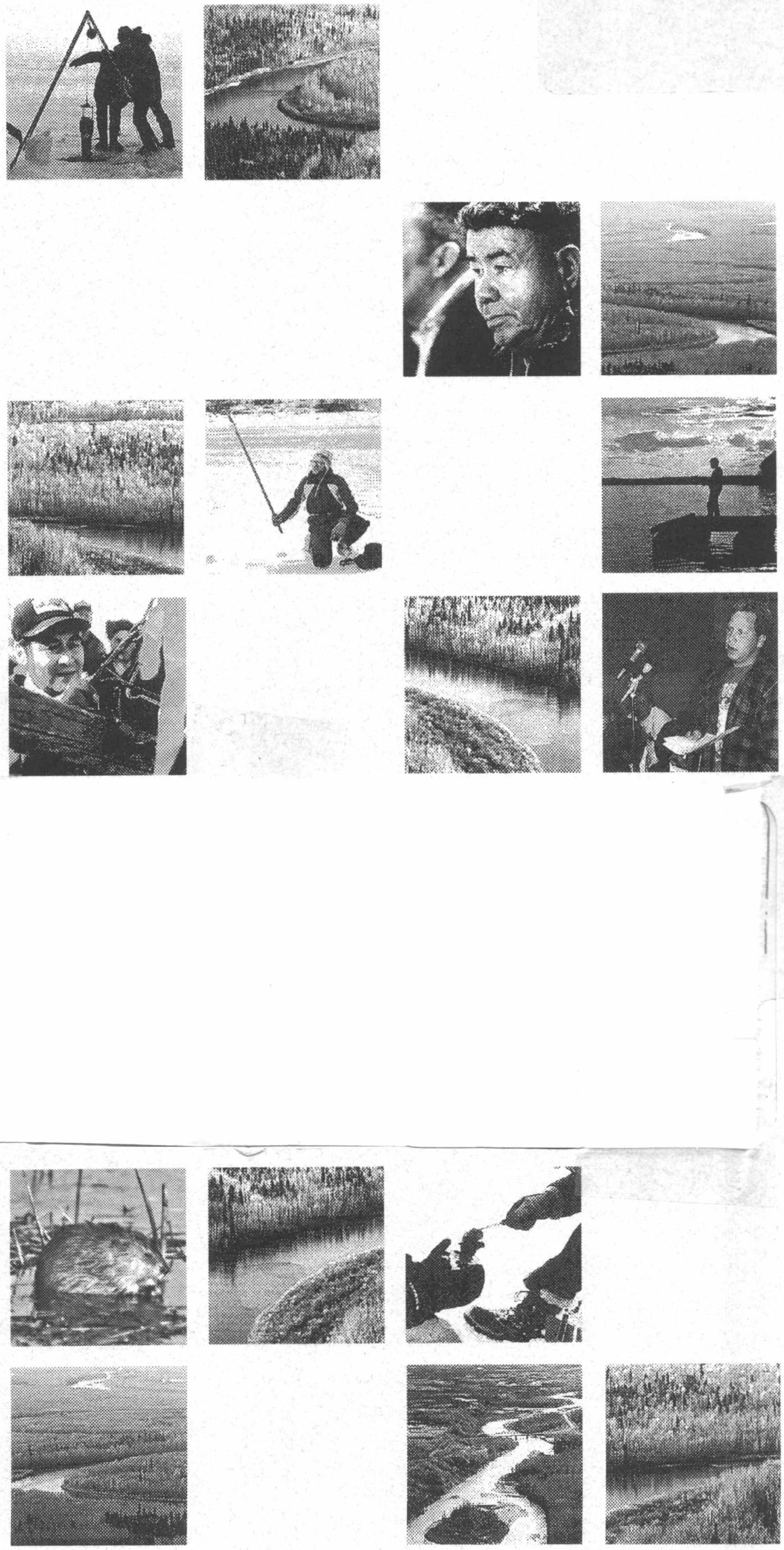
Canada Alberta Northwest Territories

Northern River Basins Study



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NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 14

WINTER LOW FLOW TRACER DYE STUDIES, ATHABASCA RIVER ATHABASCA TO BITUMOUNT FEBRUARY AND MARCH, 1992 PART II: MIXING CHARACTERISTICS

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PREFACE:

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

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

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

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

(Dr. F.J. Wrona, Ph.D., Science Director) — 26 August 1993 (Date)

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

(Dr. P. A. Larkin, Ph.D., Chair) — Sept 8/93 (Date)

Whereas it is the duty of the Operations Committee to attend to the day-to-day management of the Study on behalf of the Study Board,
IT IS THEREFORE RECOMMENDED BY THE OPERATIONS COMMITTEE THAT;
this publication be released to the public and it is reported that
THIS PUBLICATION HAS BEEN REVIEWED BY THE HEALTH ASSESSMENT COMMITTEE AND SUBSEQUENTLY FORWARDED TO APPROPRIATE HEALTH AUTHORITIES: [ ] Yes [✓] No

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

(Bev Burns, Co-chair) — 93/09/20 (Date)

NRBS.005

WINTER LOW FLOW TRACER DYE STUDIES
ATHABASCA RIVER
ATHABASCA TO BITUMOUNT
FEBRUARY AND MARCH, 1992
PART II: MIXING CHARACTERISTICS

STUDY PERSPECTIVE

> ***Related Study Questions***
>
> 13a) *What predictive tools are required to determine the cumulative effects of man made discharges on the water and aquatic environment?*
>
> 14) *What long term monitoring programs and predictive models are required to provide an ongoing assessment of the state of the aquatic ecosystems. These programs must ensure that all stakeholders have the opportunity for input.*

To properly model the transport of contaminants and pollutants within freshwater systems, the mixing or dispersion characteristics must be established. The NRBS Mixing Characteristics study focused on the calculation of mixing coefficients using field dye-tests on the Athabasca River between the towns of Athabasca and Bitumount in February - March 1992. The test was completed under low-flow, ice covered conditions in late winter (February-March 1992); the period most critical for potential impacts on the aquatic ecosystem. The calculated coefficients will be useful in modelling of the dilution of effluent along the specific study reach and, when combined with similar data from other tests (ie. Hinton to Athabasca in 1989 and Bitumount to Lake Athabasca in 1979), along the entire length of the Athabasca River.

Although the test data fit a general trend with the other Athabasca results, it is not yet possible to accurately predict coefficients for a complete range of hydraulic and ice conditions. The report does, however, contain some advice on extrapolating the results for application under other flow regimes. The present mixing values are considered adequate for the current level of water quality modelling being attempted for the river, but, as the requirements for these coefficients become better defined, additional research may have to be conducted towards the prediction of more accurate values for specific hydraulic and ice conditions.

ABSTRACT

A field investigation covering the portion of the Athabasca River between Athabasca and Bitumount was performed to define the hydraulic and mixing characteristics of the river reach. Twelve sample sites were selected within the 464 km long study area. The river was divided into three reaches in which separate tracer dye experiments were performed to determine travel times and dispersion coefficients.

The mixing process was split into a number of zones in which different processes were dominant. Vertical mixing was found to be virtually instantaneous with vertical mixing lengths between 15 m and 27 m. Transverse mixing was found to be complete between 52 km and 82 km downstream of the injection points. The linear mixing lengths which define the start of classical Fickian dispersion were estimated to be between 332 km and 2130 km, indicating that Fickian dispersion was not observed during the tests. The only type of longitudinal dispersion which occurred in the study reaches was linear dispersion.

The transverse mixing coefficients were found to range from 0.0082 m^2/s downstream of Ft.McMurray to 0.0154 m^2/s downstream of Athabasca. A lower limit of 0.0097 m^2/s was found downstream of Upper Wells. Diffusion factors, which also incorporate some of the hydraulic characteristics, were found to range from 0.0130 m^5/s^2 to 0.0228 m^5/s^2. Dimensionless transverse mixing coefficients ranged between 0.23 and 0.33 while dimensionless diffusion factors ranged between 0.00023 and 0.00032. These dimensionless values are similar to values obtained from previous tests in other reaches of the Athabasca River but there is still considerable variation. This is most likely due to the specific characteristics of the test reaches. The dimensionless mixing coefficient was found to be the best parameter to relate the transverse mixing characteristics to the hydraulic characteristics. Modelling of transverse mixing in the study reach is limited to analytical techniques until more cross-sections are obtained to adequately define the hydraulic variations.

Linear dispersion parameters were found to range from 0.00058 to 0.0072. These values are lower than values previously measured on the Athabasca River under an ice cover and also lower than values on other ice covered rivers. However, they are consistent with the trend of increasing β_x with decreasing relative roughness. This trend can be used to extrapolate values of β_x for other winter flow conditions. An alternate longitudinal dispersion model was introduced which reproduced the shape of the time-concentration curves more accurately. Unfortunately, no relationship can be established between the coefficient for this storage model and the hydraulic characteristics due to the limited data set from these tests.

ACKNOWLEDGEMENTS

This study was funded by the Northern Rivers Basin Study Board and the Surface Water Engineering Group of the Environmental Research and Engineering Department, Alberta Research Council. The field work was performed by J. Thompson, B. Trevor, P. Mostert and M. Huemmert of the Alberta Research Council. A fluorometer was provided by S. Lovell of the Hydraulics Laboratory at the University of Alberta. Both the Water Survey of Canada and the Water Survey Section of Alberta Environment provided discharge measurements for the study. The review comments provided by D. Andres and the Northern Rivers Basin Study office were incorporated into this final report.

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LIST OF SYMBOLS

B	- channel width
$\overline{C}$	- cross-section average concentration
C	- concentration
C_p	- peak concentration
C_u	- velocity coefficient
C_∞	- final downstream concentration
D_x	- Fickian dispersion coefficient
D_z	- diffusion factor
e_x	- longitudinal mixing coefficient
e_z	- transverse mixing coefficient
f(x)	- confinement function
g	- gravitational acceleration constant
h	- local flow depth
H	- average flow depth in cross-section
k_p	- position parameter
k_t	- dimensionless transverse mixing coefficient
k_T	- temperature correction factor
L_L	- Linear mixing length
L_t	- transverse mixing length
L_v	- vertical mixing length
m	- storage zone number
M	- total mass of pollutant
m_x	- longitudinal metric coefficient of curvature
m_z	- transverse metric coefficient of curvature
n	- integer
Q	- total discharge
q_c	- cumulative discharge across channel

LIST OF SYMBOLS (continued)

R - hydraulic radius

S - river slope

t - time from injection

T - sample temperature

T_e - effective time constant of storgae zone

T_o - calibration temperature

t_p - travel time of peak concentration

t_s - local time for storage model

t_β -time adjustment for Beltaos' model

u - local longitudinal flow velocity

U - average longitudinal flow velocity in cross-section

U_* - shear velocity

w - local transverse velocity

x - longitudinal distance

z - transverse distance

∞ - infinity

α_L - Linear mixing length factor

α_x - dimensionless storage constant

β_x - Beltaos' dispersion parameter

β_z - dimensionless diffusion factor

ΔT - half-duration of time-concentration distribution

η - fraction of cumulative discharge across channel

η_i - position of injection in cross-section

η_0 - centroid of dosage distribution

θ - concentration dosage

θ_{LB} - dosage at left bank

θ_{RB} - dosage at right bank

ξ - dimensionless distance

LIST OF SYMBOLS (continued)

π	- circle constant
σ_η^2	- variance of dosage distribution across channel
σ_t^2	- variance of time-concentration distributions
χ	- dimensionless distance
ψ	- shape-velocity factor

1.0 INTRODUCTION

1.1 Background

The expansion of industry into the Peace and Athabasca River basins in recent years has caused some concern about the impacts of such development on the environment. Recently, the Northern Rivers Basin study has been implemented to improve the understanding of the effects of current development on the ecological system in the study area. A number of objectives have been identified, among them the need to collect data and develop appropriate models which can be used to better understand the impact of water quality on fish and fisheries, riparian wildlife, and local communities. Among the basic data requirements of these water quality models are accurate hydraulic and mixing characteristics of the main rivers in the basin.

The most critical conditions for many water quality parameters in rivers in northern Alberta usually occur during the winter period. In most of these rivers, the lowest flows occur during the winter and these low flows reduce the effluent assimilation capacity of the rivers. As well, the ice cover which exist on these rivers during the winter blocks the reabsorption of oxygen, thus intensifying the effects of oxygen consumption by some effluents.

Tracer dye experiments are the most reliable way of accessing the hydraulic and mixing characteristics of a river reach. Field programs in which the entire dye cloud is sampled can be used to define the peak and the centroid travel times as well as to determine the lateral and longitudinal mixing rates. Information on the hydraulic and mixing characteristics for these low flow, ice-covered conditions is available for some river reaches of the Athabasca River but not for all the reaches of interest. Winter tracer dye studies have been done previously on five reaches between Hinton and the town of Athabasca (Andres, Van Der Vinne and Trevor, 1989) and between Bitumount and Embarras (Beltaos, 1979). The Alberta Research Council, which performed these previous studies, was requested by the Northern Rivers Basin Study Board to conduct tracer dye studies in the reach between Athabasca and Bitumount to complete the work. Thus, the hydraulic and mixing characteristics for winter low flow conditions will be defined for almost the entire length of the Athabasca River.

1.2 Objectives

The objectives of this study are to define the hydraulic characteristics and mixing characteristics on the Athabasca River between Athabasca and Bitumount. These objectives will be dealt with in two separate reports. The hydraulic characteristics for low flow winter conditions have been evaluated and presented in a previous report (Van Der Vinne and Andres, 1992). The transverse and longitudinal mixing characteristics will be addressed in this report. The objectives of this second report are to:

1. briefly describe the field work undertaken to define the mixing characteristics,
2. present the transverse mixing characteristic and analyze them relative to the hydraulic characteristics, and
3. present the longitudinal mixing characteristic and analyze them relative to the hydraulic characteristics.

The description of the field work has been repeated in this second report so that this report can stand alone as well as compliment the first report on travel times.

2.0 FIELD INVESTIGATION

The field investigation covered a 463.8 km reach of the Athabasca River between the town of Athabasca and Bitumount (figure 1a-b). The river flows generally from south to north in this section. The river can be split into three reaches each with different geomorphic characteristics. The upstream reach, between Athabasca and Upper Wells, is an entrenched channel with a gravel bed, exhibiting an irregular meander pattern and occasional islands. The middle reach, from Upper Wells to Fort McMurray, is similar to the first except that the valley deepens as the river drops through numerous rapids, the largest of which is Grand Rapids with a drop of about fifteen meters over a distance of one kilometre. In the downstream reach, from Fort McMurray to Bitumount, the channel is straight, the bed is composed of sand, and occasional islands and mid-channel bars are evident. The slope is much milder. Significant inflow from the Clearwater River at Fort McMurray increases the discharge in this section of the river.

The field investigation for this study was split into two stages. First, synoptic surveys were done to determine sample locations and local hydraulic conditions and second, the tracer dye experiments were performed to determine the travel times through the system. Discharge metering was also done to determine flow rates throughout the study period.

2.1 Synoptic surveys

Synoptic surveys were done as part of the planning process for the tracer dye experiments. The data gathered during these surveys was used to select the locations of the sample sites and determine the distribution of sample holes in each cross-section. This selection was done in advance because once the tracer dye experiments were initiated there would be little time to do the necessary measurements.

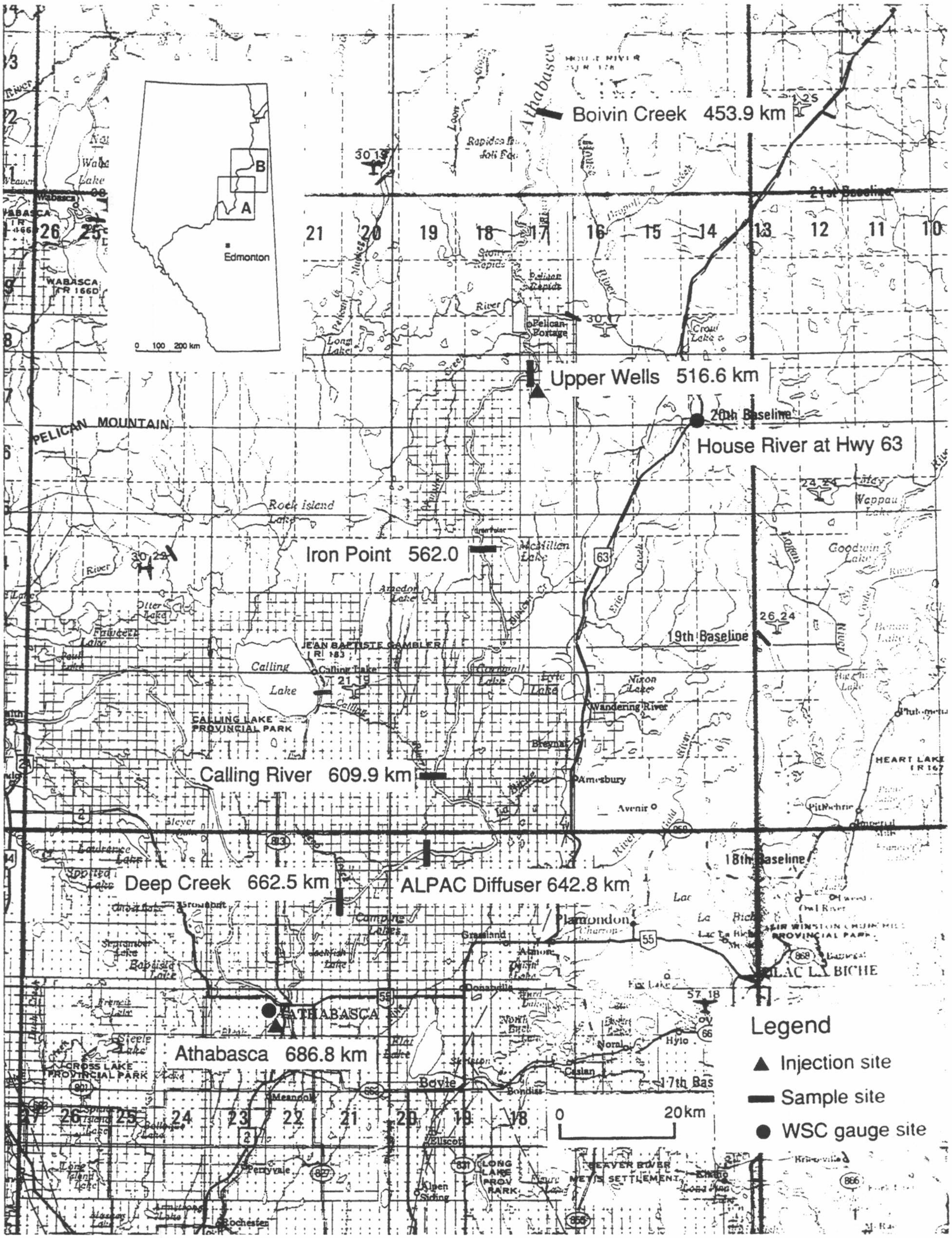

Figure 1a Location plan.

