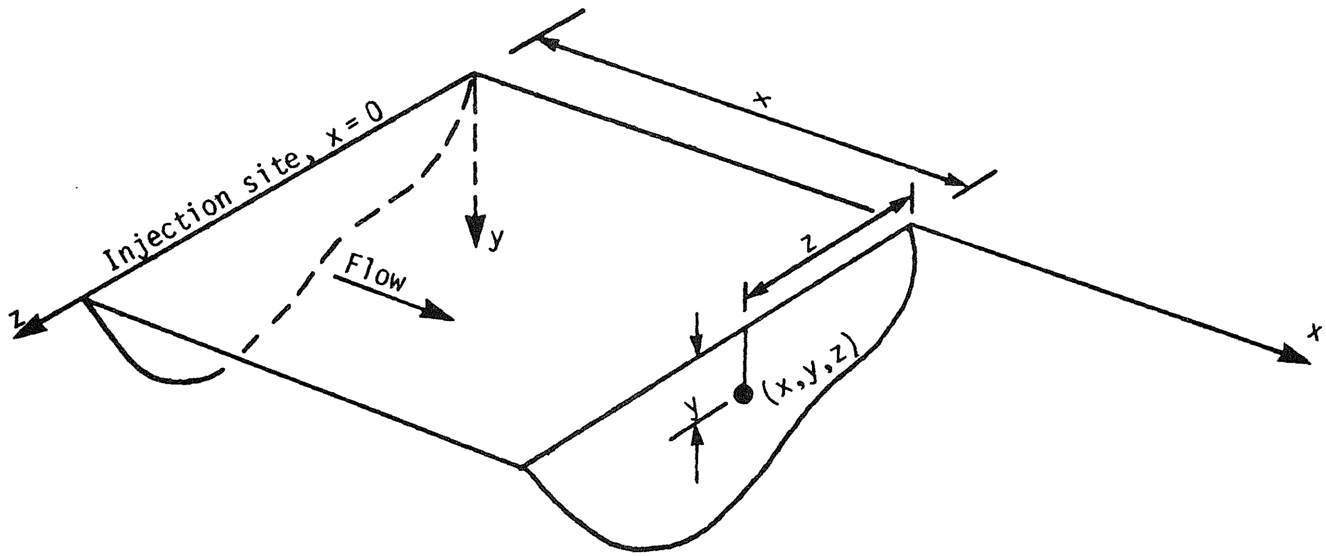

Figure 2. Definition sketch.

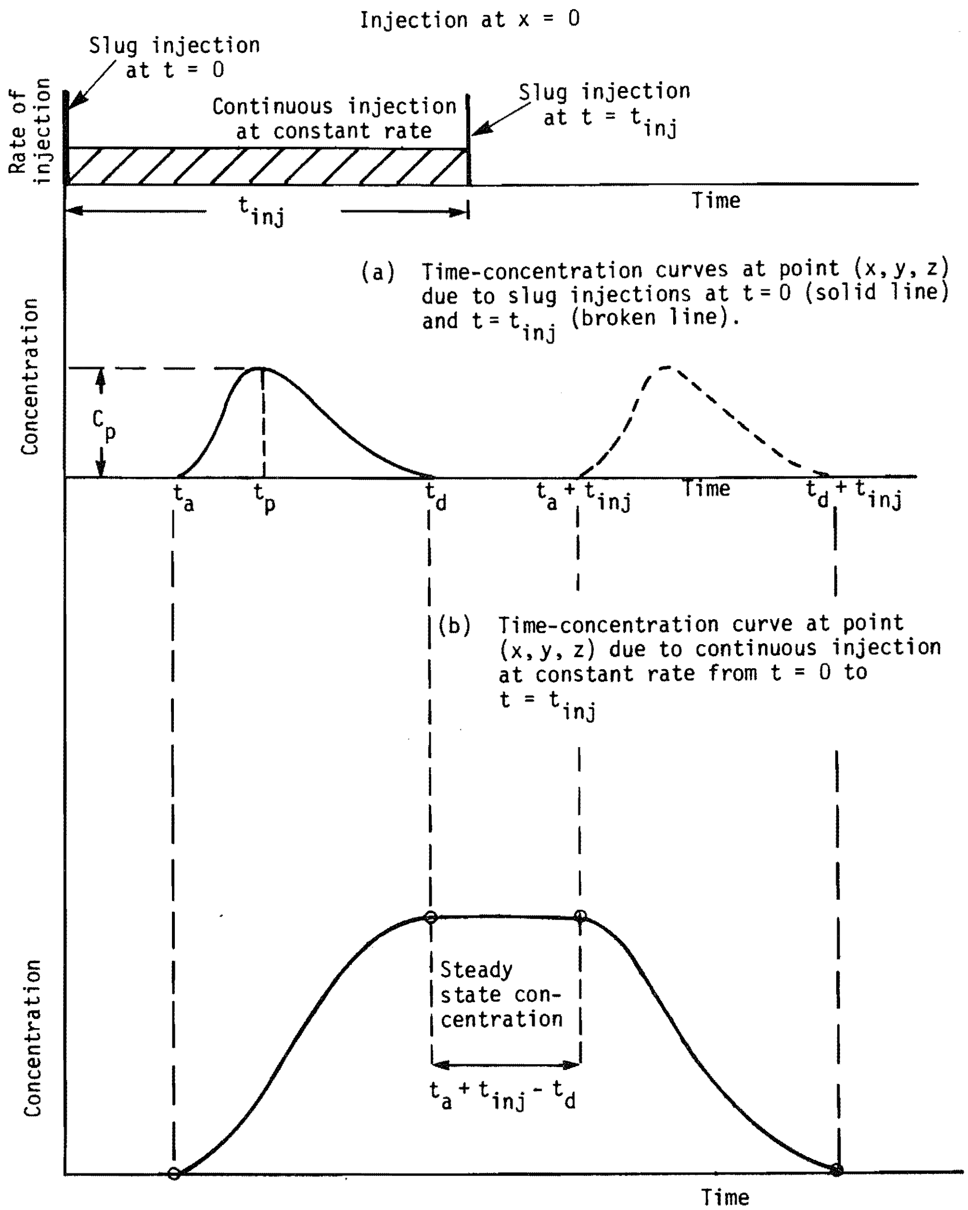

Figure 3. Schematic illustration of time-concentration curves resulting from slug and continuous injections.

a. Time-concentration curves at point (x,y,z) due to slug injections at t = 0 (solid line) and $t = t_{inj}$ (broken line).

b. Time-concentration curve at point (x,y,z) due to continuous injection at constant rate from t = 0 to $t = t_{inj}$.

at a time t_a and departs from this point at a time t_d. The difference $t_d - t_a$ is a measure of the spread of the tracer cloud. The time t_p denotes the occurrence of the highest concentration, C_p. All time characteristics, t_a, t_p, t_d and $t_d - t_a$ increase with distance downstream of the injection site whereas the peak concentration, C_p, decreases.

2. <u>Steady state mixing</u>. In this case the concentration anywhere in the channel is independent of time. This type of mixing results from continuous injection at a constant rate as it commonly occurs below sites of controlled, continuous releases of effluents. To use the principle of superposition mentioned earlier, a continuous injection can be considered to consist of a series of consecutive slugs, each causing a time-concentration variation such as the one shown in Figure 3a. Superposition of all these variations gives the time-concentration variation for the continuous injection, as shown in Figure 3b (see also Appendix 8.2). This variation has the following features: for $t \leq t_a$, $C = 0$; for $t_a \leq t \leq t_d$, the concentration C increases with time; for $t_d \leq t \leq t_a + t_{inj}$, C is independent of time; for $t_a + t_{inj} \leq t \leq t_d + t_{inj}$, C decreases with time; and for $t_d + t_{inj} \leq t$, $C = 0$. This discussion shows that an injection at constant rate beginning at $t = 0$ and lasting for a time t_{inj}, will result in time-independent concentrations at a point (x, y, z) during the period t_d to $t_a + t_{inj}$. Obviously, the injection time t_{inj}, must be sufficiently large to ensure that $t_a + t_{inj} > t_d$, i.e., t_{inj} should exceed $t_d - t_a$.

Quantitative calculation of (depth averaged) concentration as a function of x, z, and t is based on a differential equation expressing the conservation of tracer mass and the associated boundary conditions. To date, it has proved impossible to find a general analytical solution for this equation. However, two partial solutions which apply under certain restrictions can occasionally be used to advantage.

For steady-state mixing, Yotsukura and Cobb (1972) proposed a relatively simple solution based on the so-called "streamtube transformation" (see also Beltaos 1978a).

For transient mixing, it has been established that far downstream of the injection site, instantaneous cross-sectional distributions of concentration become nearly uniform. At a slight loss of accuracy, concentration predictions can then be made in terms of the cross-sectional average concentration. This depends only on x and t and can be calculated by means of relatively simple equations (see also Beltaos 1978b). As mentioned earlier, this solution applies only beyond a certain distance from the source. This final stage of transient mixing is commonly referred to as longitudinal or one-dimensional dispersion; the terminology arising from the facts that the process depends on only one space co-ordinate and is dominated by dispersive effects. The river length beyond which the one-dimensional solution applies has been found to increase as the square of river width, which implies that the practical significance of longitudinal dispersion diminishes with increasing stream size. Upstream of this length, the depth averaged concentration depends on x, z, and t and can only be calculated using numerical computation schemes.

The solutions outlined above require knowledge of detailed stream hydraulics and mixing characteristics. The latter are summarized by the transverse mixing coefficient and two longitudinal dispersion parameters. Stream hydraulics can be assessed by means of hydrometric surveys. Though much of the current research on mixing aims at relating the various mixing parameters to measurable hydraulic characteristics of natural streams, it has not been possible so far to establish satisfactory relationships of this type. Therefore the present procedure is to evaluate mixing parameters of natural streams by means of tracer tests. Ideally, several tests should be carried out at different stages in order to establish an empirical relation between mixing parameters and stage. In northern regions, the effect of the ice cover must also be assessed since an ice cover is expected to reduce mixing appreciably (Engmann and Kellerhals 1974).

1.2 MIXING IN THE ATHABASCA RIVER BELOW FORT MCMURRAY

Considering that the cost of a mixing test increases with stream size and remoteness of the study area, multiple testing in the Athabasca River below Fort McMurray would be very expensive. The minimum requirement would be one test for each condition, open water and ice-covered flow. Since winter hydrographs are fairly steady, a winter test is likely to be representative of the ice covered condition. The same is not true for the open water condition. If only one test is to be performed, this should coincide with a period of low flow, when the spreading capacity of a stream is minimum.

The Transportation and Surface Water Engineering Division of Alberta Research Council has carried out two tests in the reach between the mouths of Steepbank and MacKay rivers, under both open water and ice-covered conditions (see Figure 1). These tests are described briefly in Table 1.

The winter test described in Table 1 was intended to serve as a guide for a future, more comprehensive test. Concentration distributions were measured at only two downstream sites. Of these, only the data for the second site were sufficient for estimating the mixing coefficient. Thus the quoted value is associated with a relatively high degree of uncertainty. Greater confidence is thought to apply to the open water value, which is an overall average estimate to match the observations at six sampling sites. Whether the observations within this short study reach are representative of the entire river reach from Fort McMurray to Lake Athabasca is not known. The only favourable hint is the fact that the river exhibits a fairly uniform planform from the mouth of the Clearwater River to somewhat below Embarras.

Based on this discussion, it was felt that a minimum requirement would be an additional documentation of mixing characteristics of the river under ice covered conditions. This documentation consisted of the following:

Table 1. Mixing tests by Alberta Research Council, Athabasca River below Fort McMurray.

Date of test	Flow condition	Type of test	River discharge[a] m^3/s	Transverse mixing coefficient[b] m^2/s
01 February 1974	Ice covered	Slug injection	240	0.041
26 September 1974	Open water	Slug injection	775	0.072

[a] As estimated by Water Survey of Canada, 1975.

[b] From Beltaos, 1978a.

1. A steady state test in a 27 km long reach, beginning a few kilometres below the Ells River mouth. This test was intended to provide a more accurate determination of the transverse mixing coefficient than the one shown in Table 1;

2. A slug injection test in a 220 km long reach, beginning below the Ells River mouth and ending upstream of the Athabasca River delta. This test was intended to provide information regarding transient mixing processes such as rates of movement and spread of contaminants; and

3. Hydrometric surveys to document the hydraulic characteristics of the Athabasca River below the Ells River mouth.

This report presents the results and analysis of the above documentation as well as recommendations for future research.

2. FIELD PROCEDURES

A plan of the Athabasca River from Fort McMurray to Lake Athabasca is shown in Figure 4. The study reach begins at the injection site (0 km) and ends somewhat above the Athabasca River delta.

River cross sections where the channel geometry and/or velocity have been measured are shown in Figure 4. They are designated by their distance along the river, in kilometres from the injection site; the latter is designated as 0 km. Some of these sections were surveyed during the present study and are distinguished from sections surveyed previously, as shown in Figure 4. The initials "S.S." designate sections where tracer sampling took place.

2.1 STEADY STATE TEST

The tracer used for both tests was Rhodamine WT fluorescent dye, commercially available in 20% by weight solution. For measuring dye concentrations of the various samples, two Turner Designs Rackmount Fluorometers were used, capable of detecting concentrations as low as 0.01 $\mu g/\ell$. Permission to inject the dye in the river was granted by the Standards and Approvals Division of Alberta Environment.

For the steady state test, a 4% solution of dye was injected continuously at a rate of 3.4 cm^3/s. The injection point was located on section 0 km, 10 m off the left bank (the left and

FIGURE. 4.
ATHABASCA RIVER BELOW FORT MC MURRAY
PLAN OF STUDY REACH, FEBRUARY 1978 MIXING TESTS

NOTES: - CROSS SECTIONS ARE DESIGNATED BY RIVER DISTANCE FROM INJECTION SITE (KILOMETRES)
- STARRED SECTIONS WERE ESTABLISHED IN FEB. 78
- SAMPLING SITES ARE DESIGNATED BY "S.S."

right convention adopted herein is for an observer looking downstream). Injection commenced at 1330 hrs MST, 16 February 1978 and was discontinued at 1600 hrs on the following day. The injection setup consisted of a weir-type constant head apparatus and a 200 ℓ drum, as shown schematically in Figure 5. The injection apparatus was placed in a 4 m square tent equipped with a propane heater to prevent freezing of the dye.

Due to a malfunction of the injection apparatus, the flow of the dye was interrupted for a few hours during the early morning of 17 February. It was estimated that by prolonging the dye injection to 1600 hrs from the originally intended discontinuation time of 1300 hrs, the effects of this interruption would be nullified with the possible exception of the sampling site at 13.8 km. This expectation was confirmed later when the results of the tests were processed.

Sampling was carried out on 17 February by cutting holes in the ice cover at several points across the stream and filling small plastic bottles with water samples. The samples were analysed to determine dye concentrations on the evening of 17 February.

2.2 SLUG INJECTION TEST

A 150 kg slug of 20% dye was injected near the centroid of the flow at section 0 km at 1400 hrs, 20 February 1978. Sampling was carried out at eight sites; of these, the first three were located 19.9, 48.3, and 107.6 km below the injection site. Five points, partitioning the channel width into four, roughly

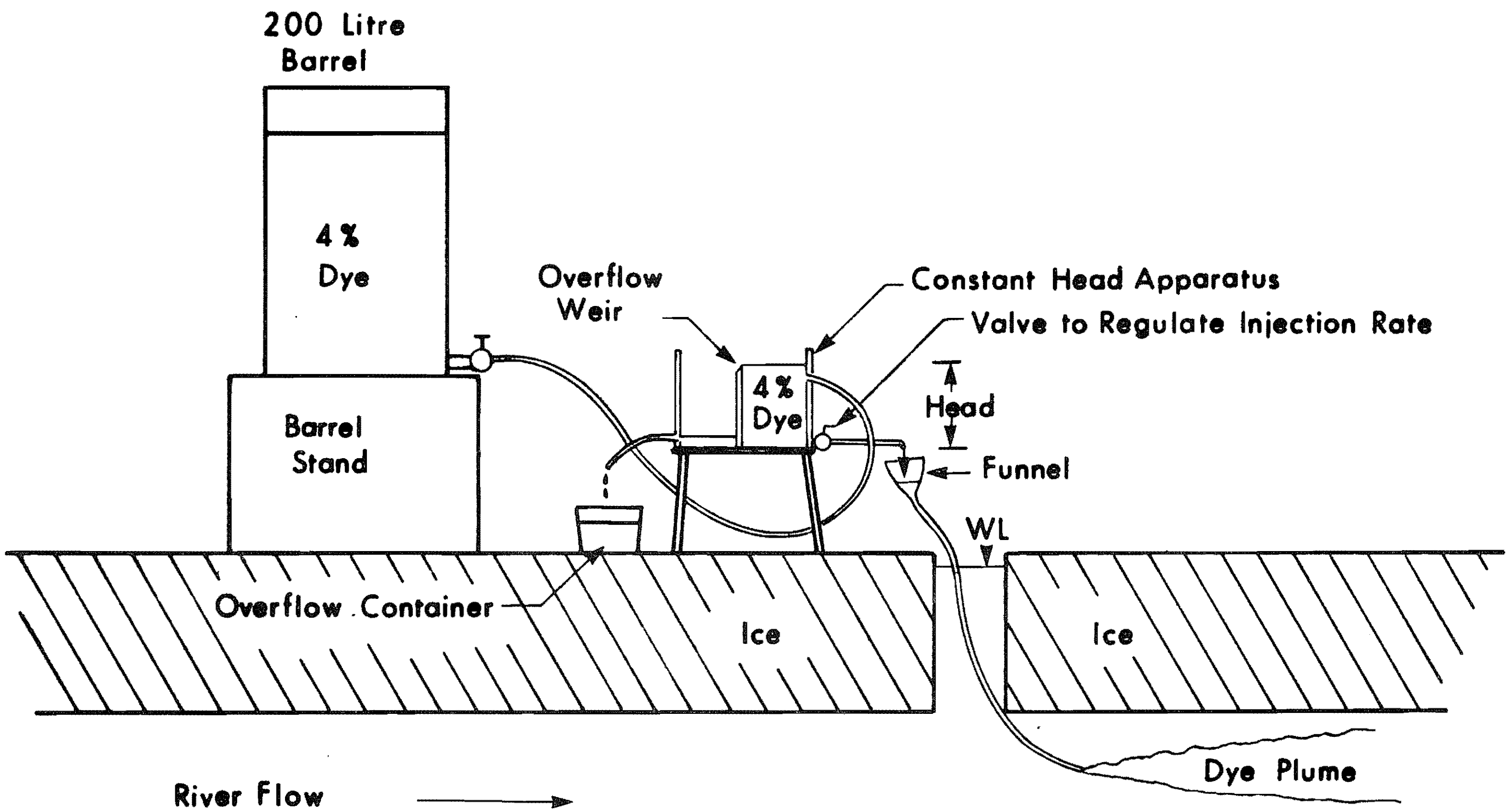

Figure 5. Sketch of injection setup; steady state test.

equal sections, were sampled as frequently as was thought necessary to define the corresponding time-concentration curves.

To determine travel times to the delta, one sampling site was established at each of the main distributary channels, i.e. Embarras River, Fletcher Channel, Goose Island Channel and Big Point Channel, as shown in Figure 4. Distances from the injection site along the main flow paths were respectively 198.7, 196.4, 212.0 and 214.2 km. Four automatic samplers were used to facilitate this part of the sampling program. It had been intended that each sampler would provide 12 samples every 24 hours while being serviced daily by a crew stationed at Fort Chipewyan. Despite comprehensive preliminary testing, the samplers malfunctioned occasionally during the sampling period. Thus, the time-concentration curves at the delta sites were not as well defined as those observed at the three Athabasca River sites.

Ultimately, a sampling site was established in Lake Athabasca near Fort Chipewyan in the hope of obtaining an estimate of the time of travel through the lake. Samples taken by the Alberta Research Council crew while at Fort Chipewyan showed that the dye had not reached this site when the distributary channel sampling was completed.

2.3 HYDROMETRIC MEASUREMENTS

The injection site and the cross sections located 4, 8.3, 13.8, 19.9, 26.95, 34.2, 48.3, 59.5, 68.5, 83.3, and 107.6 km downstream of injection were sounded to determine the cross-sectional geometry of the channel. In addition, sections 0 km and 13.8 km were current metered to determine corresponding velocity distributions.

At the end of January, a reconnaissance trip to the Athabasca River delta was undertaken to document the flows and flowpaths of the various distributary channels. In addition, flow velocities for estimating sampling times were measured. During this trip, suitable sampling sites were selected and the distributary channels were sounded and current metered at these sites.

Figure 4 shows the locations of all available cross sections in the study reach.

3. RESULTS

3.1 HYDROMETRIC DATA

Figure 6 shows the cross-sectional geometry of the sections surveyed during the test period. Velocity measurements at 0 km and 13.8 km as well as the distributary channel sections are summarized in the form of isovel contour graphs in Figure 7.

Table 2 summarizes mean daily flows in the Athabasca River for the period 20 January to 27 February 1978. These flows were estimated by the Water Survey of Canada[1], based on records for the Athabasca River gauge below Fort McMurray. Flow data at the Embarras gauge are not being recorded during the winter season. Infrequent flow measurements by Water Survey of Canada[1] for the major tributaries below Fort McMurray, indicated discharges of 0.3 m^3/s, 1.0 m^3/s, and 7 m^3/s for the MacKay, Ells, and Firebag Rivers respectively. For the dye test period, 15-28 February, the Athabasca River discharge is thus estimated as 182 and 189 m^3/s for the reaches upstream and downstream of the Firebag River respectively. The discharges calculated from current metering notes at 0 km and 13.8 km were respectively 168 and 193 m^3/s. These values are close to the value of 182 m^3/s deduced from Water Survey of Canada data. During the field operations, several photographs, showing various aspects of the river were taken. Of these, a selected set is included in Appendix 8.3.

---

[1] This work is funded by AOSERP under subproject HY 1.1.

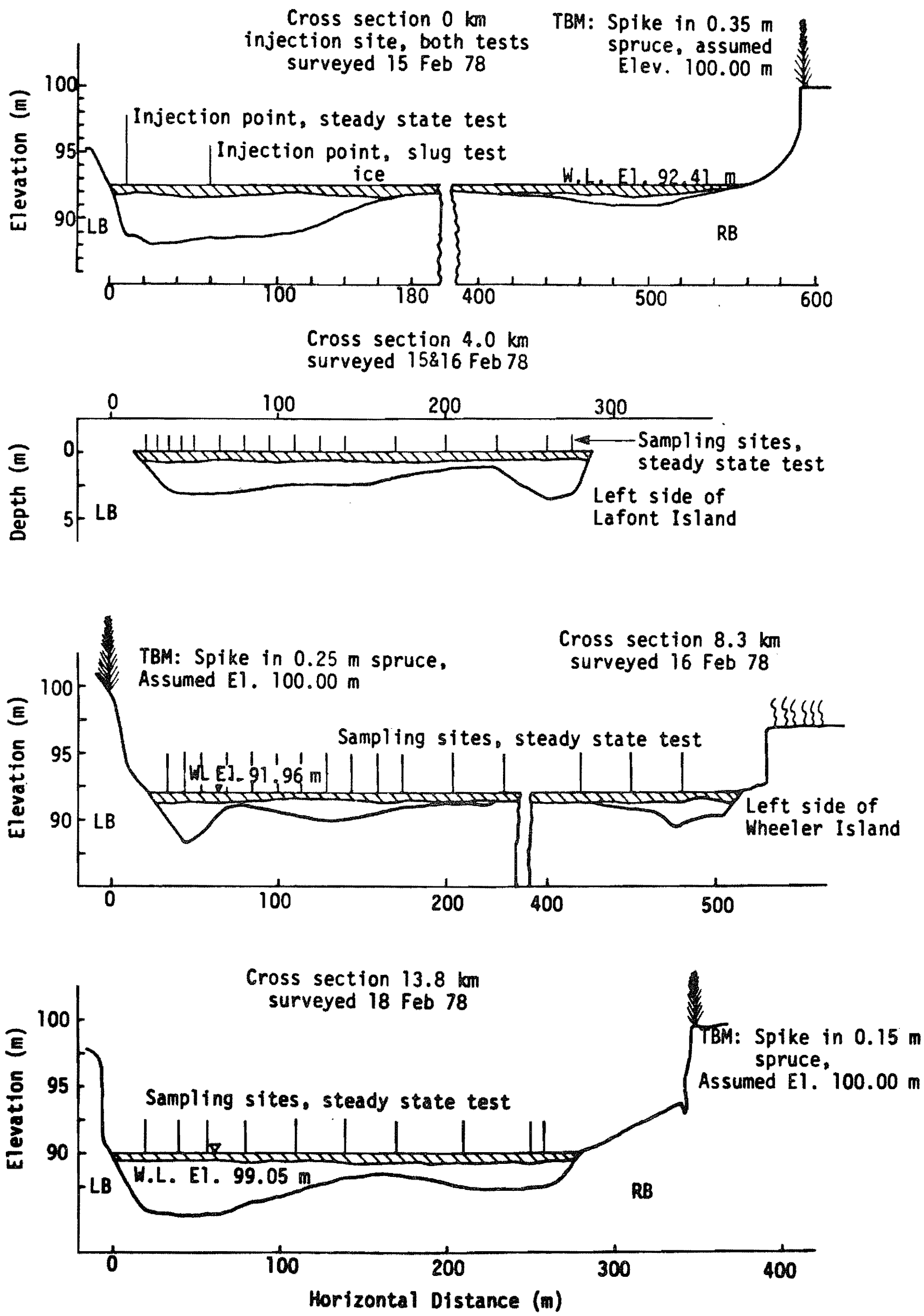

Figure 6. River cross sections surveyed at 12 sites during test period.

