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Northern River Basins Study















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by
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Alberta Research Council

NORTHERN RIVER BASINS STUDY PROJECT REPORT NO. 7

WINTER LOW FLOW TRACER DYE STUDIES

ATHABASCA RIVER
ATHABASCA TO BITUMOUNT
FEBRUARY AND MARCH, 1992
PART I: TIME OF TRAVEL

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PREFACE:

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

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

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

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

(Dr. F.J. Wrona, Ph.D., Science Director) — 2 June 93 (Date)

Whereas it is an explicit term of reference of the Science Advisory Committee "to review, for scientific content, material for publication by the Board",
IT IS HERE ADVISED BY THE SCIENCE ADVISORY COMMITTEE THAT;
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SUPPLEMENTAL COMMENTARY HAS BEEN ADDED TO THIS PUBLICATION: [ ] Yes [ ] No

(Dr. P. A. Larkin, Ph.D., Chair) — 11 June 93 (Date)

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WINTER LOW FLOW TRACER DYE STUDIES
ATHABASCA RIVER
ATHABASCA TO BITUMOUNT
FEBRUARY AND MARCH, 1992
PART I: TIME OF TRAVEL

STUDY PERSPECTIVE

Understanding the hydraulic characteristics of rivers is necessary in order to understand how effluents and their contaminants are mixed and transported, and where they are deposited in rivers. The Time-of-Travel project investigates the hydraulic characteristics of the Athabasca river under winter low flow conditions between the town of Athabasca and the Ells River. Low flow periods under ice is one of most important times of the year from the point of view of dissolved oxygen conditions and fish survival.

The study reach was divided into 3 subreaches:

1. Athabasca to Upper Wells;
2. Upper Wells to Fort McMurray; and
3. Fort McMurray to Ells River.

> ***Related Study Questions***
>
> *10) How does and how could river flow regulation impact the aquatic ecosystem?*
>
> *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.*

Prevailing flows during the experiment were less than the historical average for the two downstream reaches and therefore provided excellent conditions for low flow investigations. The results will be combined with previous studies done on the Athabasca River from Hinton to Athabasca and from Bitumount to Lake Athabasca to hydraulically characterize the entire length of the Athabasca River during low flow periods.

The authors state that these tests should be repeated over a wider range of flows and ice/no ice conditions, to be representative of the historical range of conditions experienced by the river. They also recommend that additional river cross sections be surveyed at intervals of 5-10 km to provide a better data base for hydraulic characterization and modelling. Further Northern River Basins Study hydraulic investigations of this type will be determined on the basis of water quality modelling needs. These have yet to be specified.

ABSTRACT

A field investigation covering a reach of the Athabasca River between Athabasca and Bitumount was performed to define the travel times in the river relative to the hydraulic characteristics. Discharges in the study reach ranged from 81 m^3/s to 188 m^3/s during the tracer dye experiments. Mean velocities were defined by the travel times of the peak dye concentration between sample sites. These velocities ranged from 0.38 m/s to 0.60 m/s. River slopes ranged from 0.00012 at Ells River to 0.00111 just upstream of Ft. McMurray. Under ice top widths varied from 220 m to 400 m. Mean flow depths were found to range from 0.67 m to 1.37 m in the study reach. Composite Manning roughness values ranged from 0.012 to 0.046 while the roughness heights were estimated to range between 0.0005 m and 0.5 m.

The variation of velocity with discharge can be described using a power law function derived from the Manning Equation. The velocity was found the vary with discharge to the power of 0.4. Coefficients for this equation were defined for each subreach, however they are valid only for the range of winter discharges typical for the study reach. The coefficients were found to range between 0.054 and 0.083. Chemical residence times in each subreach can be obtained by dividing the subreach length by the velocity and then multiplying by a factor of 1.03 to account for the difference between the travel times of the peak and centroid of a concentration distribution.

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.

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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. One of the most fundamental needs is to better quantify the hydraulic characteristics of the main rivers in the basin to improve the reliability of a number of water quality models.

Currently, a variety of one-dimensional water quality models are being calibrated to better define the water quality along the Athabasca River. These models, both steady state and dynamic, require a well-defined hydraulic framework on which to base the chemical computations. Errors in the time of travel used in these water quality models will lead to significant errors in defining the rate coefficients for the chemical processes in the models.

Tracer dye experiments are the most reliable way of accurately measuring the actual time-of-travel though a river reach. Time-of-travel estimates obtained from such techniques as Leopold-Maddock relationships derived solely from cross-sectional information are not accurate for low flows, especially under an ice cover. Field programs in which the entire dye cloud is sampled are superior to tracking only the peak concentrations because not only are both the peak and the centroid travel times defined but, as well, the lateral and longitudinal mixing rates are determined.

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.

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, hydraulic and mixing characteristics for low flow winter conditions will be defined for almost the entire length of the Athabasca River.

1.2 Objectives

The objectives are to define the hydraulic characteristics and mixing characteristics on the Athabasca River between Athabasca and Bitumount. These will be dealt with in two separate reports. The hydraulic characteristics and times-of-travel will be addressed in this report and the mixing characteristics will be addressed in a subsequent report. The objectives of this first report are to:

1. briefly describe the field work undertaken to carry out the time of travel measurements,

2. summarize the winter hydraulic characteristics,

3. present the travel time measurements and analyze them relative to the hydraulic characteristics, and

4. extrapolate travel times over the range of winter discharges.

A short discussion on the applicability of the Manning equation for flows with high relative roughness is also included to support the approaches used in the recommended extrapolation techniques.

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 metres 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.

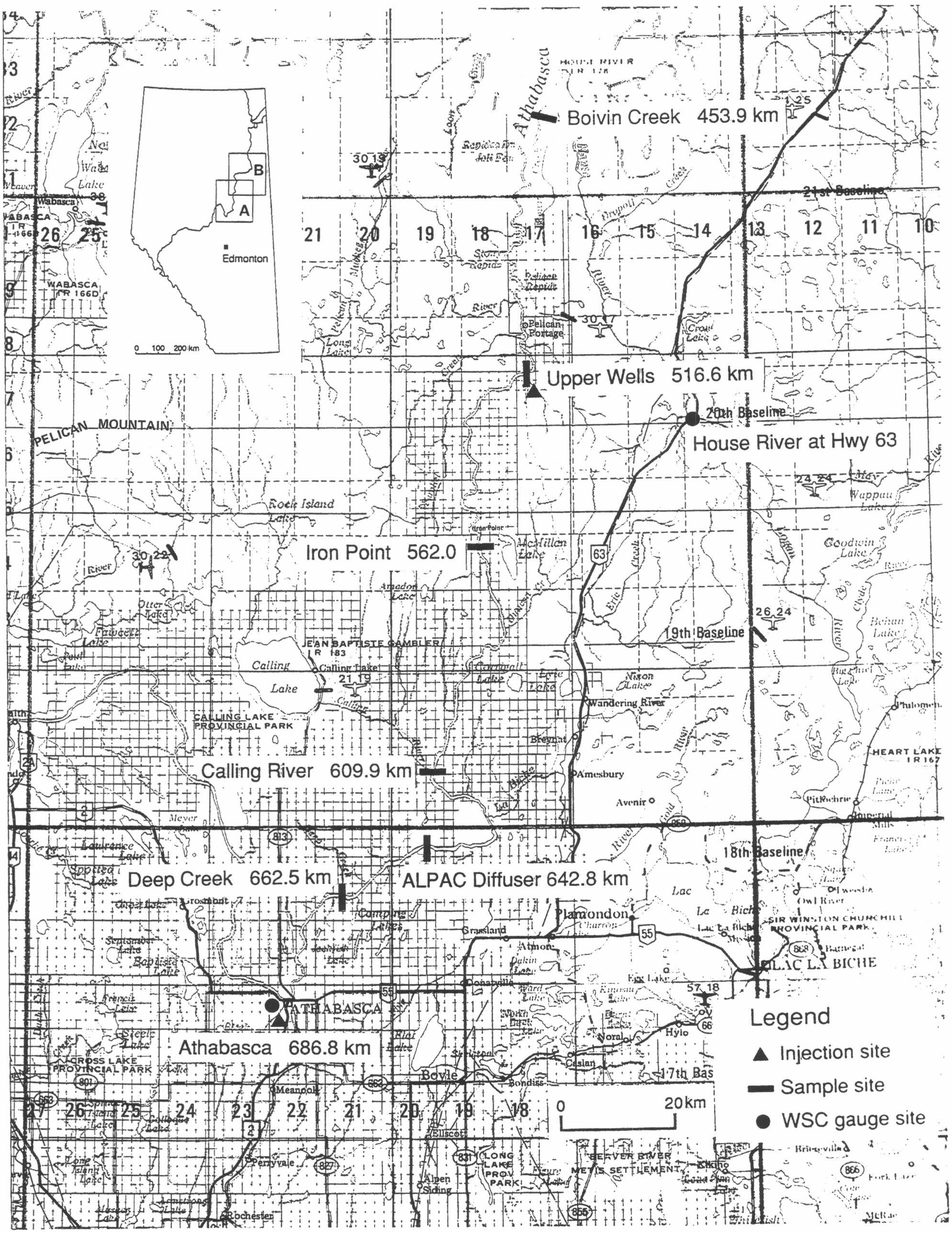

Figure 1a Location plan.