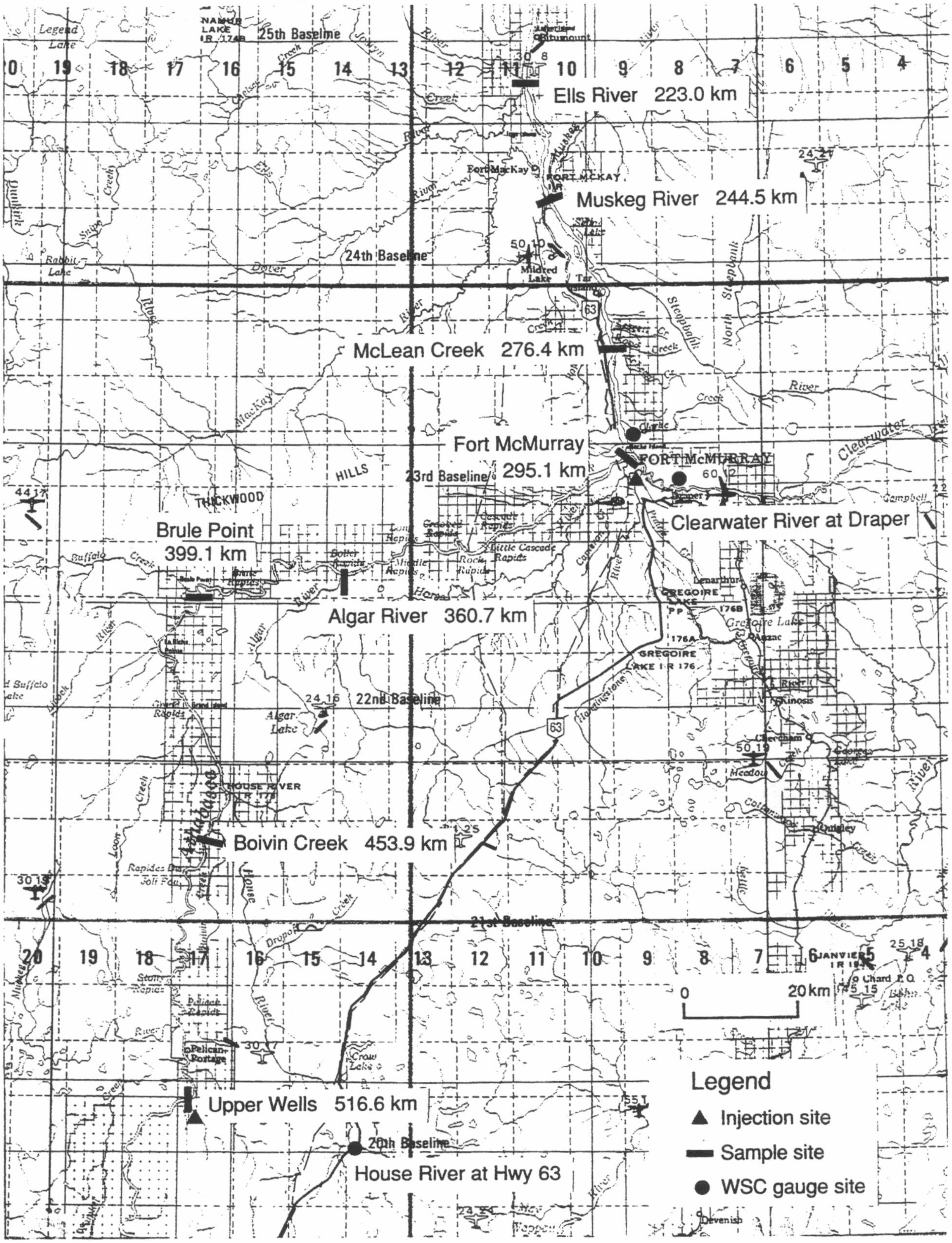

Figure 1b Location plan.

2.1.1 Site selection

Sample sites were initially selected in the office from available information. The sites were selected initially to divide the river into subreaches between 30 and 50 kilometres in length. These subreaches were selected so that the known hydraulic characteristics such as river slope were consistent within each subreach. Surface access to the river was also important in selecting the sample sites both because it was less expensive than helicopter access and because the sampling crews could bring in more equipment.

A number of sample site locations were relocated when more information on ice conditions and surface access was gathered during the synoptic surveys carried out between Feb. 3 and Feb 13, 1992. Some of the sites were moved because there were open leads in the ice cover and the sampling crew could not safely travel across the channel. Other sites were changed because there was surface access available nearby. The sample site planned for Bitumount was moved upstream five kilometres to the ice bridge at the mouth of the Ells River because there was an open lead at Bitumount. As well, a sample site planned near Middle Rapids was moved upstream to the mouth of the Algar River because open water was evident in the area of the rapids. The ice cover also was not competent in the area of Stony Rapids so that sample site was moved upstream to Upper Wells where surface access was available.

Adjusting the locations of some of the sites caused some of the subreaches to be longer than 50 km. For example, the subreach between Upper Wells and Boivin Creek became 62.7 km long. This was not expected to cause any difficulty, however, because the river characteristics in this subreach are quite uniform. The final locations of all the sample site is given in figure 1.

2.1.2 Cross-section surveys

Cross-section surveys were undertaken at each site once the site locations were determined. The cross-section surveys measured depths and ice thicknesses at approximately ten points across the channel. The cross-section plots obtained from this data are given in a previous

Table 1 Summary of local hydraulic characteristic during synoptic survey.

Location	Date	Discharge (m^3/s)	Slope	Ice Thickness (m)	Top Width (m)	Flow Depth (m)	Mean Velocity (m/s)
Athabasca	Feb 03	97.0	0.00027	0.43	203	1.30	0.37
Deep Creek	Feb 10	92.3	0.00027	0.46	360	0.68	0.38
ALPAC[1]	Feb 11	92.3	0.00027	0.35	302	1.31	0.23
Calling River	Feb 04	97.0	0.00027	0.44	216	1.39	0.32
Iron Point	Feb 05	85.0	0.00035	0.42	158	1.44	0.37
Upper Wells	Feb 05	85.0	0.00068	0.44	130	2.60	0.25
Boivin Creek	Feb 06	85.0	0.00068	0.85	167	1.58	0.32
Brule Point	Feb 07	85.0	0.00058	0.84	211	1.06	0.38
Algar River	Feb 07	85.0	0.00095	0.52	241	0.92	0.38
Ft.McMurray	Feb 13	106.5	0.00047	1.39	336	0.69	0.46
McLean Creek	Feb 12	171.3	0.00017	0.50	234	1.38	0.53
Muskeg River	Feb 13	171.3	0.00014	0.60	320	1.81	0.30
Ells River	Feb 12	171.3	0.00012	0.48	352	1.39	0.35

[1] This site is located at the Alberta-Pacific pulp and paper mill diffuser.

report (Van Der Vinne and Andres, 1992).

The mean hydraulic characteristics of each of the cross-sections was used along with map slopes to estimate travel times and mixing rates for the tracer dye experiments. These mean hydraulic characteristics are give in table 1. The mean ice thickness was found to range from 0.35 m to 1.4 m. Those ice thicknesses that were greater than 0.60 m resulted from frazil accumulations of up to two meters in thickness. The mean depth was found to vary between 0.68 m and 2.60 m while the top width varied from 130 m to 352 m. The mean velocity at the sections ranged from 0.23 m/s to 0.53 m/s.

2.1.3 Discharge distributions

Discharge distributions at each site were determined to facilitate the selection of the sample locations in the cross-section to ensure that samples would be distributed evenly across the flow. Discharge distributions can be measured directly with a current meter or they can be estimated from the local flow depths.

Actual discharge measurements were performed at six sites, the three planned dye injection sites and the sample sites immediately downstream. The distributions at these sites were judged to be more important because the dye would not be fully mixed across the channel. The distributions at the other sites were estimated from the local flow depths. The error in these estimates was evaluated at the metered sites and found to be minimal. The example shown in figure 2 shows very little deviation between the two typical cumulative discharge curves. The remaining cumulative discharge curves are given in a previous report (Van Der Vinne and Andres, 1992).

2.2 Tracer dye experiments

The 464 km portion of the Athabasca River was divided into three reaches in which separate tracer dye experiments were carried out. These three reaches were defined to reflect the three distinct segments of river, each with consistent channel characteristics. The maps in figures 1a and 1b show the dye injection locations and the sample sites as well as the river distances (from the mouth) at each location. The dye was always injected at the upstream end of each reach and the concentration measured at three to five sites downstream. The experiments progressed upstream so that no residual dye would interfere with subsequent tests. Table 2 summarizes some of the salient information for each experiment.

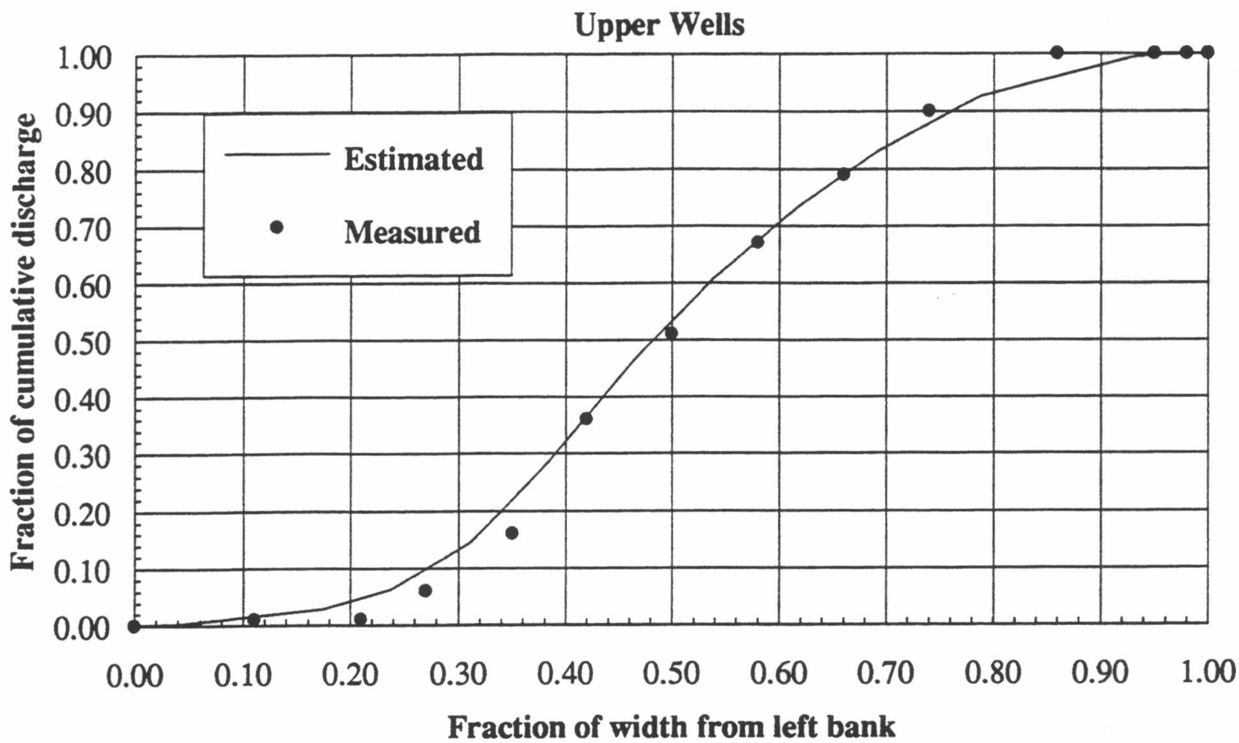

Figure 2 Comparison of an estimated discharge distribution with a measured discharge distribution

2.2.1 Injections

For each tracer dye experiment, a predetermined volume of 20% Rhodamine WT dye was mixed with an equal volume of methyl alcohol. The methyl alcohol was used to adjust the specific gravity of the mixture to that of water so that it would be neutrally buoyant and as well to prevent the dye from freezing during transport. The dye was measured and mixed in the lab and the mixtures transported to the injection sites in 20 L pails.

At the injection site, a 20 cm diameter hole was augered through the ice at a predetermined point in the cross-section. The point was selected so as to inject the dye in the centre of the flow. Additional holes were also augered nearby to serve as a water supply to flush

Table 2 Summary of tracer dye experiments.

Reach	Injection Date	Injection Time	Dye Mass (kg)	Length (km)	Duration (hrs)	Sample Sites
Ft. McMurray to Ells River	Feb 24	16:15	5.83	72.1	67.1	3
Upper Wells to Ft. McMurray	Feb 27	13:40	11.90	221.5	186.8	4
Athabasca to Upper Wells	Mar 12	13:45	9.52	170.2	105.7	5

the injection apparatus. This injection apparatus consisted of a 1.5 m length of 10 cm diameter PVC pipe. The 90° elbow on the lower end of the pipe was used to orient the dye in the direction of flow. A funnel was attached to the top of the pipe to facilitate pouring the dye and reduce spillage.

The injection apparatus was lowered into the hole such that the outlet was located near the centre of flow, midway between the bed and the bottom of the ice cover. When a longer injection tube was required, an additional 1.0 m length of pipe could attached with a friction coupling before the funnel was attached to the top of the pipe. Once the injection apparatus was properly positioned, it was held in place by a tripod placed on top of the ice. The dye mixture was then poured as quickly as possible into the tube followed immediately by a number of pails of clean river water to ensure all the dye was flushed from the injection apparatus and dye containers. All the dye was easily injected into the flow in a virtually instantaneous time period. Only minor spillage occurred and only a minute amount of dye remained in either the containers or the injection pipe.

2.2.2 Sampling

Following the injection at the upstream end of the reach being characterized, two crews of two persons followed the dye downstream, each crew sampling at alternating sites. At each site, five sample holes were augured at predetermined points across the channel. The water level was referenced to temporary benchmarks established during the synoptic surveys so that the difference in water level could be determined.

Water samples were taken from each of the five sample holes at intervals ranging from ten minutes to two hours depending on the duration of the dye cloud. The interval between samples was set so that at least 20 to 30 samples could be taken from each hole as the dye passed by the site. Also, a number of samples were taken before the dye arrived to establish the background fluorescence. Special care was taken to define the time of first rise and the time of the peak concentration. Generally, the sampling frequency was increased during these periods. On the falling limb of the concentration curve, sampling was continued until the fluorescence was reduced to at least 20% of the peak and ideally to 10% of the peak so that the tail of the curve could be confidently extrapolated.

2.2.3 Data reduction

As soon as the samples were collected, they were transported to the mobile laboratory which each crew had at its disposal. The sample temperature was recorded and then run though a Turner Designs Model 10 fluorometer and the results recorded.

Two fluorometers were used during the study - the Alberta Research Council rack mounted unit and the University of Alberta field unit. Each unit was kept with the same crew for the duration of the field program. Prior to the field work, a set of concentration standards was prepared and both instruments were calibrated at 20°C for the set of standards over a range of scales. For each fluorometer scale, a log-linear relationship was established between measured and standard concentrations using linear regression.

Three steps were necessary to convert the recorded fluorescence values into true dye concentrations. First, the calibration relationships for the correct ranges were applied to the recorded fluorescence values to obtain true fluorescence values. Next, a temperature correction factor k_T, was applied to convert the fluorescence value into an actual dye concentration. This factor was obtained from

$$[1] \qquad k_T = e^{0.026(T-T_o)}$$

where T is the temperature of the samples in degrees Celsius and T_o is the temperature of the calibration standards (Turner Designs, 1982). Finally, background concentrations were established from the initial samples and then subtracted from the temperature corrected concentrations. The actual dye concentration distributions at each site are given in a previous report (Van Der Vinne and Andres, 1992).

2.3 Discharge measurements

Discharge measurements necessary to characterize the hydraulic conditions were carried out by the Water Survey Section of Alberta Environment, the Water Survey of Canada, and by the Alberta Research Council. Two discharge measurements were made in each test reach, one at the injection site and the other at the last sample site in the reach. The measurements were made as close as possible to the times of injection and sampling. Measurements were also made on major tributaries. Table 3 lists the times and locations of each of these measurements. Figure 3 illustrates the discharge for each of the study reaches.

The Water Survey of Canada maintains four water level gauges in the region. Two of the gauges are on the Athabasca River, one at the town of Athabasca and the other just downstream of Fort McMurray. A third gauge records water levels in the Clearwater River at Draper and a fourth is located on the House River at Highway 63. The locations of these gauges are given on the maps in figures 1a and 1b. The continuous records from these gauges provide an indication of the variation in discharge during the tracer dye experiments. The discharges adopted for the subreaches are given in a previous report (Van Der Vinne and Andres, 1992).

Table 3 Summary of discharge measurements.