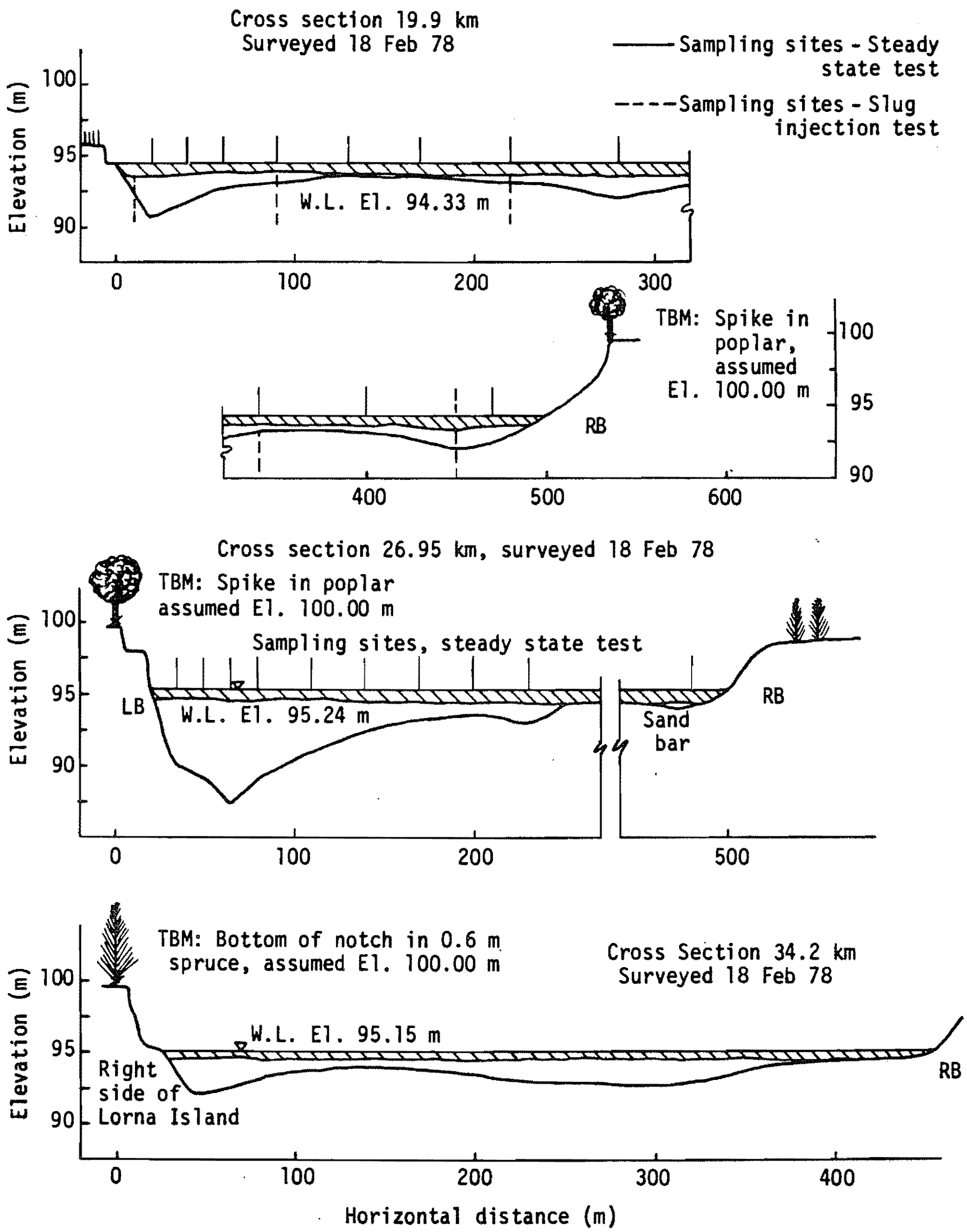

Figure 6. Continued.

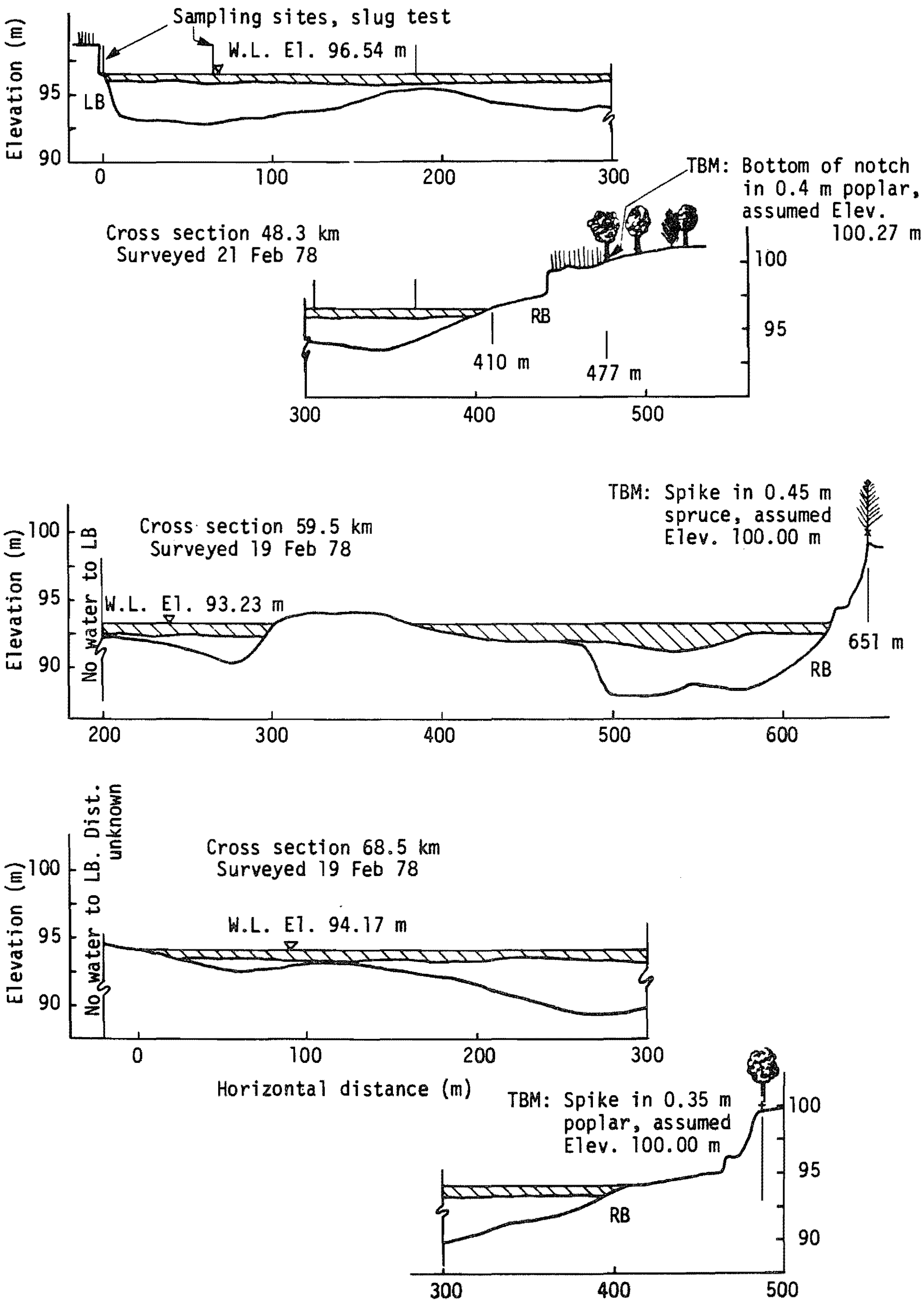

Figure 6. Continued.

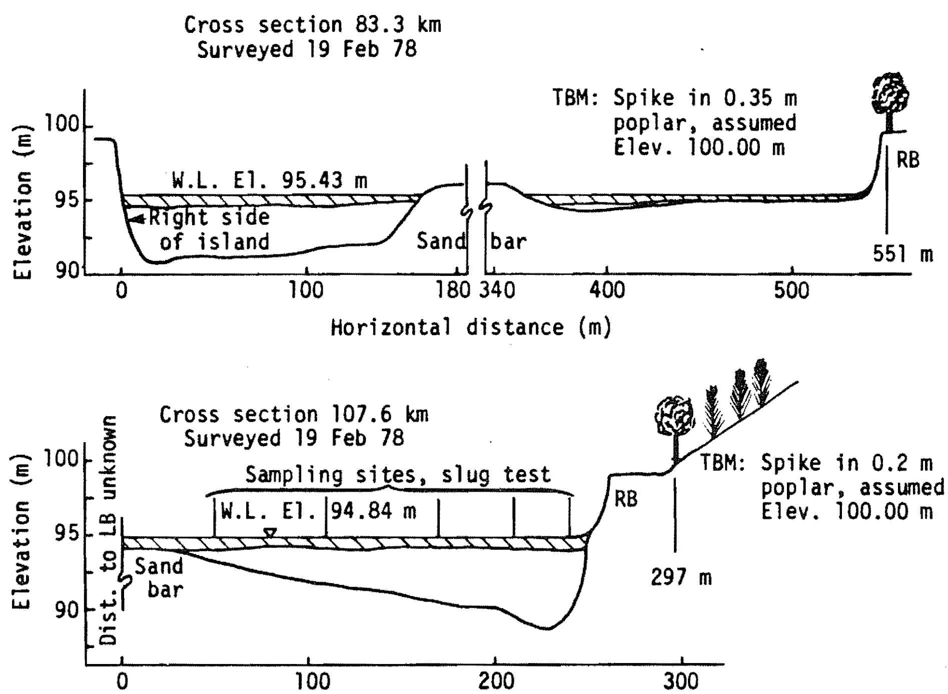

Figure 6. Concluded.

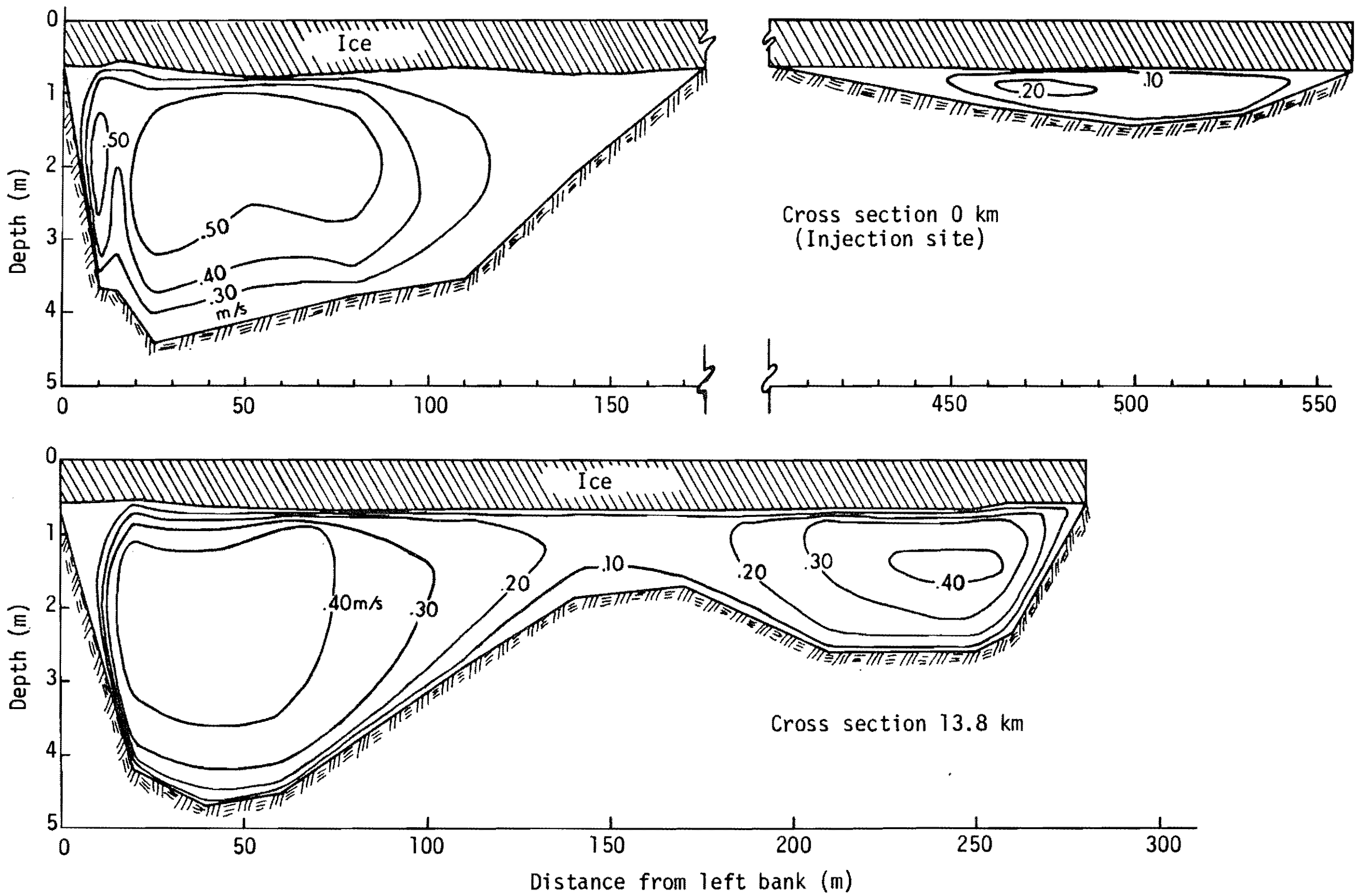

Figure 7. Equal-velocity contours at 6 sites; cross sections 0 and 13.8 km (contour values are in m/s).

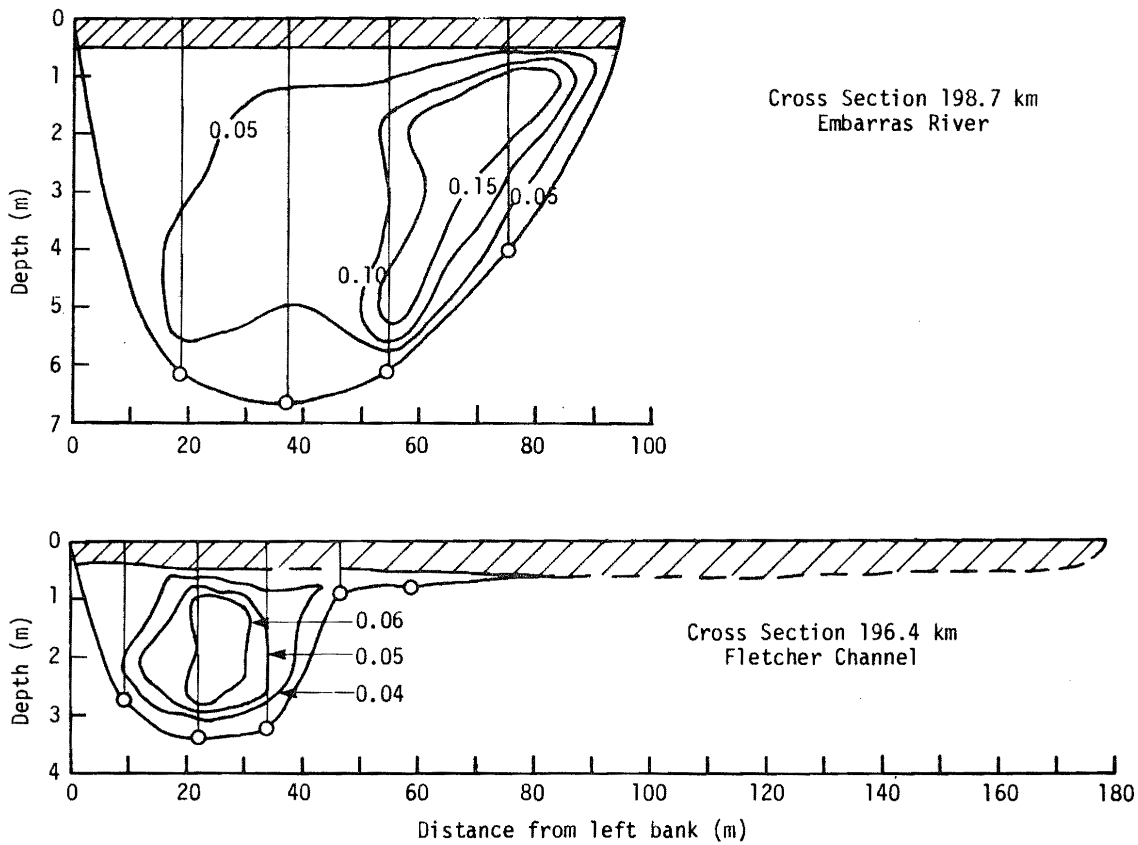

Figure 7. Continued; cross sections 198.7 km and 196.4 km (contour values are in m/s).

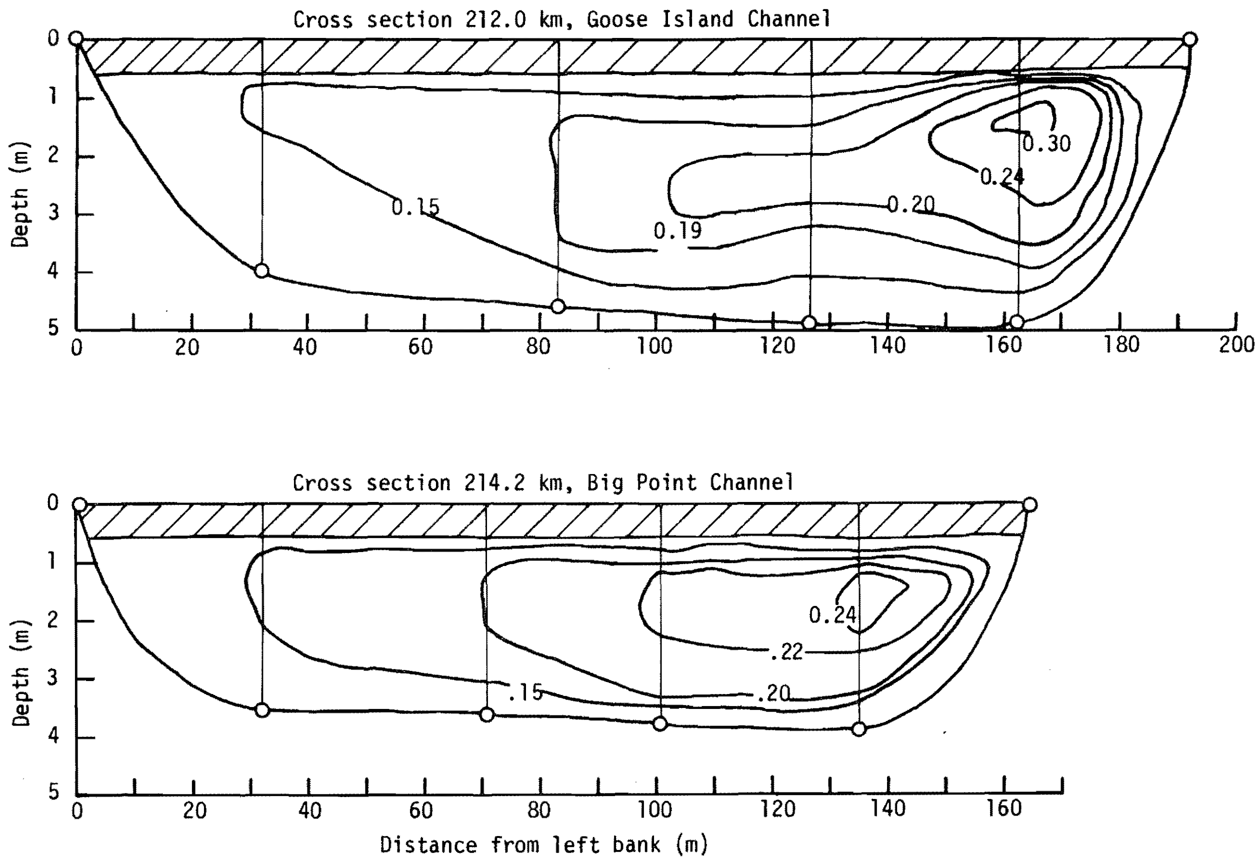

Figure 7. Concluded; cross sections 212.0 km and 214.2 km (contour values are in m/s).

Table 2. Mean daily flows, Athabasca River below Fort McMurray[a].

Date 1978	Discharge m^3/s	Date 1978	Discharge m^3/s	Date 1978	Discharge m^3/s	Date 1978	Discharge m^3/s
20 January	217	30 January	209	09 February	193	19 February	181
21 January	218	31 January	205	10 February	189	20 February	181
22 January	218	01 February	203	11 February	187	21 February	181
23 January	218	02 February	204	12 February	184	22 February	181
24 January	217	03 February	204	13 February	182	23 February	181
25 January	215	04 February	198	14 February	181	24 February	182
26 January	214	05 February	202	15 February	181	25 February	181
27 January	214	06 February	200	16 February	181	26 February	181
28 January	212	07 February	199	17 February	181	27 February	181
29 January	210	08 February	196	18 February	182	-	-

[a] Data provided by Water Survey of Canada.

The longitudinal profile of the Athabasca River has been presented by Kellerhals, Neill, and Bray (1972). Inspection of this profile showed that the water surface slope is fairly constant in the reach 0 km to the head of the Embarras River, with an average value of 0.117 m/km. The Athabasca River flattens considerably below the Embarras River having an average slope of about 0.03 m/km between this location and the delta.

Discharge measurements in the various distributary channels above Lake Athabasca are summarized in Figure 8, which is a schematic representation of the major distributary network. River distances of significant junctions from the injection site are also shown in Figure 8.

Analysis of the tracer test results requires the cumulative discharge and cumulative area distributions for the available cross sections. Cumulative discharge is the discharge between the left bank and a vertical located z m off this bank. Quantitatively, the cumulative discharge q is defined by:

$$q = \int_0^z h u_d \, dz \qquad (1)$$

where h and u_d are local values of depth and depth averaged velocity respectively (see also Figure 2). Similarly, one can define the cumulative area, a, by:

$$a = \int_0^z h \, dz \qquad (2)$$

If Q and A are used to denote the river discharge and total cross-sectional area respectively, the ratios q/Q and a/A will vary across the stream between the values 0 and 1. Plots of q/Q and

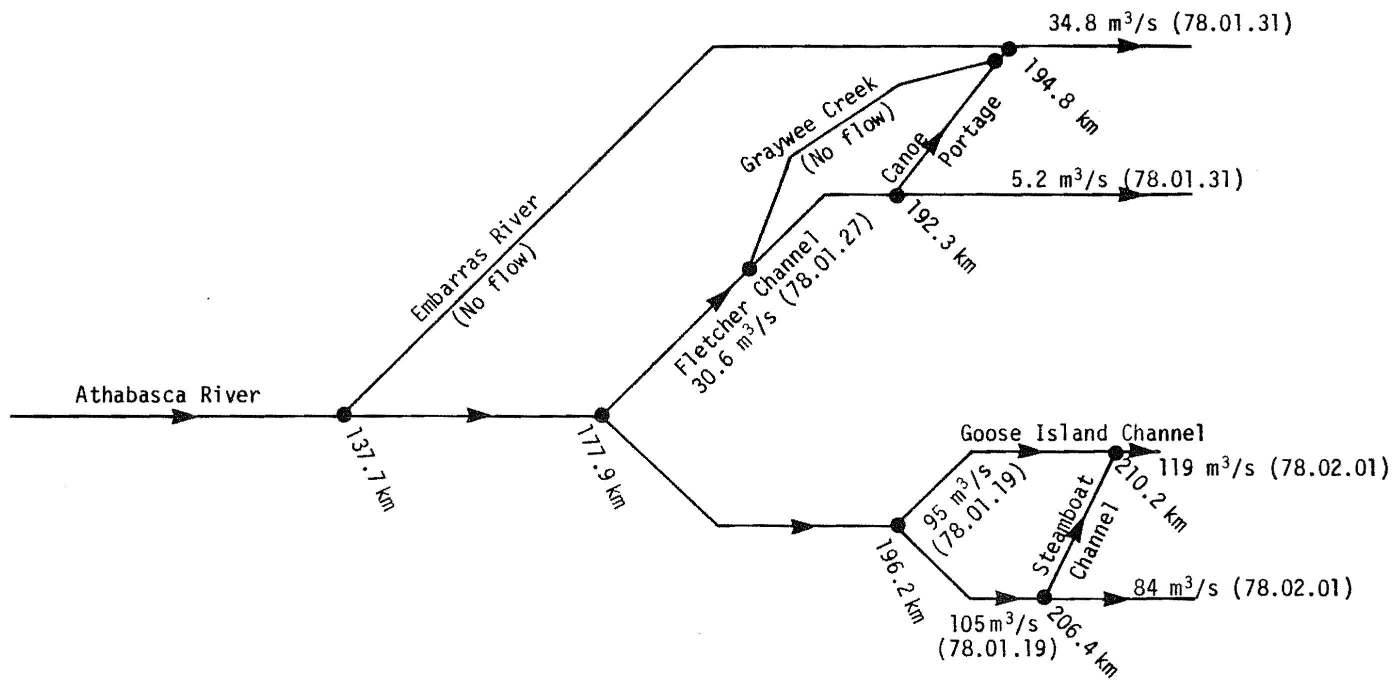

Figure 8. Schematic representation of flows in distributary channels (flows dated prior to January 31, 1978 were measured by the Fort Chipewyan Survey Branch of Alberta Environment).

a/A versus z are shown in Figure 9.

Calculation of a/A at a cross section requires only the depth profile. However, calculation of q/Q requires, in addition, the corresponding profile of the depth averaged velocity u_d. The latter can be determined from current metering notes for sections 0 km and 13.8 km. For the remaining sites, q/Q graphs were synthesized using a procedure outlined by Beltaos (1978a).

Additional hydrometric information for the study reach can be obtained by adapting cross sections surveyed in the past to the conditions prevailing during the February 1978 tests. To adapt the cross-sectional geometry of these sites to the test conditions, the following assumptions were made:

1. The difference in water levels between the date a section was surveyed and a specified date in February 1978, is equal to the corresponding difference indicated by the gauge below Fort McMurray; and

2. The ice thickness is equal to the average ice thickness determined from actual thickness measurements during the test period.

A summary of hydrometric data for all cross sections within the study reach is given in Appendix 8.4. Table 3 gives a list of these sections together with dates of surveys and average dimensions.