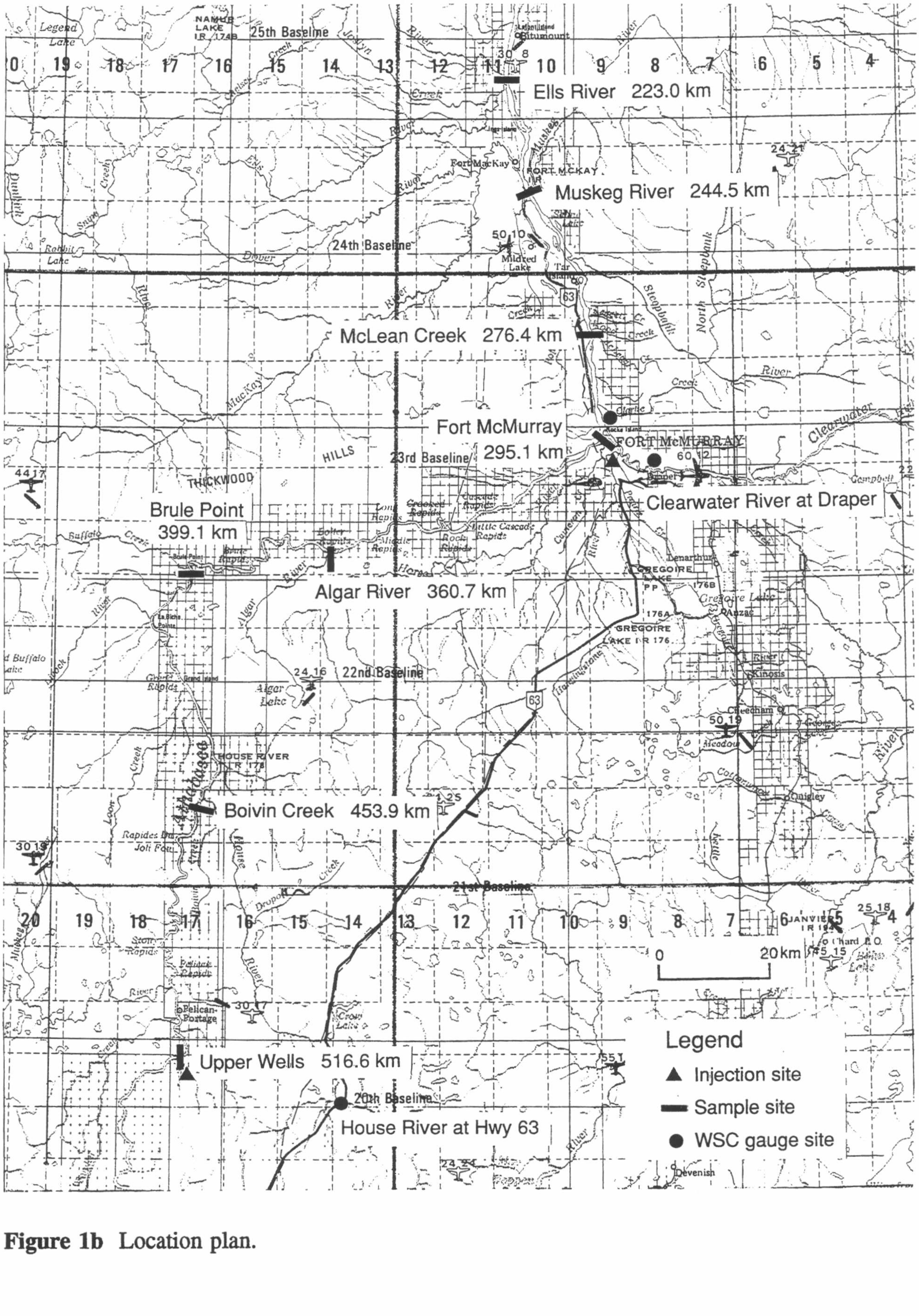

Figure 1b Location plan.

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 synoptic surveys done between Feb. 3 and Feb. 13, 1992. Some of the selected sites were moved because there were open leads in the ice cover at the selected locations so 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 the ice cover was not complete in the area of the rapids. The ice cover was also not complete in the area of Stony Rapids so the sample site planned for that location was moved to upstream to Upper Wells. The new site was located at Upper Wells because surface access is available at that location.

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 shown in Appendix A.

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. Mean ice thicknesses were found to range from 0.35 m to 1.4 m. Frazil accumulations of up to two meters in thickness produced those mean ice thicknesses that were greater than 0.60 m. Mean depths were found to vary between 0.68 m and 2.60 m while top widths varied from 130 m to 352 m. Mean velocities at these 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 three sample sites immediately downstream of these injection sites (figure 1). The discharge distributions at these sites were judged to be more important because the dye would not be fully mixed across the channel. The discharge 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 Appendix B.

2.2 Tracer dye experiments

The 464 km reach of the Athabasca River was divided into three reaches in which

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.

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 information for each experiment.

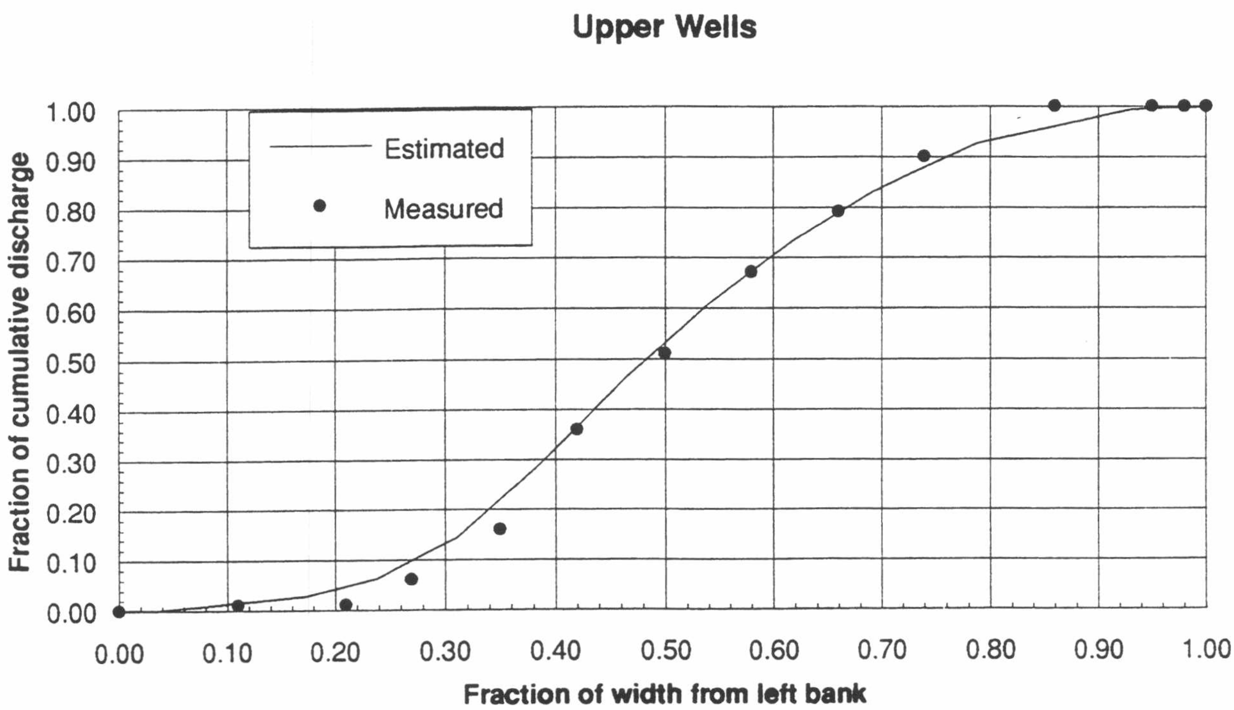

Figure 2 Comparison of an estimated discharge distribution with a measured discharge distribution

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 the injection apparatus. This injection apparatus consisted of a 1.5 m length of 10 cm diameter

Table 2 Summary of tracer dye experiments.

Reach	Injection Date	Injection Time (hrs:min)	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

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 used 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] $$k_T = e^{0.026(T-T_o)}$$

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 plotted in Appendix A.

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.

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

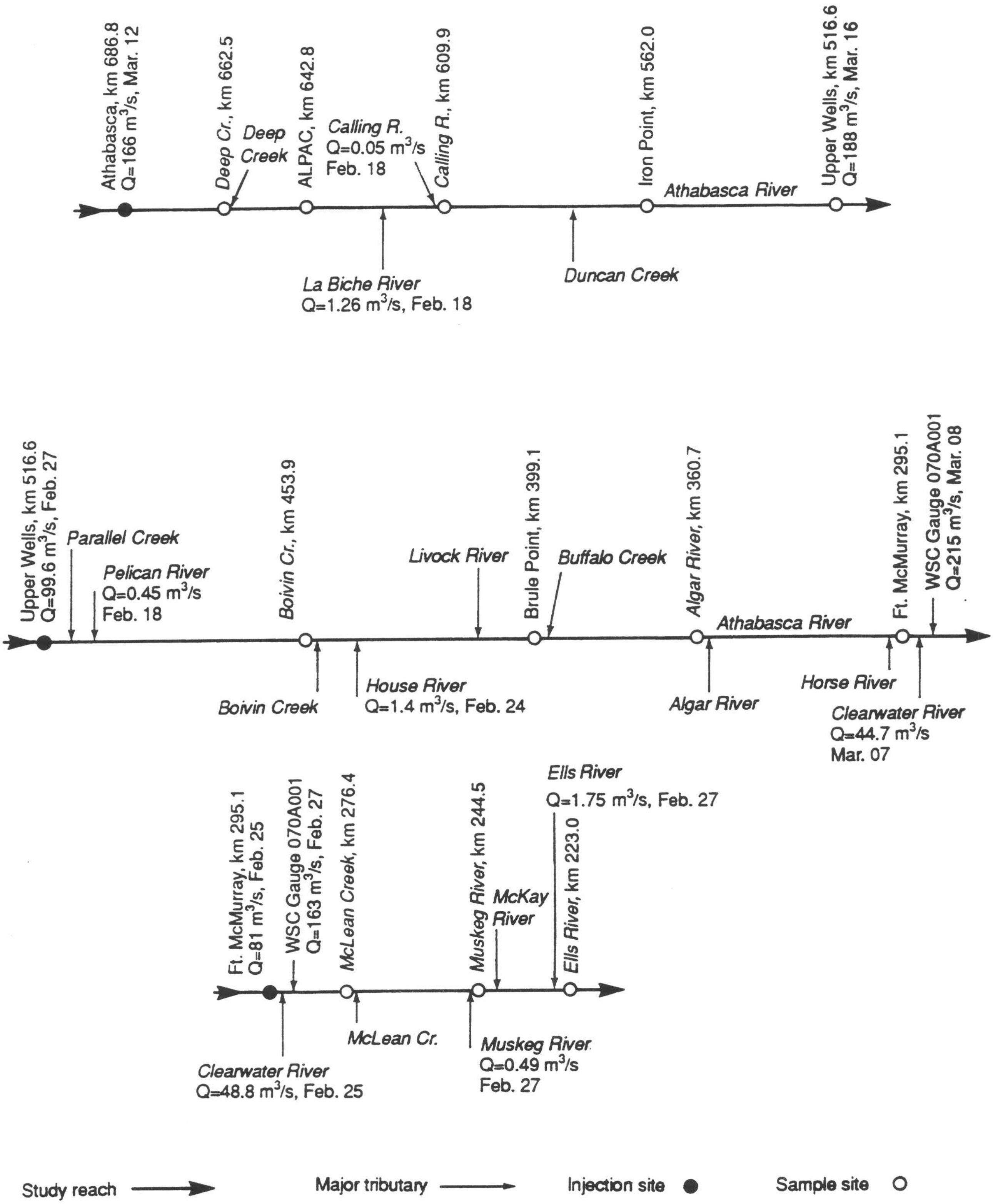

Figure 3 Distribution of discharge along the study reach.

3.0 ANALYSIS

3.1 Discharge

Discharges were measured at a number of locations during the study period. The discharges adopted for the hydraulic analysis were obtained by interpolating between these measurements. The historical variations in winter discharges were also analyzed to ensure that the field program was carried out under discharge conditions that would be typical of normal winter periods.