River	Location	Date	Discharge (m^3/s)	Agency
Athabasca	Athabasca	Feb 03	97.3	ARC
	Upper Wells	Feb 06	85.2	ARC
	Boivin Cr.	Feb 06	84.0	ARC
	Deep Cr.	Feb 10	94.3	ARC
	McLean Cr.	Feb 12	172.	ARC
	Ft.McMurray	Feb 13	107.	ARC
	Athabasca	Feb 14	87.5	AE
	House R.	Feb 24	71.7	AE
	Athabasca	Feb 25	88.0	WSC
	Horse R.	Feb 25	81.0	AE
	Upper Wells	Feb 27	99.6	AE
	Bitumount	Feb 27	132.	AE
	Ft.McMurray	Mar 08	215.	WSC
	Ells R.	Mar 09	185.	AE
	Athabasca	Mar 12	166.	AE
	Upper Wells	Mar 16	188.	AE
La Biche	Mouth	Feb 18	1.26	AE
Calling	Mouth	Feb 18	0.05	AE
Pelican	Mouth	Feb 18	0.45	AE
House	Mouth	Feb 24	1.43	AE
Clearwater	Draper	Feb 25	48.8	AE
Muskeg	Ft.McKay	Feb 27	0.49	AE
Ells	Mouth	Feb 27	1.75	AE
Clearwater	Draper	Mar 07	44.7	WSC

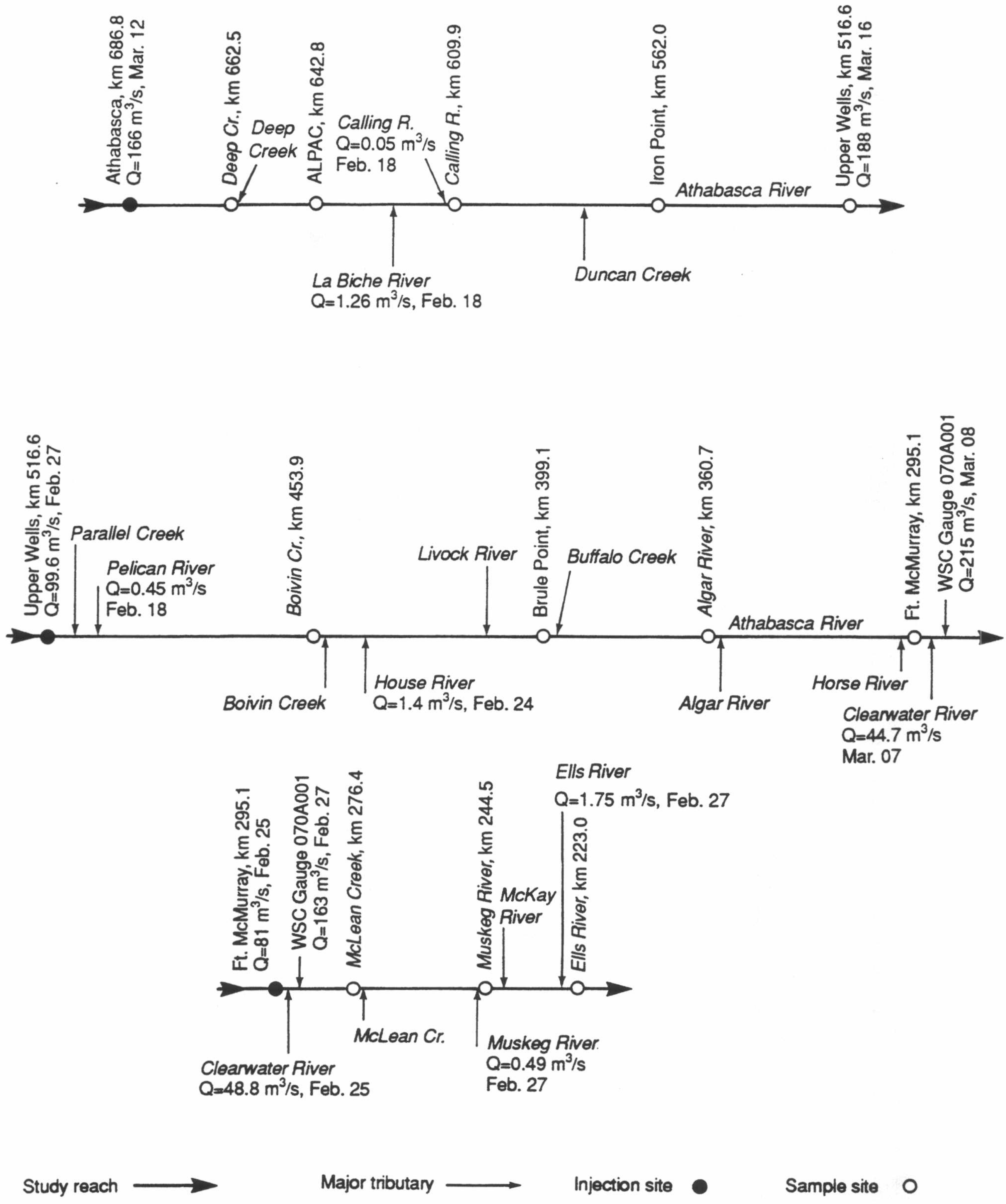

Figure 3 Distribution of discharge along the study reach.

3.0 TRANSVERSE MIXING

The mixing process in rivers begins as a three dimensional process but the concentrations quickly become uniform over the depth. According to Elhadi et al. (1984), vertical variations in concentration are less than 2% at a distance L_v downstream from a source located at mid-depth when

[2] $$L_v = 1.8H \frac{U}{U_*}$$

where U_* is the shear velocity defined by

[3] $$U_* = \sqrt{gRS}$$

in which g is the acceleration due to gravity, R is the hydraulic radius and S is the river slope.

The vertical mixing lengths ranged between about 15 m and 27 m for the three injection sites in this study (table 4). Since these lengths are considerably shorter than the lengths of the test reaches, the mixing process can be treated as a two dimensional process without any loss of accuracy.

The fundamental three-dimensional mass transport equation can be simplified for applications in the two-dimensional mixing zone by integrating the equation over the depth so that the terms representing advective and diffusive transport in the vertical direction are eliminated (Holley et al.,1972). The resulting depth-averaged equation is

[4] $$\frac{\partial}{\partial t}(hC) + \frac{\partial}{\partial x}(huC) + \frac{\partial}{\partial z}(hwC) = \frac{\partial}{\partial x}\left(he_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(he_z \frac{\partial C}{\partial z}\right)$$

where C, u and w are the depth-averaged concentration, streamwise velocity and transverse velocity, h is the local depth, and e_x and e_z are the longitudinal and transverse mixing coefficients respectively.

Table 4 Summary of mixing lengths

Reach	Vertical Mixing Length (m)	Transverse Mixing Length (km)	Linear Mixing Length (km)
Athabasca to Upper Wells	27	82	1110
Upper Wells to Ft. McMurray	15	52	332
Ft. McMurray to Ells River	24	67	2130

The complete two-dimensional equation given above can be simplified further. The second derivative of concentration with longitudinal distance can be eliminated because it is small compared to the first derivative (Sayre and Chang, 1968). Also, the time derivative term can be eliminated for steady state conditions. As well, the cartesian coordinate system used to express the above equation is cumbersome to use in natural channels so a curvilinear coordinate system was introduced by Yotsukura and Sayre (1976). This coordinate system follows the river planform and introduces the metric coefficients, m_x and m_z to account for variations in longitudinal and transverse distances caused by river curvature. Equation [4], therefore, becomes

[5]
$$\frac{\partial}{\partial x}(m_z huC) + \frac{\partial}{\partial z}(m_x hwC) = \frac{\partial}{\partial z}\left(\frac{m_x}{m_z} he_z \frac{\partial C}{\partial z}\right)$$

This equation can be solved numerically in its present form; but, in order to obtain an analytical solution, a coordinate transformation must performed using the cumulative discharge which is defined by

[6]
$$q_c = \int_0^z (m_z hu)\, dz$$

Yotsukura and Sayre (1976) performed this coordinate transformation and obtained the following equation

$$\frac{\partial C}{\partial x} = \frac{\partial}{\partial q_c}\left(u h^2 e_z \frac{\partial C}{\partial q_c} \right) \qquad [7]$$

The equation can be simplified further by introducing the diffusion factor D_z defined by

$$D_z = \frac{1}{Q}\int_0^Q (u h^2 m_x e_z)\, dq_c \qquad [8]$$

The diffusion factor, D_z can also be defined in terms of the average flow parameters (Beltaos, 1978a)

$$D_z = \psi U H^2 m_x e_z \qquad [9]$$

where U, H, m_x, and e_z are cross-section average values and ψ is a shape-velocity factor defined as

$$\psi = \int_0^1 \left(\frac{h}{H}\right)^3 \left(\frac{u}{U}\right)^2 d\left(\frac{z}{B}\right) \qquad [10]$$

where B is the river width and z is the transverse location. The value of ψ is generally between 1.0 and 3.2 for natural channels (Beltaos, 1978a), however highly irregular channels can have higher values. Values of ψ calculated from data reported by Yotsukura and Cobb (1972) were found to vary between 1.2 and 2.9, the same range as reported by Beltaos. Values of ψ for ice-covered channels will likely be higher than those for open water conditions due to the additional irregularities introduced by the ice cover.

Transverse mixing coefficients are normally evaluated using concentration data from steady state mixing experiments, however it is also possible to evaluate the coefficients using time-varying concentration data. This can be done by introducing the concept of dosage, θ which is defined as the area under the time-concentration curve

[11] $$\theta = \int_0^\infty C\, dt$$

where C is the concentration and t is the time from injection. Beltaos (1975) showed that the dosage for an instantaneous injection behaves exactly the same as the steady-state concentration for a continuous injection. Equation [7] thus becomes

[12] $$\frac{\partial\theta}{\partial x} = D_z \frac{\partial^2\theta}{\partial q_c^2}$$

3.1 Evaluation of coefficients

The diffusion factor, D_z can be evaluated using the following relationship

[13] $$D_z = \frac{Q^2\sigma_\eta^2}{2\int_0^x f(x)dx}$$

where σ_η^2 is the variance of the dosage distribution with respect to $\eta = q_c/Q$ and f(x) is a function of x which accounts for the confining effect of the river banks on the dosage distribution. This function is defined as

[14] $$f(x) = 1 - (1-\eta_0)\frac{Q}{M}\theta_{RB} - \eta_0\frac{Q}{M}\theta_{LB}$$

where η_0 is the centroid of the dosage distribution across the channel, M is the total mass of pollutant injected, and θ_{RB} and θ_{LB} are the dosages at the right and left banks respectively.

Dosage distributions for the three test reaches are shown in figure 4a-c. The right and left bank dosages shown in this figure are estimated values obtained by linearly extrapolating from dosage values calculated from the two sample holes nearest each bank. The sample sites nearest the injection locations exhibit high dosages in the centre of the channel and low dosages

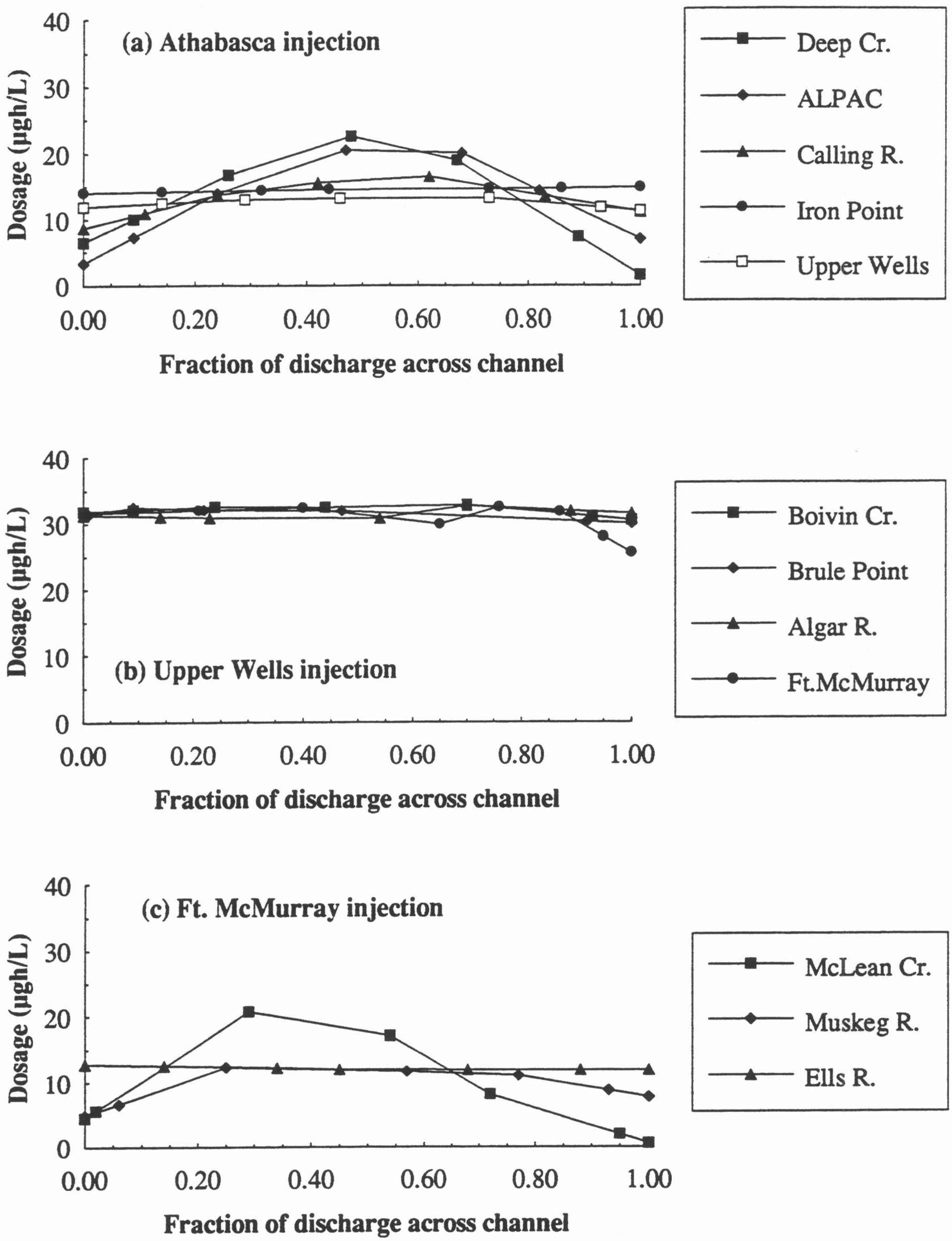

Figure 4 Distribution of dosage across the sample sections.

along the banks. This is consistent with a centreline injection. The sample sites farthest downstream from the injection sites exhibit very uniform dosage distributions indicating that transverse mixing is complete. Unfortunately, for the Upper Wells injection, even the dosage distribution at the first sample site is uniform, hence, only a lower bound can be defined for the transverse mixing coefficient in this reach.

The variance was calculated for each of the dosage distributions shown in figure 4. These values are given in table 5 along with the data required to evaluate equation [14]. The theoretical limit of the variance is 0.083 for an uniform distribution of dosage. Once the variance approaches this value, transverse mixing is complete and values downstream of this point should not be used to evaluate the diffusion factor. The diffusion factor can be evaluated for each test reach by determining the average slope of the σ_η^2 versus the integral of f(x) data shown in figure 5. The average slope is used in this analysis to reduce the effects of any measurement error. For example, much of the large change in slope at Deep Creek shown in figure 5 is likely due to imprecision in the estimates of discharge and dosage distribution. Dosage values should increase along the banks as mixing progresses, but the data given in table 5 indicates that a drop in dosage was estimated along the left bank between Deep Creek and ALPAC. The values of D_z obtained from this analysis are given in table 6. The values of e_z given in table 6 were calculated from equation [9] using the mean hydraulic characteristics of the transverse mixing zones presented in table 7.

Equation [12] can be restated using the dimensionless cumulative discharge, $\eta = q_c/Q$ and a dimensionless distance, χ = x/B. The resulting equation is

[15] $$\frac{\partial \theta}{\partial \chi} = \beta_z \frac{\partial^2 \theta}{\partial \eta^2}$$

where the dimensionless difussion factor, β_z is defined as

Table 5 Summary of dosage distribution parameters.

Reach	Distance from Injection (km)	Left Bank Dosage (µgh/L)	Right Bank Dosage (µgh/L)	Dosage Centroid	f(x)	∫f(x)dx (km)	Variance
Athabasca	0.0	0.0	0.0	0.51	1.00	0.0	0.000
Deep Creek	24.3	6.4	1.5	0.48	0.75	21.3	0.055
ALPAC diffuser	44.0	3.2	7.0	0.53	0.68	35.4	0.058
Calling River	76.9	8.7	11.2	0.51	0.33	52.0	0.071
Iron Point	124.8	14.1	14.9	0.50	0.00	59.8	0.080
Upper Wells	170.2	11.9	11.4	0.50	0.17	63.7	0.077
Upper Wells	0.0	0.0	0.0	0.47	1.00	0.0	0.000
Boivin Creek	62.7	31.8	30.4	0.50	0.031	32.3	0.079
Brule Point	117.5	31.3	29.9	0.50	0.028	33.9	0.074
Algar River	155.9	31.2	31.4	0.50	0.004	34.6	0.080
Ft. McMurray	221.5	31.6	25.6	0.49	0.076	37.2	0.079
Ft. McMurray	0.0	0.0	0.0	0.47	1.00	0.0	0.000
McLean Creek	18.7	4.45	0.56	0.42	0.83	17.1	0.049
Muskeg River	50.6	4.88	7.75	0.51	0.50	38.2	0.068
Ells River	72.1	12.8	12.0	0.49	0.00	43.5	0.081

[16]
$$\beta_z = \frac{D_z B}{Q^2} = \frac{\psi m_x e_z}{UB}$$

This dimensionless diffusion factor proposed by Gowda (1984) is independent of discharge and channel width; however, it does exhibit some dependence on channel aspect ratio and relative roughness (figure 6).

Fischer (1979) recommended the following dimensionless transverse mixing coefficient

[17]
$$k_t = \frac{e_z}{U_* H}$$

which is related to β_z by

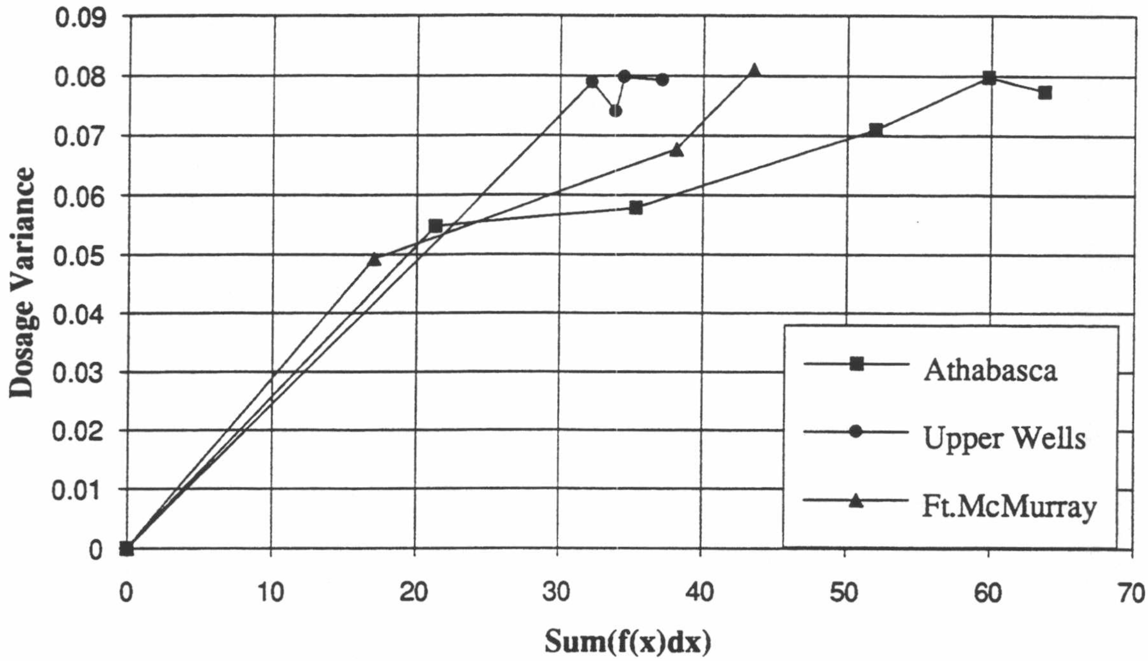

Figure 5 Change in dosage variance across channel with distance function.

[18]
$$\beta_z = \frac{U_* H}{U B} \psi m_x k_t$$

Equation [18] describes the variation of β_z with U/U$_*$ and B/H assuming that k_t is independent of these hydraulic characteristics. This variation is consistent with the trend in the data shown in figure 6. The data shown in figure 7 also indicates that k_t is independent of the relative roughness and the aspect ratio. There is considerable scatter in the values of k_t although some of this scatter can be attributed to river sinuosity (Lau and Krishnappan, 1981).