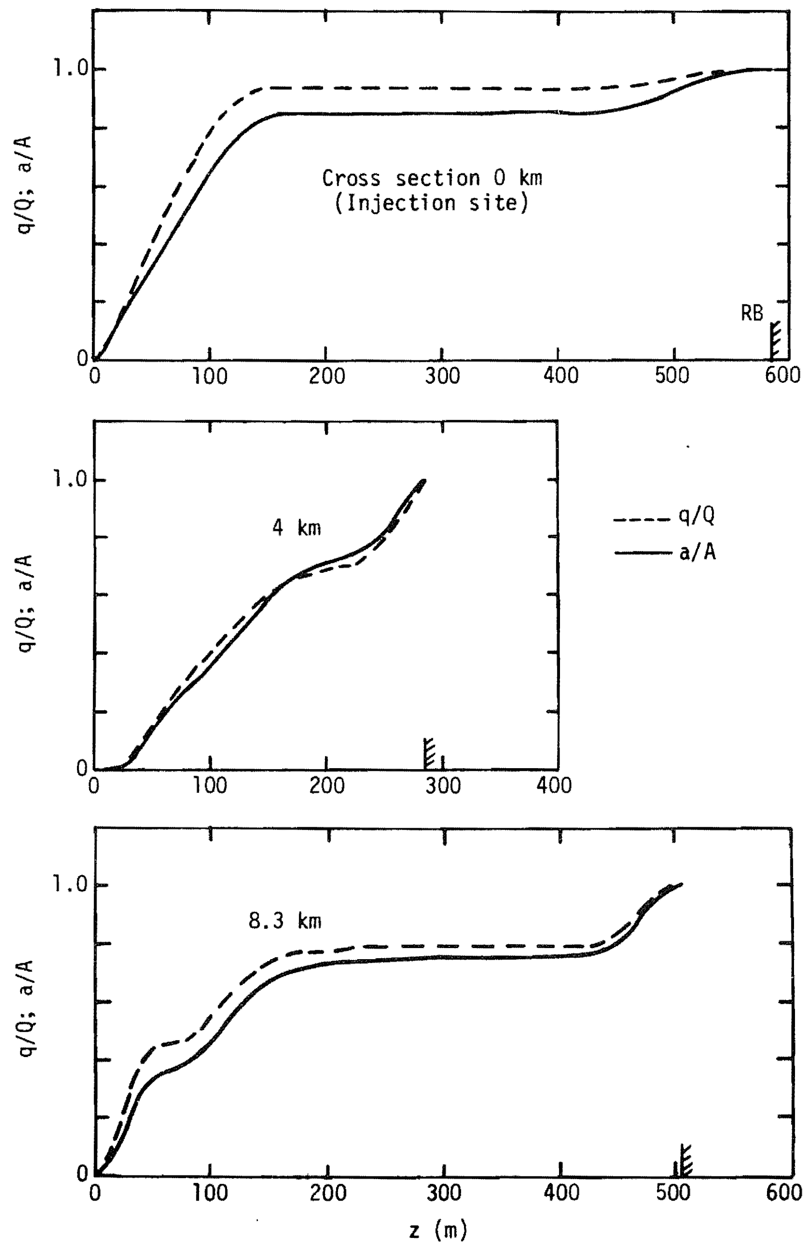

Figure 9. Cumulative area and discharge graphs for 12 sites.

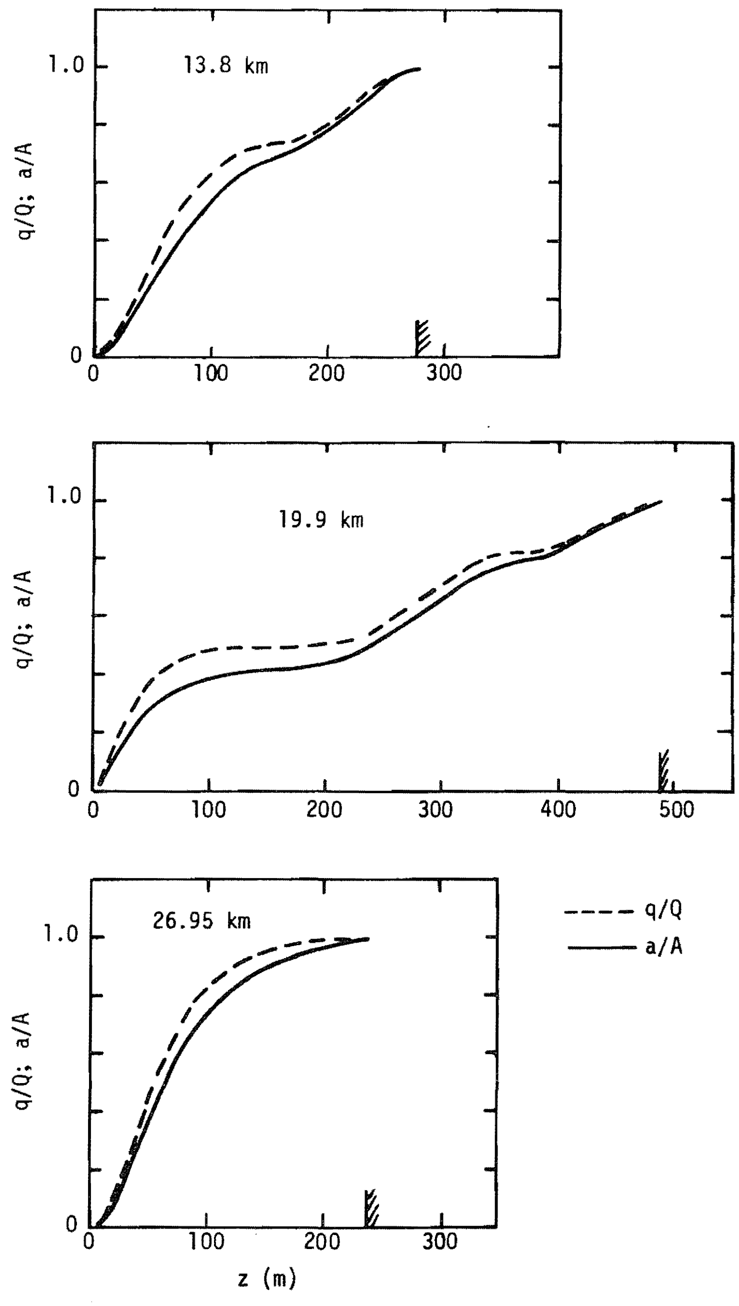

Figure 9. Continued.

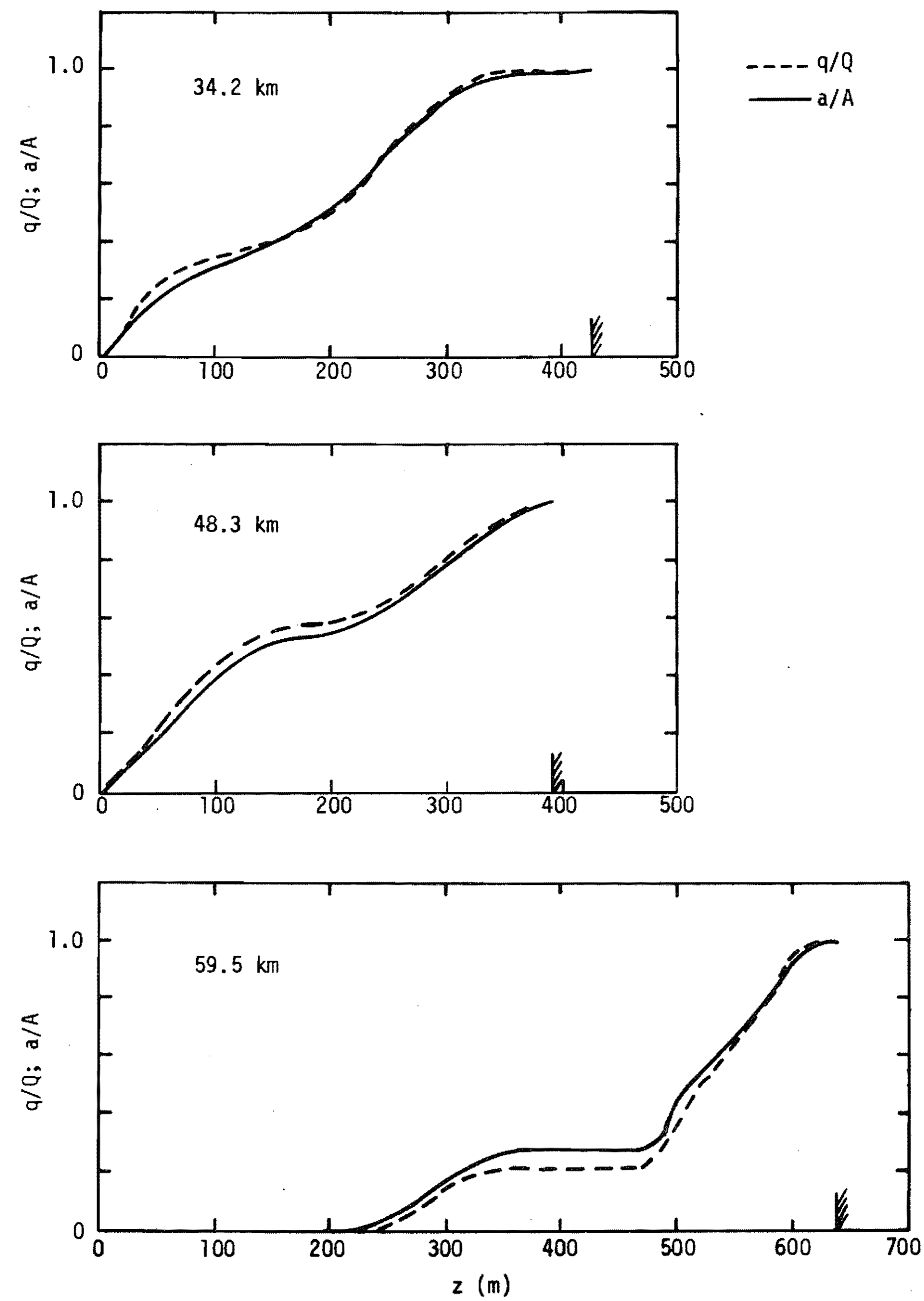

Figure 9. Continued.

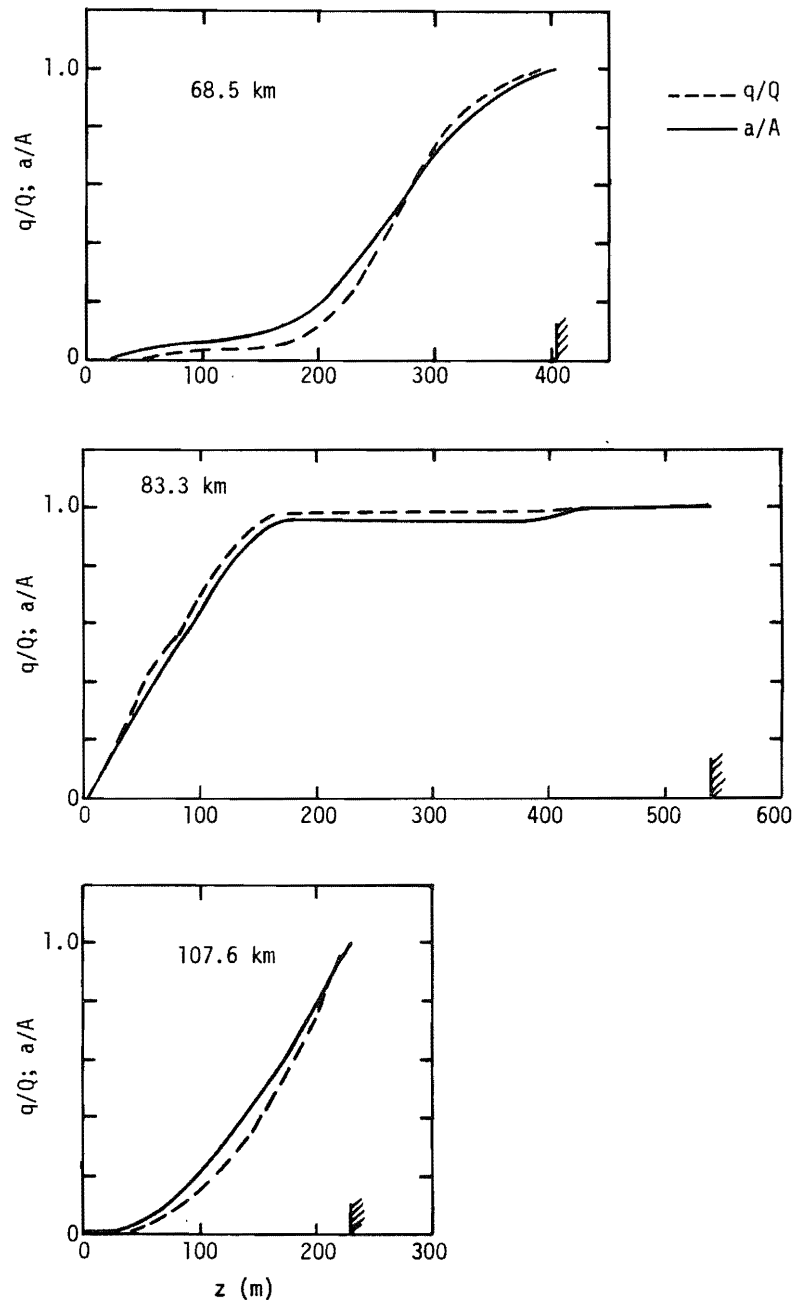

Figure 9. Concluded.

Table 3. Summary of cross-sectional data.

Cross section (km)	Date surveyed	Area (m^2)	Width (m)	Average depth (m)
0.0	15.02.78	499.6	365	1.37
4.0	15,16.02.78	432.5	287	1.51
6.7	15.08.73[a]	812.2	476	1.71
8.3	16.02.78	337.2	356	0.95
11.0	16.08.73[a]	720.9	354	2.04
13.8	18.02.78	599.1	280	2.14
19.9	18.02.78	452.2	490	0.92
25.3	15.08.73[a]	787.7	430	1.83
26.95	16.02.78	634.5	240	2.64
30.1	15.08.73[a]	583.8	182	3.21
34.2	18.02.78	476.6	425	1.12
38.2	14.08.73[a]	485.0	467	1.04
44.5	14.08.73[a]	448.0	408	1.10
48.3	21,23.02.78	704.6	395	1.78
51.6	12.08.73[a]	779.8	556	1.40
59.5	19.02.78	681.8	580	1.18
68.5	19.02.78	637.1	410	1.55
83.3	19.02.78	521.3	345	1.51
93.5	25.08.70[a]	488.6	298	1.64
101.4	25.08.70[a]	826.8	303	2.73
107.6	19.02.78	589.3	230	2.56

[a] Area, width, and depth adapted to February 1978 flow conditions.

3.2 TRACER TEST DATA

3.2.1 Steady State Test

Profiles of measured steady state concentrations across each of the five sampling sites are shown in Figure 10. Using the cumulative discharge graphs of Figure 9, these concentrations can be replotted versus q/Q as shown in Figure 11. This figure seems to give a more consistent picture of the mixing process than does Figure 10. Figure 11 shows that concentration profiles tend to spread laterally with increasing distance from the source while the maximum concentration tends to decline. This trend is not fitted by the profile at 13.8 km. As mentioned earlier, the discontinuation of injection during the early morning of 17 February 1978 was expected to have a significant effect on the measured concentrations at this site. Using the results of the slug injection test as a guide, it was estimated that, during the period of sampling at 13.8 km, the concentration would be in a steady state only near the channel banks. Concentrations near the midstream would be less than the corresponding steady state value and decreasing.

3.2.2 Slug Injection Test

Time-concentration curves observed at the various sampling sites during this test are shown in Figures 12, 13, 14, and 15. Figures 12 to 14 show the curves obtained in the Athabasca River while Figure 15 shows the curves observed at the four distributary channels near the delta.

The upper graphs of Figures 12 to 14 show the time-concentration curves observed in the main channel of the river and

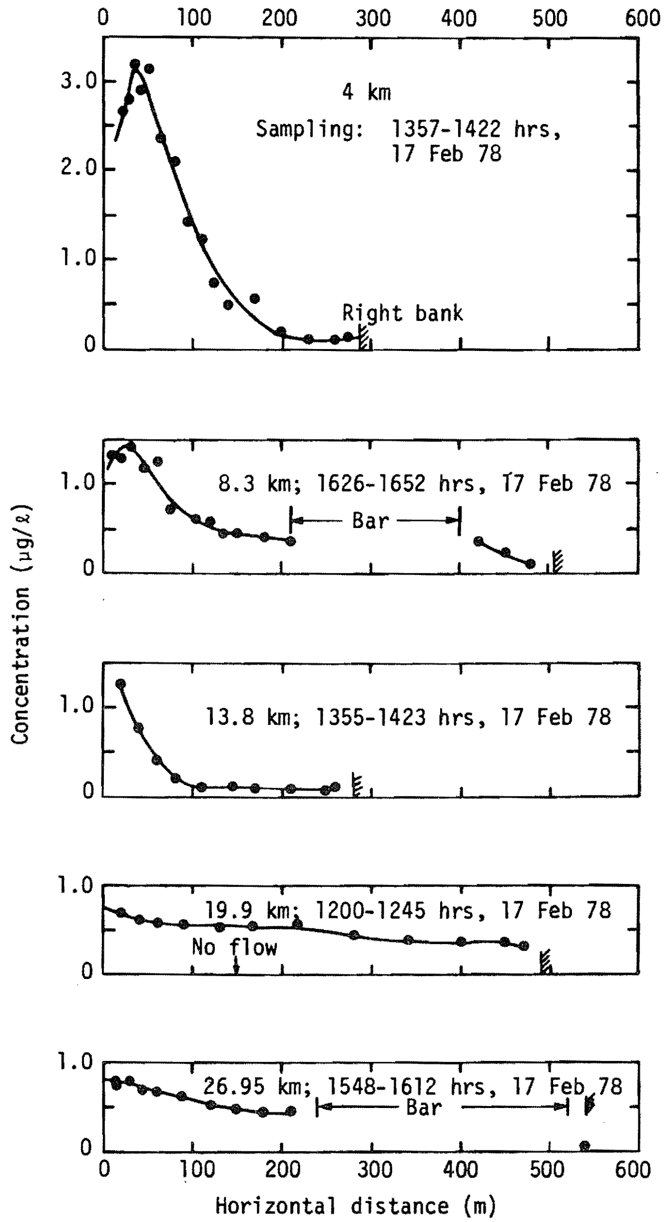

Figure 10. Observed concentration profiles; steady state test.

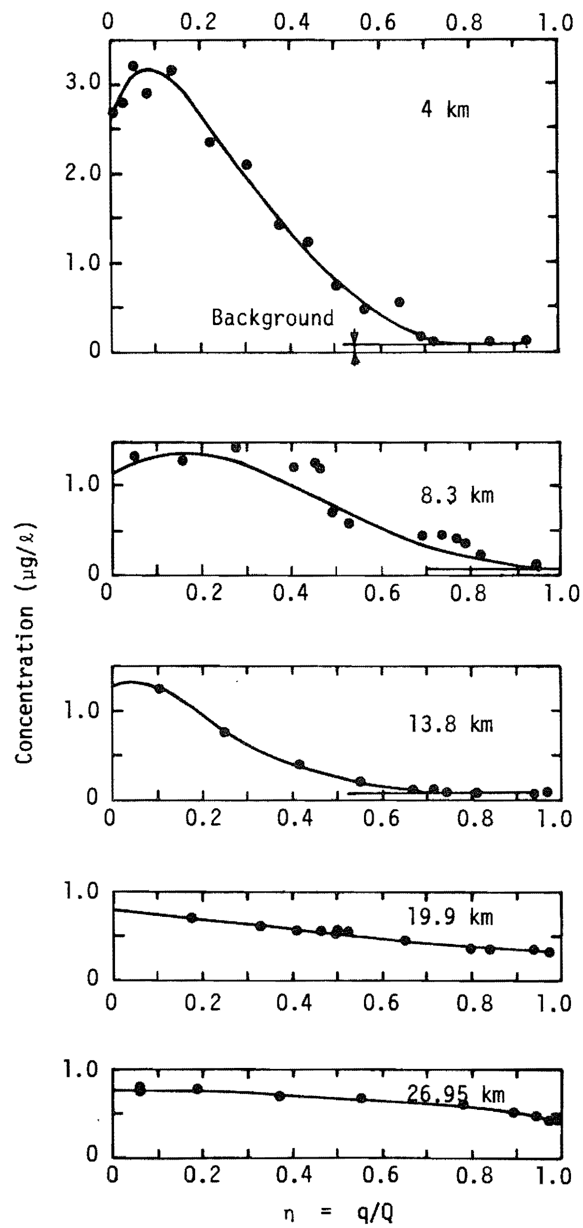

Figure 11. Concentration profiles in terms of cumulative discharge; steady state test.

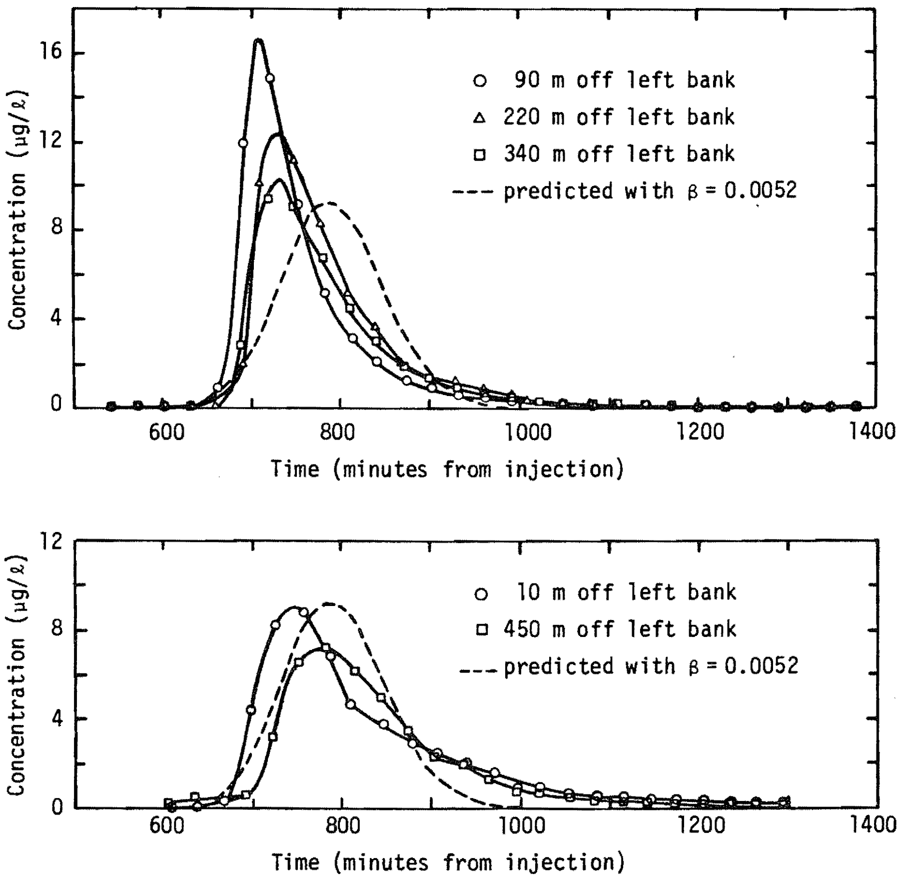

Figure 12. Time-concentration variations; slug test, 19.9 km.

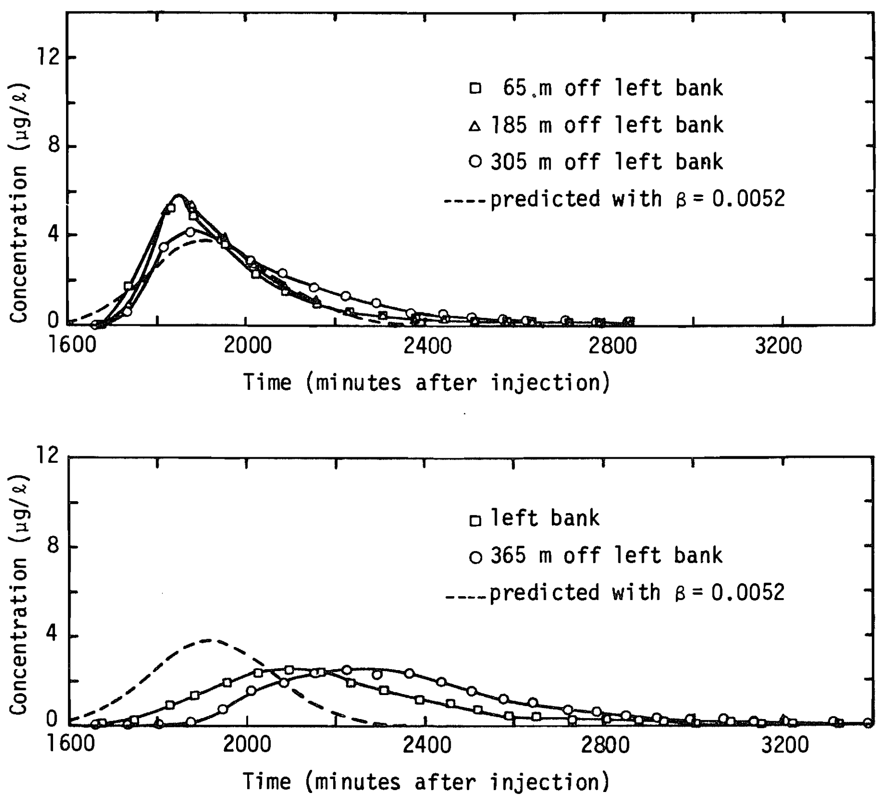

Figure 13. Time-concentration variations; slug test, 48.3 km.

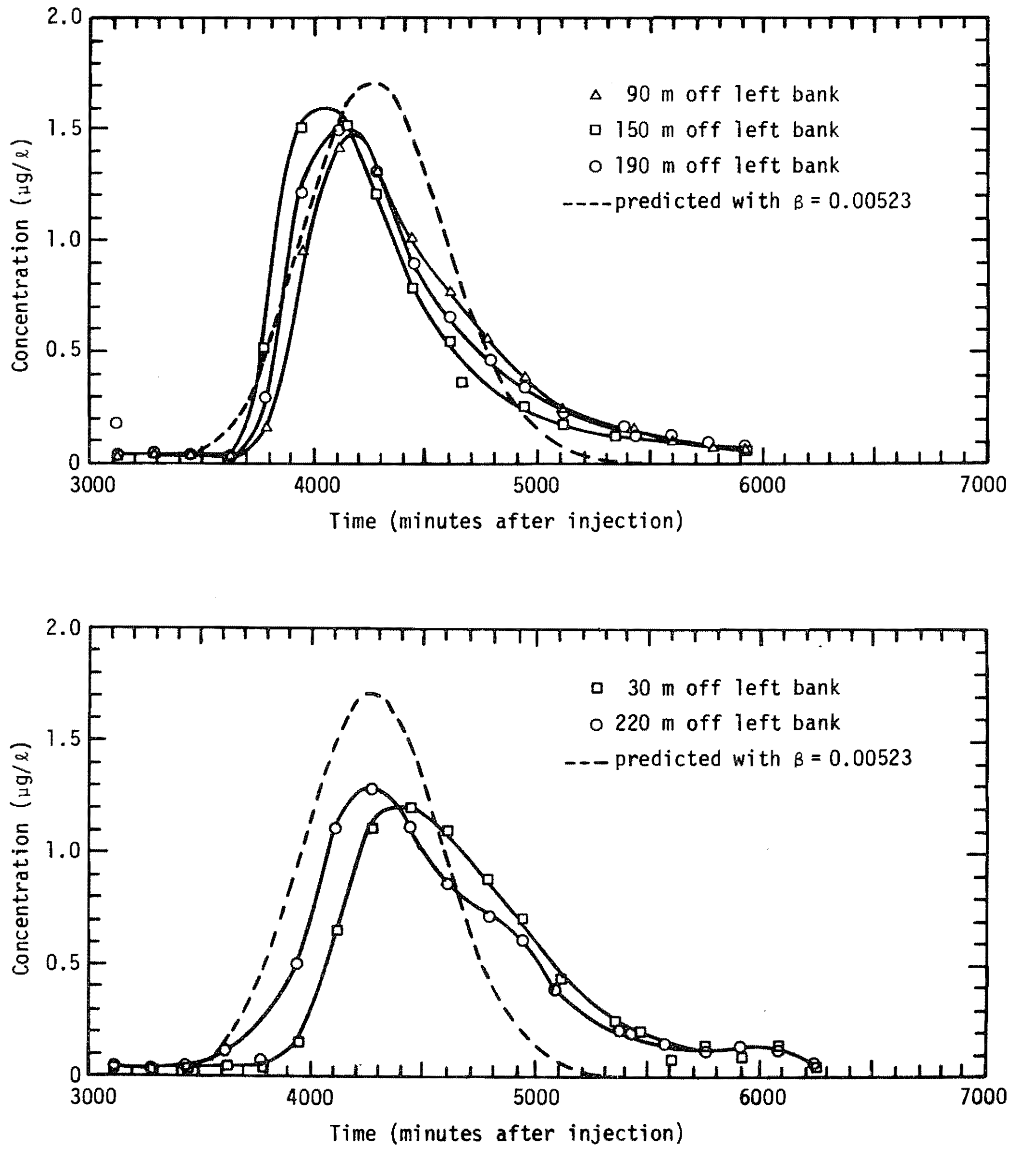

Figure 14. Time-concentration variations; slug test, 107.6 km.