3.1.1 Study Discharges

Discharges at each of the sample sites were estimated by interpolating between the discharge measurements at the two ends of each reach, allowing for distributed inflow as well as inflow from tributaries as illustrated in figure 3. An upper limit to the discharge could also be set at each sample site because the discharge multiplied by the mean dye concentration could not exceed the mass of the dye injected. Table 4 summarizes the adopted discharges at each sample site. These discharges are the average discharges over the sampling period which are used in the mass balance and mean travel time calculations. Table 5 summarizes the adopted discharges for each subreach. These discharges are the average flows which transported the dye cloud through the subreaches and are used in the analysis of the subreach average hydraulic characteristics.

Determining the discharge values for the first test reach from Ft. McMurray to Ells River was quite straight forward. The discharge at Ft. McMurray was constant and there was very little inflow from the small tributaries. The measured contributions from the major tributaries added to the measured inflow into the upstream end of the reach was identical to the measured outflow from the downstream end of the reach.

The discharges in the second test reach were determined using the discharge

Table 4 Summary of adopted discharges at sample sites.

Location	Date	Discharge (m^3/s)
Athabasca	Mar 12	166
Deep Creek	Mar 13	168
ALPAC Diffuser	Mar 13	170
Calling River	Mar 14	179
Iron Point	Mar 15	183
Upper Wells	Mar 16	188
Upper Wells	Feb 27	100
Boivin Creek	Feb 28 - Feb 29	103
Brule Point	Mar 01 - Mar 02	105
Algar River	Mar 02 - Mar 03	105
Ft.McMurray	Mar 03 - Mar 05	107
Ft.McMurray	Feb 24	81
McLean Creek	Feb 25	129
Muskeg River	Feb 26	129
Ells River	Feb 26 - Feb 27	132

measurements at Upper Wells and on the House River but the measurement at the Ft. McMurray gauge on March 8 was made too late to be of direct use because sampling was completed on March 5. This delay in the discharge measurement complicated the analysis somewhat because the flows were unsteady at some times during the field study. There was some question about exactly how much of an effect this had on this particular test. However, the strip chart record from the WSC gauge indicated that, fortunately, most of the increase in discharge occurred in the two days between the end of the test and the discharge measurement. Water level records and discharge measurements obtained at the WSC gauge at Draper indicate the discharge in the

Table 5 Summary of adopted discharges for the subreaches.

Subreach	Date	Discharge (m^3/s)
Athabasca - Deep Cr.	Mar 12 - Mar 13	167
Deep Cr. - ALPAC	Mar 13	169
ALPAC - Calling R.	Mar 13 - Mar 14	174
Calling R. - Iron Pt.	Mar 14 - Mar 15	181
Iron Pt. - Upper Wells	Mar 15 - Mar 16	186
Upper Wells - Boivin Cr.	Feb 27 - Feb 28	103
Boivin Cr. - Brule Pt.	Feb 28 - Mar 01	105
Brule Pt. - Algar R.	Mar 01 - Mar 02	105
Algar R. - Ft.McMurray	Mar 02 - Mar 03	106
Ft.McMurray - McLean Cr.	Feb 24 - Feb 25	129
McLean Cr. - Muskeg R.	Feb 25 - Feb 26	129
Muskeg R. - Ells R.	Feb 26 - Feb 27	130

Clearwater River was almost constant at 45 m^3/s during the period of this test. Using this data and the upper limits of discharge obtained from the dye mass calculations, it was determined that the discharge in the test reach increased only slightly during the test period. This slight increase was attributed to inflow from tributaries; 1 m^3/s from Parallel Creek; 2 m^3/s from the Pelican River; 2 m^3/s from the House River; 1 m^3/s from the Algar River; and 1 m^3/s from the Horse River.

In the most upstream test reach, however, snowmelt runoff increased both the tributary discharges and the distributed inflow along the channel. During the period of this test from Mar. 12 to Mar. 16, there was a 13% increase in the flow between Athabasca and Upper Wells. From the relative magnitudes of the original tributary flow measurements on Feb. 18 (table 3), the dye mass calculations, and from observations from the sampling crews, it was determined that the La Biche River contributed the only significant concentrated inflow. Therefore, the 22 m^3/s of inflow between Athabasca and Upper Wells was apportioned into a distributed inflow of 0.1 $m^3/s/km$ with the remaining 5 m^3/s attributed to inflow from the La Biche River.

3.1.2 Historical Flows

An estimate of the flow durations is required to ensure that the field program was carried out under discharge conditions that would be typical of normal winter periods. The historical variations in winter discharges in the study reach were quantified by developing flow duration curves using daily mean discharges from Water Survey of Canada gauge records for the months of December, January, February and March for a thirty year period from December, 1960 to March, 1990. These four months were used because only discharges under ice conditions were of interest. The records from three gauges were used: Athabasca River at Athabasca, Athabasca River below Ft. McMurray, and Clearwater River at Draper. The daily Clearwater River discharge was subtracted from the daily Ft. McMurray discharge to generate data for the reach above Ft. McMurray. The flow-duration curves are shown in figure 4. Flows above Ft. McMurray are typically about 25 m^3/s higher than those at Athabasca and the flows below Ft. McMurray are typically 50 m^3/s higher than those above Ft. McMurray.

The flow duration curves define each discharge by the percent of time that it is exceeded in the period of record. Discharges for a range of these exceedance values are presented in table 6. At Athabasca, the winter discharge exceeded 104 m^3/s for 50% of the time and was between 63 m^3/s and 161 m^3/s for 90% of the time. Above Ft. McMurray, the winter discharge exceeded 125 m^3/s for 50% of the time and was between 68 m^3/s and 188 m^3/s for 90% of the time. Below Ft. McMurray, the winter discharge exceeded 182 m^3/s for 50% of the time and was between 112 m^3/s and 264 m^3/s for 90% of the time.

The results of the flow duration analysis indicate that the discharges which occurred during the Athabasca to Upper Wells test occur less than 5% of the time in the winter. This is

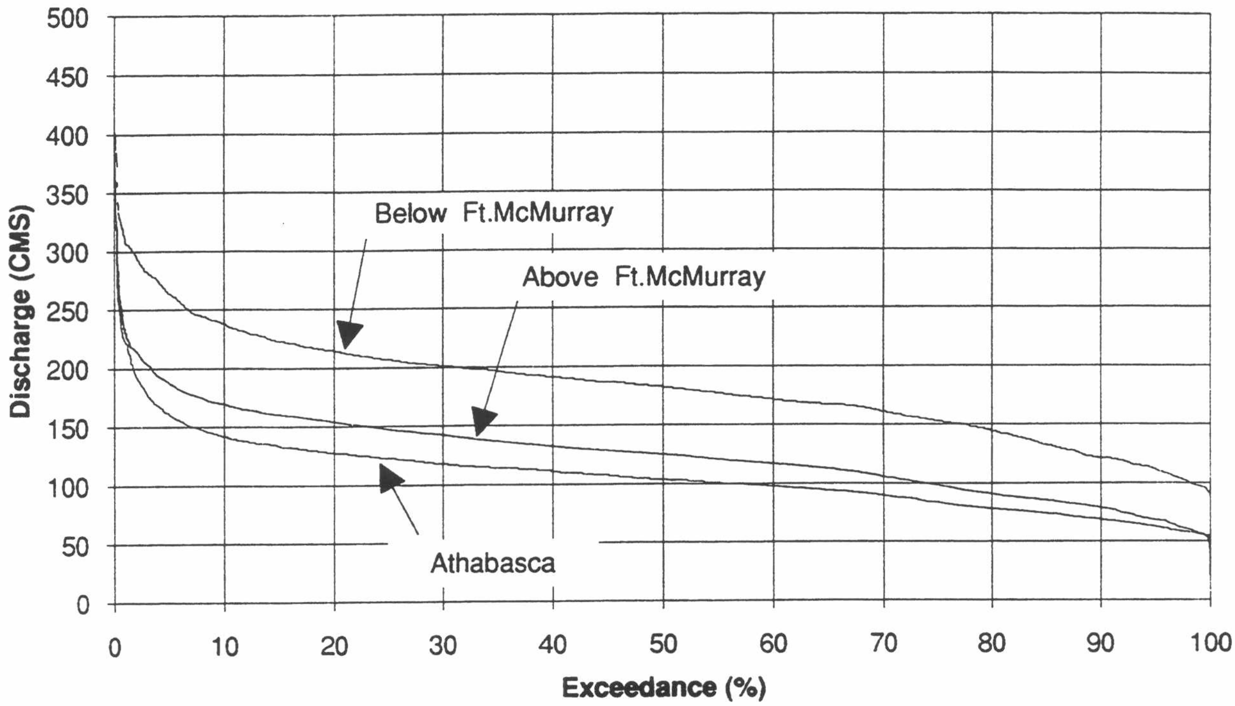

Figure 4 Flow duration curves for the study reach for the period between December 1 and March 31.

due to the snowmelt runoff produced by the unseasonable warm temperatures which occurred during the test period. The results of this test, therefore, must be generalized so that they can be applied to lower, more typical flow rates. This generalization of the results will be discussed later in this report. The adopted discharges for the tests in the other two reaches were lower than the median discharges and were more typical of the historical flow rates in those reaches.

3.2 Travel times

Four unique time-of-travel parameters are required to characterize a concentration distribution. The leading edge defines when the concentration first begins to rise at a site, the peak defines when the maximum concentration occurs, the centroid defines the centre of mass of the cloud, and the trailing edge defines when the concentration returns to near background

Table 6 Selected flow-duration data for the Athabasca River.

Exceedance (%)	Discharge at Athabasca (m^3/s)	Discharge above Ft.McMurray (m^3/s)	Discharge below Ft.McMurray (m^3/s)
1	224	233	311
5	161	188	264
10	142	170	238
50	104	125	182
90	69	90	121
95	63	68	112
99	56	57	97

levels. All of these travel times vary across the channel, typically being shorter in the centre of the channel and longer near the banks. The centroids of the five concentration distributions measured across the channel at each site were converted into a mean value for that site by numerically integrating the centroid distribution with respect to the cumulative mass distribution across the channel. The other three mean time-of-travel values were obtained by integrating their lateral distributions with respect to the cumulative discharge across the channel. A summary of these travel times for all the sample reaches is given in table 7.

In most cases, the travel times of the peaks are slightly less than those of the centroid. However, in the two subreaches between Boivin Creek and Algar River the travel time of the centroid appears to be less than that of the peak. This only occurs because the centroid lags significantly behind the peak in the first subreach from Upper Wells to Boivin Creek. The centroid never actually overtakes the peak, as can be seen from the variations in cumulative travel times with distance from injection for each test shown in figures 5a-c. The slope of the lines in these figures are inversely proportional to the velocities. For example, the velocity of the peak is typically about 3% greater than that of the centroid.

Table 7 Summary of time of travel data for the subreaches.