Other transverse mixing data are available for the Athabasca River. Two steady-state mixing tests were done from Athabasca to Sawdy Creek, just upstream of Deep Creek, one under open water conditions in 1974 and one under ice conditions in 1975 (Beltaos, 1978a). In 1974,

Table 6 Summary of transverse mixing parameters

Reach	Diffusion Factor (m^5/s^2)	Transverse Mixing Coefficient (m^2/s)	Dimensionless Diffusion Factor β_z	Dimensionless Transverse Mixing Coefficient k_t
Below Athabasca (Beltaos,1978)				
Open water	0.416	0.0670	0.00042	0.41
Ice cover	0.0134	0.0100	0.00034	0.28
Athabasca to Calling River	0.0228	0.0154	0.00023	0.33
Upper Wells to Boivin Creek*	0.0130	0.0097	0.00029	0.23
Ft. McMurray to Ells River	0.0160	0.0082	0.00032	0.31
Below Ft.McMurray (Beltaos,1978)				
Open water	1.26	0.093	0.00077	0.75
Ice cover	0.0474	0.041	0.00021	0.58
Bitumount (Beltaos, 1979)	0.14	0.033	0.00134	0.72

*lower limits

two similar tests (one in open water and one under ice an cover) were also done downstream of Ft. McMurray between Suncor and Ft. MacKay (Beltaos, 1978a). In 1978, an additional steady-state test was performed downstream of Bitumount under ice covered conditions (Beltaos, 1979). The mixing and hydraulic characteristics for these tests are presented in tables 6 and 7 along with the data from the present experiments.

There is considerable variation in the mixing characteristics measured in the various

Table 7 Summary of hydraulic characteristics in the transverse mixing zone.

Reach	Discharge (m^3/s)	Width (m)	Depth (m)	Velocity (m/s)	Shear Velocity (m/s)	Shape-Velocity Factor
Below Athabasca (Beltaos, 1978)						
Open water	565	320	2.05	0.86	0.079	1.7
Ice cover	105	276	0.96	0.40	0.038	3.6
Athabasca to Upper Wells	170.5	292	1.19	0.49	0.040	2.1
Upper Wells to Ft. McMurray	103.0	240	0.81	0.53	0.052	3.8
Ft. McMurray to Ells River	129.3	339	0.93	0.41	0.029	5.5
Below Ft.McMurray (Beltaos, 1978)						
Open water	779	373	2.20	0.95	0.056	3.0
Ice cover	238	252	1.92	0.49	0.037	2.6
Bitumount (Beltaos,1979)	189	370	1.22	0.42	0.030	4.0

experiments even when the hydraulic characteristics are taken into account. However, each of the winter tests was performed on a unique reach of the river so it is expected that some variations would occur due to differences in such characteristics as channel curvature. The choice of coefficient for modelling purposes should be made by deciding which test best represents the reach to be modelled. That is, a short reach just downstream of Athabasca should be modelled using the previous mixing data but a long reach from Athabasca to Calling River should be modelled using the current data. Also, the current data probably best reflects the

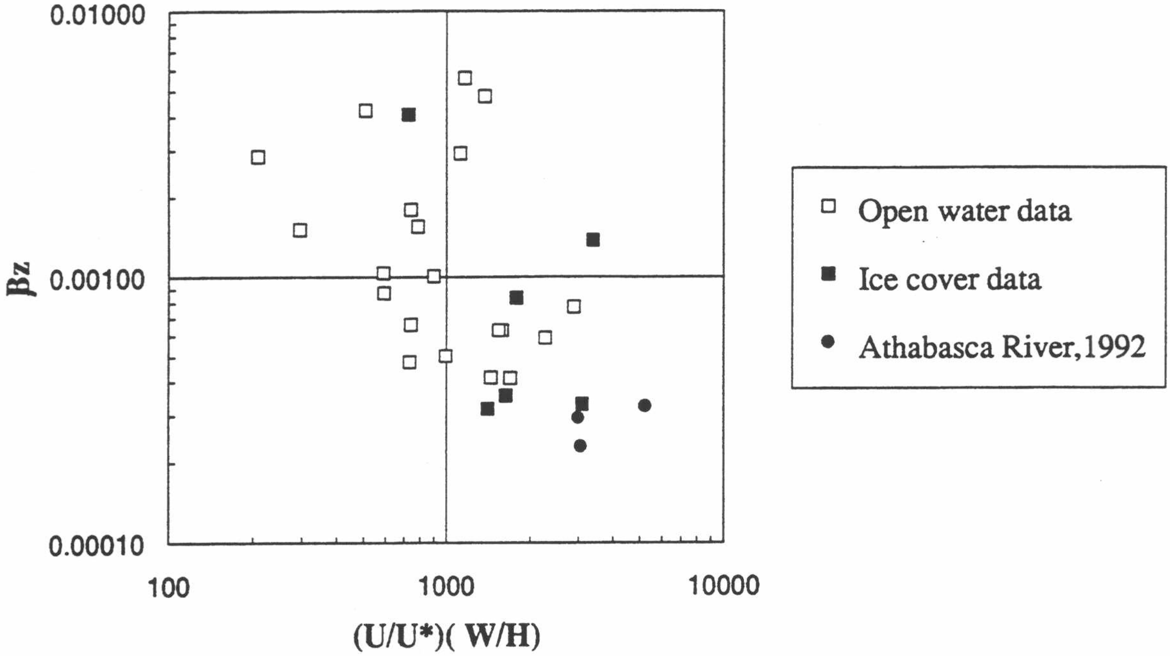

Figure 6 Variation of the dimensionless diffusion factor with channel aspect ratio and relative roughness.

mixing characteristics of the reach downstream of the ALPAC diffuser where two-dimensional modelling will likely be required.

The open water data was included for comparison with the winter data. The dimensionless mixing parameters tend to be higher for open water conditions. The effects of an ice cover on the mixing in natural channels has not been satisfactorily resolved (Elhadi, 1984). In a straight laboratory channel, Engmann (1974) found that the presence of a top cover reduced e_z to about one-half of its open water value; however, the dimensionless mixing coefficient did not change when it was defined in terms of the hydraulic radius (generally H/2 in natural channels) instead of the flow depth. Data from ice covered natural channels do not support this conclusion; dimensionless mixing coefficients for natural channels were more consistent when flow depth was used in the ratio.

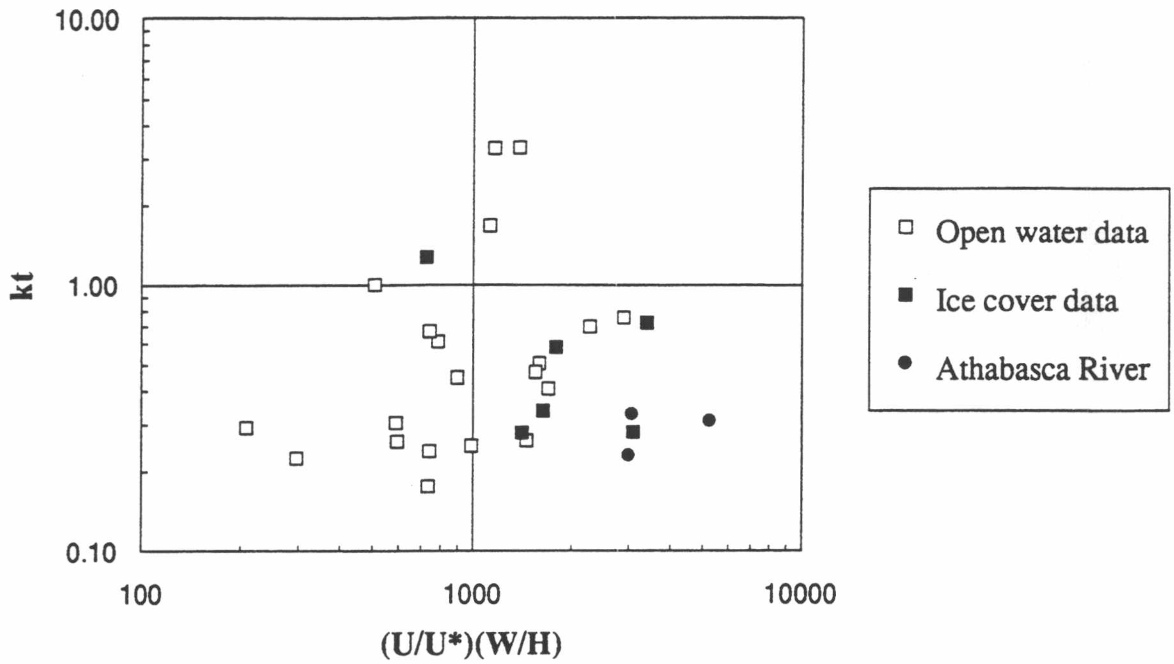

Figure 7 Variation of the dimensionless mixing coefficient with aspect ratio and relative roughness.

3.2 Prediction models

Two different solution techniques are available to model transverse mixing: analytical solutions which assume reach average values for the hydraulic and mixing characteristics and numerical solutions which use local hydraulic and mixing values. Analytical models are useful for preliminary analysis because they are relatively quick and easy to use. Analytical models are also sufficient if there is little or no field data available . For example, the evaluation of the transverse mixing coefficients in this report were done using an analytical model because there were insufficient cross-sections available to warrant the use of a numerical model. That is, the numerical model would provide similar results with a greater effort.

An analytical solution of the two-dimensional mixing equation (equation [5]) for a point

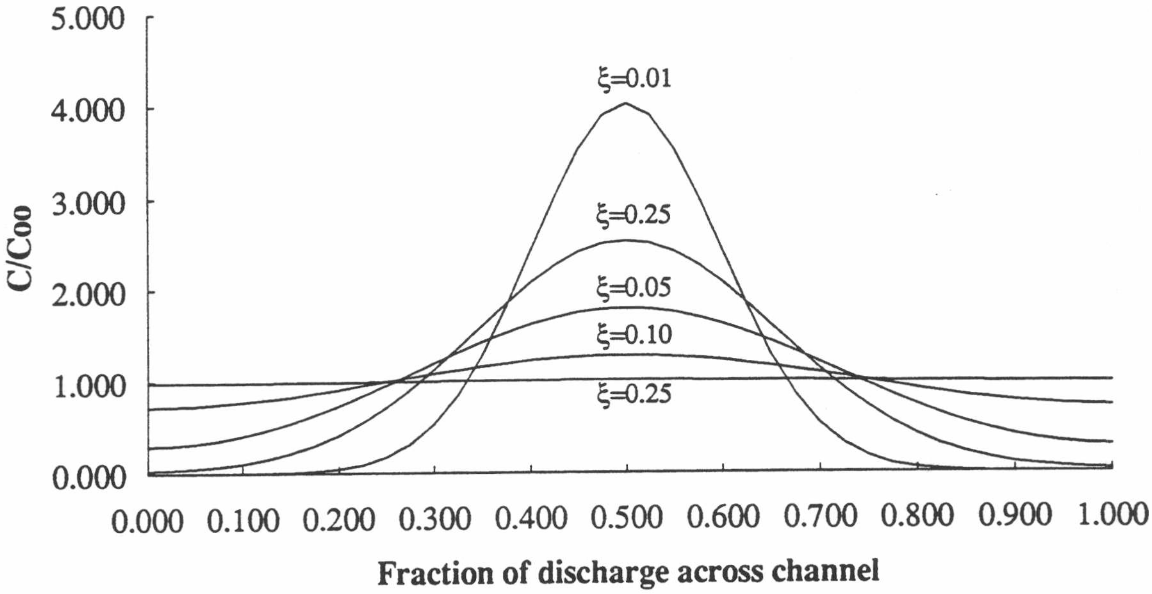

Figure 8 Dimensionless concentration distributions predicted by the analytical transverse mixing model.

source located at η_i is

$$[19] \qquad \frac{C}{C_\infty} = \frac{1}{\sqrt{2\pi\xi}} \sum_{n=-\infty}^{\infty} \left[\exp\left(-\frac{(\eta - 2n + \eta_i)^2}{2\xi} \right) + \exp\left(-\frac{(\eta - 2n - \eta_i)^2}{2\xi} \right) \right]$$

where C_∞ is defined as the injected mass per unit time, $\partial M/\partial t$ divided by the total discharge, Q; $\eta = q_c/Q$ is the cumulative fraction of discharge; $\xi = 2xD_z/Q^2$ is a dimensionless distance, and n is an integer which accounts for the reflections from the opposite bank (Fischer et al., 1979). The nondimensional solutions obtained from this equation for a centreline injection ($\eta_i = 0.5$) are shown in figure 8.

Numerical models such as TRANSMIX (Putz, 1984) or RIVMIX (Lau and Krishnappan,

1982) are more accurate than the above analytical model when there are sufficient cross-sections available to characterize the variations in width and depth in each subreach. The numerical models do, however, take more time and effort to obtain results because of the increased data requirements.

The models discussed above all deal with steady state conditions but in some cases it is necessary to model two-dimensional unsteady mixing similar to the field experiments described in this report. This type of modelling must be done numerically; there is no analytical solution available. Some numerical models such as MIX2DARC (Beltaos and Arora, 1988) are available but, as with other numerical models, they require additional cross-sections to model the mixing properly. When these additional cross-sections are surveyed, it may feasible to calibrate this type of model for the Athabasca river.

4.0 LONGITUDINAL MIXING

Longitudinal mixing becomes the dominant mixing process once transverse mixing is completed. For unsteady injections such as those of the field tests, mixing continues to occur due to longitudinal dispersion, the process which increases the spread of pollutant along the channel length as the pollutant travels downstream. However, for steady state injections, no further mixing occurs once transverse mixing is completed.

Transverse mixing can be considered complete when the concentrations become essentially uniform over the entire width of the channel. This can be defined as the point where the variations in concentration across the channel are less than 5% of the mean concentration. The distance from the source at which this occurs is called the transverse mixing length, L_t which can be estimated from

[20] $$L_t = \frac{1}{\psi k_t k_p} \frac{U B^2}{U_* H}$$

where k_p is a position parameter introduced by Yotsukura and Cobb (1972) which varies with the position of the source in the cross-section. For a centreline injection, k_p = 15.7; other values of this parameter for various source positions are given in table 8. The shape factor, ψ has been included in equation [20] because average hydraulic characteristic are used.

Transverse mixing lengths for the study reach are given in table 4. These estimates agree closely with the dosage distribution data given in figure 4. The dosage distribution is uniform at Iron Point, 125 km downstream of the injection while the estimated transverse mixing length for this reach is 82 km. The dosage is also uniform at Boivin Creek, 63 km from the source while equation [20] estimates a mixing length of 52 km. Transverse mixing also appears to be complete at Ells River, 72 km from the injection whereas the transverse mixing length was estimated at 67 km.

To compute the longitudinal mixing characteristics, it is necessary to use cross-section

Table 8 Position parameters for various injection positions and 95% complete mixing

Fraction of cumulative Discharge from nearest bank	Position Parameter
0.0	3.8
0.1	3.9
0.2	4.5
0.3	5.8
0.4	7.2
0.5	15.7

average values of concentration to eliminate the transverse variations. By using average values of concentration, the longitudinal dispersion rates can be evaluated for the transverse mixing zone as well. The unsteady, two-dimensional mixing equation can be reduced to one dimension by averaging equation [5] over the cross section. The resulting equation is

[21] $$\frac{\partial}{\partial t}\bar{C} + U\frac{\partial}{\partial x}\bar{C} = \frac{\partial}{\partial x}\left(D_x\frac{\partial \bar{C}}{\partial x}\right)$$

The mixing process described by equation [21] is termed Fickian dispersion. The solution to equation [21], for a mass, M instantaneously released throughout a cross section is

[22] $$\bar{C} = \frac{MU}{2Q\sqrt{\pi D_x t}}\,\mathbf{exp}\left[-\frac{(x-Ut)^2}{4D_x t}\right]$$

The properties of this analytical solution indicate that the dispersion coefficient, D_x can be defined by

[23] $$D_x = \frac{U^3}{2}\frac{d\sigma_t^2}{dx}$$

That is, the rate of change of the variance of the time-concentration distribution, σ_t^2 with distance is constant.

Fickian dispersion does not occur immediately after transverse mixing is complete. Data from a large number of field studies by numerous investigators indicate that the onset of Fickian dispersion is delayed for some distance downstream after transverse mixing is completed (Beltaos, 1978b). At first, differential advection and variations in channel geometry cause longitudinal mixing to occur more quickly than predicted by the Fickian solution. The field measurements suggest that in this intermediate zone the standard deviation, σ_t of the time-concentration distribution grows linearly with distance; hence, this type of dispersion is called 'linear' dispersion.

No analytical solution exists for linear dispersion however Beltaos (1978b) proposed the following empirical solution based on the empirical data

[24]
$$\bar{C} = \frac{MU}{Qx\sqrt{2\pi\beta_x}}\left[\frac{Ut}{x}\exp\left(1-\frac{Ut}{x}\right)\right]^{1/\beta_x}$$

where β_x is a parameter defined by

[25]
$$\beta_x = \left(\frac{U\sigma_t}{x}\right)^2$$

The location of the transition from linear dispersion to Fickian dispersion can be estimated using

[26]
$$L_L = \alpha_L \frac{UB^2}{U_* H}$$

where α_L is a factor varying between 0.48 and 1.8 depending on the degree of channel irregularity. The transition occurs between L_L and $3L_L$; however, in most cases it sufficient to define the transition at $2L_L$. The linear mixing lengths estimated by assuming $\alpha_L = 1.0$ are given in table 4. The high values of these estimates indicate that Fickian dispersion does not occur over the length of the tests, therefore the Fickian dispersion coefficients cannot be evaluated from the test data.

Some researchers such as Beer and Young (1983) and Sabol and Nordin (1978) have proposed that the non-Fickian behaviour observed in the linear zone is the result of the storage and subsequent release of pollutant in 'dead zones'. These dead zones are areas of the river such as eddies in which little or no net flow occurs. Beer and Young (1983) added an additional term to equation [21] to account for storage effects. As well, experimental data from channels with dead zones suggest that this storage term is dominant (Beer and Young, 1983), therefore the dispersive term can be eliminated to simplify the equation. The resulting equation is

[27] $$\frac{\partial}{\partial t}\bar{C} + U\frac{\partial}{\partial x}\bar{C} = \frac{1}{T_e}\left(C_s - \bar{C}\right)$$

which can be used to describe an aggregated dead zone model in which each reach of the river is treated as being composed of a length in which the solute undergoes pure translational flow with a concentration C_s and then enters a mixing tank, emerging with a concentration, $\bar{C}$ That is, the reach length is defined so that the aggregated effects of the dead zones can be represented by a single dead zone with an effective time constant, T_e (Beer and Young, 1983). It is assumed that this time constant is proportional to the travel time through the reach, t_p since the mixing tank at the end of the reach represents the aggregate effects of storage during the translational portion of the model. That is

[28] $$\alpha_x = \frac{t_p}{T_e}$$

A solution can be obtained for equation [27] if the output from one reach is used as the input for the next reach so that

[29] $$\bar{C} = \frac{M\alpha_x}{t_p Q m!}\left(\alpha_x \frac{t_s}{t_p}\right)^m \exp\left(-\alpha_x \frac{t_s}{t_p}\right)$$

where m is an integer representing the number of storage zones each with a length corresponding to the transverse mixing length, L_t. This solution assumes that the pollutant is completely mixed across the channel in a storage zone before entering the next zone. The distance required to completely mix the pollutant across the channel is the transverse mixing length, therefore this length can be used to define the length of the storage zones. The time, t_s is defined as

[30]
$$t_s = t - \frac{x}{U} + \frac{m}{\alpha_x}\frac{x}{U}$$

where the first term, t is the total time from injection, the second term, x/U represents the translational time component, or the time-to-peak, t_p, and the third term accounts for the increasing lag of the peak concentration after the leading edge as the pollutant spreads.