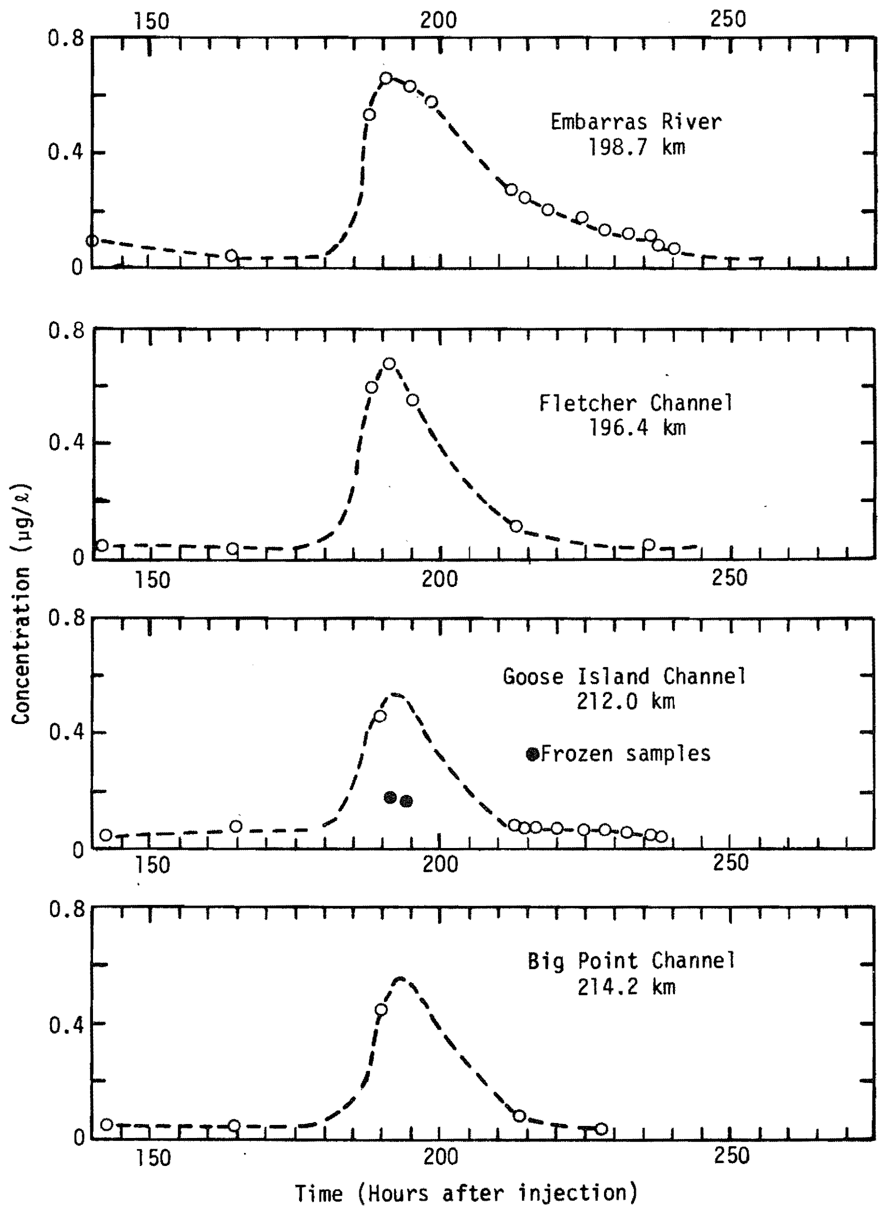

Figure 15. Time-concentration variations; slug test, distributbutary channels.

the lower graphs show the curves observed near the banks. As it was expected, the bank curves exhibit lower peaks and longer durations than the main channel curves. This is due to the relatively low velocities prevailing near the banks. However, differences between main channel and bank curves tend to diminish with increasing distance from the injection site, which reflects the tendency of the mixing process to approach a state of one-dimensionality. This can be further illustrated by examining lateral variations of some characteristic parameters of time-concentration curves. Figure 16 shows profiles of the time to peak concentration, t_p. This time provides a measure of the time of travel of the tracer (Beltaos 1978b) and its variation across the stream is seen in Figure 16 to be minor. A measure of the temporal spread, or residence time, of the tracer is given by the quantity ΔT, which is defined as the duration of concentrations exceeding one-half of the peak concentration. Profiles of ΔT are shown in Figure 17. Unlike t_p, ΔT varies considerably across the river, being least at midstream and largest near the banks. A similar, but reversed, trend is exhibited by the profiles of the peak concentration C_p, as shown in Figure 18.

A useful parameter in transient mixing studies is the dosage θ, defined as the area under a time-concentration curve, viz:

$$\theta = \int_0^\infty C\,dt \qquad (3)$$

Obviously, θ does not depend on time. Moreover the variation of θ

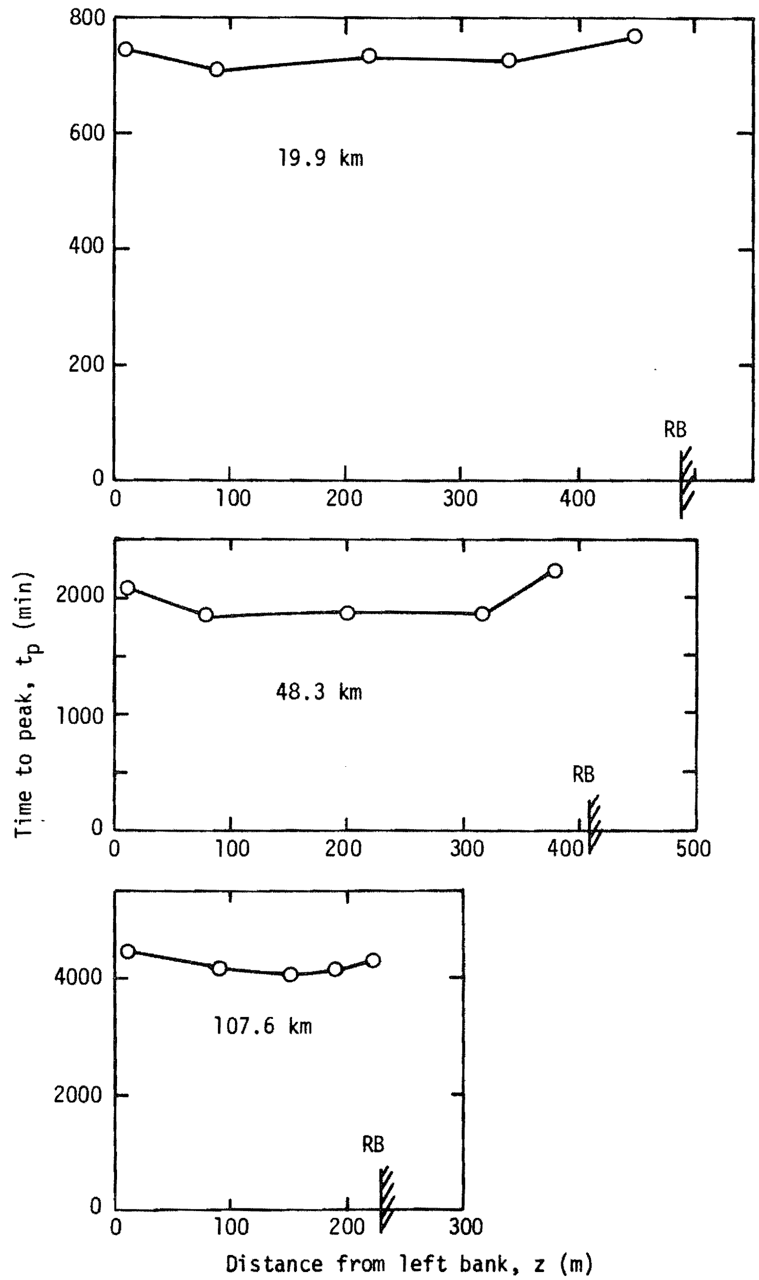

Figure 16. Lateral variations of time to peak concentration, t_p; slug test.

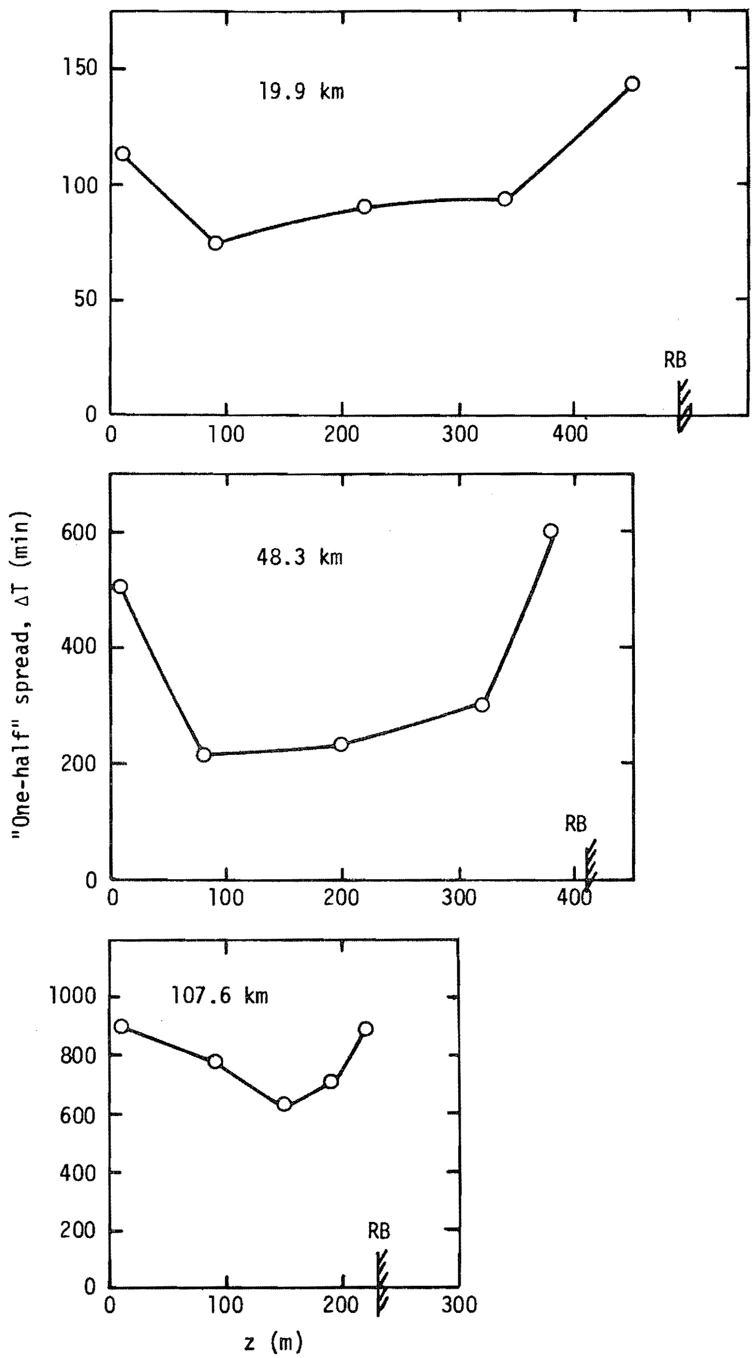

Figure 17. Lateral variations of "one-half" time spread, ΔT; slug test.

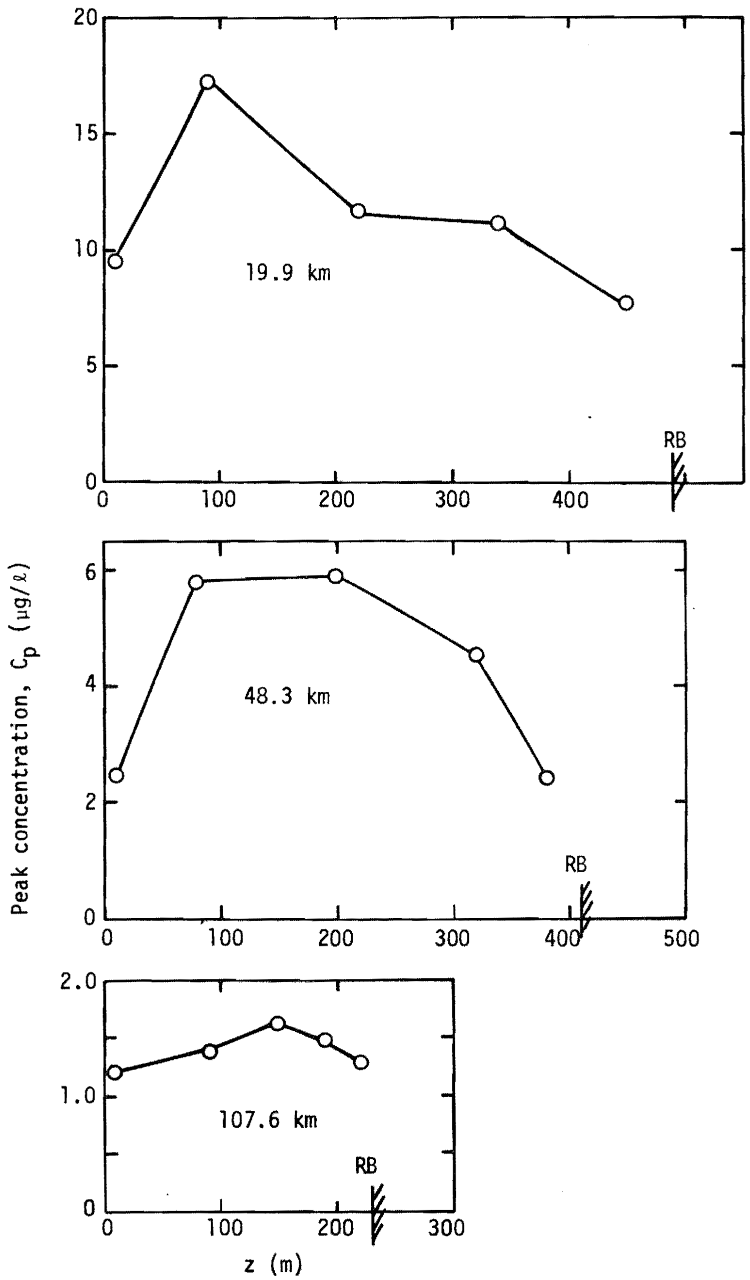

Figure 18. Lateral variations of peak concentration, C_p; slug test.

along and across the stream is identical to that of the steady state concentration which would result from continuous injection at the same point(s) as the one(s) used for the slug injection (Beltaos 1975). The discharge-weighted average value of θ at any one sampling site can be used to calculate the total tracer mass passing through the site via the equation:

$$Q \, \overline{\theta} = M \qquad (4)$$

where M is the tracer mass passing through a site and $\overline{\theta}$ is the discharge-weighted average dosage. For a neutral tracer, M should be equal to the injected mass M_o. Hence for constant river discharge, Equation 4 shows that $\overline{\theta}$ should not change along the stream, being everywhere equal to M_o/Q.

Figure 19 shows dosage profiles across the three Athabasca River sampling sites. These seem to indicate a well mixed condition for $\overline{\theta}$. The value of $\overline{\theta}$ does not seem to change significantly along the stream, being about 1400 μg min/ℓ. Using M_o = 150(0.20) = 30 kg and Q = 182 m^3/s, gives M_o/Q = 2750 μg min/ℓ which is twice the above figure. This discrepancy can be due to either, or both, of the following: substantial dye losses occurred in the first 20 km of the study reach, and the actual concentration in the dye containers used for the test was less than the value of 20% quoted by the dye manufacturer. Considering that much of the dye used for this test was several years old and an abrupt disappearance of losses below 20 km appears odd, the latter explanation is thought to be more likely.

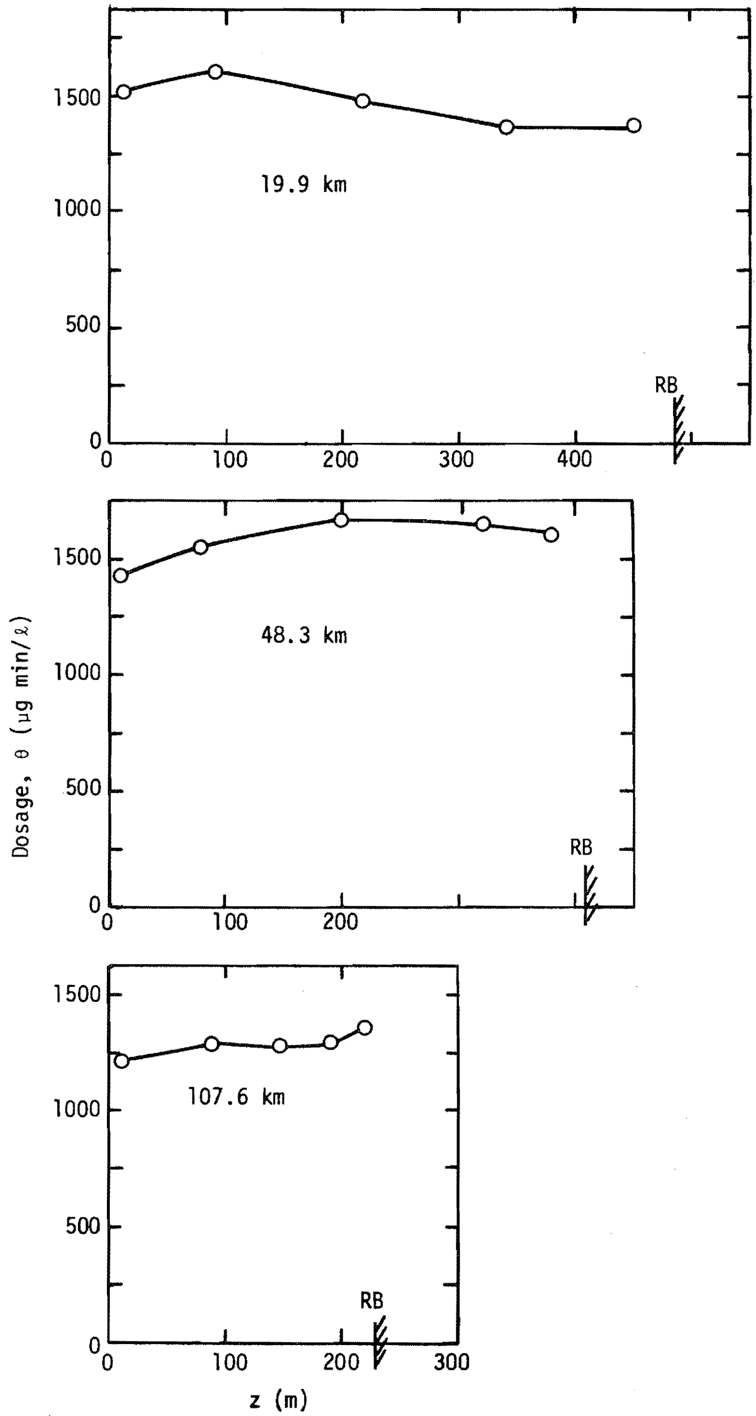

Figure 19. Lateral variations of dosage, θ; slug test.

4. ANALYSIS OF RESULTS

4.1 CHANNEL HYDRAULICS

Using the cross-sectional data summarized in Table 2, the average channel width and depth were calculated as 370 m and 1.55 m respectively[1]. The average cross-sectional area is then $370 \times 1.55 = 575\ m^2$, which implies an average stream velocity $V = 189/575 = 0.33$ m/s. A more reliable estimate of V is given by the observed times of travel of the tracer during the slug injection test. As will be seen later, this evaluation gave $V = 0.42$ m/s, which is about 26% larger than the previously quoted value. Two possible reasons can be cited for this discrepancy: (1) the channel cross sections used in computing average channel hydraulics are not representative of the true cross-sectional geometry of the stream, and (2) the discharge estimates provided by Water Survey of Canada might be inaccurate. Normally, the error associated with such estimates is in the range ± 10% - 15%, but this range could be somewhat larger for ice-covered flow conditions.

Using a slope of 0.117 m/km for the Athabasca River above the head of the Embarras River, the average shear velocity V_*, is $V_* = \sqrt{9.8(1.55/2)0.000117} = 0.030$ m/s. With $V = 0.42$ m/s, the friction factor f, is $f = 8(0.03/0.42)^2 = 0.040$, and the overall

---

[1] Averaging has been carried out using the equations proposed by Beltaos and Day (1976), viz: average width = stream surface/stream length; average depth = stream volume/stream surface. Stream volume and surface were estimated assuming that areas and widths vary linearly between successive cross sections.

Manning coefficient n_o for the ice-covered, composite roughness flow is $n_o = (1.55/2)^{2/3}(0.000117)^{1/2}/0.42 = 0.022$.

Using the cross-sectional measurements at each of the four distributary channels near the delta, approximate values of hydraulic parameters were calculated and are summarized in Table 4.

4.2 STEADY STATE TEST: THE TRANSVERSE MIXING COEFFICIENT

A common method for evaluating the transverse mixing coefficient from steady state tests is the so-called method of moments. Letting η denote the normalized cumulative discharge q/Q, it can be shown that (Beltaos 1978a):

$$\sigma_\eta^2 = \frac{2D_z}{Q^2} \int_o^x f(x)\,dx \qquad (5)$$

where σ_η^2 is the variance of a C - η profile, such as the profiles shown in Figure 11, and D_z is defined by

$$D_z = \psi E_z V H^2 \qquad (6)$$

In Equation 6, E_z is the reach average value of the transverse mixing coefficient and ψ a shape-velocity coefficient given by

$$\psi = \int_o^1 \left(\frac{h}{H}\right)^3 \left(\frac{u_d}{V}\right)^2 d\left(\frac{z}{W}\right) \qquad (7)$$

The function f(x) is:

$$f(x) = 1 - (1 - \eta_o)\,C'_{RB} - \eta_o\,C'_{LB} \qquad (8)$$

where the suffixes RB and LB stand for "right bank" and "left bank" respectively; C' is the value of C divided by the discharge

Table 4. Summary of distributary channel hydraulics.

Channel	Location of section (km)	Date of survey (1978)	Discharge (m^3/s)	Average velocity (m/s)	Average depth (m)	Friction factor[a]
Embarras River	198.7	31 January	34.8	0.084	4.4	-
Fletcher[b]	179.7	27 January	30.6	0.13	2.1	0.15
Fletcher	196.4	31 January	5.2	0.05	0.6	-
Goose Island[b]	197.8	19 January	94.9	0.15	5.4	0.28
Goose Island	212.0	01 February	119.2	0.18	3.5	0.13
Big Point[b]	198.1	19 January	105.4	0.15	4.9	0.26
Big Point	214.2	01 February	83.6	0.19	2.7	0.09
Canoe Portage	192.3	31 January	34.9	0.31	1.3	-
Steam Boat[c]	-	31 January	24.3	-	-	-

[a] Estimated assuming a slope of 0.03 m/km.

[b] Measured by Fort Chipewyan Survey Branch, Alberta Environment.

[c] Deduced from other data.

weighted average concentration (for instance, in Figure 11 this concentration would be the area under a $C - q/Q$ curve).

Equation 5 shows that a plot of σ_η^2 versus $_o\int^x f(x)\,dx$ should give a straight line with a slope equal to $2D_z/Q^2$. This property can be used to compute D_z and thence E_z. Table 5 summarizes pertinent data for evaluating D_z and shows also that the site 13.8 km does not fit the trends of the various parameters listed. This is in agreement with previous discussion concerning the reliability of the measurements at this site. Figure 20 shows σ_η^2 plotted versus $_o\int^x f(x)dx$. It is seen that, with the exception of the 13.8 km section, the data points define a straight line of slope $8.0(10^{-6})\ m^{-1}$. It follows that $D_z = 0.5(8)10^{-6}(182)^2 =$ $= 0.13\ m^5/s^2$ and $E_z = 0.13/3.95(0.42)(1.55) = 0.033\ m^2/s$[1]. The dimensionless value of the transverse mixing coefficient E_z/V_*H is $0.033/0.03(1.55) = 0.72$.

Using the above value of D_z and the degree of mixing calculations of Yotsukura and Cobb (1972), we can determine the distance below the source at which "full" mixing of concentration would have been established (see also Beltaos 1978a). Defining "full" mixing as a condition corresponding to a degree of mixing[2] equal to 98%, gives a stream length of 94 km. For a degree of mixing equal to 95% the corresponding length is 66 km. For a

---

[1] For the steady state test reach, the average value of ψ was computed as 3.95, using all available cross sections.

[2] For a definition of the degree of mixing see Yotsukura and Cobb or Beltaos (1978a).

Table 5. Steady state test data for evaluating E_z.