Subreach	Length (km)	Travel Times Leading Edge (hrs)	Peak (hrs)	Centroid (hrs)	Trailing Edge (hrs)
Athabasca - Deep Cr.	24.3	11.61	12.56	12.67	20.77
Deep Cr. - ALPAC	19.7	10.95	11.82	11.99	12.04
ALPAC - Calling R.	32.9	18.04	18.70	19.44	21.75
Calling R. - Iron Pt.	47.9	20.77	22.22	23.22	40.93
Iron Pt. - Upper Wells	45.4	18.76	20.85	21.60	18.64
Upper Wells - Boivin Cr.	62.7	28.22	32.97	36.20	53.31
Boivin Cr. - Brule Pt.	54.8	34.19	39.43	38.11	44.87
Brule Pt. - Algar R.	38.4	19.97	25.16	25.15	45.11
Algar R. - Ft.McMurray	65.6	37.73	38.69	42.95	61.81
Ft.McMurray - McLean Cr.	18.7	8.66	10.03	10.27	17.00
McLean Cr. - Muskeg R.	31.9	20.99	23.60	23.67	32.66
Muskeg R. - Ells R.	21.5	12.40	12.92	13.74	28.88

This difference in velocity between the peak and the centroid raises the question of which quantity best represents the average velocity of the water. Obviously the centroid is the measure of the average velocity of the dye mass, but this velocity only corresponds to the average water velocity in a uniform laboratory-type channel where all areas of the channel contribute to the flow. In natural streams, however, the cross-section variability caused by bars, islands, and meander bends produces zones of stagnant or very slow moving water. These zones contribute little or nothing to the discharge therefore they should not be included in the determination of average velocity. The travel time of the centroid is affected by these stagnant zones because the storage and slow release of dye from these zones produces long drawn-out receding limbs on the

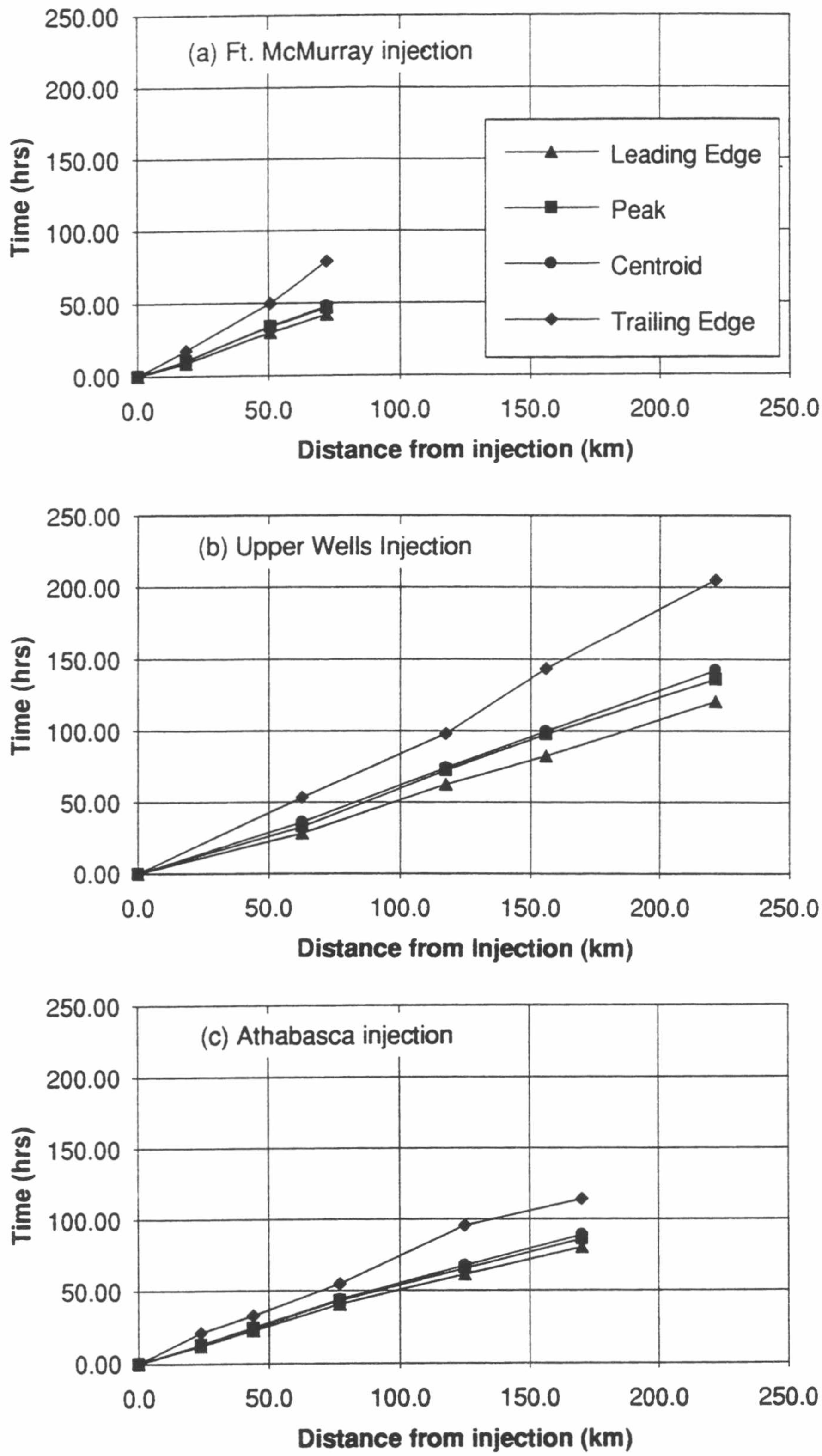

Figure 5 Growth of travel times with distance from injection.

concentration distributions. Alternatively, the cross-section average velocity of the peak concentration incorporates the cross-sectional variations in velocity but does not include the effects of the storage and release of dye from stagnant areas. Therefore, the velocity of the peak should be used to calculate the hydraulic characteristics of a river reach but the centroid should be used to calculate transit times for pollutants.

Using the time of travel of the peak to determine the mean velocity may lead to over-estimating the velocity if mixing across the channel is not fully established. That is, the dye moves primarily in the zone of high velocity and, hence, the velocity is over-estimated because the entire flow is not represented. A previous study by the Alberta Research Council on the North Saskatchewan River found that the velocity could be over-estimated by as much as 10% in the initial reach downstream of an injection site (Van Der Vinne, 1991).

3.3 Hydraulic characteristics

The hydraulic characteristics of the study reach must be defined so that velocities and travel times may be extrapolated for discharges other than those which occurred during the study period.

3.3.1 Field Measurements

Channel characteristic for each subreach were obtained from a variety of sources. The water surface slopes, S were obtained from Kellerhals, Neill and Bray (1972). The mean subreach top widths, B were obtained by averaging the channel widths measured every three to four kilometres on 1:50,000 scale maps and then adjusting these values using the measured under ice top widths obtained from the synoptic surveys. The mean velocity, U was defined as x/t_p, where x is the reach length and t_p is the time it takes for the peak of the dye cloud to pass through the reach. These values are summarized in table 8. The mean velocity and the adopted discharge, Q were used to determine the flow area, A for each subreach. The mean depth, H and the hydraulic radius, approximated as $R=A/2B$, were calculated from the flow area and the top

Table 8 Summary of hydraulic characteristic for the sample sites.

Location	Discharge (m^3/s)	Slope	Top Width (m)	Flow Depth (m)	Mean Velocity (m/s)	Manning[1] Roughness	Roughness[2] Height (m)
Hondo-Athabasca*	75	0.00038	200	1.01	0.37	0.033	0.201
Athabasca-Deep Cr.	167	0.00027	290	1.07	0.54	0.020	0.021
Deep Cr.-ALPAC	169	0.00027	330	1.11	0.46	0.024	0.052
ALPAC-Calling R.	174	0.00027	270	1.32	0.49	0.025	0.073
Calling R.-Iron Pt.	181	0.00035	220	1.37	0.60	0.024	0.059
Iron Pt.-Upper Wells	186	0.00068	240	1.28	0.60	0.032	0.189
Upper Wells-Boivin Cr.	103	0.00068	240	0.81	0.53	0.027	0.084
Boivin Cr.-Brule Pt.	105	0.00058	240	1.13	0.39	0.043	0.446
Brule Pt.-Algar R.	105	0.00095	250	0.99	0.42	0.046	0.488
Algar R.-Ft. McMurray	106	0.00111	220	1.02	0.47	0.045	0.489
Ft.McMurray-McLean Cr.	129	0.00032	370	0.67	0.52	0.017	0.007
McLean Cr.-Muskeg R.	129	0.00014	280	1.23	0.38	0.023	0.042
Muskeg R.-Ells R.	130	0.00012	400	0.70	0.46	0.012	0.0005
Ells R.-Embarras**	189	0.00012	370	1.22	0.42	0.019	0.014

* Andres, Van Der Vinne and Trevor, 1989

** Beltaos, 1979

[1] see equation [3]

[2] see equation [5]

width. The approximations of hydraulic radius are used because, in natural channels where the width is very much greater than the depth, there is virtually no difference between the actual hydraulic radius and the approximation, A/2B.

There are distinct differences in the hydraulic characteristics of the three test reaches. This agrees with the initial observations that there appeared to be three distinct segments of river in the study reach. The river slope is 0.27 m/km between Athabasca and Calling River then gradually increases to 1.11 m/km just upstream of Ft. McMurray. Downstream of Ft. McMurray the slope rapidly decreases to 0.12 m/km. The river width was found to be approximately 300 m between Athabasca and Calling River, about 240 m between Calling River and Ft. McMurray, and between 300 m and 400 m in the reach from Ft. McMurray to Ells River. Mean flow depths ranged from 0.67 m to 1.37 m in the study reach. Mean velocities in the subreaches ranged from 0.38 m/s to 0.60 m/s.

Ice cover formation on the Athabasca river occurs by a combination of the juxtaposition of ice flows and by the consolidation of a juxtaposed cover in locations where the longitudinal forces on the advancing cover exceed the strength due to downward freezing of the juxtaposed cover. Downstream of Ft. McMurray and upstream of Upper Wells, where the slopes are relatively mild, the predominant process is juxtaposition. This process produced an ice cover of relatively uniform thickness in the order of 0.4 - 0.6 m. Between Upper Wells and Ft.McMurray, where the river slope is steeper, more of the ice cover formed by consolidation, resulting in a thicker ice cover as well as frazil ice accumulations approaching two meters in thickness.

High local velocities and the existence of numerous open leads in the rapids sections result in the formation and subsequent deposition of significant amounts of frazil slush. This frazil tends to deposit in low velocity areas hence concentrating the flow in the portion of the river cross-section which offers the least resistance to flow. This produces greater variation in the ice cover thickness in the steep middle reach compared to the upstream and downstream reaches.

The Manning roughness was found to vary from 0.020 to 0.032 between Athabasca and Upper Wells, from 0.027 to 0.046 between Upper Wells and Ft. McMurray and from 0.012 to 0.023 between Ft. McMurray and Ells River. The change in roughness was abrupt near Ft. McMurray but gradual between Iron Point and Boivin Creek.