4.1 Evaluation of coefficients

The evaluation of β_x from measured concentrations can be simplified by defining the pollutant spread in terms of the half-duration, ΔT rather than the standard deviation. This eliminates the problems in evaluating σ_t due to incomplete measurements on the receding limb of the concentration profile. The half-duration is defined as the period of time during which the concentration is greater than one-half of the peak concentration (figure 9). The half-duration of the empirical curve described by equation [24] is equal to 2.36 σ_t; therefore β_x can be defined in terms of ΔT as follows

[31]
$$\beta_x = 0.18\left(\frac{\Delta T}{t_p}\right)^2$$

The values of half-duration and time-to-peak for each subreach are given in table 9 along with other variables which describe the cross-section average time-concentration distributions. The times-to-peak in table 9 are slightly different from those given in the report on travel times. These values were obtained from the cross-section average concentrations whereas the previous values were obtained from an average of the measured times-to-peak across the sections.

Reach-average values of β_x for the Athabasca River can be obtained from the slopes of the best fit lines through the accumulated half-duration versus time-to-peak data shown in figure10; however, the reaches used in this analysis were slightly different from the reaches

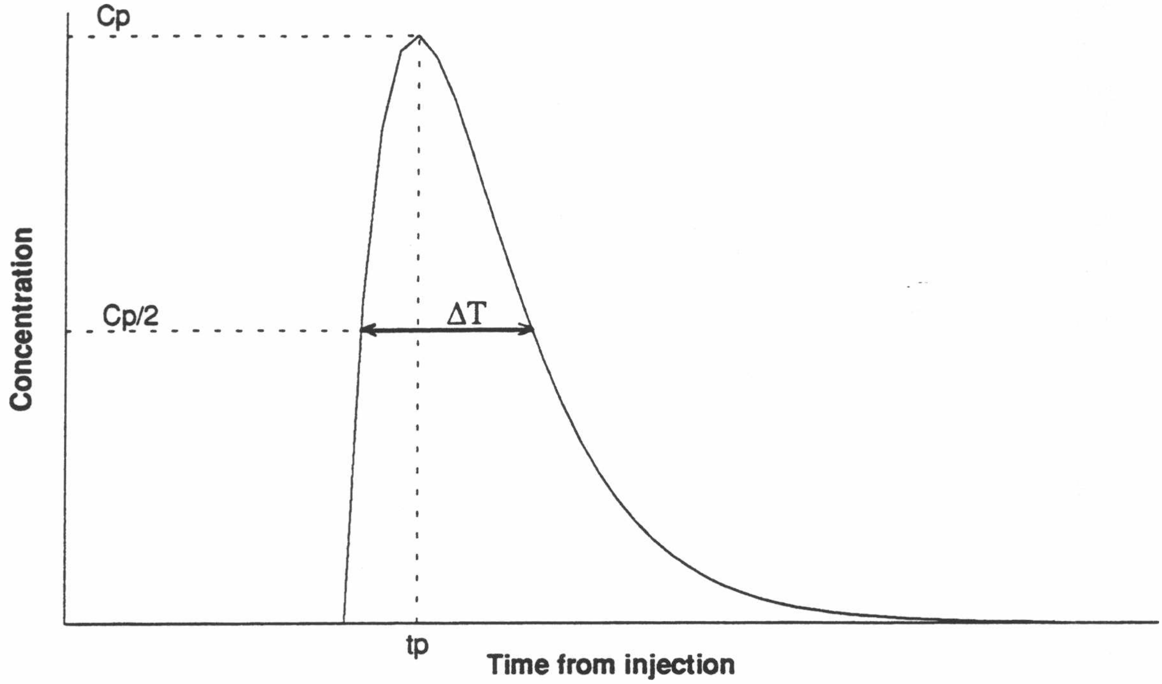

Figure 9 Definition sketch for time-concentration distribution variables.

defined by the dye injections. The data shown in figure 10 indicates that there are three reaches of river with distinct longitudinal dispersion parameters: Athabasca to Calling River; Calling River to Ft. McMurray; and Ft. McMurray to Ells River. The data can be accumulated in this manner because, once the concentrations have been averaged across the sections, the values of β_x obtained for the initial transverase mixing zone are similar to the those for the Linear zone. For example, in figure 10, the transverse mixing zone below the Upper Wells injection cannot be distinguished from the reaches immediately upstream and downstream.

Values of β_x for the three reaches are listed in table 10 along with the associated mean hydraulic characteristics. The hydraulic characteristics are different from those listed in table 4 in the previous chapter because these values are for the total reaches rather than just for the transverse mixing zone. These values of β_x are lower than values measured previously on the

Table 9 Summary of cross-section average time-concentration distribution variables.

Location	Distance from Injection (km)	Time to Peak (hrs)	Half-duration (hrs)	Variance (hrs^2)	Peak Concen-tration (µg/L)	Mass Recovery Ratio
Deep Cr.	24.3	12.43	0.83	0.82	15.03	0.933
ALPAC	44.0	23.96	1.25	7.67	8.75	0.942
Calling R.	76.9	42.02	2.46	6.26	4.11	0.936
Iron Point	124.8	64.80	6.44	53.97	1.73	1.008
Upper Wells	170.2	84.78	10.62	56.11	1.01	0.908
Boivin Cr.	62.7	32.87	8.43	23.16	3.38	1.002
Brule Point	117.5	71.93	17.12	64.10	1.74	0.998
Algar R.	155.9	96.37	18.23	182.67	1.51	0.997
Ft.McMurray	221.5	136.42	26.96	255.72	1.02	1.011
McLean Cr.	18.7	9.57	1.76	1.38	5.91	0.945
Muskeg R.	50.6	31.05	3.80	26.30	1.94	0.832
Ells R.	72.1	46.47	6.25	33.70	1.57	0.991

Athabasca River under an ice cover and also lower than values on other ice covered rivers; however, they are consistent with the trend of increasing β_x with U_*/U shown in figure 11 (Beltaos, 1978b). This trend can be described by

[32] $$\beta_x = 0.5\left(\frac{U_*}{U}\right)^2$$

however, the deviations from this line are considerable. For example, the linear dispersion parameter predicted by equation [32] for the reach between Athabasca and Calling River is 0.0024 whereas the measured value is 0.00046. The actual rate of longitudinal dispersion in this reach may greater than that indicated from the measurements because transverse mixing is not complete in this reach; however, as stated previously, the other transverse mixing zones are indistinguishable from the rest of the river in terms of β_x.

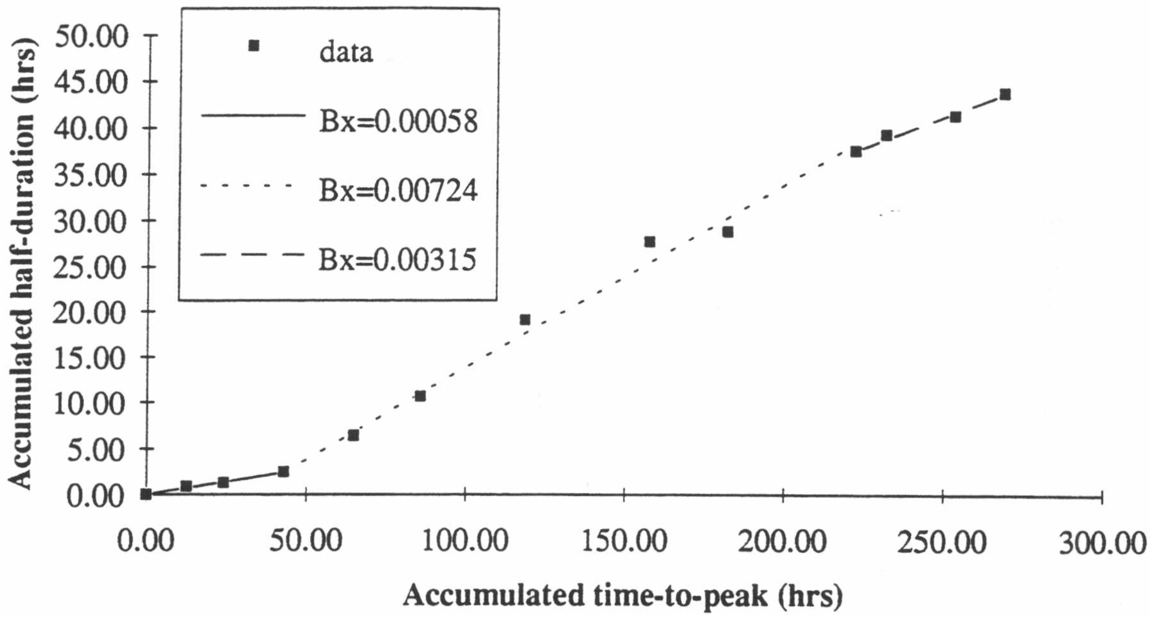

Figure 10 Variation of half-duration with time-to-peak.

Measured values of β_x should be used when ever possible; equation [32] should be used only to extrapolate β_x for other flow conditions. That is, β_x for another discharge can be estimated by multiplying the measured value by the ratio of the square of the relative roughnesses

[33] $$\beta_{x\,new} = \beta_{x\,old} \frac{\left(\frac{U_*}{U}\right)^2_{new}}{\left(\frac{U_*}{U}\right)^2_{old}}$$

This extrapolation technique is only valid for other winter flow conditions. As well, the error of the estimate increases as the difference in flow conditions increases.

The coefficients of the storage model can also be evaluated from the test data. The

Table 10 Reach average hydraulic and linear dispersion characteristics.

Reach	Width (m)	Depth (m)	Velocity (m/s)	Shear Velocity (m/s)	Linear Dispersion Parameter (β)
Hinton to Berland River	105	0.65	0.48	0.063	0.0136
Berland River to Whitecourt	115	0.63	0.54	0.064	0.0165
Whitecourt to Vega Ferry	128	0.94	0.35	0.061	0.0155
Vega Ferry to Smith	211	0.81	0.28	0.033	0.0064
Smith to Athabasca	204	0.98	0.37	0.043	0.0086
Athabasca to Calling River	292	1.08	0.54	0.038	0.00058
Calling River to Ft.McMurray	244	1.22	0.45	0.068	0.00724
Ft.McMurray to Ells River	339	0.86	0.44	0.028	0.00315
Bitumount to Embarras	370	1.55	0.42	0.030	0.00523

storage zone number, m for a given site can be obtained from

[34] $$m = \left(1 + \frac{x}{L_t}\right)$$

where m is truncated to a whole number. The behaviour of the model is such that as m increases with distance, the shape of the concentration distributions becomes less skewed so that, when m becomes greater than about 10, the storage model predicts symmetrical distributions typical of

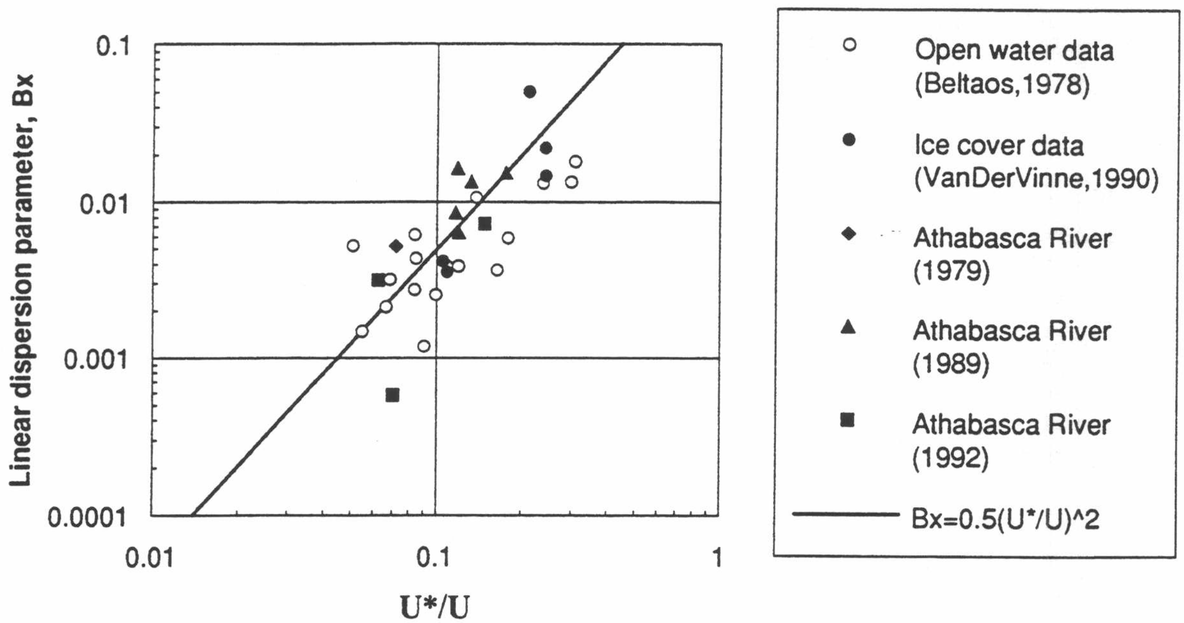

Figure 11 Variation of Beltaos' longitudinal dispersion parameter with relative roughness.

Fickian dispersion (figure 12). The storage model results shown in figure 12 indicate that a significant change in shape occurs with changes in m; however, L_t can usually be estimated within a factor of 2, therefore the error in the predicted peak concentration will not be as large as the range shown in figure 12.

An expression for the storage coefficient was obtained by taking the derivative of equation [29] to find the time at which the peak concentration occurs and then substituting this term back into equation [29] to obtain an equation for the peak concentration, C_p. This equation was then rearranged to define the storage coefficient

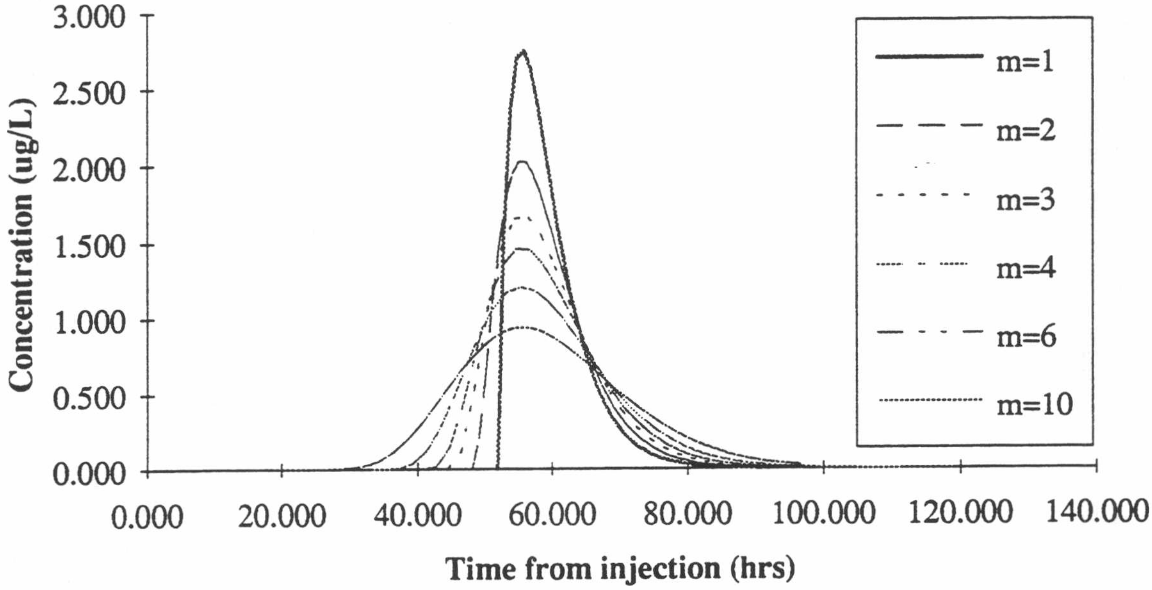

Figure 12 Sensitivity of storage model to variations in storage zone number m for α_x = 15.

[35]
$$\alpha_x = \frac{C_p Q x}{M U}\left(\frac{m!}{m^m e^{(-m)}}\right)$$

in terms of directly measureable parameters as well as the zone number, m.

The dimensionless term, C_pQx/MU was found to be essentially constant for two of the test reaches (figure 13); however, in the Athabasca to Upper Wells reach, this term decreases with distance indicating an increase in storage along this reach. If the term, C_pQx/MU can be evaluated for a particular river, then the storage coefficient can be calculated using equation [35] and the error in peak concentration introduced by estimating the transverse mixing length will be absorbed in the storage coefficient. The analytical formulation of the storage model presented here lumps together all the subreaches between the injection site and sample site, however a numerical formulation can be developed for which independent values of the storage coefficient

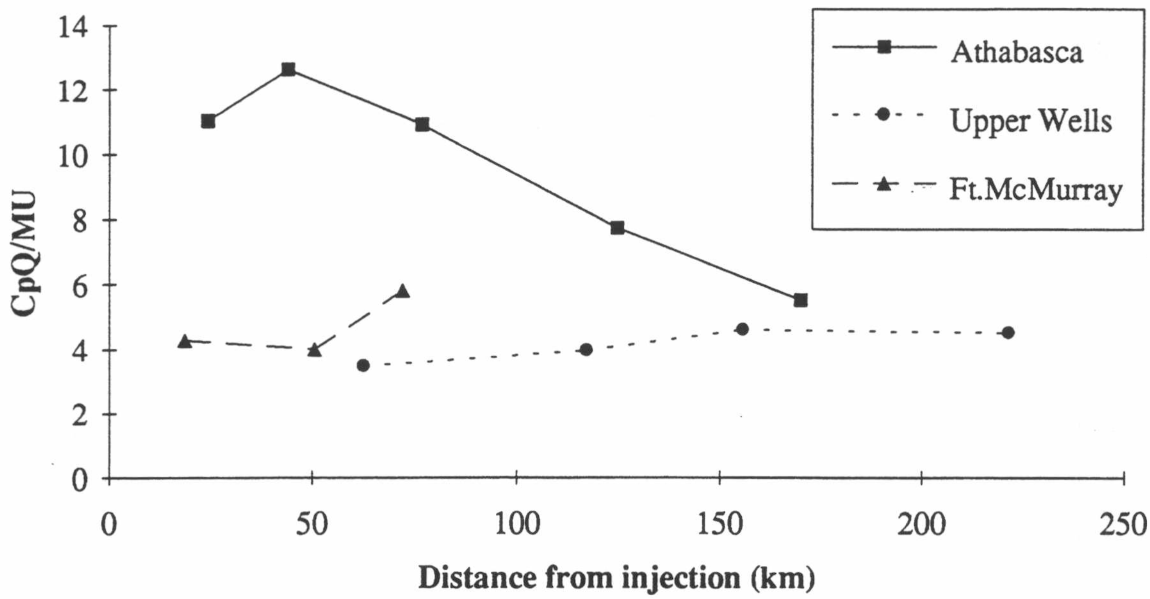

Figure 13 Variation of dimensionless peak concentration with distance.

can be allocated to each subreach.