Section (km)	η_o	σ_η^2	f(x)	$\int_o^x f(x)\,dx$ (km)
0	0.08[a]	0	1.0	0
4	0.225	0.0247	0.50	3.0
8.3	0.300	0.0388	0.52	5.2
13.8	0.189	0.0206	0.34	7.9
19.9	0.404	0.0750	0.05	9.1
26.95	0.455	0.0772	0.14	9.8

[a] Location of source.

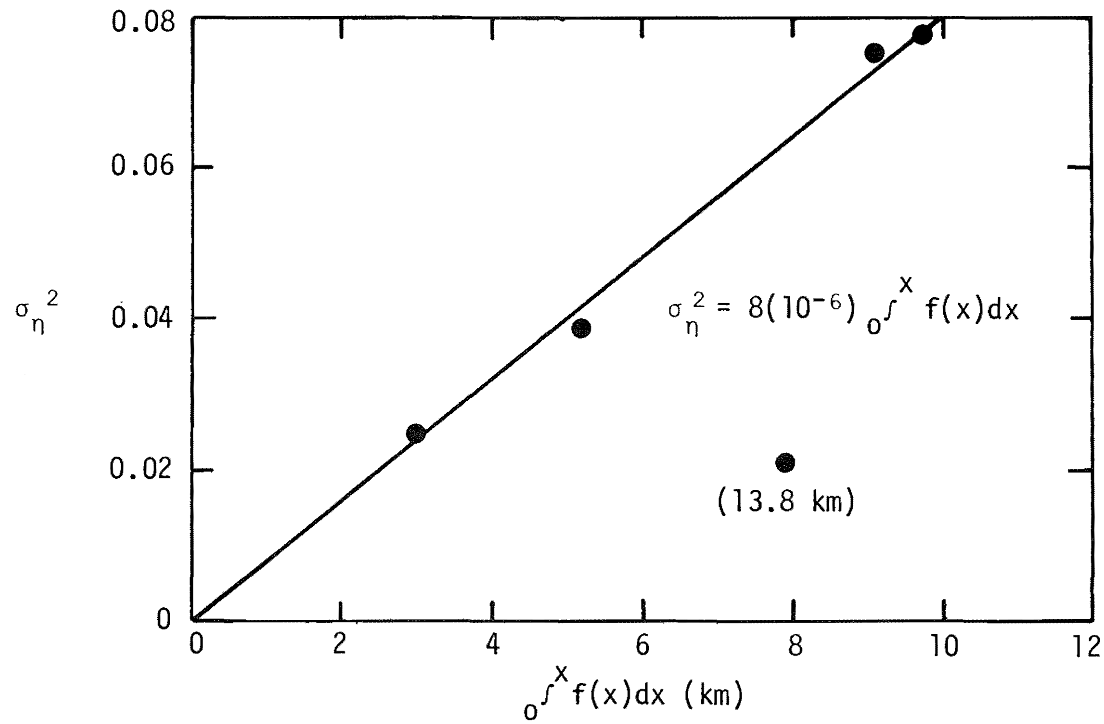

Figure 20. Plot of variance versus modified distance; steady state test.

point source located at the centroid of flow, these lengths would be 25 km and 17 km respectively. In view of previous discussion on the correspondence between steady state concentrations and transient mixing dosages, the above calculations explain the near uniformity of the dosage profiles shown in Figure 19.

It is of interest to compare the present findings with those of the preliminary test carried out in February 1974. This comparison is summarized in Table 6. The relatively high values of ψ and W/H applicable to the present test suggest a more irregular channel configuration for the present reach than the reach tested in 1974. One may thus be tempted to attribute the differences between respective values of E_z and E_z/V_*H to different stream configurations. However, the percent differences between the mixing coefficients shown in Table 6 are within experimental error and therefore cannot be assumed to be genuine.

Based on this discussion, it is recommended that an average value of E_z/V_*H be used for the entire reach from Fort McMurray to Embarras River. Because the 1974 evaluation of E_z involved one only sampling site, relative weights of 0.2 and 0.8 were assigned to the past and present tests respectively, to find:

$$E_z/V_*H = 0.70 \tag{9}$$

Making the transverse mixing coefficient dimensionless with the product of depth and shear velocity has become customary after Elder's (1959) work. Elder showed experimentally that, for two-dimensional open channel flow, the value of $E_z/V_* H$ was 0.16. Subsequent laboratory experiments in prismatic flumes have shown $E_z/V_* H$ to depend somewhat on the aspect ratio (width/average depth) and the friction factor of the stream. Engmann (1974) suggested that use of the hydraulic radius R_h (flow area/wetted perimeter), in place of the average depth H, removes most of the aspect ratio dependence for open channel flow. Moreover, Engmann's experiments showed that, in straight channels, $E_z/V_* R_h$ was about the same for both ice covered and open water conditions. Beltaos (1978a) reanalysed published laboratory data in straight flumes and found that, within experimental error, $E_z/V_* R_h$ was a weak function of the friction factor and generally varied between 0.1 and 0.3.

When dealing with natural streams, however, it should be kept in mind that flow curvature causes transverse *dispersion* which enhances the apparent value of the transverse mixing coefficient. Beltaos (1978a) reviewed pertinent field data and found $E_z/V_* H$ to vary between 0.1 and 3.3. These data included four river reaches where tests were performed under both ice covered and open water conditions. Contrary to Engmann's (1974) finding, these results suggested that, for a given reach, $E_z/V_* H$ is about the same for both ice covered and open water conditions[1]. Values

---

[1] Of the four reaches under consideration, only one gave the same value of $E_z/V_* R_h$ for both conditions (Engmann and Kellerhals 1974). However, the method used for analysing the results of this test was somewhat unorthodox and might have influenced the reported values of the mixing coefficients (Beltaos 1978a).

Table 6. Summary of 1978 steady state and 1974 test results.

Test reach	Date of test	Discharge Q (m^3/s)	Width W (m)	$\frac{W}{H}$	V (m/s)	f	ψ	E_z (m^2/s)	$\frac{E_z}{V_* H}$
11.8 km long, beginning at Syncrude dock	01.02.74	240	252	131	0.49	0.044	2.56	0.041	0.58
27 km long. beginning 6 km below mouth of Ells River	17.02.78	182	370	238	0.42	0.040	3.95	0.033	0.72

of $E_z/V_* R_h$ under an ice cover were up to 2.5 times those corresponding to open water conditions.

4.3 SLUG INJECTION TEST

4.3.1 One-dimensional analysis: Longitudinal dispersion parameters

As outlined earlier, the time dependent, mixing process which results from a slug injection of a tracer, eventually becomes nearly one-dimensional. In this final stage, instantaneous cross-sectional distributions of concentration become nearly uniform and therefore satisfactory predictions can be made in terms of the cross-sectional average value of concentration, C_A. This process is known as longitudinal or one-dimensional dispersion.

Inspection of Figures 12, 13 and 14 shows that the time concentration curves observed across the channel were perceptibly different from each other. This implies that one-dimensionality had not been established within the study reach. On the other hand, Figures 16 to 19 show that bulk characteristics of these curves (t_p, ΔT, C_p and θ) vary from respective average values by factors not exceeding about 2.0. Therefore predictions based on a one-dimensional model would generally be accurate to within the same factor. This degree of accuracy is considered very good for natural streams, even when a numerical simulation algorithm is used to account for lateral concentration variations. It follows that there is considerable practical interest in applying a one-dimensional type of analysis to the slug test results.

Based on an extensive reanalysis of published field data involving 52 dispersion experiments, Beltaos (1978b) proposed the following model for the longitudinal dispersion process.

The growth of the time to peak concentration t_p with x can be used to provide a good approximation for the average flow velocity V, via the relation:

$$V = (dt_p/dx)^{-1} \qquad (10)$$

The "one-half" temporal spread of tracer ΔT, increases with x according to the relation:

$$\Delta T^2 = 11.1 \beta \left(\frac{L}{V}\right)^2 \left(\frac{x}{L} + e^{-x/L} - 1\right) \qquad (11)$$

where β is a dimensionless coefficient and L is a characteristic river length. The coefficient β reflects the degree of non-uniformity of cross-sectional velocity distributions of the channel and, broadly speaking, is a function of the ratio V_*/V or the friction factor $f(= 8V_*^2/V^2)$. The characteristic length, L, is given by a relation of the form:

$$L = \alpha_L (W^2/R_h)(V/V_*) \qquad (12)$$

in which R_h is the hydraulic radius of the stream; for ice covered flow $R_h \simeq H/2$. The coefficient of proportionality α_L, defined in Equation 12, was found to be between 0.48 and 4.5, though exclusion of a few "odd" data points would reduce the upper limit of this range to 1.8.

Examination of Equation 11 shows the following:

1. For small values of x/L, Equation 11 simplifies to

$$\Delta T = \sqrt{5.55\,\beta}\,(x/V) \tag{13}$$

which implies that ΔT increases in proportion to x. A set of experimental data points on a ΔT vs. x graph may appear to define a straight line even if x is as large as L. If this is indeed the case, the slope of this straight line can be used to determine β. All that could be said about L would be that it exceeds the length of the study reach, i.e. the value of x associated with the farthest downstream sampling site. Once the coefficient β has been evaluated, the complete C_A - t curve can be predicted using the equations given below[1]:

$$C_A = C_{Ap}\left[\frac{Vt}{x}\,e^{1-(Vt/x)}\right]^{1/\beta} \tag{14}$$

in which C_{Ap} is the peak value of C_A and, for a neutral tracer, is given by:

$$C_{Ap} = 0.94\;M_o/Q\;\Delta T \tag{15}$$

To account for tracer losses, Equation 15 is usually recast in the form:

$$C_{Ap} = 0.94\;\overline{\theta}/\Delta T \tag{16}$$

2. When x/L exceeds 3, Equation 11 simplifies to:

$$\Delta T^2 = 11.1\,\beta\left(\frac{L}{V}\right)^2\left(\frac{x}{L} - 1\right) \tag{17}$$

In this case, a graph of ΔT^2 vs. x will appear linear and this final stage of longitudinal dispersion is described by Taylor's

---

[1] After rearranging the relationships presented by Beltaos (1978b).

(1954) theory, viz:

$$C_A = \frac{Q\bar{\theta}}{2A\sqrt{\pi D t}} e^{-\frac{(x^1 - Vt)^2}{4Dt}} \tag{18}$$

in which $x^1 = x - L$, and $D = \beta LV$ = dispersion coefficient.

3. For values of x/L in the range 1 to 3, no explicit equation for C_A has been found. Beltaos (1978b) suggested an approximate method for computing C_A in this range. As will be shown shortly, the process in the Athabasca River was well within the first range, x/L < 1; for this reason the above method will not be discussed herein.

Using Equation 12 and the values of W, R_h, V and V_* determined for the study reach of the Athabasca River, the value of L is calculated in kilometres as:

$$L = \alpha_L (.370) \left[370/(1.55/2)\right] \left[0.42/0/03\right] = 2470\ \alpha_L.$$

Using a lower limit of 0.48 for α_L, as outlined earlier, gives L = 1190 km. Evidently the mixing process in the study reach of the Athabasca River was in the "small" x/L range.

Utilizing the cumulative area graphs shown in Figure 9, appropriate weighting factors were assigned to the five sampling points across each of the three sampling sections and, using the C - t curves of Figures 12 to 14, corresponding C_A - t curves were derived. Bulk characteristics of these curves are summarized in Table 7.

Considering the peak concentration, the data of Table 7 show the quantity $C_{Ap}\ \Delta T/\bar{\theta}$ to take values of 0.84, 0.89 and 0.81 for the sections 19.9, 48.3, and 107.6 km respectively. These are

Table 7. Characteristics of C_A - t curves.

Section (km)	t_p (min)	C_{Ap} ($\mu g/\ell$)	ΔT (min)	$\overline{\theta}$ (μg min/ℓ)
19.9	730	10.0	112	1330
48.3	1850	4.2	284	1340
107.6	4175	1.4	760	1310

in good agreement with the value of 0.94 predicted by Equation 16.

Figure 21 shows plots of t_p versus x and ΔT versus x. As anticipated, both of these graphs are seen to be linear. Using the slopes of the straight lines fitted through the data points and making use of Equations 10 and 13 gives $V = 0.42$ m/s and $\beta = 0.00523$. Using these values and Equations 14, 16 and 13 gives:

$$C_A = \frac{5.5\overline{\theta}}{x/V} \left[\frac{Vt}{x} e^{1-(Vt/x)}\right]^{191} \tag{19}$$

Using $\overline{\theta} \simeq 1330$ µg min/ℓ, Equation 19 was evaluated at x = 19.9, 48.3 and 107.6 km and the results are shown plotted in Figures 12, 13 and 14 for comparison with the observed curves. The overall agreement between predicted and observed concentrations is within a factor of about two.

Beltaos (1978b) showed that β is approximately proportional to $(V_*/V)^2$. Using the values of β, V_* and V applicable to the present test gives:

$$\beta = 1.0(V_*/V)^2 \tag{20}$$

It was mentioned earlier that the slope of the Athabasca River changes at the head of the Embarras River which is located 137.7 km below the injection point (see Figure 8). Figure 21 shows that the value of t_p at this location would be about 5400 min. Using the values of t_p indicated in Figure 15 for the distributary channels, average velocities between 137.7 km and corresponding sampling sites can be determined. These are summarized in Table 8. Average velocities are seen to vary between

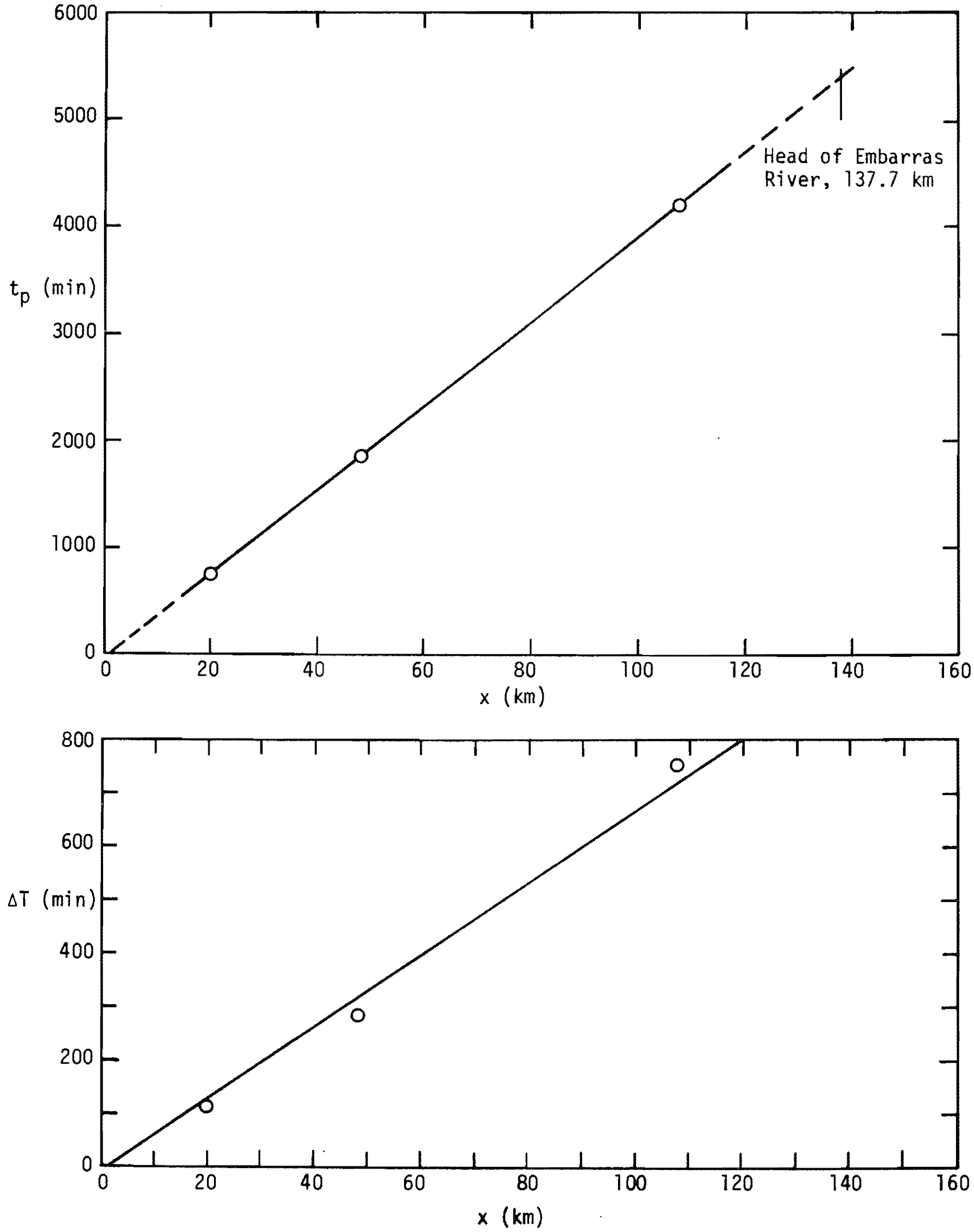

Figure 21. Variations of t_p and ΔT with x; slug test.

Table 8. Average rates of travel in distributary channels.

Channel	Location	t_p (hrs)	V (m/s)
Embarras River	198.7	191	0.17
Fletcher	196.4	192	0.16
Goose Island	212.0	193	0.20
Big Point	214.2	193	0.21

0.16 and 0.21 m/s and are in good agreement with pertinent measurements shown in Table 4. Because of the relatively poor definition of the time concentration curves shown in Figure 15, evaluation of dispersive parameters will not be attempted.

4.3.2 Numerical Simulation in Two Dimensions

Before a state of approximate one-dimensionality is established, time concentration curves across the stream, resulting from a slug injection, differ considerably amongst themselves. The variation of concentration in the transverse direction, z, must therefore be taken into account in the early stages of the process. As mentioned earlier, this task can only be accomplished by means of numerical simulation techniques. A numerical algorithm, intended to eliminate numerical diffusion, has been developed by Beltaos and Arora (unpublished) and is briefly described by Beltaos (1978a). This algorithm uses an irregular space grid which is generated from cross-sectional velocity and depth distribution data.

Use of this algorithm consists of the following steps:

1. Prepare q/Q vx. z diagrams for all available cross sections. Select an appropriate subdivision of the channel into streamtubes[1]. Determine values of z corresponding to streamtube boundaries and corresponding values of depth; tabulate;

---

[1] In plan view, a streamtube is defined by two lines on which the cumulative discharge is a constant, say q_1 and q_2. The discharge along this streamtube is also constant and equal to $q_2 - q_1$.

2. Select a value for the transverse mixing coefficient. In the present application the value determined from the steady state test, $E_z = 0.033\ m^2/s$, will be used;
3. Select a value for the time step Δt. Since $\Delta x \simeq u\Delta t$, where u is the average velocity in a streamtube, one can roughly calculate Δx. The ratio $\Delta x/\Delta z$ should be kept small, no more than about 10;
4. Assign distances from injection to each of the available cross sections (injection site should be included);
5. Decide on a manner and location of injection and number of time steps required;
6. Key-punch the above information and run the pertinent computer program;
7. This program assumes that z co-ordinates and depths vary linearly across and along the stream between cross sections, and solves a third degree polynomial equation for determining longitudinal boundaries of elements for each streamtube. The co-ordinates of each grid point are part of the printout;
8. Subsequently, the simulation is carried out for the specified number of time steps. For the present run, 260-300s long, time steps were used; and
9. Normally, the printout gives values of concentration in all elements of each streamtube at each time step. Occasionally, however, it may be more convenient to have the results in terms of time-concentration tables

at specified sites. A sub-routine to produce this type of output has been incorporated in the program.

To test the capability of this algorithm to simulate the slug test results as well as verify the value of E_z determined from the steady state test, it was decided to run the program for the first 19.9 km of the study reach. To reproduce the river geometry in this reach, the following cross sections were used: 0, 4, 6.7, 8.3, 11, 13.8, and 19.9 km. As can be seen in Figure 6, some of these sections are located at islands or bars and thus consist of two separate subsections, as shown schematically in Figure 22a. For computation purposes, these sections were modified as shown in Figure 22b. This modification results in a geometry that resembles single channel sections, with the exception that it contains one or more nodal points; that is, points where the flow depth is nil. The utility of this adaptation lies in avoiding unnecessary computations with zero values of concentration. As well, it permits direct use of the algorithm in its present form without laborious modifications for simultaneous computation in two or more separate channels. However, in order to ensure that no lateral transfer of tracer occurs between separate channels, it is important that the nodal points be located on streamtube boundaries (see also Beltaos 1978a).

When the simulation was tried without other refinement than the one discussed above, it was found that physically implausible results were obtained. Because this algorithm has given

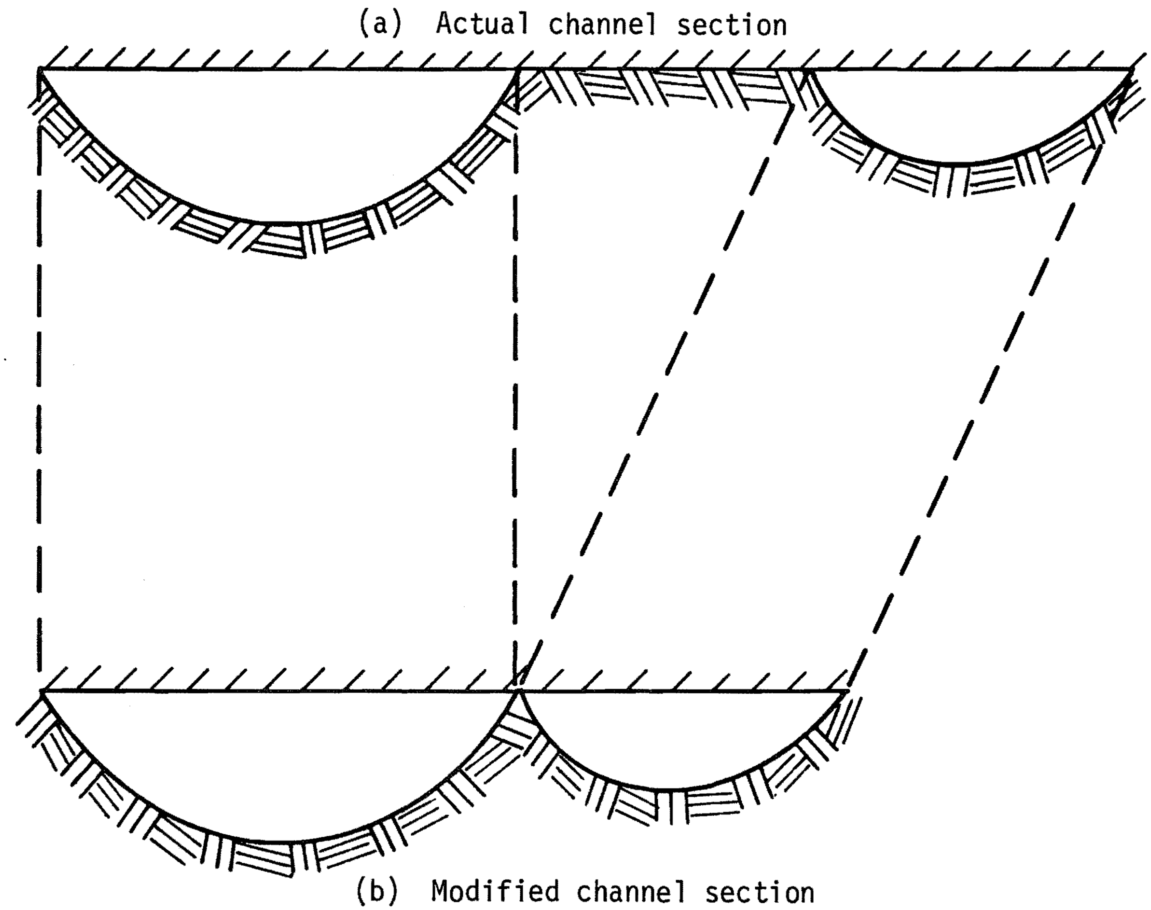

Figure 22. Adaptation of multiple channel sections for numerical simulation of transient mixing.

satisfactory results in channels without islands (Beltaos 1978a), it is believed that the introduction of the nodal points described earlier may be related to the present discrepancy. To generate the space grid, the program assumes linear variations of depth and width between successive sections. This would give undue weight to multiple channel reaches, if such reaches are, as is usually the case, of very local nature. To test this hypothesis, another run was tried, in which the various bars or islands were arbitrarily assumed to extend 300 m upstream and downstream of the corresponding sections. Thus, sections at 0, 4, 8.0, 8.3, 8.6, 11.0, 13.8, 19.6, and 19.9 km were used. The "fictitious" sections at 8.0, 8.6, and 19.6 km were assumed to have identical geometry as sections 4, 11.0, and 13.8 km respectively. This approach resulted in considerable improvement of the simulated time-concentration curves. The results are shown in Figure 23 together with the observed time-concentration curves. It is seen that there is fair agreement between observation and simulation.

Comparison of Figures 12 and 23 shows that there is little to distinguish the accuracy of concentration predictions by means of the numerical simulation from that of predictions based on the one-dimensional analysis outlined earlier. However, it should be kept in mind that the present test involved a slug injection at the centroid of flow. In practice, such injections are likely to take place near one of the river banks. The length required for applicability of one-dimensional models would then be magnified by a factor of about four. Within this length,

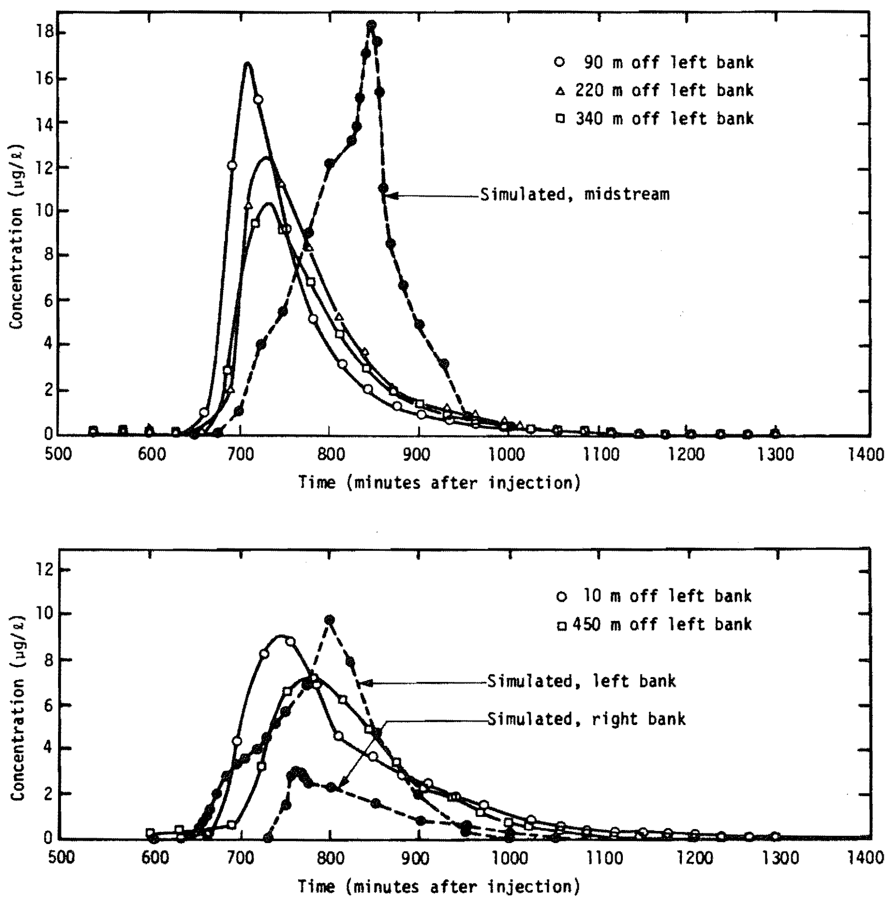

Figure 23. Comparison of simulated with observed time-concentration variations; slug test, 19.9 km.

concentration predictions would require use of a numerical simulation.