The roughness of 0.012 calculated between Muskeg River and Ells River is quite low compared to the values in the other similar subreaches. As well, a composite Manning roughness of 0.019 was calculated from hydraulic parameters reported in a previous study done by the Alberta Research Council between Ells River and Embarras, 113 km downstream (Beltaos, 1979). The low value may be due to inaccuracies in estimating the under ice top width. This segment of river has numerous islands and bars which may cause the flow width to be much narrower under an ice cover than in open water conditions because much of the shallow portions of the channel will be blocked with ice. More detailed under ice cross-section surveys are needed to determine if this is indeed the problem.

Another study by the Alberta Research Council found a composite roughness of 0.033 in a 119 km long reach just upstream of the town of Athabasca (Andres, Van Der Vinne and Trevor, 1989). This is higher than the typical value of 0.024 found in the present study downstream of Athabasca, however, the river was much narrower in the reach upstream of Athabasca and there was a large difference in discharges between the two studies, about 175 m^3/s in the present study and only 75 m^3/s in the previous study. Another contributing factor producing the difference in roughness was the condition of the ice cover. The previous study upstream of Athabasca was done under mid-winter conditions, whereas the present study was done while the ice cover was deteriorating prior to breakup.

3.3.2 Extrapolation

The travel times and associated velocities measured in this study are only valid for the discharge at which the measurements were carried out because velocity, and therefore travel time, varies monotonically with discharge in most cases. The extrapolation to other discharges can be made by combining the equation of continuity

$$Q = UBH \tag{2}$$

with a resistance equation such as the Manning equation

$$U = \frac{R^{2/3} S^{1/2}}{n_c} \tag{3}$$

where n_c is the composite Manning roughness parameter which is a measure of the roughness for the top and bottom boundaries combined. The composite Manning roughness values determined for the subreaches are listed in table 8.

Combining equations [2] and [3] produces

$$U = \left(\frac{Q}{2B}\right)^{0.4} \left(\frac{S^{0.5}}{n_c}\right)^{0.6} \tag{4}$$

which defines the mean velocity in terms of discharge, top width, slope and composite roughness. Thus for a given river reach with known values of B, S and n_c, the velocity, and hence the travel time, can be obtained for any given discharge. Figure 6 shows equation [4] in graphical form along with the data from the study. The curves show a general trend of increasing velocity with increased discharge for various values of slope and roughness.

Equation [4] was developed assuming that the width and roughness of the channel remained constant. In the case of top width, this assumption is reasonable since the edges of the ice-water interface do not move significantly even for large fluctuations in water level because the ice is frozen to the banks. The Manning roughness, however, can increase significantly with decreasing discharge because the form roughness of the channel increases in relation to the flow depth (Chow, 1959). A more fundamental approach is required to account for this effect.

The Manning equation is an approximation of the physically-based resistance equation

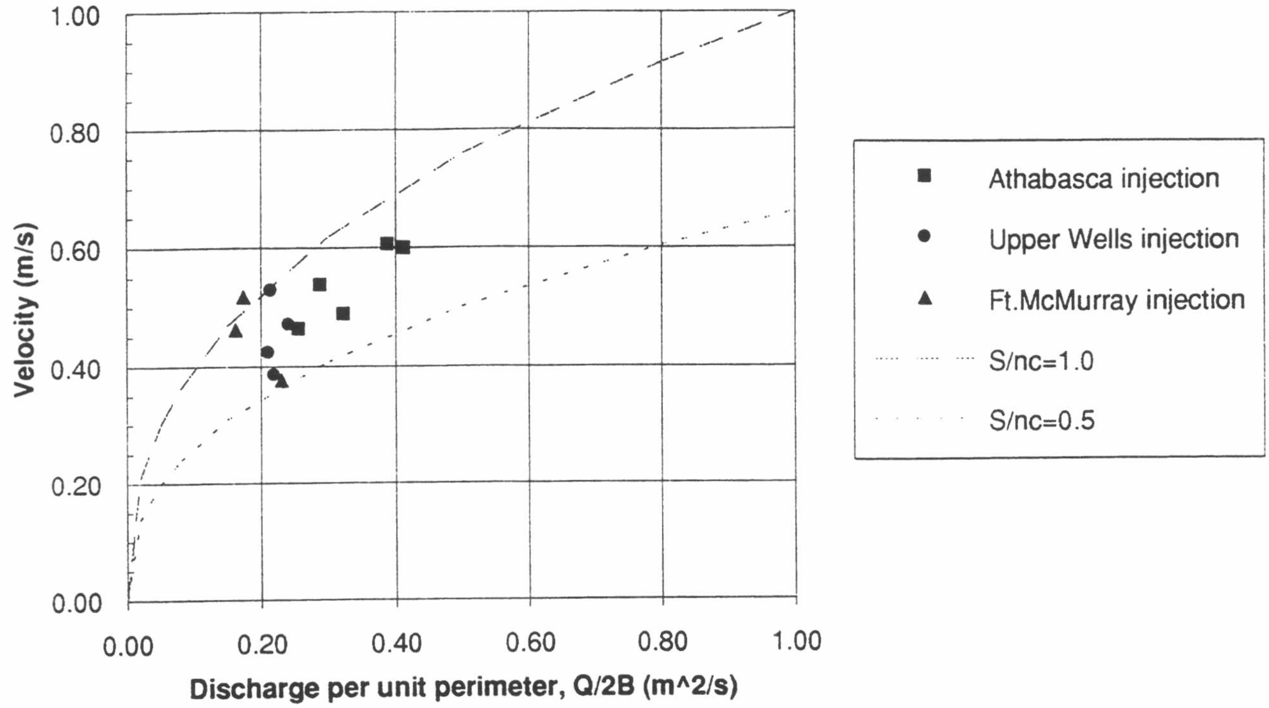

Figure 6 Variation of velocity with discharge per unit perimeter.

[5] $$\frac{U}{U_*} = 2.5 \ln\left(12\frac{R}{k}\right)$$

which is derived from the assumption of a logarithmic vertical velocity profile, where k is the height of the roughness elements in meters, U_* is the shear velocity defined by

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

and g is the acceleration due to gravity. Values of roughness height, k for the various subreaches are listed in table 8. Equation [5] is difficult to use in practice because both the velocity and the hydraulic radius are functions of the discharge. Therefore an iterative technique must be used to obtain the velocity for each different value of discharge.

The relationship between n_c and k can be found by combining equations [3] and [5] and rearranging to obtain

[7]
$$n_c = \frac{0.128 R^{1/6}}{\ln\left(12\frac{R}{k}\right)}$$

The variation of n_c with relative roughness, R/k is shown in figure 7. The Manning roughness is virtually constant for values of relative roughness greater than ten but for values of relative roughness less than ten, the Manning roughness increases with decreasing relative roughness. Unfortunately, a number of the subreaches were found to have these low values of relative roughness during the study period. This means that the Manning equation can only be applied over a small range of discharge similar to the study discharge where the error in predicting velocity is not large. Fortunately, winter flows under the ice cover are fairly stable on the Athabasca River as was demonstrated by the flow-duration analysis. If the range of discharge is defined by the 1% and 99% exceedance discharges, the error in velocity predictions due to using equation [4] rather than equation [5] is less than ten percent in most cases and still less than fifteen percent in the extreme case. The error introduced by this approximation is similar to some of the errors in measurement. For example, the discharge, top width and slope measurements are also only accurate to within ten percent of their measured values.

Equation [4] can be simplified by combining all the variables other than discharge into one coefficient so that

[8]
$$U = C_u \, Q^{0.40}$$

where C_u is defined by

[9]
$$C_u = 0.76 \, S^{0.3} B^{-0.4} n_c^{-0.6}$$

The coefficient C_u depends on the constants S, B, and n_c so the coefficient should be

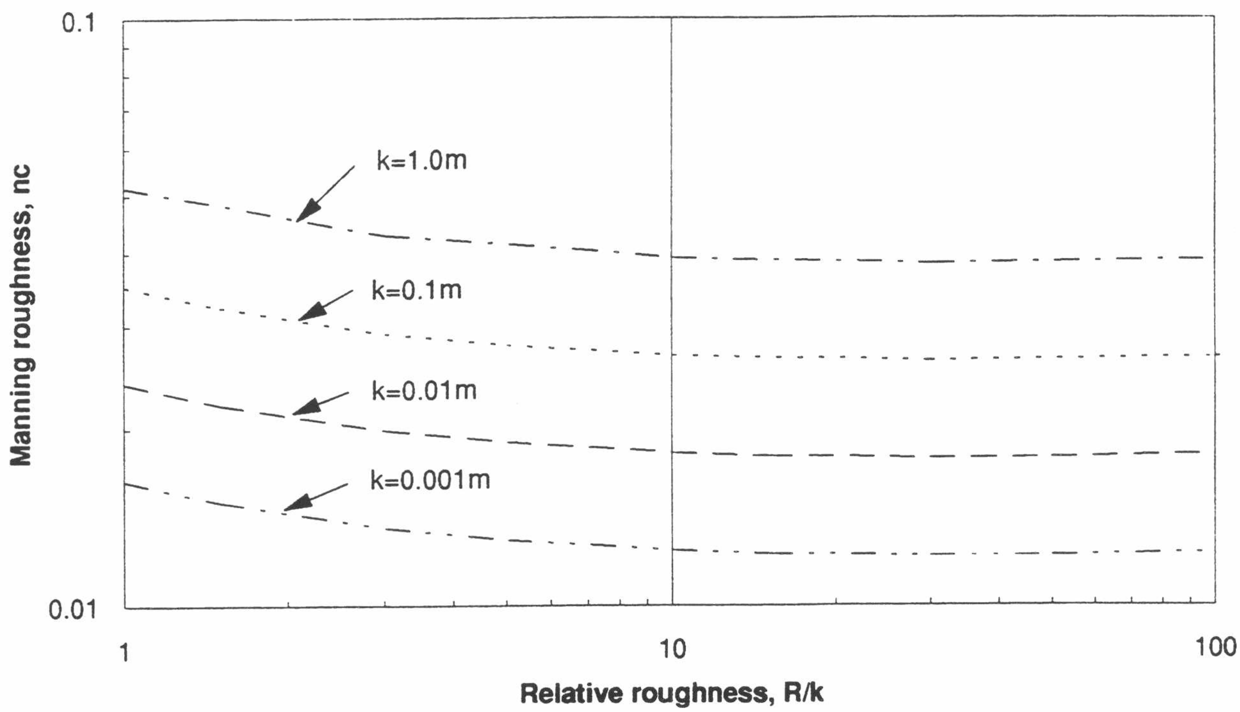

Figure 7 Variation of Manning roughness with relative roughness.

virtually constant for a particular subreach. This may not be the case during a period of time before the breakup of the ice cover. The higher river water temperatures from snowmelt runoff produce melting of the underside of the ice cover and this tends to increase the height of the roughness elements (Ashton, 1986). This increase in k causes a corresponding increase in n_c and therefore a decrease in C_u.