The values of C_pQx/MU, m and α_x for each subreach are given in table 11. No relationship can be established between the storage coefficient and the hydraulic characteristics at this time due to the limited data set from these tests. However, the storage coefficient would likely increase with increasing discharge because the storage area in a typical cross-section in the river would be reduced relative to the effective flow area. For winter flows, where the discharge variations are small relative to open water discharge variations, α_x can be assumed constant. Further work is needed to determine the sensitivity of α_x to the hydraulic characteristics.

Table 11 Storage model parameters.

Location	CpQx / MU	Zone Number m	Storage Coefficient α_x	Hydraulic Coefficient C_u
Deep Creek	11.0	1	33	0.075
ALPAC diffuser	12.6	1	37	0.064
Calling River	10.9	1	31	0.067
Iron Point	7.7	2	27	0.081
Upper Wells	5.5	3	25	0.080
Boivin Creek	3.5	2	17	0.083
Brule Point	4.0	3	23	0.060
Algar River	4.6	4	30	0.066
Ft.McMurray	4.5	5	32	0.073
McLean Creek	4.3	1	12	0.074
Muskeg River	4.0	1	13	0.054
Ells River	5.8	2	22	0.066

4.2 Dispersion model predictions

The accuracy of both the Beltaos model and the storage model can be improved if t_p is calculated as the sum of the subreach travel times rather than from an reach-average velocity. The time-to-peak, t_p can be defined as

[36]
$$t_p = \sum \frac{x_i}{C_u Q_i^{0.4}}$$

where C_u is the velocity coefficient for each subreach between the injection and the site of interest defined in Part I of this two part report (Van Der Vinne and Andres, 1992). Values of C_u for each subreach are given in table 11. This technique has been used to generate the model predictions shown in figure 14 (These predictions are shown in greater detail in Appendix A).

If the dispersion parameter for Beltaos' model changes at some point in the modelled reach, sites downstream of the location of the change cannot be modelled correctly unless the time values are modified to account for the change the dispersion rate. The time adjustment for the second subreach is defined by

[37]

$$t_\beta = [t_p]_1 \left[1 - \left(\frac{\beta_1}{\beta_2} \right)^{1/2} \right]$$

and should be subtracted from all of the time values in equation [24] including the time to peak, t_p=x/U.

The peak concentrations predicted by the storage model are accurate because the measured peaks were used to evaluate the storage coefficient. The peak concentrations predicted by the Beltaos model vary from the measured peaks by as much as 40% because the dispersion parameter for this model is calculated from the rate of change of variance of the concentration distributions rather than from the peak concentrations.

The great advantage of the storage model is its ability to model the shape of the concentration distribution more accurately. As can be seen in figure 14 (and in Appendix A), the deviations between the model predictions and the data are minor. The Beltaos model, however, does not reproduce the skewed distributions exhibited by the data.

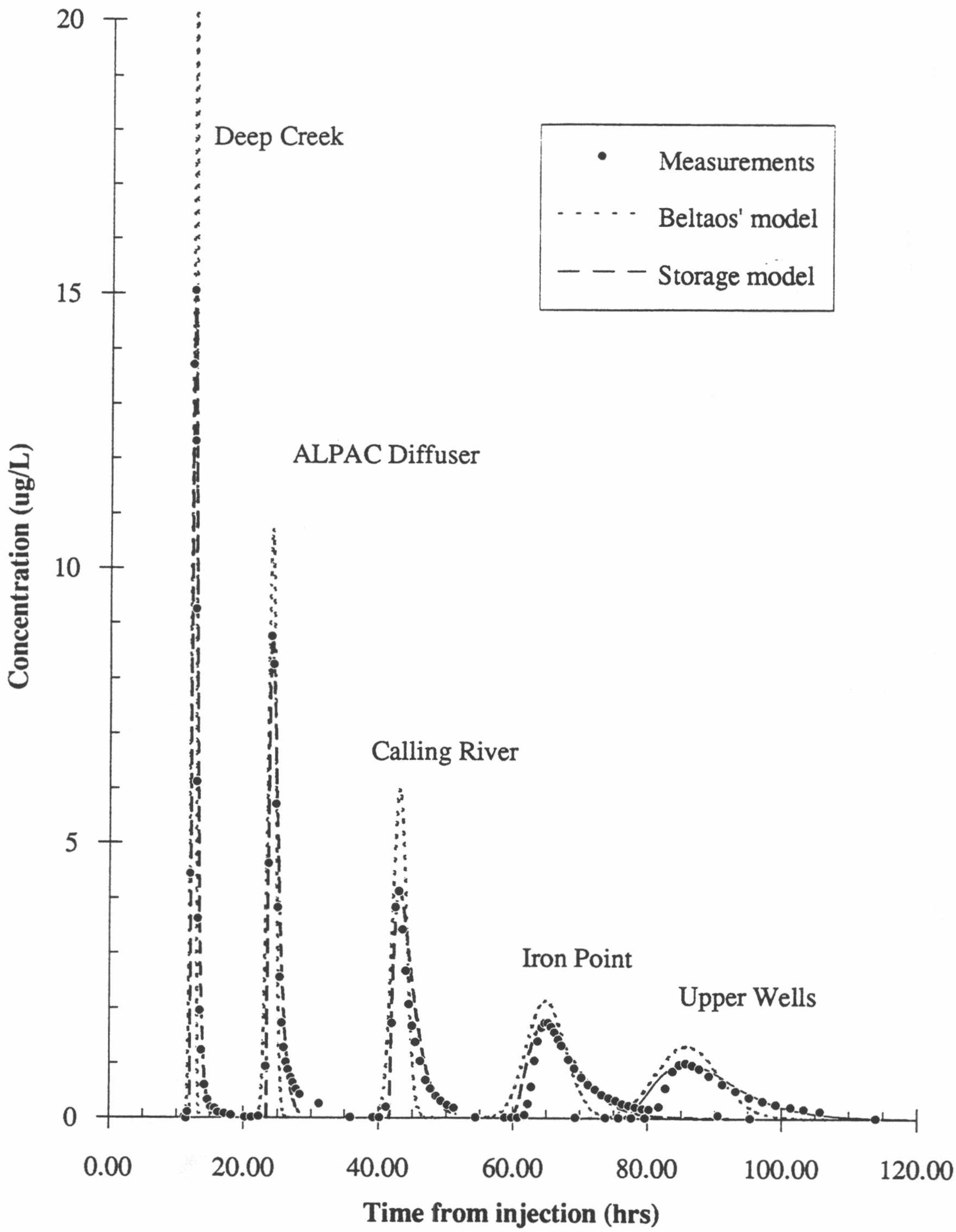

Figure 14a Comparison of measured concentrations with predicted concentrations between Athabasca and Upper Wells.

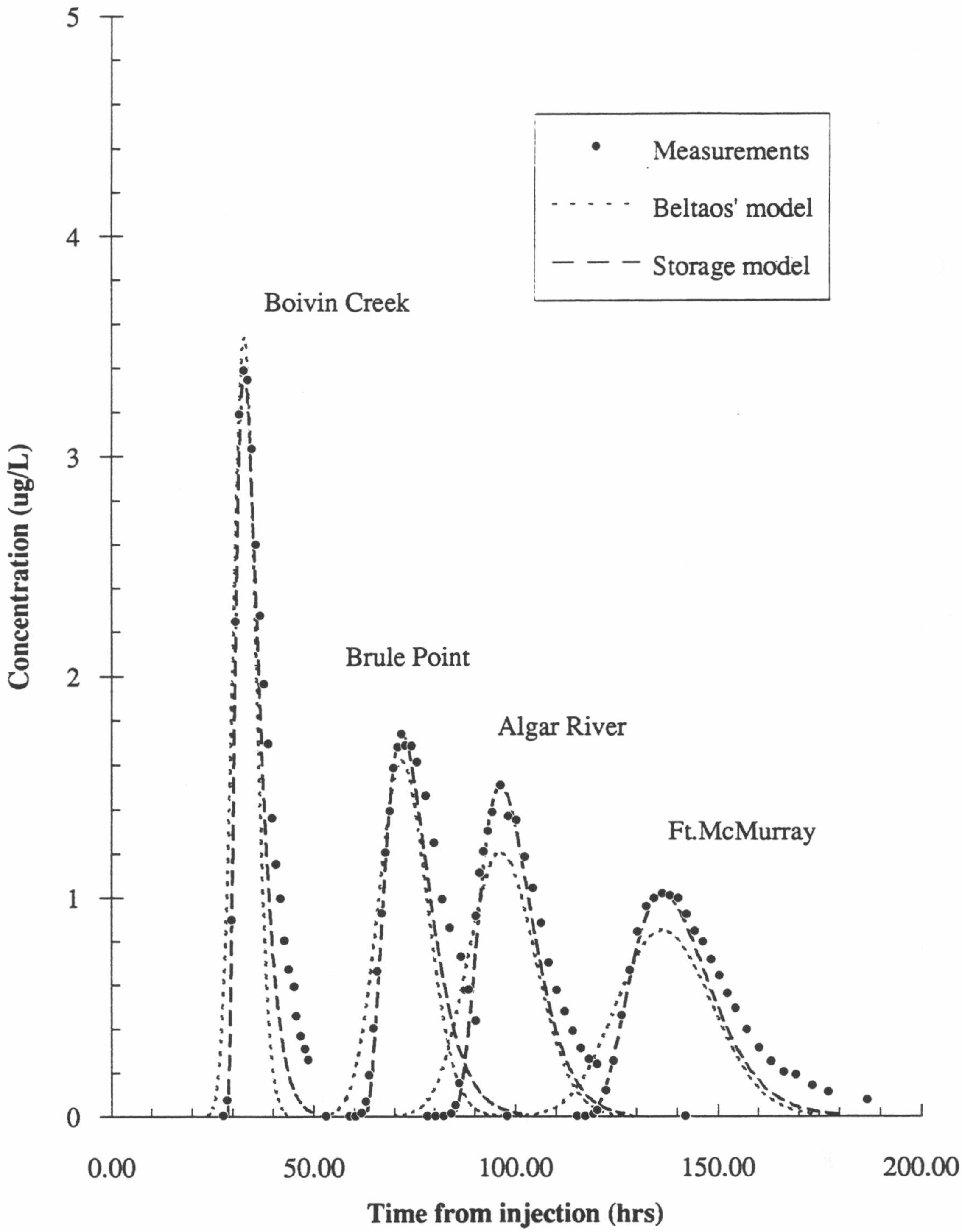

Figure 14b Comparison of measured concentration with predicted concentrations between Upper Wells and Ft. McMurray.

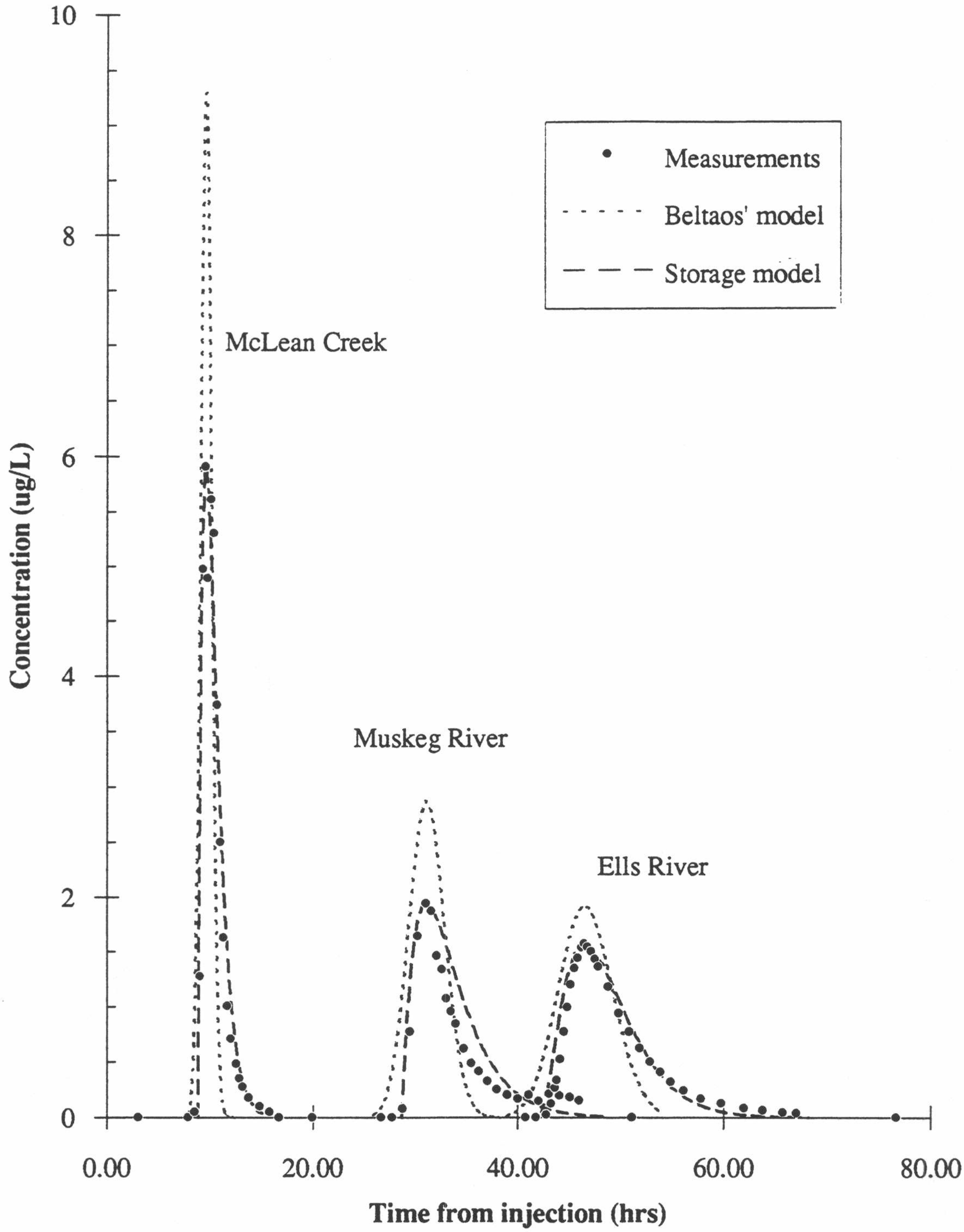

Figure 14c Comparison of measured concentrations with predicted concentrations between Ft. McMurray and Ells River.

5.0 SUMMARY

A field investigation covering a section of the Athabasca River between Athabasca and Bitumount was performed to define the hydraulic and mixing characteristics. Twelve sample sites were selected over the 464 km study length. The river geometry was defined from cross-section surveys at the sample sites while the discharges throughout the study reach were determined from discharge measurements at various locations along the river as well as at the mouths of major tributaries. The study reach was divided into three reaches in which separate tracer dye experiments were executed to determine travel times and dispersion coefficients.

Average discharges in the transverse mixing zone ranged from 103 m^3/s downstream of Upper Wells to 170.5 m^3/s downstream of Athabasca. Average velocities in these zones ranged from 0.41 m/s to 0.53 m/s. Average top widths ranged from 240 m to 339 m while average depths ranged from 0.81 m to 1.19 m. The average hydraulic characteristics used for the longitudinal dispersion analysis were slightly different from those in the transverse mixing zones due to the greater lengths of the reaches. The discharges used in the longitudinal dispersion analysis varied from 105 m^3/s to 178 m^3/s while the velocities ranged between 0.44 m/s and 0.54 m/s. Average top widths ranged from 236 m to 339 m while average depths ranged from 0.86 m to 1.28 m. Detailed hydraulic characteristics for each of the subreaches can be found in Part I of this report which deals with time of travel.

The mixing process was split into a number of zones in which different processes were dominant. Vertical mixing was found to be virtually instantaneous with vertical mixing lengths between 15 m and 27 m. Transverse mixing was found to be complete between 52 km and 82 km downstream of the injection points. The linear mixing lengths which define the start of classical Fickian dispersion were estimated to be between 332 km and 2130 km. These great distances indicate that Fickian dispersion did not occur during the tests. The only type of longitudinal dispersion which occurred in the study reaches was linear dispersion.

Transverse mixing coefficients were found to range from 0.0082 m^2/s downstream of

Ft.McMurray to 0.0154 m^2/s downstream of Athabasca. A lower limit of 0.0097 m^2/s was found downstream of Upper Wells. Diffusion factors, which also incorporate some of the hydraulic characteristics, were found to range from 0.0130 m^5/s^2 to 0.0228 m^5/s^2. Dimensionless transverse mixing coefficients ranged between 0.23 and 0.33 while dimensionless diffusion factors ranged between 0.00023 and 0.00032. These dimensionless values are similar to values obtained from previous tests in other reaches of the Athabasca River but there is still considerable variation between the values, most likely due to the specific characteristics of the test reaches. The dimensionless mixing coefficient was found to be the best parameter to relate the transverse mixing characteristics to the hydraulic characteristics. Modelling of transverse mixing in the study reach is limited to analytical techniques until more cross-sections are obtained to adequately define the hydraulic variations.

Linear dispersion parameters were found to range from 0.00058 to 0.0072. These values are lower than values previously measured on the Athabasca River under an ice cover and also lower than values on other ice covered rivers; however, they are consistent with the trend of increasing β_x with decreasing relative roughness. This trend can be used to extrapolate values of β_x for other winter flow conditions.

An alternate longitudinal dispersion model for the linear zone was introduced which reproduced the shape of the time-concentration curves more accurately. This model is based on the concept of the storage and subsequent release of pollutant from zones of little or no flow. Unfortunately, no relationship can be established between the storage coefficient and the hydraulic characteristics due to the limited data set from these tests.

The accuracy of both longitudinal dispersion models can be improved by calculating the time-to-peak from the subreach average velocities rather than from the reach-average velocity. As well, a numerical formulation of the storage model can be developed for which independent values of velocity and storage coefficient can be allocated to each subreach.