5. APPLICATION OF RESULTS

The findings reported in the previous sections can be utilized to predict concentration patterns due to any source of neutral effluent in the Athabasca River below Fort McMurray under ice covered conditions.

To illustrate the procedures involved in mixing calculations, two hypothetical examples dealing with steady state and transient mixing processes are discussed.

5.1 CONTINUOUS INJECTION AT CONSTANT RATE

A point source located on the left bank of the Athabasca River discharges effluent continuously during the winter season at a rate of 1 m^3/s. The effluent contains a toxic substance at a concentration of 2 mg/ℓ. This substance can be harmful at concentrations exceeding 25 μg/ℓ and it is thus required to define the stream area which is subjected to such concentrations. The river discharge is estimated as 200 m^3/s.

The fully mixed concentration C_∞ is calculated as $C_\infty = 2000[1/(200+1)] \simeq 10$ μg/ℓ. This is less than 25 μg/ℓ, therefore harmful concentrations will not persist downstream of the mixing length.

For a point source at one of the river banks, Beltaos (1978a) showed that a very simple equation can be used to calculate the concentration distribution, viz:

$$C = C_\infty \sqrt{2/\pi\xi} \; e^{-\eta^2/2\xi} \qquad (21)$$

in which $\xi = 2D_z x/Q^2$, x = distance below the source, and $\eta = q/Q$. Equation 21 is accurate within the distance required for the effluent to reach the opposite bank; this can be shown to correspond to $\xi = 0.167$. Downstream of this location, the equation describing C is much more complex than Equation 21 and thus it is of interest to determine whether the problem at hand can be answered by means of Equation 21.

Assuming that, within narrow ranges of discharge, the friction factor and river width do not change appreciably, it can be shown that $V \propto Q^{1/3}$, $V_* \propto Q^{1/3}$, $H \propto Q^{2/3}$, and ψ = const. Assuming further that the reach of interest has similar hydraulic parameters as the February 1978 study reach, we find:
$V = 0.42(200/182)^{1/3} = 0.43$ m/s, $V_* = 0.03(200/182)^{1/3} = 0.031$ m/s, $H = 1.55(200/182)^{2/3} = 1.65$ m, and $\psi = 3.95$. Using Equations 9 and 6, we find further: $E_z = 0.7(1.65)0.031 = 0.033$ m^2/s, $D_z =$ $= 3.95(0.033)0.43(1.65)^2 = 0.153$ m^5/s^2, and $\xi = 2(0.153)1000x/(200)^2 =$ $= 0.00765x$ where x is measured in kilometres.

The distance corresponding to $\xi = 0.167$ is $x = 0.167/0.00765 = 21.8$ km. At this distance, Equation 21 gives the maximum (left bank - $\eta = 0$) concentration as $C = 10\sqrt{2/\pi(0.167)} = 19.5$ μg/ℓ. This is less than 25 μg/ℓ, therefore the area subjected to harmful concentrations is located entirely within the reach 0 - 21.8 km. Within this reach Equation 21 is valid.

Setting $C = 25\ \mu g/\ell$ and $C_\infty = 10\ \mu g/\ell$ in Equation 21 and rearranging gives the equation of the line which represents the outer boundary of the area subjected to harmful concentrations:

$$\eta(25\ \mu g/\ell) \quad = \quad \{2\xi\, \ell n\, (0.4 \sqrt{2/\pi\xi})\}^{1/2} \qquad (22)$$

Calculations based on Equation 22 are summarized in Table 9.

The values of z shown in Table 9 were estimated assuming that the q/Q vs. z curve at any one location x is the same as the average curve determined for the February 1978 study reach. (Of course, much more reliable determinations of z would be possible if the cross-sectional characteristics at specific locations x were available. These could be used to generate the corresponding q/Q vs. z curves.) Using the values of x and z shown in Table 9, it is estimated that harmful concentrations will be confined within an area of about 0.5 km^2.

An interesting problem that may arise in practice is how to account for the effects of tributaries located in the reach of interest. Because mixing processes can be superposed linearly, the appropriate procedure would be to compute the concentration patterns for the effluent and the tributary(ies) separately, and then total the concentrations occurring at the same points. Lipsett and Beltaos (1978) presented an analysis of tributary mixing and showed that a tributary can be approximated by a line source of effluent. Equations for calculating C due to line sources have been presented by Yotsukura and Cobb (1972).

Table 9. Area subjected to harmful concentrations.

ξ	x(km)	η(25 μg/ℓ)	≈z(25 μg/ℓ) (m)
0	0	0	0
0.005	0.65	0.12	30
0.01	1.3	0.15	35
0.02	2.6	0.18	41
0.04	5.2	0.19	43
0.06	7.8	0.18	41
0.08	10.5	0.14	33
0.100	13.1	0.04	12
0.102	13.3	0	0

5.2 SIDE INJECTION OF A SLUG

An accidental release of 1000 kg of a toxic substance occurs at the left river bank, during ice covered conditions. The release takes place over a brief period of time, and, for practical purposes, can be assumed to be a slug injection. The river discharge is estimated at 200 m^3/s. It is required to determine whether two water intakes located on the right bank, 20 km and 100 km below the point of release, will be subjected to concentrations exceeding 25 $\mu g/\ell$. If so, during what periods should they be shut down to avoid drawing water with such concentrations?

Based on the test results described previously, it is estimated that, for side injections, a one-dimensional model would provide fair concentration estimates below 80 km from injection. Therefore to assess the impact at the 100 km intake, we can use Equation 14:

$$C = C_p \left[\frac{Vt}{x} e^{1-(Vt/x)}\right]^{1/\beta} \qquad (14)$$

in which C_p is given by Equation 15; ΔT is given by Equation 13; and β is given by Equation 20.

For Q = 200 m^3/s, we found earlier that $V_* = 0.031$ m/s and V = 0.43 m/s. Thus $\beta = 1.0(0.031/0.43)^2 = 0.0052$. Using Equations 13 and 15 to rearrange Equation 14 gives:

$$C = \frac{5.5\,M}{Q(x/V)} \left[\frac{Vt}{x} e^{1-(Vt/x)}\right]^{192.4} \qquad (23)$$

For x = 100 km and M = 1000 kg, Equation 23 reduces to:

$$C = 118 \left[\left(\frac{t}{64.6}\right) e^{1-(t/64.6)}\right]^{192.4} \qquad (24)$$

where t is in hours and C is in $\mu g/\ell$. Equation 24 is plotted in Figure 24. This figure can be used to determine the times of shutting down and reopening the water intake at 100 km. Introducing a safety factor of 2.5, Figure 24 gives these times as 54.8 and 75.5 hrs. Assuming that average stream velocity estimates are associated with an uncertainty of $\pm 25\%$, these times are adjusted to 54.8(0.75) = 41 hrs and 75.5(1.25) = 94 hrs respectively.

For the intake located at 20 km, calculation can only be done by means of a numerical simulation, utilizing as many cross sections as possible. In view of previous discussion, it appears that the effects of islands and bars are of localized nature. Inclusion of such sections in generating the space grid might cause unnecessary complications unless bars and islands are thoroughly documented. That is, for each bar or island, a minimum of four cross sections, located at the tips and the points where the effects of these tips become negligible, would be necessary. Such detailed documentation, however, would be rather impractical. If river cross sections are not available and a quick estimate is required, the simulation could be carried out in terms of an average cross-sectional geometry. The 'average' cross section could be defined using hydrometric at-station relations, as outlined by Beltaos (1978a).

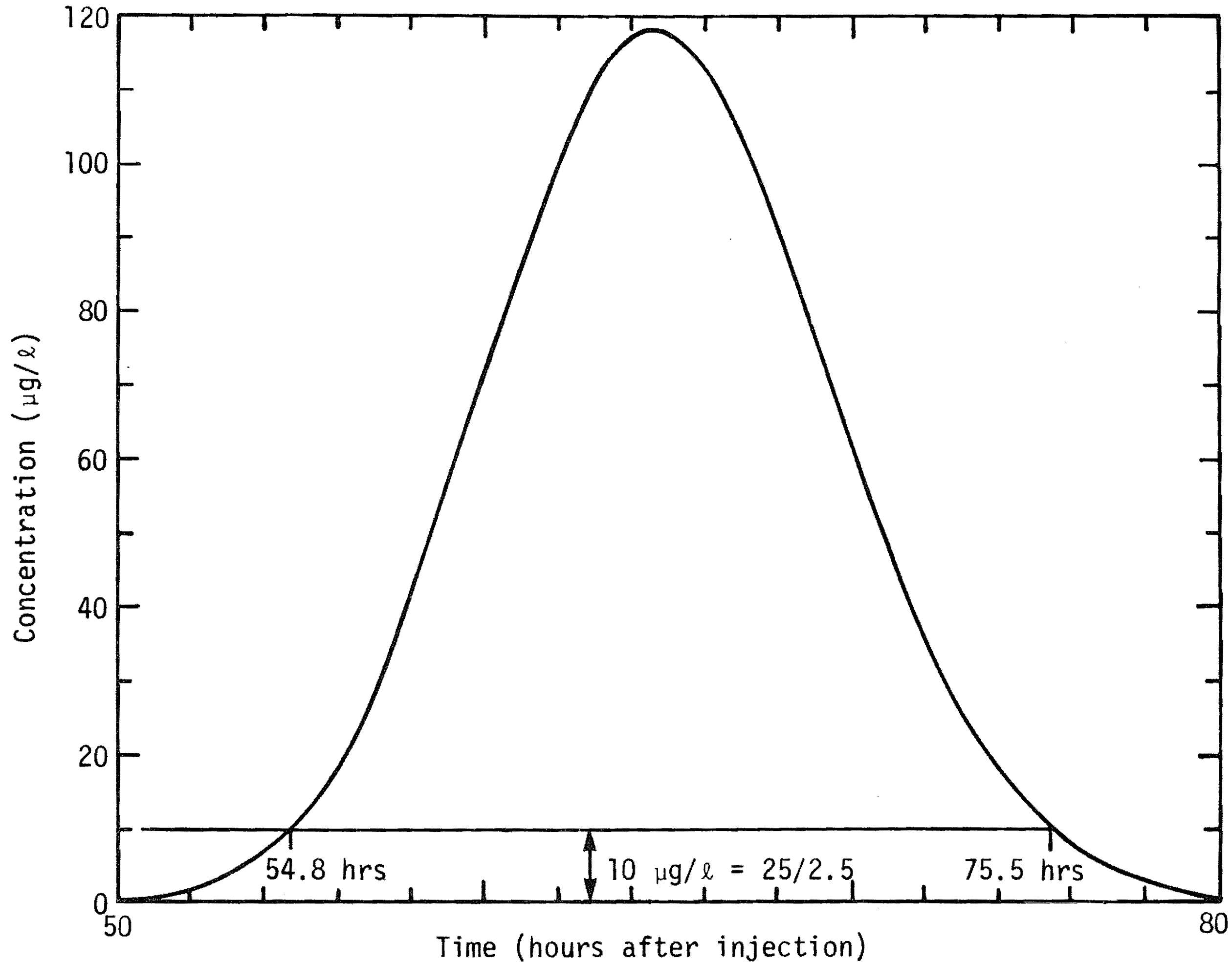

Figure 24. Example of determining water intake shutdown period to avoid contamination.

6. DISCUSSION AND SUMMARY

The results of a study on the mixing characteristics of the Athabasca River below Fort McMurray under ice-covered flow conditions have been reported herein. This study has been based on the results of two tracer tests, carried out in February 1978.

The dimensionless transverse mixing coefficient, E_z/V_*H was found to have a value of 0.72. This value was determined directly from the data of a steady state test and verified indirectly by comparing a numerical simulation of transient mixing with the data of a slug injection test. A preliminary test in February 1974 gave $E_z/V_*H = 0.58$. The difference between these two values of E_z/V_*H was attributed to experimental error, even though it was recognized that the corresponding test reaches differed somewhat in configuration.

For open water conditions, it is believed that extrapolation of the above finding is not unreasonable. Therefore for low stages, one could use the value of E_z shown in Table 1 for open water conditions. Beltaos (1978a) gave the corresponding value of E_z/V_*H as 0.75. However, it is not known at present whether this value can be extrapolated to high water stages. A mixing study, similar to the one presented herein, at a high (open water) stage is thus deemed desirable.

The results of a slug injection test showed that there is considerable scope for application of a simple one-dimensional model to predict time-concentration variations. This model depends on knowledge of a dimensionless coefficient β, which can be calculated if the friction factor of the stream is known. For bank injections, it is estimated that the one-dimensional approach would provide reasonable estimates of concentration at distances exceeding 80 km from injection. Within the first 80 km from the injection site, satisfactory transient mixing calculations can only be done by means of a numerical simulation of the process. Application of a numerical algorithm (outlined by Beltaos 1978a) to the results of the slug injection test, showed that the effects of various bars and islands are of local nature. Omission of associated cross sections in generating space grids is felt to be justified from the practical point of view.

It is noted that the results presented herein apply to the Athabasca River *below* Fort McMurray. Above this location, the portion of the river within the AOSERP Study Area has very different hydraulic characteristics from those of the portion studied herein. Therefore extrapolation of the present findings to the Athabasca River above Fort McMurray is not recommended. For very crude estimates, a tabulation of pertinent field data presented by Beltaos (1978a) may be consulted and a transverse mixing coefficient selected on the basis of hydraulic characteristics. Regarding longitudinal dispersion parameters of the Athabasca River above Fort McMurray, field data taken during the Athabasca Blackfly Abatement Program[1] may be utilized to some advantage. It is

---

[1] A consolidated report including various contributions will become available in the near future.

noted, however, that these data pertain to a non-neutral tracer.

Knowledge of stream hydraulics is obviously a prerequisite for any attempt to predict mixing patterns. At present, there exists adequate coverage of the Athabasca River in terms of cross-sectional hydrometric surveys. This information, however, is not directly usable for mixing computations, because the stage must be adjusted at each cross section so as to correspond to the discharge of interest. Therefore a project consisting of the items listed below, is deemed desirable:

1. Collate all available cross sections and store geometry in computer, in tabular form;
2. Develop a method for adjusting water stage at each of these cross sections to any given discharge; include both open water and ice covered conditions;
3. Program the above procedure and include a program to compute cumulative discharge curves; outputs in both tabular and graphical forms are desirable;
4. Develop and program a procedure to interpolate water depths corresponding to specified streamtube boundaries. Link this program to the program associated with a numerical simulation of transient mixing processes; and
5. For distinct subreaches of the Athabasca River below Fort McMurray, compute average hydraulic parameters for a representative range of flow discharges; define corresponding at-station relations.

Finally, it may be of interest to consider briefly the question of mixing in the Athabasca delta system. This problem is so complex that a preliminary, feasibility-type study would be necessary before studying more specific questions. Such a study would be expected to consist of the following items:

1. Collate, summarize and assess published information pertinent to lake mixing; include data obtained by remote sensing techniques;
2. Carry out preliminary field observations as required; and
3. Assess the feasibility of using numerical and/or analytical models to predict mixing of effluents in the delta system.

If it is concluded that quantitative modelling of mixing is feasible, it will be necessary to identify the main distributary channels which will act as sources of effluent into Lake Athabasca; and to develop a capability for predicting the strengths of these sources as functions of the effluents discharged into the Athabasca River. A very pertinent conclusion, that can be based on the results of the February 1978 tests, is that effluents discharged near the existing locations of oil sands industrial plants will be well mixed before entering the various distributary channels. It should be noted, however, that for transient mixing, it is not known how such effluents will spread whilst in transit to the lake. Some crude estimates for ice-covered flow could be obtained using the time-concentration curves shown in Figure 15. Similar information for open water flow will be provided if tracer tests similar to those of February 1978 are conducted at high stage. Associated hydrometric surveys to define the hydraulics of the distributary channels would then be desirable.

7. REFERENCES CITED

Beltaos, S. 1975. Evaluation of transverse mixing coefficients from slug tests. Journal of Hydraulic Research 13(4):351-360.

Beltaos, S., and T. J. Day. 1976. Longitudinal dispersion in a natural stream: Lesser Slave River, Alberta. Transportation and Surface Water Engineering Division Report No. REH/76/1, Alberta Research Council. 58 pp.

Beltaos, S. 1978a. Transverse mixing in natural streams. Transportation and Surface Water Engineering Division Report No. SWE-78/01, Alberta Research Council. 99 pp.

Beltaos, S. 1978b. An interpretation of longitudinal dispersion data in rivers. Transportation and Surface Water Engineering Division Report No. SWE-78/03, Alberta Research Council. 52 pp.

Elder, J. W. 1959. The dispersion of marked fluid in turbulent shear flow. Journal of Fluid Mechanics. 5(4):544-560.

Engmann, J. E. O. 1974. Transverse mixing characteristics of open and ice-covered channel flows. Ph.D. Thesis. Department of Civil Engineering, University of Alberta. 280 pp.

Engmann, J. E. O., and R. Kellerhals. 1974. Transverse mixing in an ice-covered river. Water Resources Research. 10(4):775-784.

Gerard, R. 1977. Project description and estimates for first phase of work to define the assimilative capacity of the Athabasca River system. Interim proposal submitted to former Hydrology Committee of AOSERP. 9 pp.

Kellerhals, R., C. R. Neill, and D. I. Bray. 1972. Hydraulic and geomorphic characteristics of rivers in Alberta. River Engineering and Surface Hydrology Report 72-1, Alberta Research Council. 51 pp.

Lipsett, A. W., and S. Beltaos. 1978. Tributary mixing characteristics using water quality parameters. Transportation and Surface Water Engineering Division Report No. SWE-78/04, Alberta Research Council. 41 pp.

Taylor, G. I. 1954. The dispersion of matter in turbulent flow through a pipe. Proceedings of Royal Society of London. Series A. 223:446-468.

Turner, J. S. 1973. Buoyancy effects in fluids. Cambridge University Press, New York. 367 pp.

Water Survey of Canada. 1975. Surface water data, Alberta 1974. Fisheries and Environment Canada. Inland Waters Directorate. Water Resources Branch. Ottawa. 218 pp.

Yotsukura, N., and E. D. Cobb. 1972. Transverse diffusion of solutes in natural streams. U.S. Geological Survey Professional Paper 582-C. 19 pp.

8. APPENDICES

8.1 SYMBOLS

a	cumulative area
A	total cross-sectional area
C	concentration
C_A	cross-sectional average concentration
C_p	peak concentration
C_∞	fully mixed, steady state, concentration
D	dispersion coefficient
D_z	transverse diffusion factor
e	base of natural logarithms
E_z	transverse mixing coefficient
f	a function, friction factor
h	local depth
H	average depth
L	characteristic stream length
M	tracer mass
$\dot{M}$	rate of tracer mass injection
M_o	injected tracer mass
n_o	Manning coefficient
q	cumulative discharge
Q	river discharge
R_h	hydraulic radius
t	time after injection
t_p	time to peak concentration

u_d	depth averaged velocity
V	average stream velocity
V_*	shear velocity
W	stream width
x	longitudinal co-ordinate (distance from injection)
y	vertical co-ordinate
z	transverse co-ordinate
α_L	dimensionless coefficient
β	dimensionless dispersion parameter
ΔT	duration of concentrations exceeding one-half of peak value
η	normalized cumulative discharge, q/Q
θ	dosage
ξ	dimensionless longitudinal co-ordinate
$\sigma_\eta^{\ 2}$	variance of $C - \eta$ profile
τ	a time interval
ψ	dimensionless shape-velocity factor

8.2 RELATIONSHIP BETWEEN TRACER CONCENTRATIONS DUE TO SLUG AND CONTINUOUS INJECTIONS

Firstly, consider injection of tracer at a constant mass rate for an infinitely long time period. This injection is assumed to occur at $x = 0$ and commence at $t = 0$. Let $M f(t)$ be the function describing the tracer concentration resulting from injection of a slug of mass M at time $t = 0$.

With reference to Figure 25a, continuous injection at a rate $\dot{M}$ can be considered to consist of a series of elementary slug

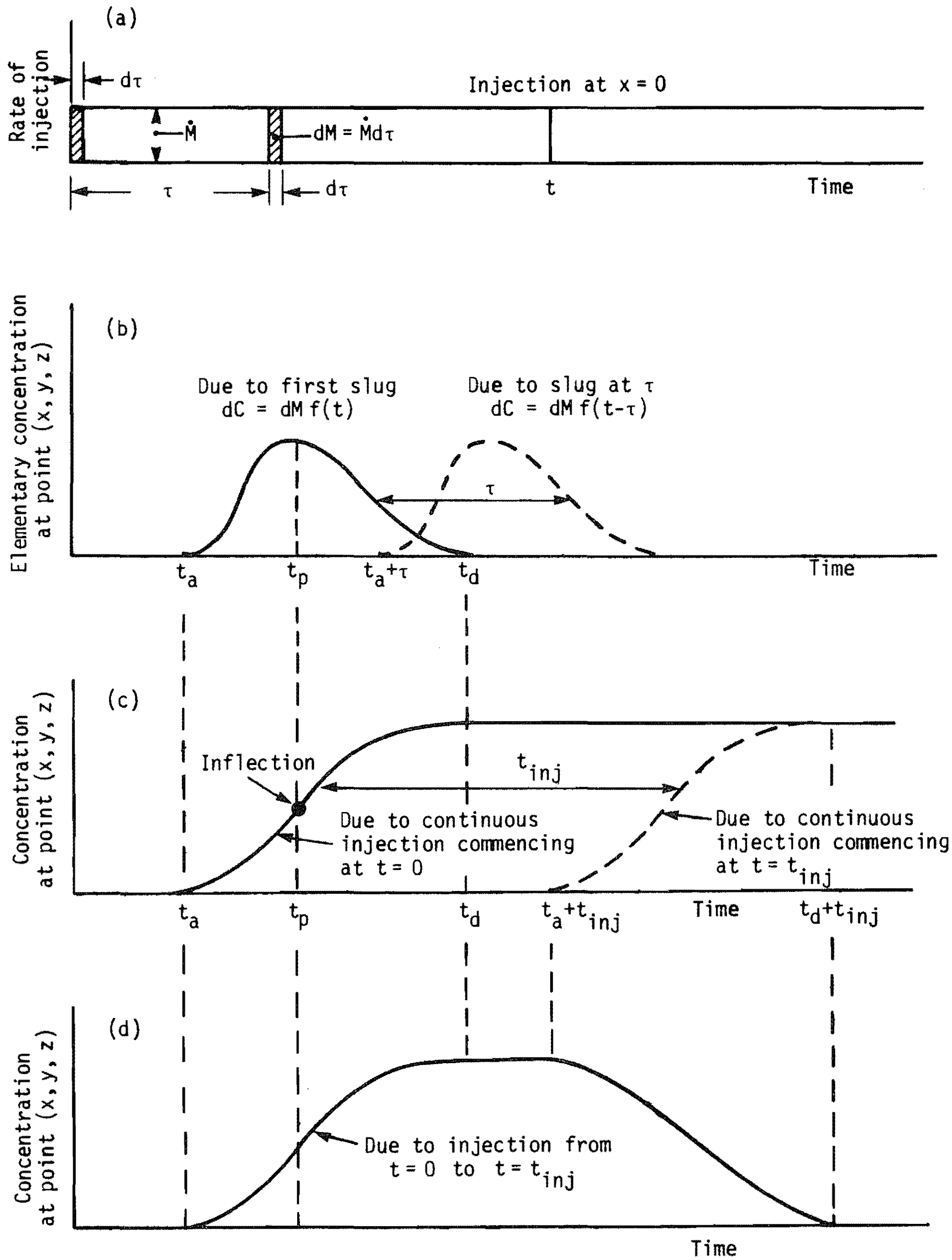

Figure 25. Superposition of concentrations due to slug injections to determine concentrations due to continuous injection.

injections, each of mass $dM = \dot{M}d\tau$. The elementary concentration functions resulting from the slugs at $t = 0$ and $t = \tau$ respectively are as sketched in Figure 25b and can be expressed as $dC = dM\, f(t)$ and $dM\, f(t - \tau)$. Applying linear superposition gives the concentration as a function of time for all the elementary slugs between $t = 0$ and $t = t$, as follows:

$$C(t) = \dot{M} \int_{\tau=0}^{t} f(t-\tau)\, d\tau \qquad (25)$$

which simplifies to:

$$C(t) = \dot{M} \int_{0}^{t} f(t')\, dt' \qquad (26)$$

in which $t'(= t-\tau)$ is a dummy variable of integration. It follows that $C(t)$ will be of the form sketched in Figure 25c (solid line) and has the following features: $C = 0$ for $t \leq t_a$; C increases for $t_a \leq t \leq t_d$ and has a point of inflexion at $t = t_p$; $C = \text{const.}$ for $t_d \leq t$. If injection had commenced not at $t = 0$ but at a time equal to t_{inj}, the resulting concentration would be as shown by the dashed line in Figure 25c. That is, it could be determined by simply shifting the solid line by the time interval t_{inj}.

Clearly, the difference between the solid and the dashed lines in Figure 25c gives the concentration due to an injection of finite duration, commencing at $t = 0$ and ending at $t = t_{inj}$. This is sketched in Figure 25d, assuming that $t_{inj} > t_d - t_a$. The characteristics of this curve are exactly as outlined in the text.

8.3 CROSS-SECTIONAL HYDRAULIC DATA

This appendix contains supplementary information regarding cross-sectional hydraulic data and visual documentation of the study reach of the Athabasca River. Cross-sectional data are presented in tabular form in Table 10. The following notation has been used for this tabulation.