Due to unseasonably warm weather, the upstream tracer dye experiment, from Athabasca to Upper Wells, was done during the period of melt immediately before breakup. To determine the effect of the melt on k, the roughness height for the reach between Iron Point and Upper Wells was compared to that for the similar reach downstream between Upper Wells and Boivin Creek, which was not affected by warmer water. The roughness height for the melt period was found to be double that of the earlier value. As well, data obtained during discharge metering at Athabasca and Upper Wells show that the roughness heights obtained during the melt period (March 12 and March 16) were two to four times greater than the earlier values (table 9). Assuming that the subreach average increase in roughness height is the most representative, the roughness heights for the reach from Athabasca to Upper Wells should be reduced to one-half their measured values to be representative of mid-winter conditions. This translates into a reduction of ten percent in the values of n_c and an increase of seven percent in the values of C_u. The recommended mid-winter values for C_u are listed in table 10.

The values of C_u in table 10 can be used along with equation [8] to predict water velocities in each of the subreaches for mid-winter discharges ranging from about 50 m^3/s to 200 m^3/s. If it is necessary to estimate travel times during the melt period, the values of C_u should be increased by about 7% to account for the increased roughness of the bottom of the ice cover. It must be remembered that this value of 7% is only a best approximation from the existing data. Melt period roughness heights could vary substantially from the values calculated from the data. The coefficients obtained from equation [9] should not be used for open water conditions. If necessary, a separate equation should be developed for open water conditions using open water hydraulic measurements.

Actual values of C_u may also vary from year to year due to variations in the characteristics of both the bed and the ice. Year to year variations in ice cover roughness can occur due to variations in meteorological conditions. As well, the roughness of the river bed may change if a large summer flood occurs. These floods can change the bed form characteristics which in turn affect the roughness. These types of changes cannot be defined from the results of one tracer dye study however these changes in roughness are not expected to be large. Large shifts in the rating curves from the Water Survey of Canada gauges should provide an indication of any significant changes in roughness.

The dye centroid velocities were found to be about 3% slower than the hydraulic velocities therefore the chemical residence times in each subreach should be estimated by

Table 9 Summary of hydraulic characteristic at selected discharge metering sites.

Athabasca WSC gauge site Slope = 0.00027

Date	Discharge (m^3/s)	Top Width (m)	Flow Depth (m)	Mean Velocity (m/s)	Manning Roughness	Roughness Height (m)
Mar 12	166	140	1.56	0.76	0.018	0.012
Feb 25	88	150	0.91	0.65	0.015	0.003
Feb 14	88	140	0.99	0.63	0.016	0.006
Feb 04	108	150	0.97	0.74	0.014	0.001

Ft.McMurray WSC gauge site Slope = 0.00032

Date	Discharge (m^3/s)	Top Width (m)	Flow Depth (m)	Mean Velocity (m/s)	Manning Roughness	Roughness Height (m)
Mar 08	215	435	1.01	0.49	0.023	0.045
Feb 27	163	440	0.85	0.44	0.023	0.043

Upper Wells sample site Slope = 0.00068

Date	Discharge (m^3/s)	Top Width (m)	Flow Depth (m)	Mean Velocity (m/s)	Manning Roughness	Roughness Height (m)
Mar 16	188	282	1.16	0.58	0.031	0.168
Feb 27	100	280	0.70	0.51	0.026	0.065

Table 10 Summary of velocity coefficients for the subreaches.

Subreach	C_u
Athabasca - Deep Cr.	0.075
Deep Cr. - ALPAC	0.064
ALPAC - Calling R.	0.067
Calling R. - Iron Pt.	0.081
Iron Pt. - Upper Wells	0.080
Upper Wells - Boivin Cr.	0.083
Boivin Cr. - Brule Pt.	0.060
Brule Pt. - Algar R.	0.066
Algar R. - Ft.McMurray	0.073
Ft.McMurray - McLean Cr.	0.074
McLean Cr. - Muskeg R.	0.054
Muskeg R. - Ells R.	0.066

[10]
$$t_c = 1.03 \frac{x}{U}$$

where U is defined by equation [8] for each subreach. Total residence times can be obtained by summing the individual subreach residence times.

This ratio of centroid and peak travel times is assumed to be constant but is actually a function of the mixing rate which in turn depends on the discharge. Elhadi et al. (1984) suggest that the mixing rate decreases with increasing discharge and the ratio of the centroid to the peak increases with increasing mixing rate. Therefore the travel time ratio would be smaller at higher discharges and larger at lower discharges. These variations are not quantifiable with data from one tracer dye study, however the variation should be only a few percent for the range of flows of interest.

4.0 SUMMARY

A field investigation covering a reach of the Athabasca River between Athabasca and Bitumount was performed to define the travel times in the river relative to the hydraulic characteristics. Twelve sample sites were selected over the 464 km study reach. 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 velocities for each of the twelve subreaches.

Discharges in the study reach ranged from 81 m^3/s to 188 m^3/s during the tracer dye experiments. These discharges were fairly representative of the typical winter discharges in the Athabasca River. Mean velocities were defined by the travel times of the peak dye concentration between sample sites. These velocities ranged from 0.38 m/s to 0.60 m/s. The mean flow depths were found to range from 0.67 m to 1.37 m for adopted under ice top widths which varied from 220 m to 400 m. The computed composite Manning roughness values ranged from 0.012 to 0.046 on the basis of the adopted river slopes which ranged from 0.00012 at Ells River to 0.00111 just upstream of Ft. McMurray. The associated roughness heights were calculated to vary between 0.0005 m and 0.5 m.

The variation of velocity with discharge can be described using equation [8], a power law function derived from the Manning Equation. The velocity was found the vary with discharge to the power of 0.4. Coefficients for this equation were defined for each subreach, however they are valid only for winter discharges ranging from 50 m^3/s to 200 m^3/s. They are not valid for open water flow. The coefficients were found to vary between 0.054 and 0.083. Chemical residence times in each subreach can be obtained by dividing the subreach length by the velocity and then multiplying by a factor of 1.03 to account for the difference between the travel times of the peak and centroid of a concentration distribution.

One of the main difficulties of this study was the necessity to make a somewhat crude representation of the channel geometry and water surface slopes. There are currently only about 15 cross-sections over some 400 km of river between Athabasca and Ft. McMurray. It is recommended that additional cross-sections are surveyed at an interval of about 5 to 10 km to provide an appropriate data base for future unsteady flow modelling and sediment transport studies. This data would also serve to better define the channel widths which would in turn improve the confidence of equation [8] to extrapolate the travel times to other discharges.