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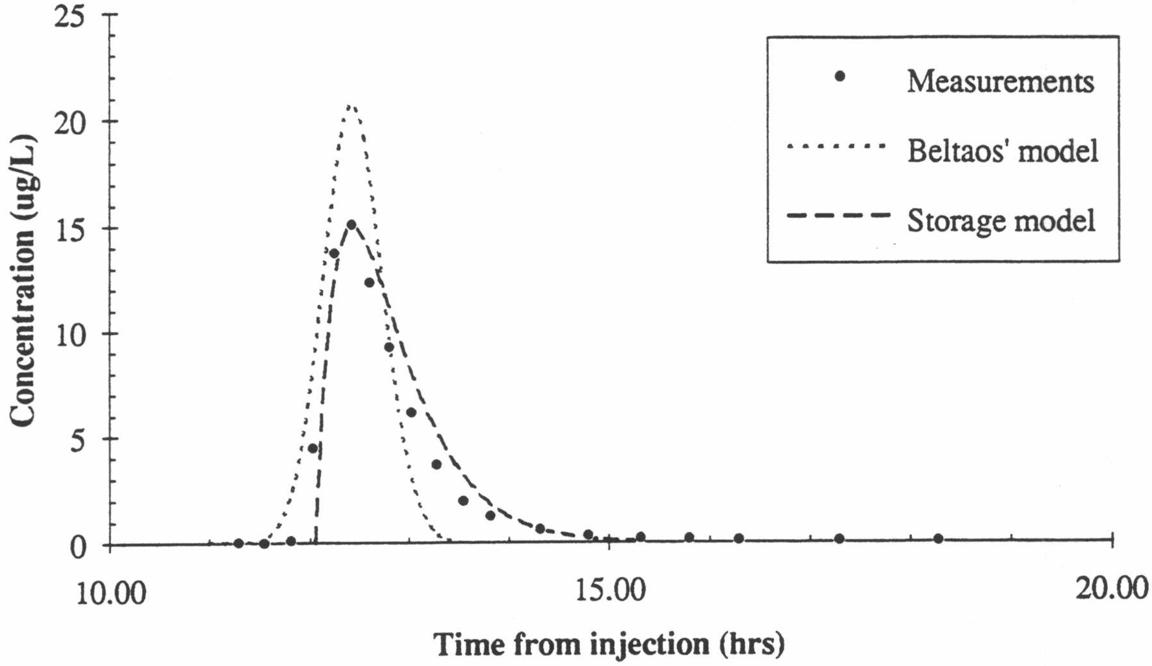
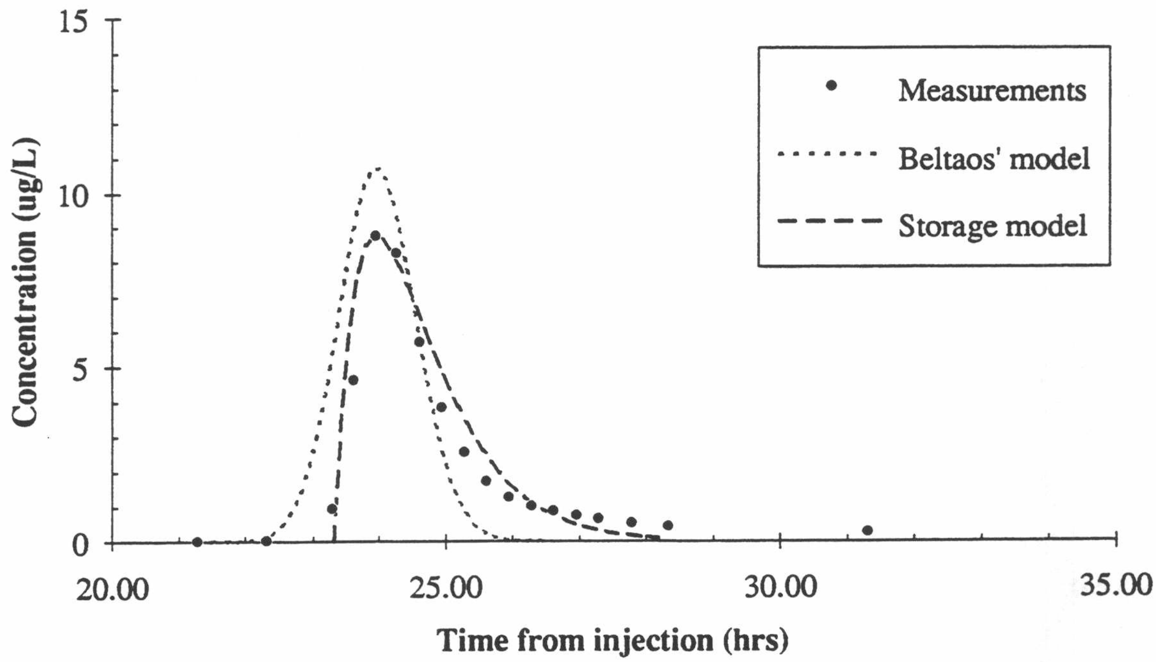
APPENDIX A