Z	:	distance from left bank in metres
Z/W	:	value of Z divided by river width
H(Z)	:	flow depth at Z m from the left bank
U(Z)	:	depth averaged velocity at Z m from the left bank
H/MD	:	flow depth divided by mean depth
A'	:	cumulative area divided by total cross-sectional area
Q'	:	cumulative discharge divided by total river discharge

Table 10. Cross-sectional hydraulic data.

Z	Z/W	H (Z)	U (Z)	H/MD	A'	Q'
			0 km (Injection Site)			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.017	3.05	0.44	3.571	0.0305	0.0405
15.0	0.026	3.17	0.36	3.712	0.0616	0.0780
25.0	0.043	3.78	0.42	4.426	0.1312	0.1604
50.0	0.085	3.30	0.44	3.864	0.3083	0.3900
80.0	0.137	3.05	0.45	3.571	0.4990	0.6459
110.0	0.188	2.90	0.26	3.395	0.6776	0.8386
140.0	0.239	1.35	0.14	1.581	0.8052	0.9240
170.0	0.291	0.19	0.03	0.222	0.8514	0.9416
180.0	0.308	0.0	0.0	0.0	0.8533	0.9418
400.0	0.684	0.0	0.0	0.0	0.8533	0.9418
440.0	0.752	0.20	0.05	0.234	0.8613	0.9430
470.0	0.803	0.57	0.14	0.667	0.8844	0.9512
500.0	0.855	0.79	0.14	0.925	0.9252	0.9684
530.0	0.906	0.60	0.14	0.702	0.9670	0.9860
585.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			4 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.5	0.044	0.0	0.0	0.0	0.0	0.0
25.0	0.087	1.00	0.36	0.664	0.0145	0.0104
35.0	0.122	2.25	0.55	1.493	0.0520	0.0470
50.0	0.174	2.40	0.56	1.593	0.1327	0.1358
80.0	0.279	2.10	0.53	1.394	0.2887	0.3051
110.0	0.383	1.75	0.48	1.161	0.4223	0.4393
140.0	0.488	1.78	0.48	1.181	0.5447	0.5568
170.0	0.592	1.15	0.39	0.763	0.6463	0.6471
200.0	0.697	0.67	0.30	0.445	0.7094	0.6918
230.0	0.801	0.56	0.27	0.372	0.7521	0.7160
260.0	0.906	2.82	0.61	1.871	0.8693	0.8451
275.0	0.958	2.62	0.59	1.739	0.9637	0.9575
287.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			6.7 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
15.0	0.032	2.70	0.28	1.582	0.0249	0.0280
30.0	0.063	2.40	0.27	1.407	0.0720	0.0794
50.0	0.105	2.10	0.25	1.231	0.1274	0.1363
85.0	0.179	1.40	0.20	0.820	0.2028	0.2054
130.0	0.273	0.60	0.13	0.352	0.2582	0.2455
170.0	0.357	0.60	0.13	0.352	0.2878	0.2612
200.0	0.420	0.60	0.13	0.352	0.3100	0.2729
240.0	0.504	1.00	0.17	0.586	0.3494	0.2975
280.0	0.588	1.50	0.21	0.879	0.4109	0.3452
320.0	0.672	2.00	0.24	1.172	0.4971	0.4237
360.0	0.756	2.40	0.27	1.407	0.6055	0.5338
400.0	0.840	2.90	0.29	1.700	0.7360	0.6794
443.0	0.931	3.50	0.32	2.051	0.9054	0.8870
452.0	0.950	3.70	0.33	2.168	0.9453	0.9387
465.0	0.977	1.70	0.22	0.996	0.9885	0.9897
476.0	1.000	0.0	0.0	0.0	1.0000	1.0000

continued ...

Table 10. Continued.

Z	Z/W	H (Z)	U (Z)	H/MD	A'	Q'
			8.3 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.020	2.50	1.11	3.751	0.0371	0.0475
20.0	0.040	2.90	1.19	4.351	0.1171	0.1543
30.0	0.059	2.95	1.20	4.426	0.2039	0.2744
40.0	0.079	2.30	1.06	3.451	0.2817	0.3772
50.0	0.099	1.30	0.80	1.951	0.3351	0.4369
60.0	0.119	0.20	0.31	0.300	0.3573	0.4558
70.0	0.138	0.50	0.50	0.750	0.3677	0.4611
80.0	0.158	0.90	0.67	1.350	0.3885	0.4756
100.0	0.198	1.40	0.83	2.101	0.4567	0.5359
120.0	0.237	1.65	0.90	2.476	0.5471	0.6266
140.0	0.277	1.20	0.77	1.801	0.6316	0.7091
150.0	0.296	0.86	0.65	1.290	0.6622	0.7345
180.0	0.356	0.31	0.39	0.465	0.7142	0.7694
210.0	0.415	0.32	0.40	0.480	0.7422	0.7822
250.0	0.494	0.0	0.0	0.0	0.7612	0.7908
400.0	0.791	0.0	0.0	0.0	0.7612	0.7908
420.0	0.830	0.18	0.30	0.270	0.7666	0.7927
450.0	0.889	0.74	0.60	1.110	0.8075	0.8184
460.0	0.909	1.78	0.94	2.671	0.8448	0.8545
470.0	0.929	1.58	0.88	2.371	0.8947	0.9069
480.0	0.949	1.17	0.76	1.756	0.9354	0.9460
495.0	0.978	1.00	0.70	1.500	0.9837	0.9868
506.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			11.0 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.028	2.60	0.28	1.277	0.0180	0.0190
24.0	0.068	2.60	0.28	1.277	0.0685	0.0724
55.0	0.155	2.20	0.26	1.080	0.1717	0.1774
115.0	0.325	1.10	0.19	0.540	0.3090	0.2978
146.0	0.412	1.00	0.18	0.491	0.3542	0.3281
176.0	0.497	1.40	0.21	0.687	0.4041	0.3643
207.0	0.585	2.00	0.25	0.982	0.4772	0.4275
238.0	0.672	2.90	0.30	1.424	0.5826	0.5369
268.0	0.757	3.30	0.32	1.620	0.7116	0.6859
299.0	0.845	3.00	0.31	1.473	0.8470	0.8435
329.0	0.929	2.40	0.27	1.178	0.9594	0.9650
343.0	0.969	1.00	0.18	0.491	0.9924	0.9950
354.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			13.8 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
20.0	0.071	3.70	0.37	1.729	0.0618	0.0765
40.0	0.143	4.05	0.40	1.893	0.1911	0.2435
60.0	0.214	3.90	0.38	1.823	0.3238	0.4168
80.0	0.286	3.20	0.31	1.496	0.4423	0.5551
110.0	0.393	2.15	0.20	1.005	0.5763	0.6742
140.0	0.500	1.20	0.11	0.561	0.6602	0.7213
170.0	0.607	1.00	0.13	0.467	0.7152	0.7433
210.0	0.750	1.95	0.26	0.911	0.8137	0.8145
250.0	0.893	1.90	0.34	0.888	0.9422	0.9433
258.0	0.921	1.80	0.28	0.841	0.9670	0.9690
280.0	1.000	0.0	0.0	0.0	1.0000	1.0000

continued ...

Table 10. Continued.

Z	Z/W	H (Z)	U (Z)	H/MD	A'	Q'
			19.9 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.020	3.60	0.84	3.901	0.0398	0.0622
20.0	0.041	3.15	0.79	3.413	0.1144	0.1754
40.0	0.082	2.08	0.64	2.254	0.2301	0.3320
60.0	0.122	1.18	0.48	1.278	0.3022	0.4100
90.0	0.184	0.85	0.41	0.921	0.3695	0.4665
130.0	0.265	0.12	0.15	0.130	0.4124	0.4966
150.0	0.306	0.0	0.0	0.0	0.4150	0.4973
170.0	0.347	0.16	0.18	0.173	0.4186	0.4985
220.0	0.449	0.62	0.35	0.672	0.4617	0.5236
280.0	0.571	1.50	0.54	1.625	0.6023	0.6508
290.0	0.592	1.60	0.56	1.734	0.6366	0.6860
340.0	0.694	0.60	0.34	0.650	0.7582	0.7993
370.0	0.755	0.40	0.28	0.433	0.7914	0.8190
400.0	0.816	0.60	0.34	0.650	0.8245	0.8386
450.0	0.918	1.43	0.53	1.549	0.9368	0.9377
490.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			25.3 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.0	0.014	2.50	0.27	1.365	0.0095	0.0091
12.0	0.028	4.90	0.38	2.675	0.0377	0.0429
18.0	0.042	4.30	0.36	2.347	0.0727	0.0882
27.0	0.063	5.50	0.40	3.002	0.1287	0.1631
30.0	0.070	5.20	0.39	2.838	0.1491	0.1914
52.0	0.121	5.10	0.39	2.784	0.2929	0.3877
86.0	0.200	3.50	0.32	1.911	0.4785	0.6221
118.0	0.274	1.60	0.22	0.873	0.5821	0.7267
136.0	0.316	1.10	0.18	0.600	0.6129	0.7486
156.0	0.363	0.80	0.15	0.437	0.6371	0.7628
186.0	0.433	0.90	0.16	0.491	0.6694	0.7808
230.0	0.535	0.80	0.15	0.437	0.7169	0.8071
300.0	0.698	0.90	0.16	0.491	0.7924	0.8491
350.0	0.814	0.90	0.16	0.491	0.8496	0.8816
380.0	0.884	1.90	0.24	1.037	0.9029	0.9214
410.0	0.953	2.00	0.24	1.092	0.9772	0.9837
420.0	0.977	0.80	0.15	0.437	0.9949	0.9973
430.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			26.95 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
15.0	0.063	4.60	0.40	1.740	0.0544	0.0579
30.0	0.125	5.38	0.43	2.035	0.1723	0.1891
45.0	0.188	7.02	0.50	2.655	0.3189	0.3715
60.0	0.250	5.40	0.43	2.043	0.4657	0.5543
90.0	0.375	3.52	0.35	1.331	0.6766	0.7792
120.0	0.500	2.10	0.27	0.794	0.8095	0.8924
150.0	0.625	1.38	0.22	0.522	0.8917	0.9472
180.0	0.750	0.90	0.18	0.340	0.9456	0.9762
210.0	0.875	0.70	0.16	0.265	0.9835	0.9931
240.0	1.000	0.0	0.0	0.0	1.0000	1.0000

continued ...

Table 10. Continued.

Z	Z/W	H (Z)	U (Z)	H/MD	A'	Q'
			30.1 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.0	0.027	1.60	0.22	0.499	0.0069	0.0041
9.0	0.049	1.00	0.17	0.312	0.0158	0.0091
25.0	0.137	6.50	0.44	2.026	0.1185	0.1237
28.0	0.154	5.90	0.42	1.839	0.1504	0.1615
31.0	0.170	6.50	0.44	2.026	0.1822	0.1993
60.0	0.330	5.20	0.40	1.621	0.4728	0.5355
100.0	0.549	3.40	0.32	1.060	0.7674	0.8312
140.0	0.769	1.70	0.23	0.530	0.9421	0.9697
160.0	0.879	0.80	0.16	0.249	0.9849	0.9936
182.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			34.2 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.024	2.40	0.59	2.140	0.0252	0.0318
15.0	0.035	2.50	0.60	2.229	0.0509	0.0646
20.0	0.047	2.42	0.59	2.158	0.0767	0.0976
50.0	0.118	1.69	0.50	1.507	0.2060	0.2506
80.0	0.188	0.78	0.34	0.695	0.2838	0.3246
110.0	0.259	0.65	0.31	0.580	0.3288	0.3558
140.0	0.329	0.85	0.35	0.758	0.3760	0.3893
170.0	0.400	1.12	0.40	0.999	0.4380	0.4398
200.0	0.471	1.47	0.46	1.311	0.5195	0.5160
230.0	0.541	1.70	0.50	1.516	0.6192	0.6186
260.0	0.612	1.90	0.53	1.694	0.7325	0.7427
290.0	0.682	1.85	0.52	1.650	0.8505	0.8745
320.0	0.753	1.00	0.38	0.892	0.9402	0.9647
350.0	0.824	0.10	0.12	0.089	0.9748	0.9912
380.0	0.894	0.20	0.17	0.178	0.9843	0.9943
410.0	0.965	0.20	0.17	0.178	0.9969	0.9989
425.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			38.2 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
30.0	0.061	0.30	0.21	0.304	0.0093	0.0040
76.0	0.155	1.10	0.39	1.113	0.0757	0.0539
91.0	0.185	0.60	0.29	0.607	0.1019	0.0738
126.0	0.257	1.10	0.39	1.113	0.1633	0.1203
156.0	0.318	1.70	0.49	1.721	0.2499	0.2034
186.0	0.379	2.50	0.59	2.531	0.3798	0.3554
236.0	0.481	1.90	0.52	1.923	0.6065	0.6253
290.0	0.591	0.0	0.0	0.0	0.7123	0.7415
314.0	0.640	0.0	0.0	0.0	0.7123	0.7415
336.0	0.684	0.40	0.24	0.405	0.7214	0.7461
354.0	0.721	0.40	0.24	0.405	0.7362	0.7536
376.0	0.766	0.10	0.12	0.101	0.7476	0.7587
420.0	0.855	1.00	0.38	1.012	0.7974	0.7960
466.0	0.949	2.00	0.53	2.025	0.9397	0.9406
484.0	0.986	0.90	0.36	0.911	0.9935	0.9951
491.0	1.000	0.0	0.0	0.0	1.0000	1.0000

continued ...

Table 10. Continued.

Z	Z/W	H (Z)	U (Z)	H/MD	A'	Q'
			44.5 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.0	0.029	1.60	0.49	1.457	0.0214	0.0216
40.0	0.098	1.40	0.46	1.275	0.1152	0.1131
80.0	0.196	1.20	0.42	1.093	0.2312	0.2187
120.0	0.294	0.70	0.32	0.637	0.3160	0.2862
160.0	0.392	0.30	0.21	0.273	0.3607	0.3129
200.0	0.490	0.10	0.12	0.091	0.3785	0.3198
240.0	0.588	0.30	0.21	0.273	0.3964	0.3268
290.0	0.711	1.10	0.40	1.002	0.4745	0.3853
340.0	0.833	2.40	0.60	2.185	0.6698	0.6017
370.0	0.907	2.30	0.58	2.094	0.8271	0.7938
401.0	0.983	2.20	0.57	2.003	0.9828	0.9797
408.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			48.3 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.025	2.66	0.33	1.491	0.0189	0.0211
30.0	0.076	2.88	0.35	1.614	0.0975	0.1108
60.0	0.152	3.05	0.36	1.710	0.2237	0.2598
80.0	0.203	2.75	0.34	1.542	0.3060	0.3560
110.0	0.278	2.23	0.31	1.250	0.4120	0.4711
140.0	0.354	1.38	0.24	0.774	0.4889	0.5433
170.0	0.430	0.46	0.14	0.258	0.5281	0.5715
200.0	0.506	0.62	0.16	0.348	0.5511	0.5832
230.0	0.582	1.48	0.25	0.830	0.5958	0.6166
260.0	0.658	2.00	0.29	1.121	0.6698	0.6841
290.0	0.734	1.90	0.28	1.065	0.7529	0.7636
320.0	0.810	2.01	0.29	1.127	0.8361	0.8434
350.0	0.886	2.29	0.31	1.284	0.9276	0.9355
380.0	0.962	0.74	0.18	0.415	0.9921	0.9954
395.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			51.6 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.0	0.015	2.10	0.32	1.842	0.0135	0.0149
32.0	0.047	0.80	0.19	0.702	0.0544	0.0556
58.0	0.085	1.50	0.27	1.316	0.0927	0.0882
100.0	0.146	1.50	0.27	1.316	0.1735	0.1639
200.0	0.292	1.40	0.26	1.228	0.3595	0.3355
270.0	0.395	1.20	0.24	1.053	0.4761	0.4377
330.0	0.482	0.70	0.18	0.614	0.5492	0.4936
367.0	0.537	0.0	0.0	0.0	0.5659	0.5043
495.0	0.724	0.0	0.0	0.0	0.5659	0.5043
504.0	0.737	0.90	0.21	0.789	0.5710	0.5081
554.0	0.810	2.00	0.31	1.754	0.6640	0.5985
604.0	0.883	3.00	0.38	2.631	0.8243	0.7955
650.0	0.950	1.70	0.28	1.491	0.9629	0.9630
684.0	1.000	0.0	0.0	0.0	1.0000	1.0000

continued ...

Table 10. Continued.

Z	Z/W	H(Z)	U(Z)	H/MD	A'	Q'
			59.5 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
195.0	0.305	0.0	0.0	0.0	0.0	0.0
230.0	0.359	0.38	0.17	0.357	0.0098	0.0036
275.0	0.430	2.09	0.40	1.962	0.0913	0.0681
290.0	0.453	2.20	0.41	2.065	0.1385	0.1097
310.0	0.484	1.80	0.37	1.690	0.1971	0.1597
350.0	0.547	0.50	0.19	0.469	0.2646	0.2084
370.0	0.578	0.20	0.12	0.188	0.2749	0.2123
400.0	0.625	0.0	0.0	0.0	0.2793	0.2135
460.0	0.719	0.0	0.0	0.0	0.2793	0.2135
470.0	0.734	0.80	0.25	0.751	0.2851	0.2167
480.0	0.750	3.20	0.49	3.004	0.3145	0.2450
490.0	0.766	3.90	0.54	3.661	0.3665	0.3042
500.0	0.781	3.80	0.53	3.567	0.4230	0.3707
520.0	0.813	3.40	0.51	3.192	0.5286	0.4912
550.0	0.859	2.68	0.45	2.516	0.6624	0.6320
580.0	0.906	4.08	0.55	3.830	0.8111	0.7989
590.0	0.922	4.20	0.56	3.943	0.8718	0.8731
600.0	0.938	3.00	0.48	2.816	0.9246	0.9339
610.0	0.953	1.82	0.37	1.708	0.9600	0.9676
640.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			68.5 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
20.0	0.049	0.10	0.08	0.064	0.0016	0.0003
30.0	0.073	0.20	0.11	0.129	0.0039	0.0009
60.0	0.146	0.80	0.22	0.515	0.0275	0.0131
80.0	0.195	0.51	0.17	0.328	0.0480	0.0240
90.0	0.220	0.40	0.15	0.257	0.0552	0.0271
120.0	0.293	0.31	0.14	0.199	0.0719	0.0335
150.0	0.366	0.72	0.21	0.463	0.0961	0.0454
180.0	0.439	1.22	0.27	0.785	0.1418	0.0750
210.0	0.512	2.34	0.37	1.506	0.2256	0.1496
240.0	0.585	3.41	0.45	2.194	0.3610	0.2990
270.0	0.659	4.00	0.49	2.574	0.5354	0.5152
300.0	0.732	3.26	0.44	2.098	0.7063	0.7253
330.0	0.805	2.24	0.36	1.441	0.8358	0.8651
360.0	0.878	1.65	0.31	1.062	0.9274	0.9478
390.0	0.951	0.86	0.23	0.553	0.9865	0.9920
410.0	1.000	0.0	0.0	0.0	1.0000	1.0000

continued ...

Table 10. Continued.

Z	Z/W	H(Z)	U(Z)	H/MD	A'	Q'
			83.3 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
5.0	0.009	3.10	0.66	3.211	0.0149	0.0152
10.0	0.019	3.65	0.72	3.781	0.0472	0.0498
15.0	0.028	3.70	0.72	3.833	0.0825	0.0890
30.0	0.056	3.65	0.72	3.781	0.1882	0.2067
50.0	0.093	3.50	0.71	3.626	0.3254	0.3572
70.0	0.130	3.40	0.69	3.522	0.4578	0.4999
110.0	0.204	2.83	0.63	2.932	0.6968	0.7455
140.0	0.259	2.85	0.64	2.952	0.8602	0.9053
160.0	0.296	1.20	0.41	1.243	0.9379	0.9735
170.0	0.315	0.0	0.0	0.0	0.9495	0.9808
365.0	0.676	0.0	0.0	0.0	0.9495	0.9808
375.0	0.694	0.20	0.17	0.207	0.9514	0.9813
390.0	0.722	0.50	0.27	0.518	0.9614	0.9850
420.0	0.778	0.42	0.24	0.435	0.9879	0.9955
450.0	0.833	0.0	0.0	0.0	1.0000	1.0000
540.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			93.5 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
22.0	0.074	0.90	0.27	0.549	0.0203	0.0136
31.0	0.104	0.60	0.22	0.366	0.0341	0.0222
55.0	0.185	1.10	0.30	0.671	0.0758	0.0503
69.0	0.232	1.00	0.29	0.610	0.1059	0.0721
76.0	0.255	1.50	0.35	0.915	0.1238	0.0865
82.0	0.275	1.00	0.29	0.610	0.1392	0.0988
94.0	0.315	1.10	0.30	0.671	0.1650	0.1175
110.0	0.369	1.70	0.38	1.037	0.2108	0.1565
130.0	0.436	1.70	0.38	1.037	0.2804	0.2207
150.0	0.503	1.90	0.40	1.159	0.3541	0.2907
180.0	0.604	2.30	0.44	1.403	0.4830	0.4233
230.0	0.772	2.90	0.49	1.769	0.7491	0.7282
270.0	0.906	1.90	0.40	1.159	0.9456	0.9469
298.0	1.000	0.0	0.0	0.0	1.0000	1.0000

continued ...

Table 10. Concluded.

Z	Z/W	H(Z)	U(Z)	H/MD	A'	Q'
			101.4 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
30.0	0.099	0.80	0.12	0.293	0.0145	0.0072
60.0	0.198	1.80	0.18	0.660	0.0617	0.0388
90.0	0.297	2.10	0.19	0.770	0.1324	0.0939
120.0	0.396	2.70	0.22	0.989	0.2195	0.1693
138.0	0.455	3.20	0.24	1.173	0.2837	0.2308
142.0	0.469	3.00	0.23	1.099	0.2987	0.2455
160.0	0.528	3.60	0.25	1.319	0.3706	0.3183
184.0	0.607	4.00	0.27	1.466	0.4809	0.4380
190.0	0.627	3.70	0.25	1.356	0.5088	0.4685
215.0	0.710	4.40	0.28	1.612	0.6313	0.6059
245.0	0.809	3.80	0.26	1.393	0.7800	0.7737
270.0	0.891	3.80	0.26	1.393	0.8949	0.8982
275.0	0.908	3.20	0.24	1.173	0.9161	0.9203
288.0	0.950	3.20	0.24	1.173	0.9664	0.9703
296.0	0.977	2.00	0.19	0.733	0.9915	0.9933
303.0	1.000	0.0	0.0	0.0	1.0000	1.0000
			107.6 km			
0.0	0.0	0.0	0.0	0.0	0.0	0.0
30.0	0.130	0.53	0.15	0.207	0.0135	0.0054
60.0	0.261	1.61	0.26	0.628	0.0680	0.0391
90.0	0.391	2.35	0.31	0.917	0.1688	0.1175
120.0	0.522	2.77	0.34	1.081	0.2991	0.2315
150.0	0.652	3.53	0.38	1.378	0.4594	0.3876
180.0	0.783	3.99	0.41	1.557	0.6509	0.5904
190.0	0.826	4.11	0.41	1.604	0.7196	0.6658
210.0	0.913	5.37	0.47	2.096	0.8805	0.8581
220.0	0.957	4.36	0.43	1.702	0.9630	0.9579
230.0	1.000	0.0	0.0	0.0	1.0000	1.0000

8.4 VISUAL DOCUMENTATION

This appendix contains supplementary information regarding visual documentation of the study reach of the Athabasca River in Figures 26 to 38.

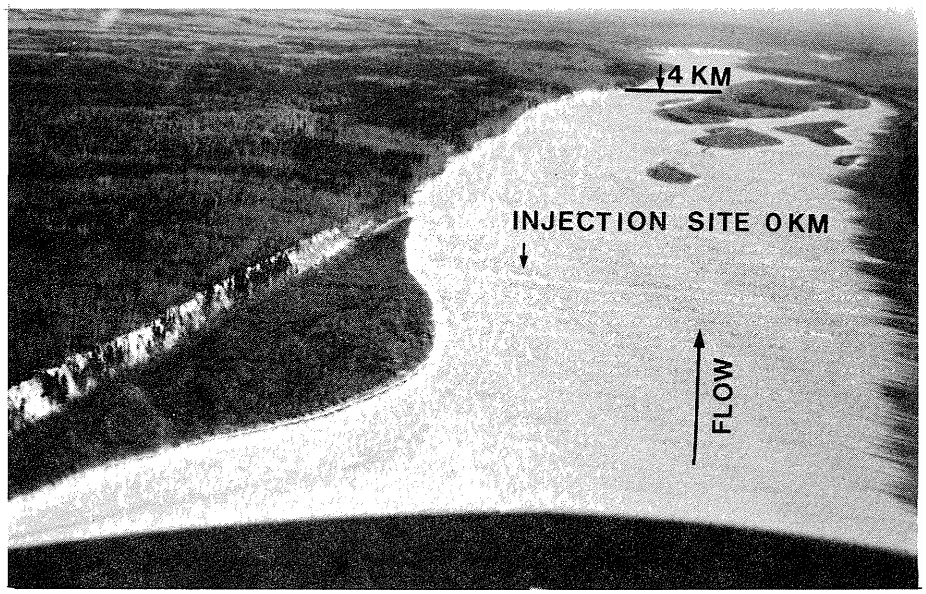

Figure 26. Study reach, 0 km, 16 February 1978.

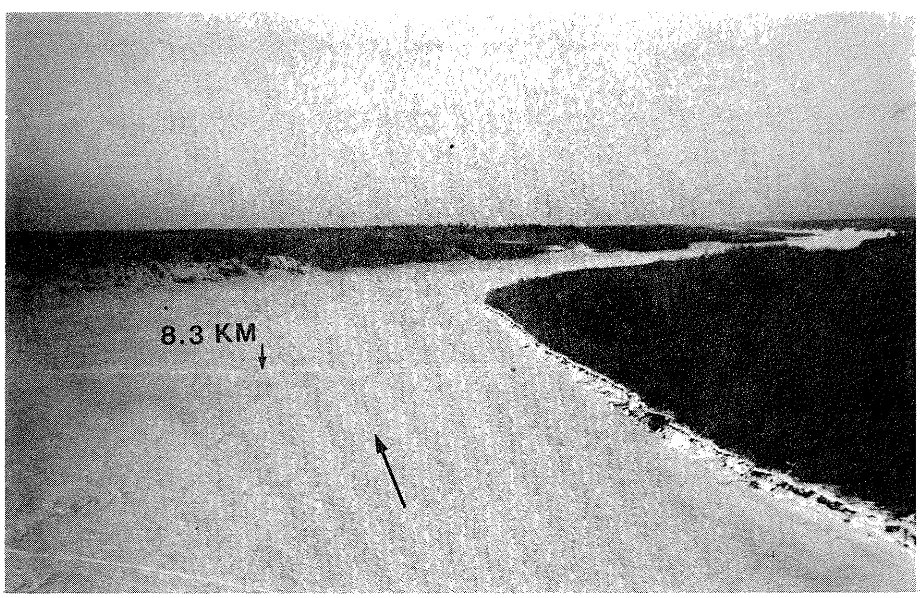

Figure 27. Study reach, 8.3 km, 17 February 1978.