5.0 REFERENCES

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APPENDIX A

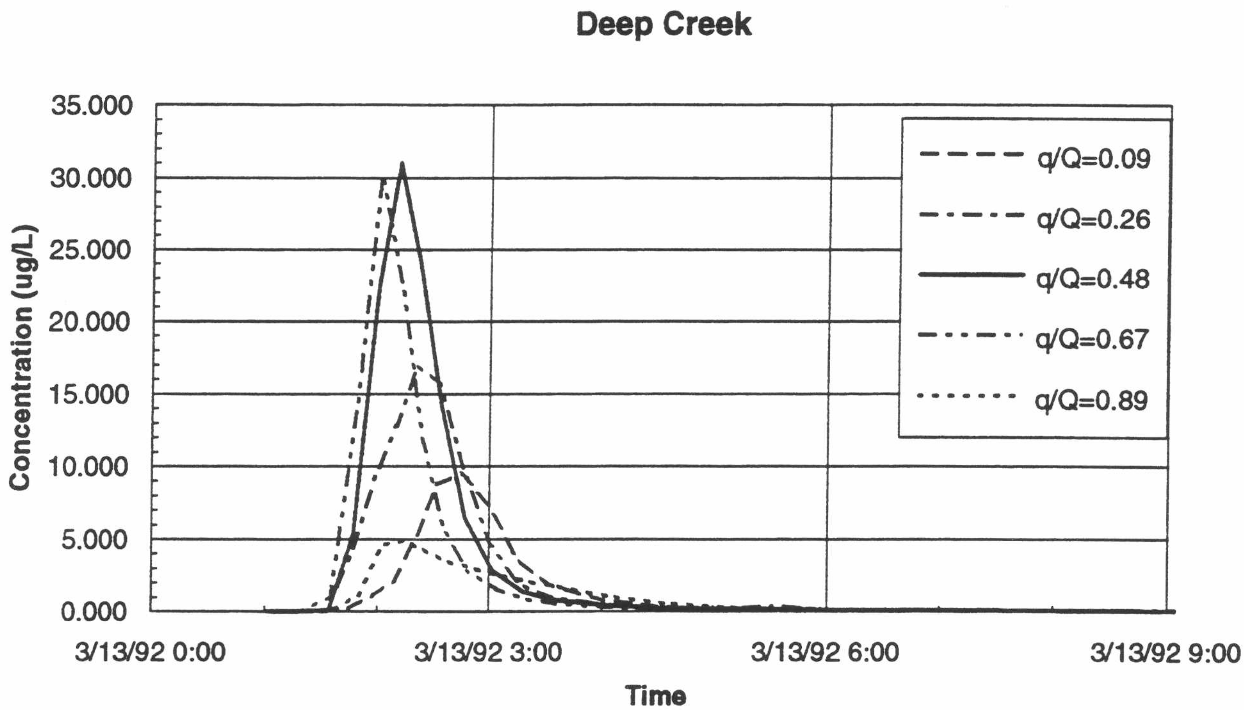
Concentration distributions

and

cross-section plots

at the

sample sites


Deep Creek
Concentration (ug/L)
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
3/13/92 0:00
3/13/92 3:00
3/13/92 6:00
3/13/92 9:00
Time
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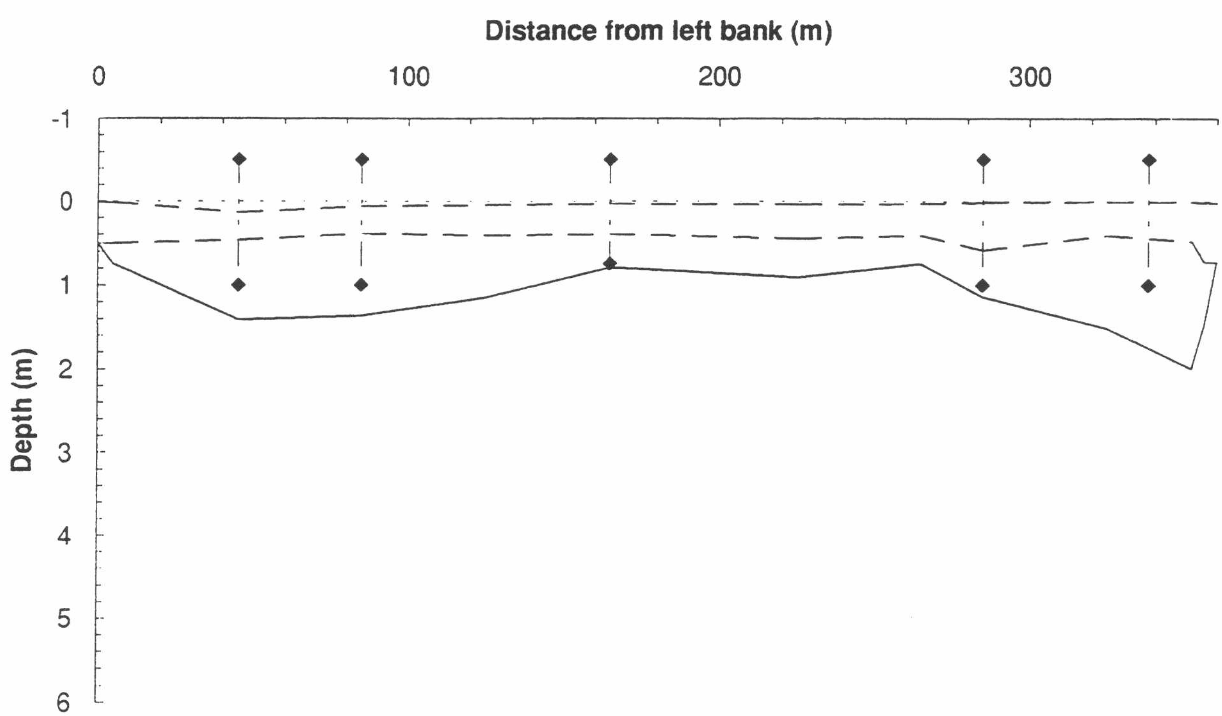
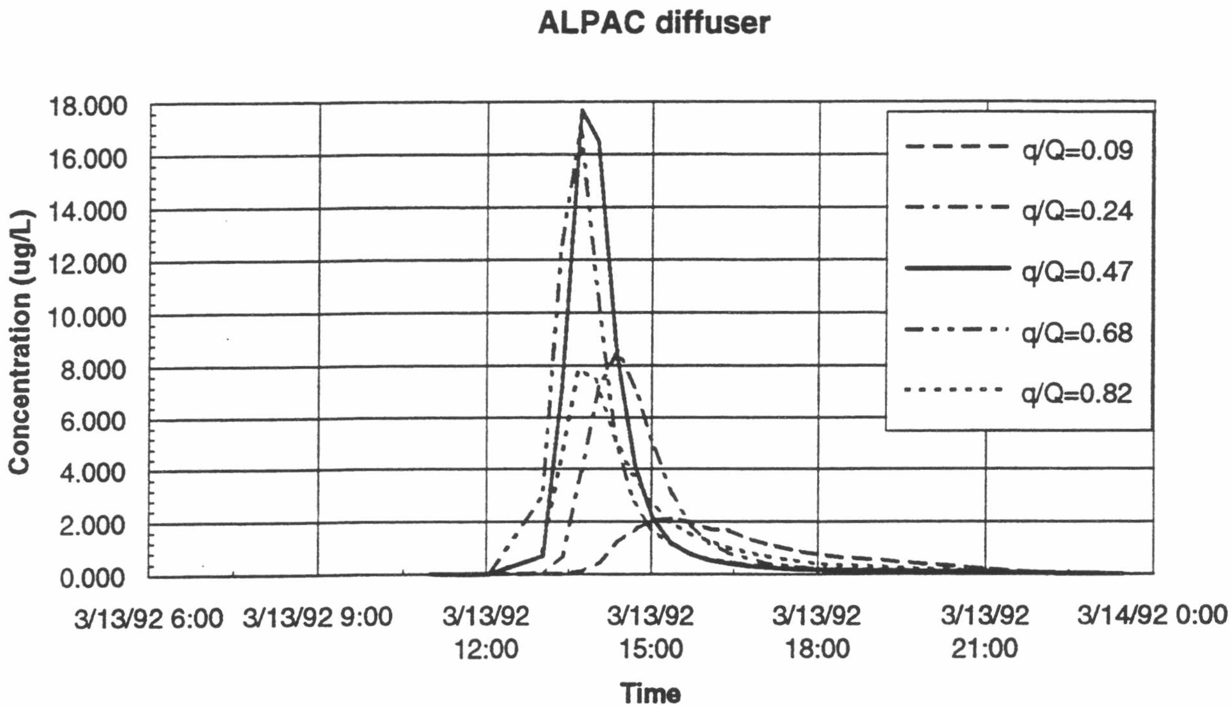
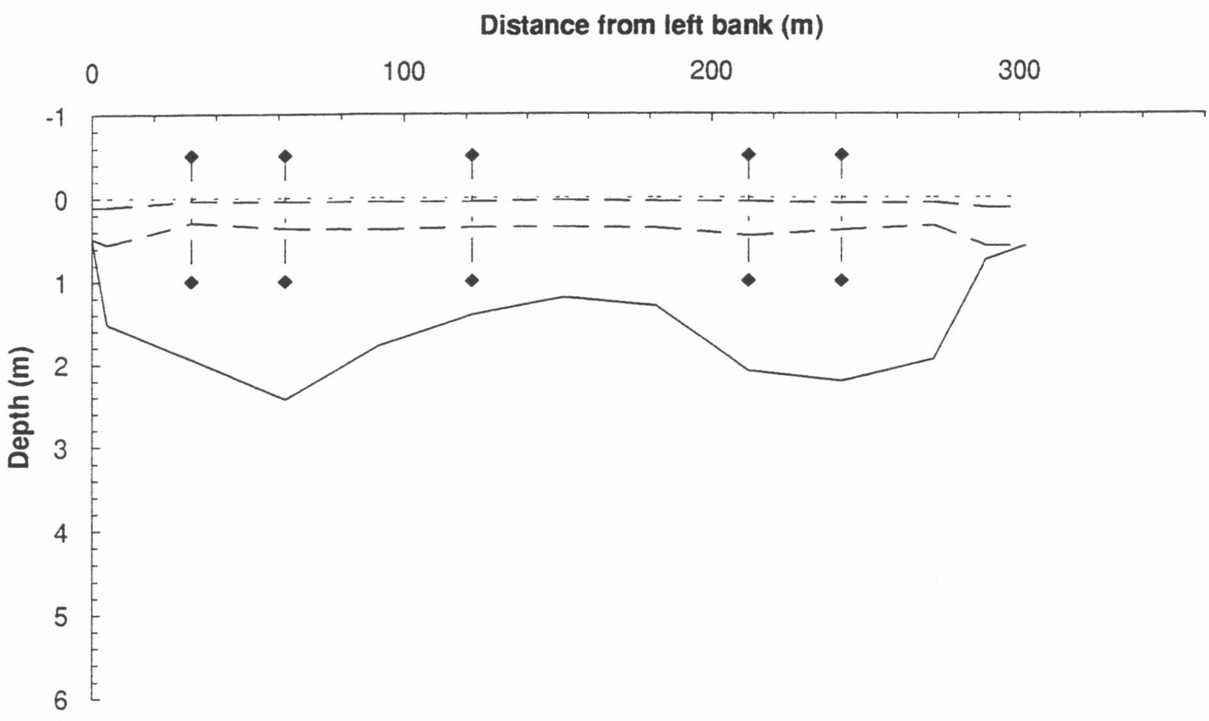
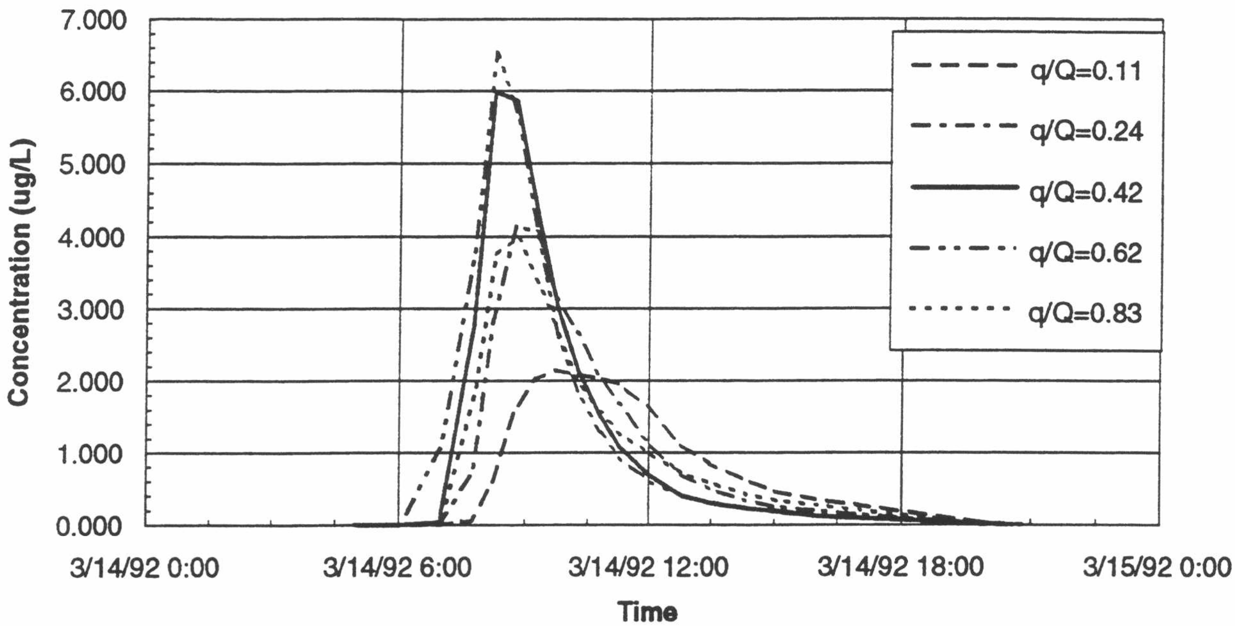
q/Q=0.26
q/Q=0.48
q/Q=0.67
q/Q=0.89