Measured and predicted
cross-section average
time-concentration distributions

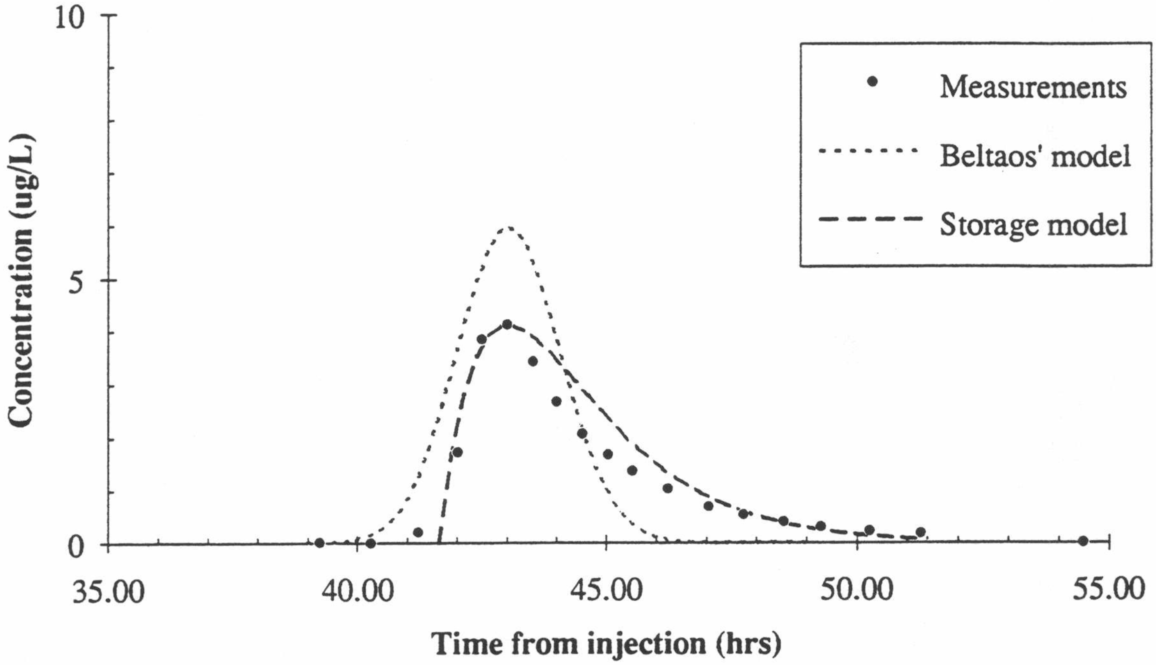
Deep Creek



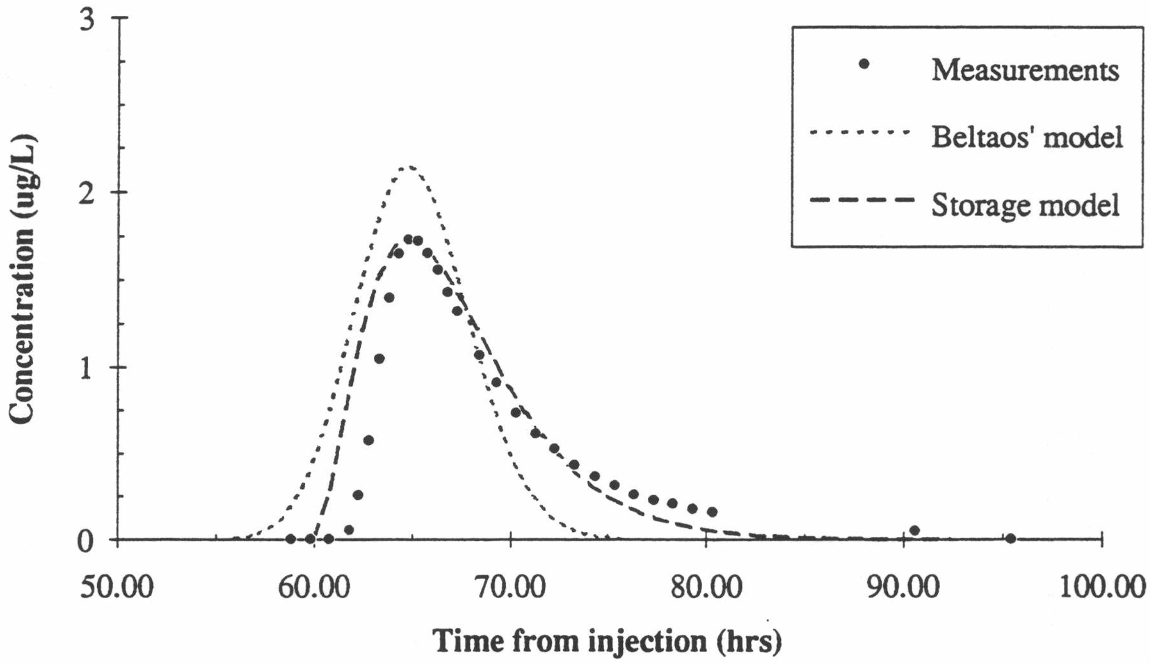
ALPAC diffuser

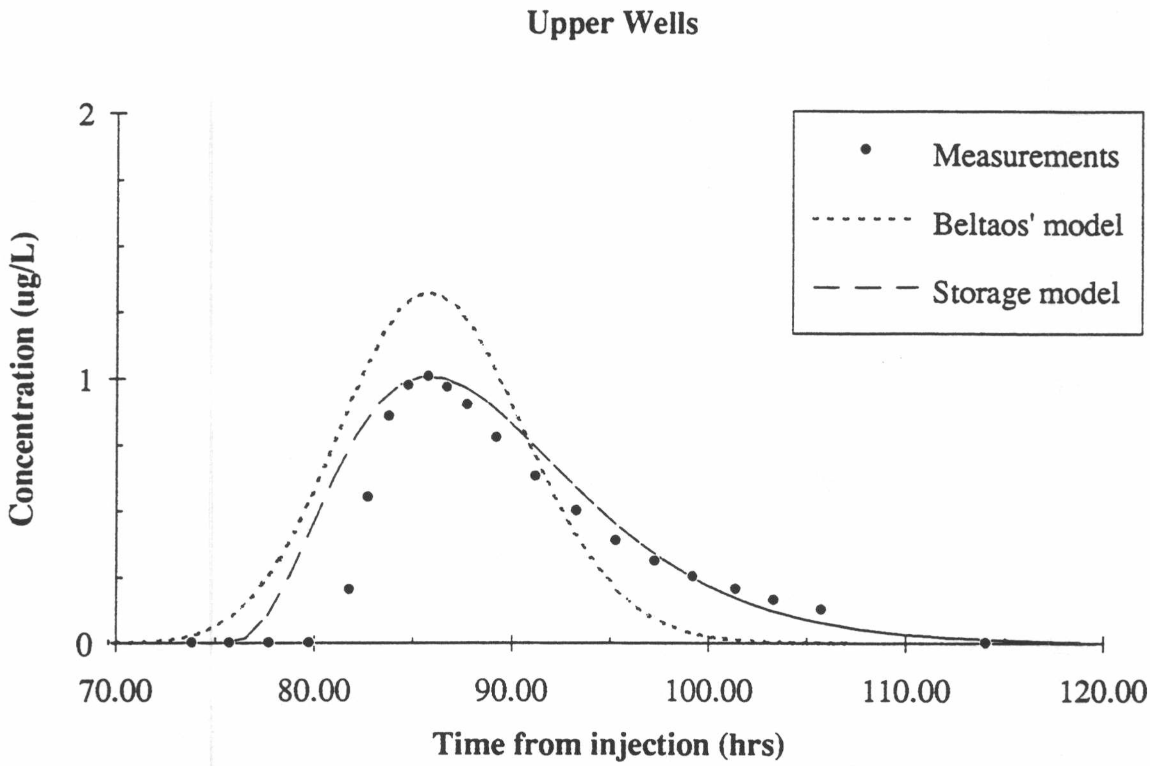


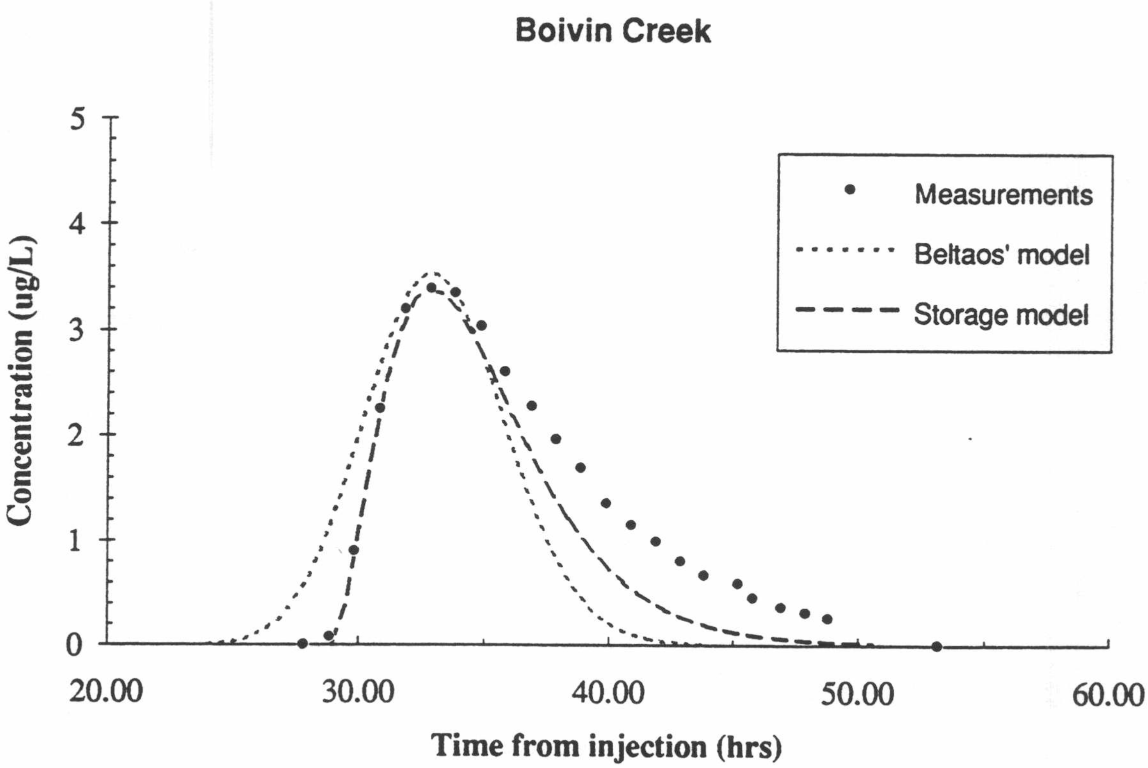
Calling River

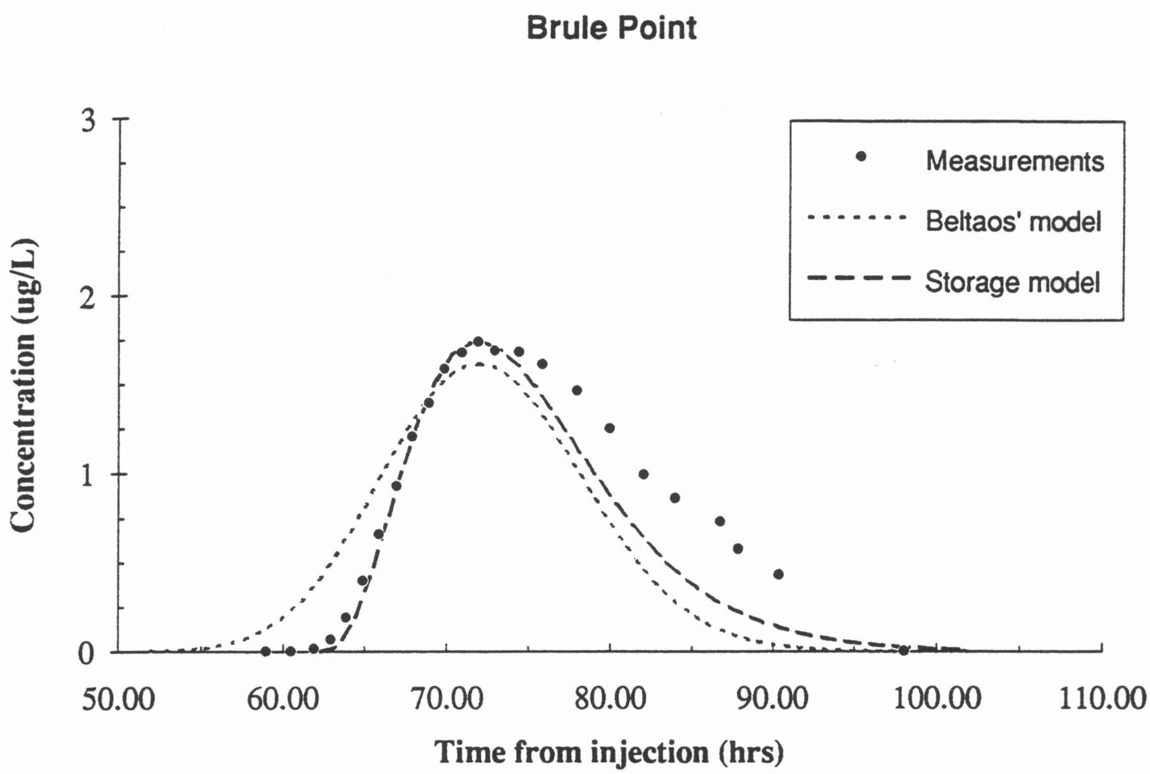


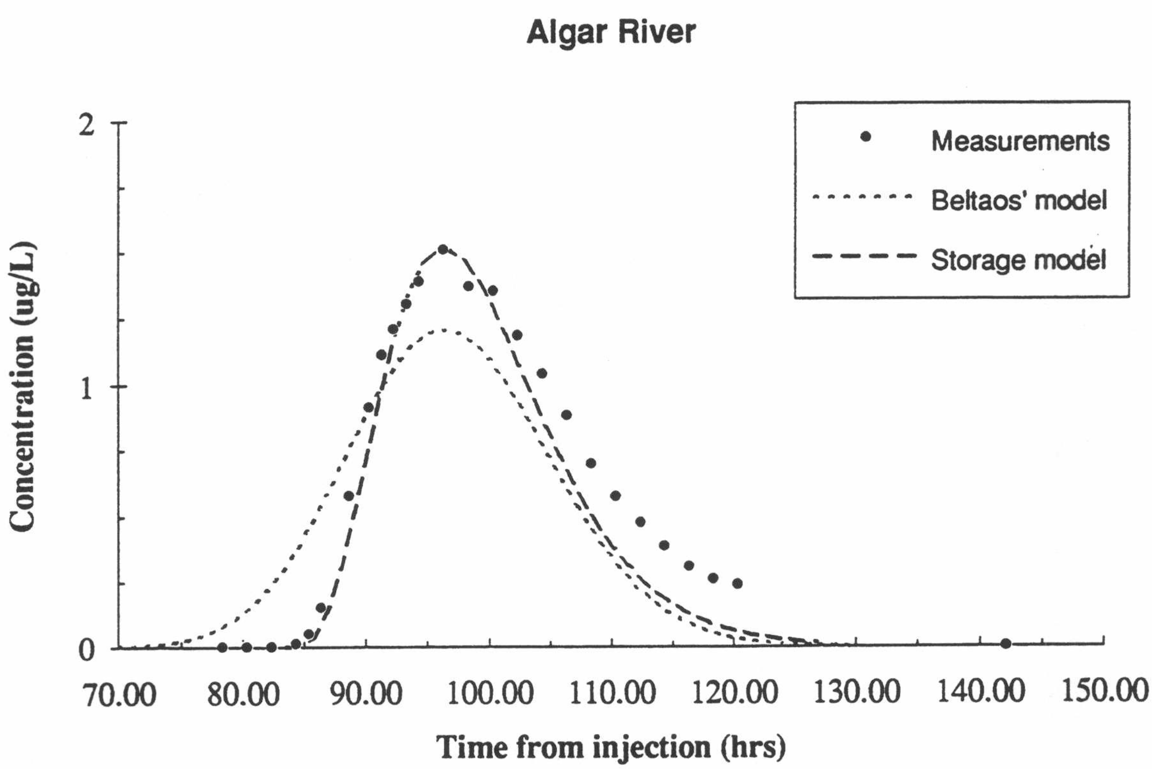
Iron Point



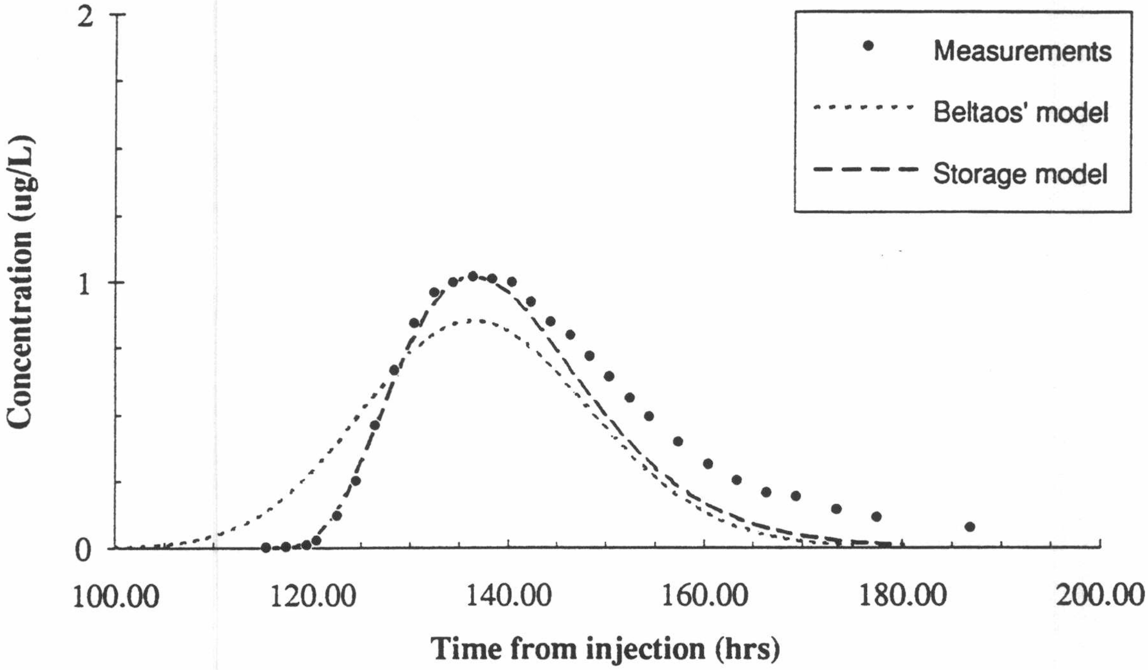

Upper Wells
Concentration (ug/L)
2
1
0
Measurements
Beltaos' model
Storage model
70.00
80.00
90.00
100.00
110.00
120.00
Time from injection (hrs)


Boivin Creek
Concentration (ug/L)
5
4
3
2
1
0
Measurements
Beltaos' model
Storage model
20.00
30.00
40.00
50.00
60.00
Time from injection (hrs)

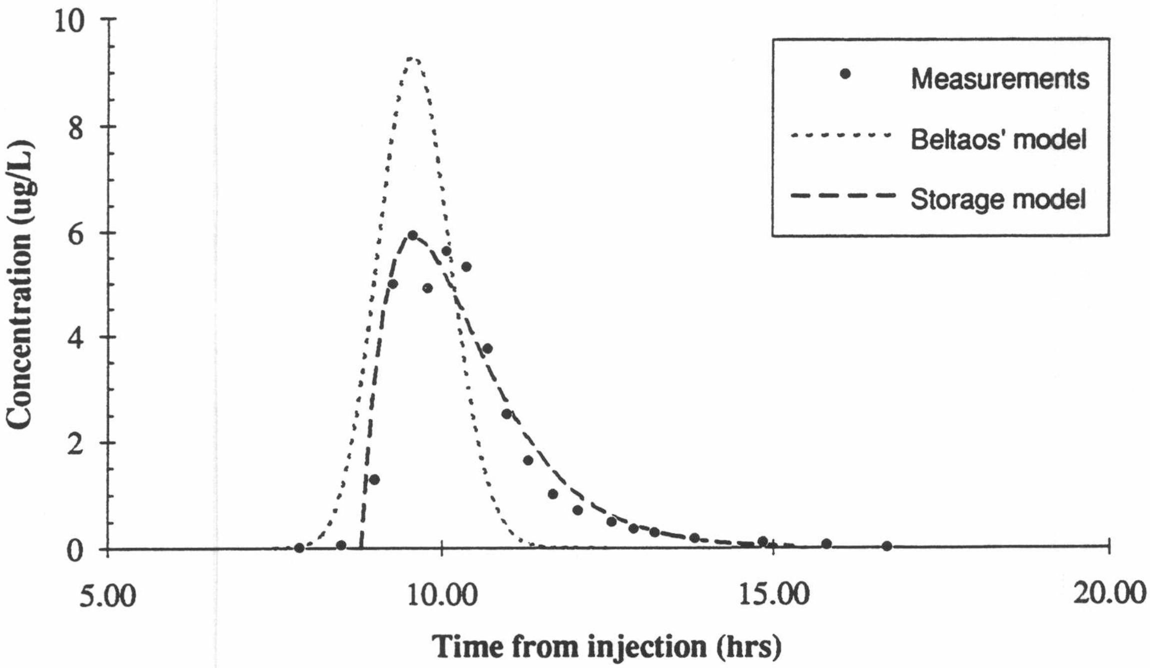

Brule Point
3
2
1
0
Concentration (ug/L)
Measurements
Beltaos' model
Storage model
50.00
60.00
70.00
80.00
90.00
100.00
110.00
Time from injection (hrs)


Algar River
2
1
0
Concentration (ug/L)
Measurements
Beltaos' model
Storage model
70.00
80.00
90.00
100.00
110.00
120.00
130.00
140.00
150.00
Time from injection (hrs)

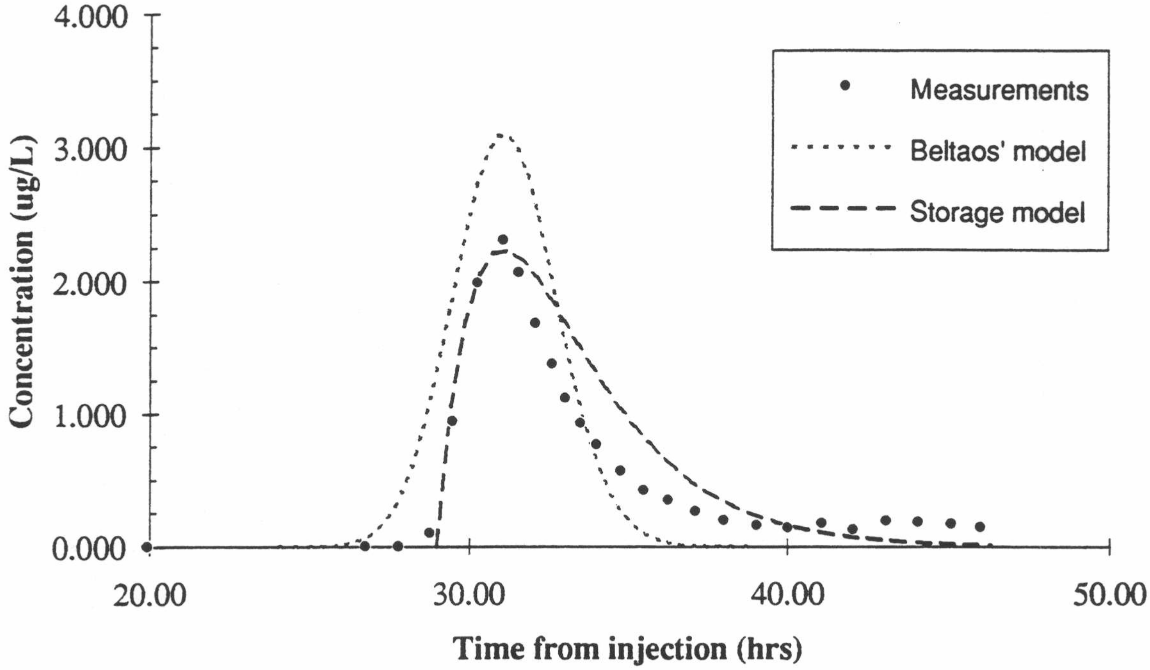
Fort McMurray



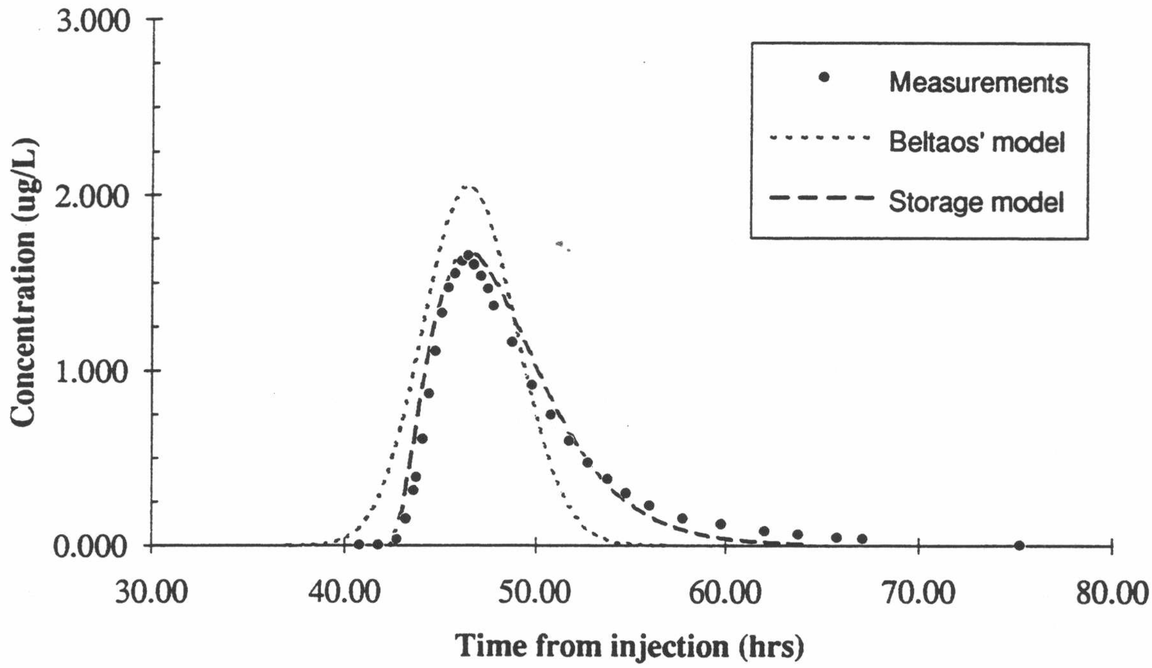
McLean Creek

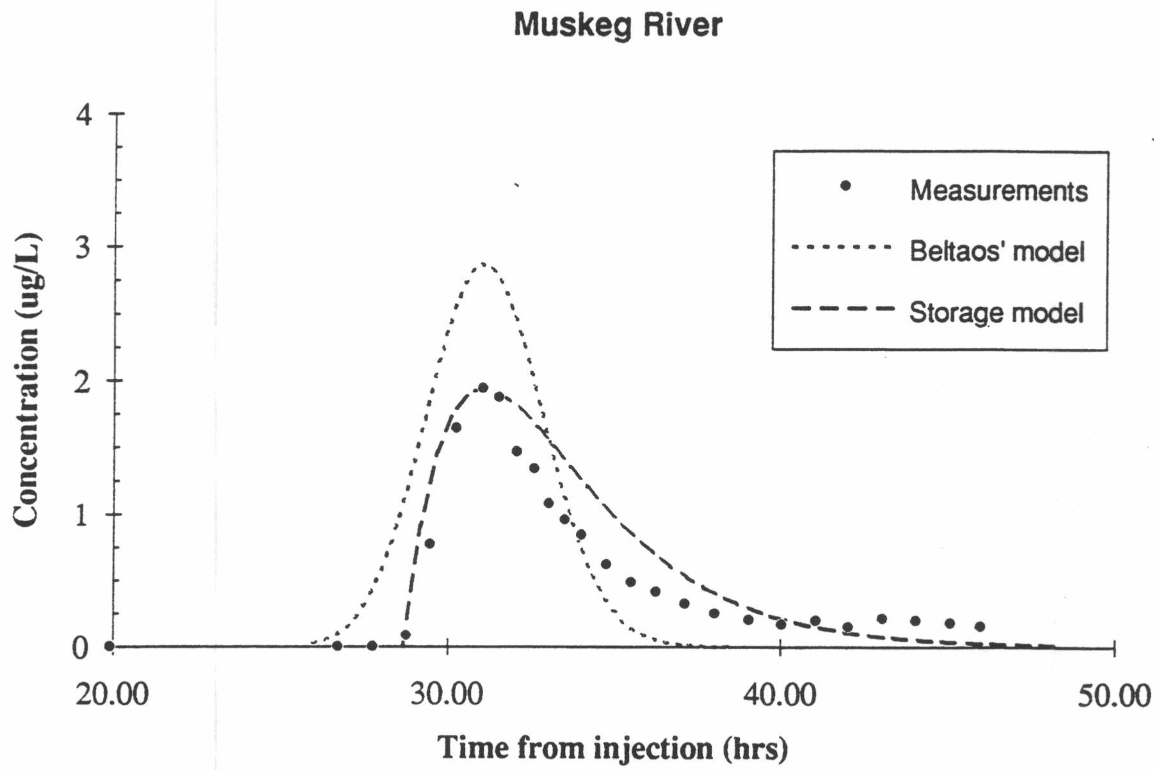


Muskeg River

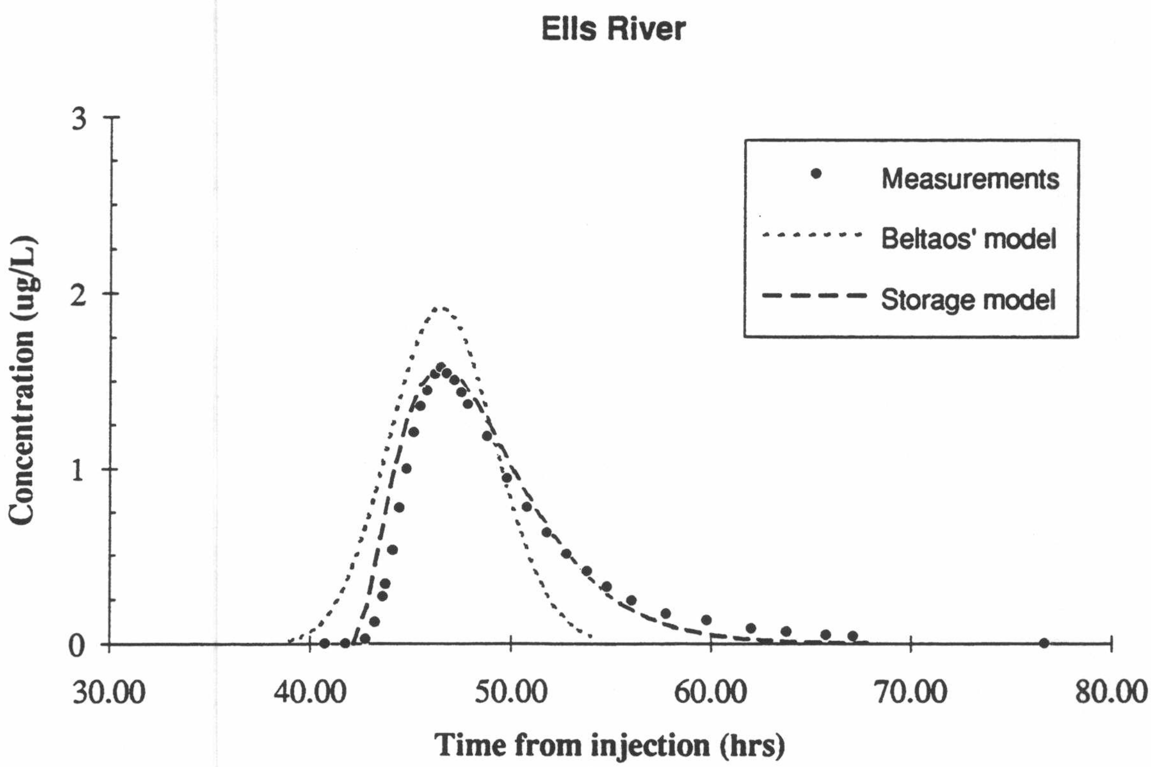


Ells River





Muskeg River
Measurements
Beltaos' model
Storage model
Concentration (ug/L)
0
1
2
3
4
20.00
30.00
40.00
50.00
Time from injection (hrs)



Ells River
Measurements
Beltaos' model
Storage model
Concentration (ug/L)
0
1
2
3
30.00
40.00
50.00
60.00
70.00
80.00
Time from injection (hrs)

APPENDIX B

Terms of Reference

NORTHERN RIVER BASINS STUDY
SCHEDULE OF TERMS OF REFERENCE
PROJECT 120-A1: TIME OF TRAVEL, ATHABASCA TO BITUMOUNT

Alberta Research Council will:

1. Carry out three under ice cover dye tests in the Athabasca River between the towns of Athabasca and Bitumount during the months of February and March 1992, at locations mutually agreeable to ARC and the Study, for the purpose of measuring river time-of-travel and dispersion characteristics.

2. Obtain a letter of permission from the Standards and Approvals Division of Alberta Environment for the application of any dye or other materials to the river system.

3. Provide a summary report of field activities on or before March 31, 1992.