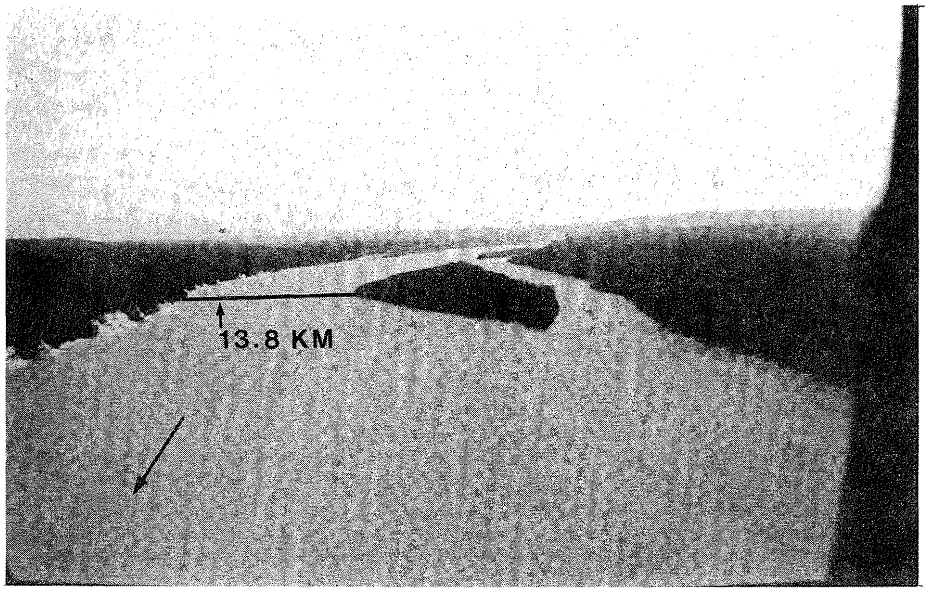

Figure 28. Study reach, 13.8 km, 17 February 1978.

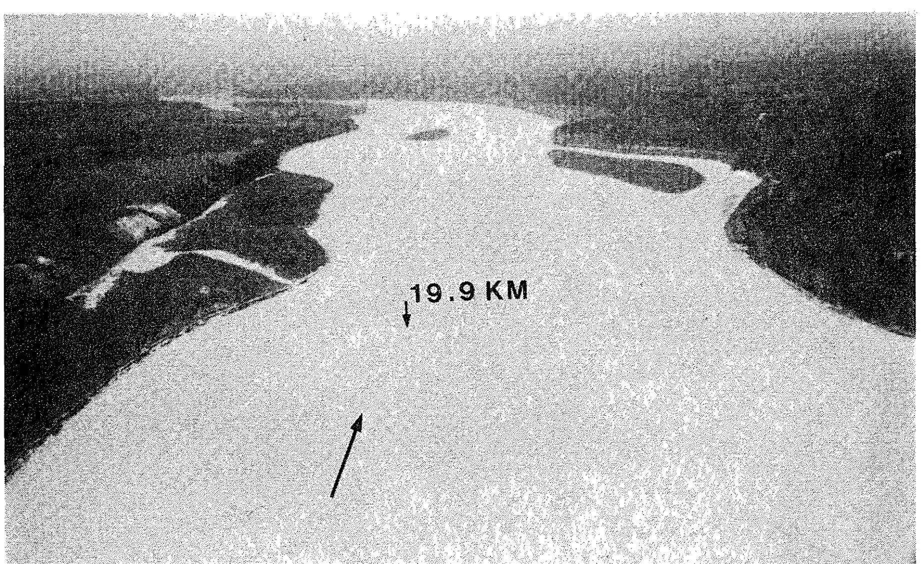

Figure 29. Study reach, 19.9 km, 17 February 1978.

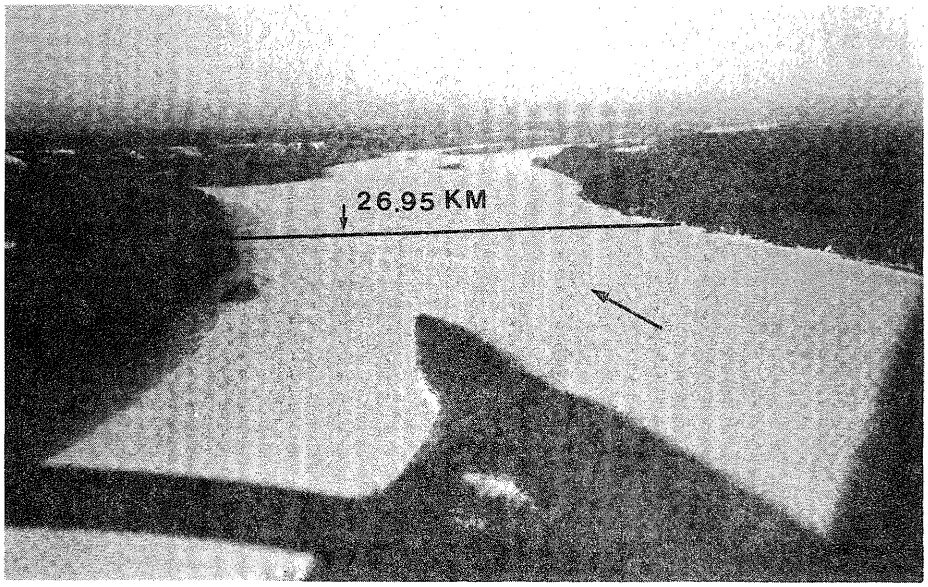

Figure 30. Study reach, 26.95 km, 17 February 1978.

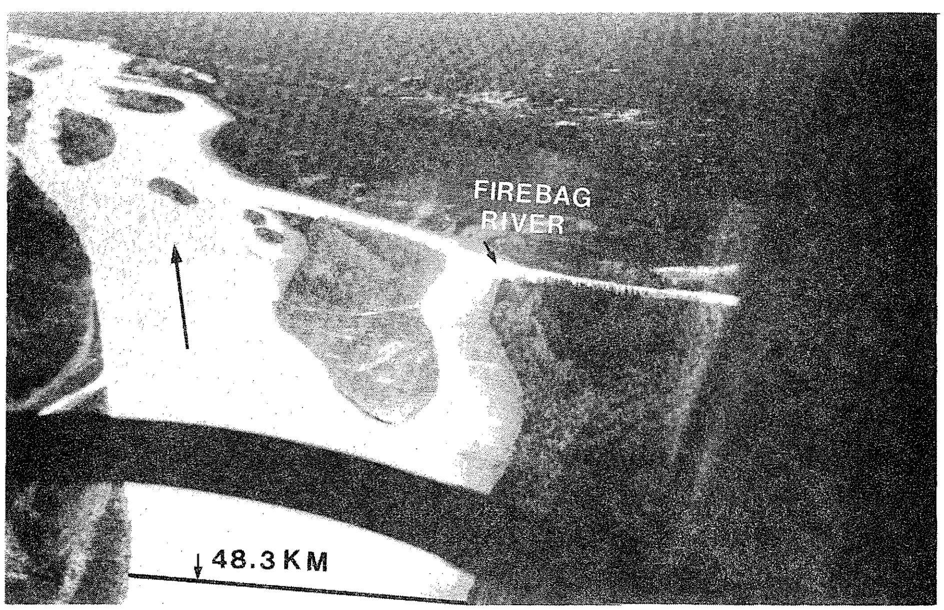

Figure 31. Study reach, 48.3 km, 18 February 1978.

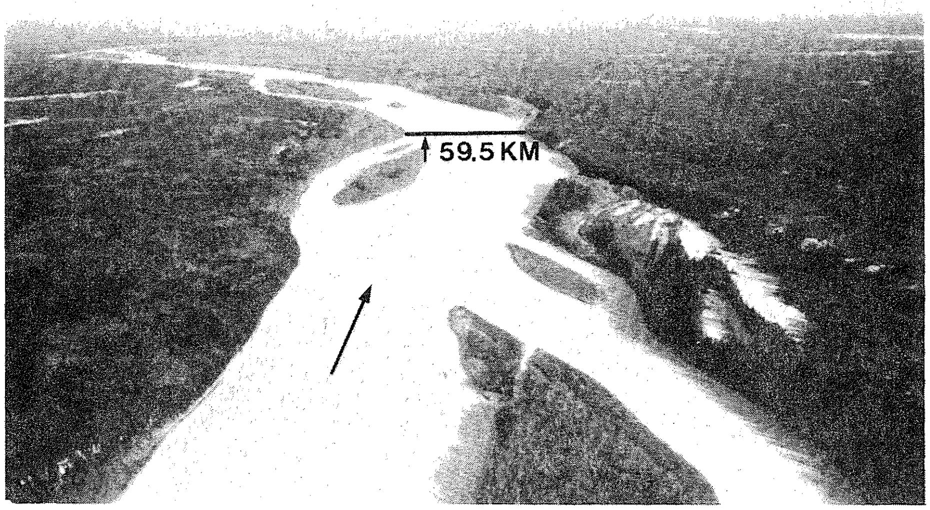

Figure 32. Study reach, 59.5 km, 18 February 1978.

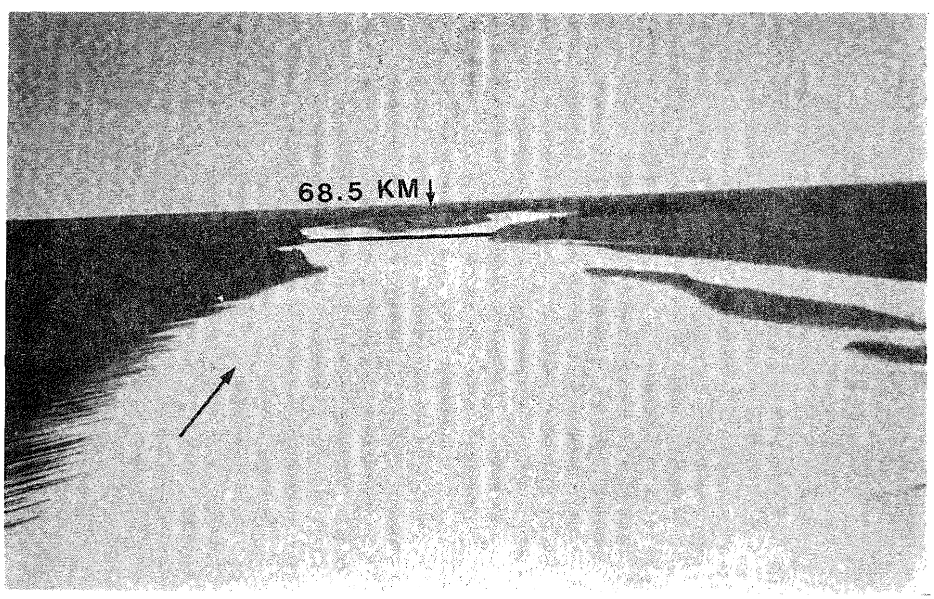

Figure 33. Study reach, 68.5 km, 19 February 1978.

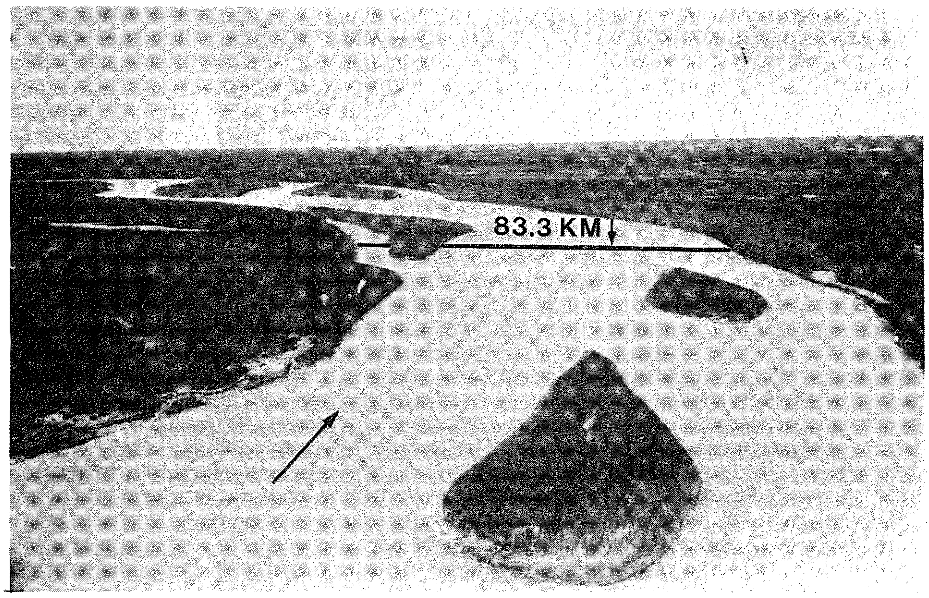

Figure 34. Study reach, 83.3 km, 19 February 1978.

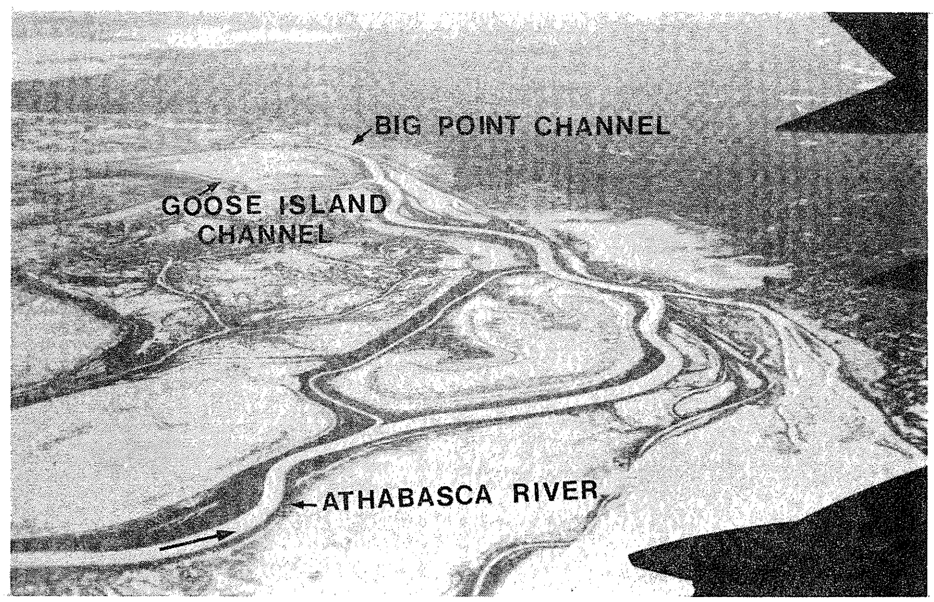

Figure 35. Study reach, beginning of Goose Island and Big Point Channels, 2 February 1978.

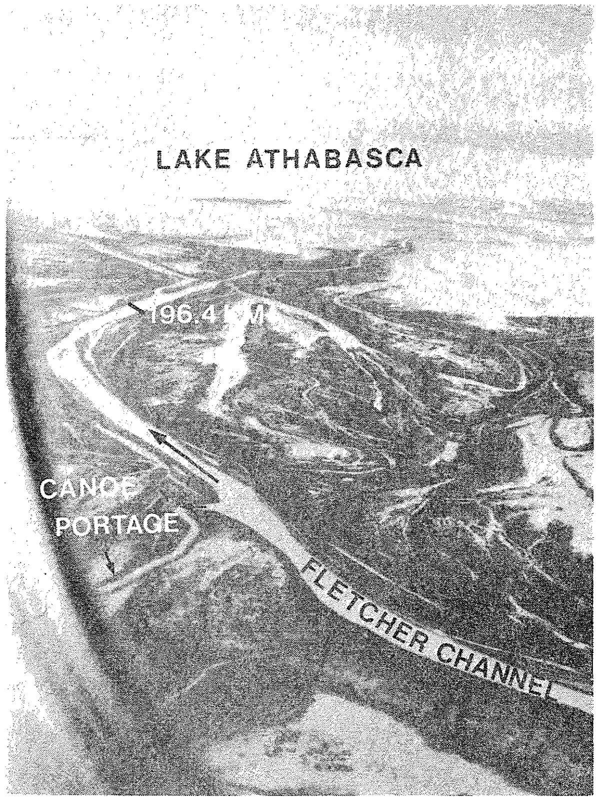

Figure 36. Study reach, 196.4 km, 2 February 1978

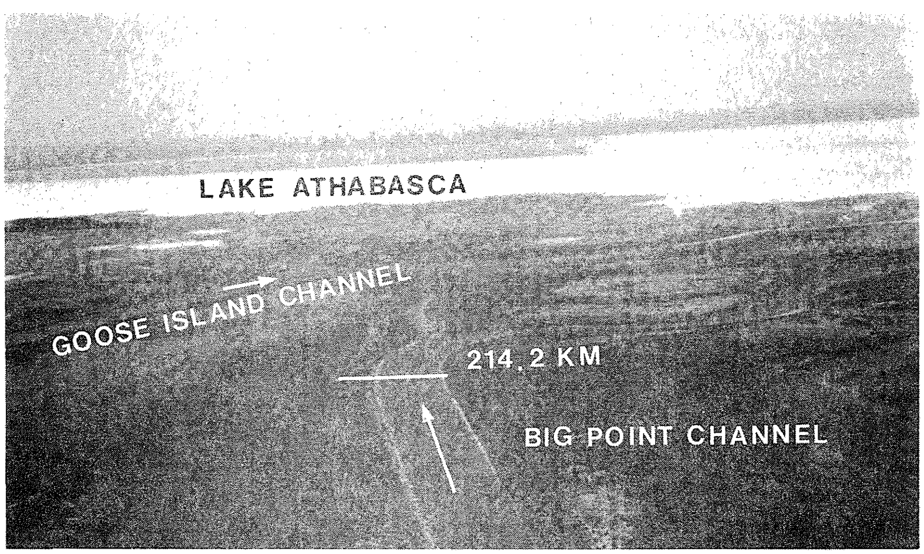

Figure 37. Study reach, 214.2 km, 27 April 1977.

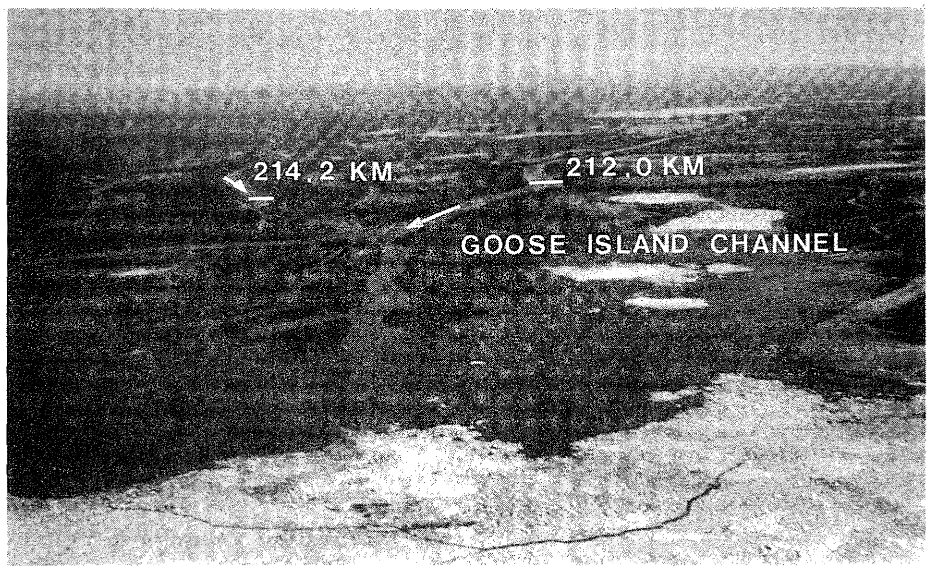

Figure 38. Study reach, 212.0 km and 214.2 km, 27 April 1977.

9. AOSERP RESEARCH REPORTS

1.		AOSERP First Annual Report, 1975
2.	AF 4.1.1	Walleye and Goldeye Fisheries Investigations in the Peace-Athabasca Delta--1975
3.	HE 1.1.1	Structure of a Traditional Baseline Data System
4.	VE 2.2	A Preliminary Vegetation Survey of the Alberta Oil Sands Environmental Research Program Study Area
5.	HY 3.1	The Evaluation of Wastewaters from an Oil Sand Extraction Plant
6.		Housing for the North--The Stackwall System
7.	AF 3.1.1	A Synopsis of the Physical and Biological Limnology and Fisheries Programs within the Alberta Oil Sands Area
8.	AF 1.2.1	The Impact of Saline Waters upon Freshwater Biota (A Literature Review and Bibliography)
9.	ME 3.3	Preliminary Investigations into the Magnitude of Fog Occurrence and Associated Problems in the Oil Sands Area
10.	HE 2.1	Development of a Research Design Related to Archaeological Studies in the Athabasca Oil Sands Area
11.	AF 2.2.1	Life Cycles of Some Common Aquatic Insects of the Athabasca River, Alberta
12.	ME 1.7	Very High Resolution Meteorological Satellite Study of Oil Sands Weather: "a Feasibility Study"
13.	ME 2.3.1	Plume Dispersion Measurements from an Oil Sands Extraction Plant, March 1976
15.	ME 3.4	A Climatology of Low Level Air Trajectories in the Alberta Oil Sands Area
16.	ME 1.6	The Feasibility of a Weather Radar near Fort McMurray, Alberta
17.	AF 2.1.1	A Survey of Baseline Levels of Contaminants in Aquatic Biota of the AOSERP Study Area
18.	HY 1.1	Interim Compilation of Stream Gauging Data to December 1976 for the Alberta Oil Sands Environmental Research Program
19.	ME 4.1	Calculations of Annual Averaged Sulphur Dioxide Concentrations at Ground Level in the AOSERP Study Area
20.	HY 3.1.1	Characterization of Organic Constituents in Waters and Wastewaters of the Athabasca Oil Sands Mining Area

21. AOSERP Second Annual Report, 1976-77
22. HE 2.3 Maximization of Technical Training and Involvement of Area Manpower
23. AF 1.1.2 Acute Lethality of Mine Depressurization Water on Trout Perch and Rainbow Trout
24. ME 4.2.1 Air System Winter Field Study in the AOSERP Study Area, February 1977.
25. ME 3.5.1 Review of Pollutant Transformation Processes Relevant to the Alberta Oil Sands Area

26. AF 4.5.1 Interim Report on an Intensive Study of the Fish Fauna of the Muskeg River Watershed of Northeastern Alberta
27. ME 1.5.1 Meteorology and Air Quality Winter Field Study in the AOSERP Study Area, March 1976
28. VE 2.1 Interim Report on a Soils Inventory in the Athabasca Oil Sands Area
29. ME 2.2 An Inventory System for Atmospheric Emissions in the AOSERP Study Area
30. ME 2.1 Ambient Air Quality in the AOSERP Study Area, 1977

31. VE 2.3 Ecological Habitat Mapping of the AOSERP Study Area: Phase I
32. AOSERP Third Annual Report, 1977-78
33. TF 1.2 Relationships Between Habitats, Forages, and Carrying Capacity of Moose Range in northern Alberta. Part I: Moose Preferences for Habitat Strata and Forages.
34. HY 2.4 Heavy Metals in Bottom Sediments of the Mainstem Athabasca River System in the AOSERP Study Area
35. AF 4.9.1 The Effects of Sedimentation on the Aquatic Biota

36. AF 4.8.1 Fall Fisheries Investigations in the Athabasca and Clearwater Rivers Upstream of Fort McMurray: Volume I
37. HE 2.2.2 Community Studies: Fort McMurray, Anzac, Fort MacKay
38. VE 7.1.1 Techniques for the Control of Small Mammals: A Review
39. ME 1.0 The Climatology of the Alberta Oil Sands Environmental Research Program Study Area
40. WS 3.3 Mixing Characteristics of the Athabasca River below Fort McMurray - Winter Conditions.

41. AF 3.5.1 Acute and Chronic Toxicity of Vanadium to Fish
42. TF 1.1.4 Analysis of Fish Production Records for Registered Traplines in the AOSERP Study Area, 1970-75
43. TF 6.1 A Socioeconomic Evaluation of the Recreational Fish and Wildlife Resources in Alberta, with Particular Reference to the AOSERP Study Area. Volume I: Summary and Conclusions
44. VE 3.1 Interim Report on Symptomology and Threshold Levels of Air Pollutant Injury to Vegetation, 1975 to 1978
45. VE 3.3 Interim Report on Physiology and Mechanisms of Air-Borne Pollutant Injury to Vegetation, 1975 to 1978

46.	VE 3.4	Interim Report on Ecological Benchmarking and Biomonitoring for Detection of Air-Borne Pollutant
47.	TF 1.1.1	A Visibility Bias Model for Aerial Surveys of Moose on the AOSERP Study Area
48.	HG 1.1	Interim Report on a Hydrogeological Investigation of the Muskeg River Basin, Alberta
49.	WS 1.3.3	The Ecology of Macrobenthic Invertebrate Communities in Hartley Creek, Northeastern Alberta
50.	ME 3.6	Literature Review on Pollution Deposition Processes
51.	HY 1.3	Interim Compilation of 1976 Suspended Sediment Data in the AOSERP Study Area
52.	ME 2.3.2	Plume Dispersion Measurements from an Oil Sands Extraction Plant, June 1977
53.	HY 3.1.2	Baseline States of Organic Constituents in the Athabasca River System Upstream of Fort McMurray
54.	WS 2.3	A Preliminary Study of Chemical and Microbial Characteristics of the Athabasca River in the Athabasca Oil Sands Area of Northeastern Alberta.
55.	HY 2.6	Microbial Populations in the Athabasca River
56.	AF 3.2.1	The Acute Toxicity of Saline Groundwater and of Vanadium to Fish and Aquatic Invertebrates
57.	LS 2.3.1	Ecological Habitat Mapping of the AOSERP Study Area (Supplement): Phase I

These reports are not available upon request. For further information about availability and location of depositories, please contact:

Alberta Oil Sands Environmental Research Program
15th Floor, Oxbridge Place
9820 - 106 Street
Edmonton, Alberta T5K 2J6