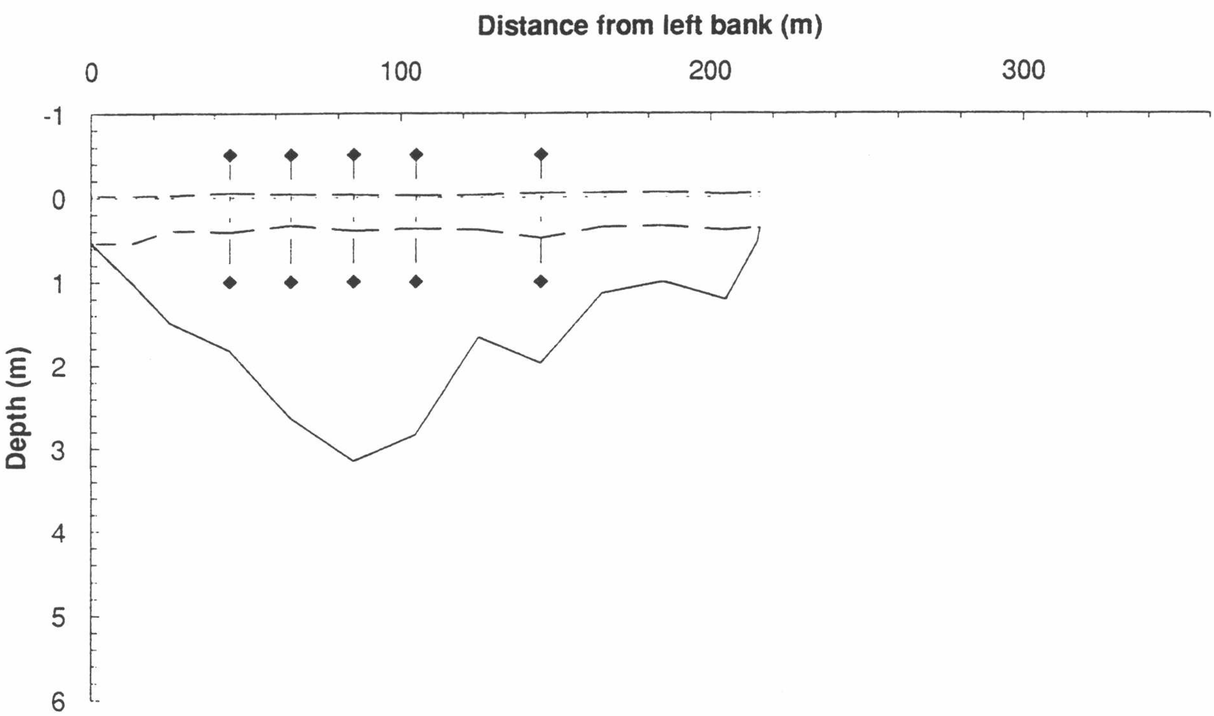

Distance from left bank (m)
0
100
200
300
Depth (m)
-1
0
1
2
3
4
5
6


ALPAC diffuser
Concentration (ug/L)
18.000
16.000
14.000
12.000
10.000
8.000
6.000
4.000
2.000
0.000
3/13/92 6:00
3/13/92 9:00
3/13/92 12:00
3/13/92 15:00
3/13/92 18:00
3/13/92 21:00
3/14/92 0:00
Time
q/Q=0.09
q/Q=0.24
q/Q=0.47
q/Q=0.68
q/Q=0.82

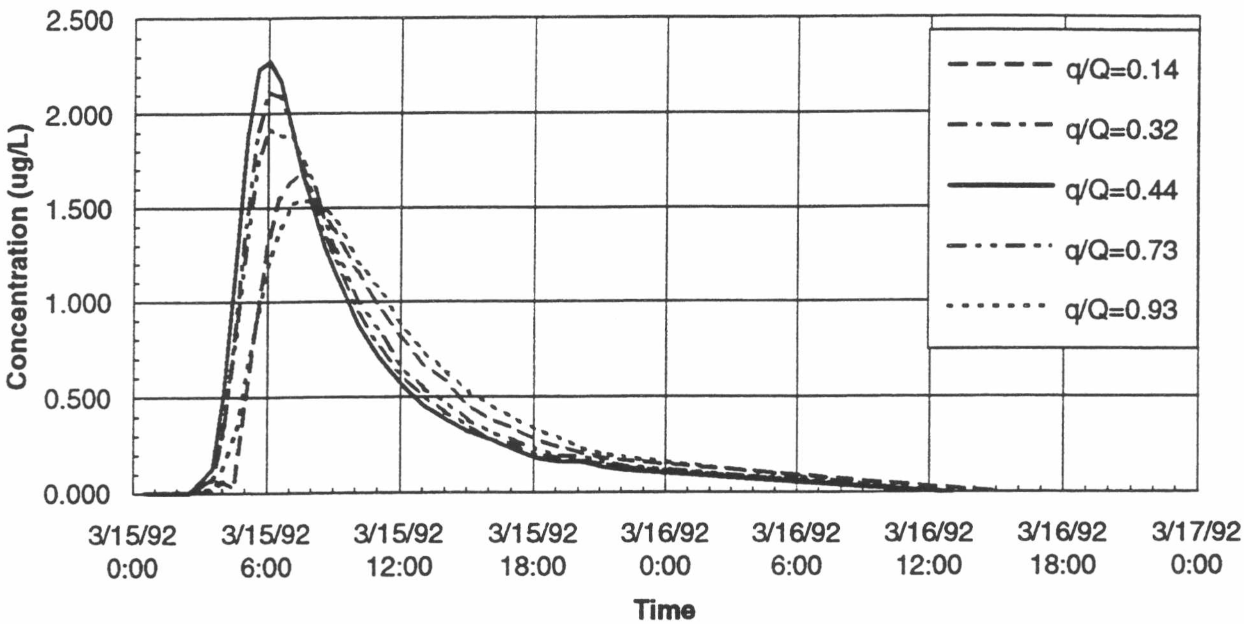

Distance from left bank (m)
0
100
200
300
Depth (m)
-1
0
1
2
3
4
5
6

Calling River

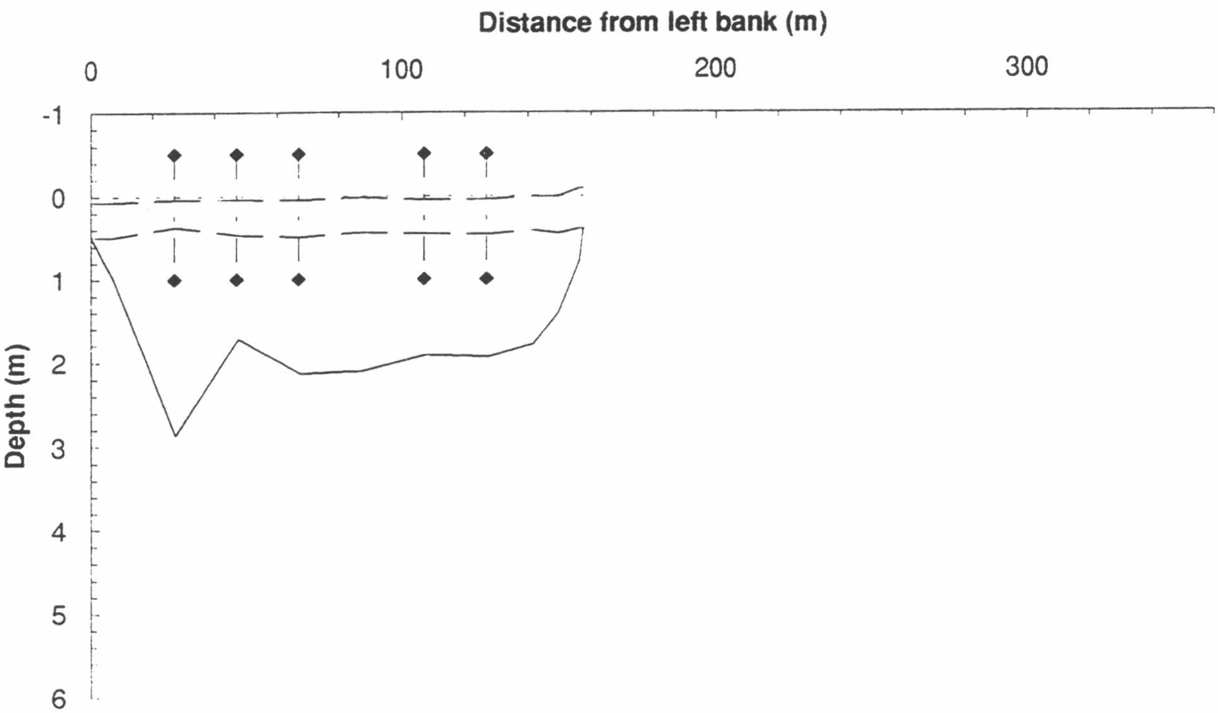




Iron Point

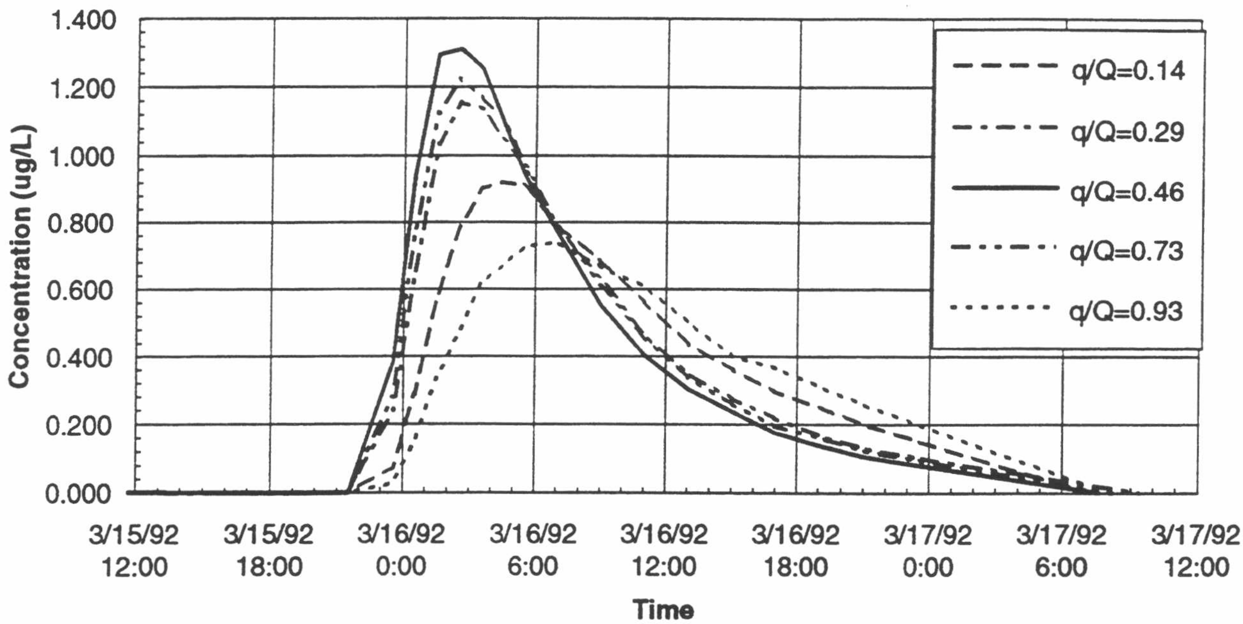


2.500
2.000
1.500
1.000
0.500
0.000
Concentration (ug/L)
q/Q=0.14
q/Q=0.32
q/Q=0.44
q/Q=0.73
q/Q=0.93
3/15/92 0:00
3/15/92 6:00
3/15/92 12:00
3/15/92 18:00
3/16/92 0:00
3/16/92 6:00
3/16/92 12:00
3/16/92 18:00
3/17/92 0:00
Time

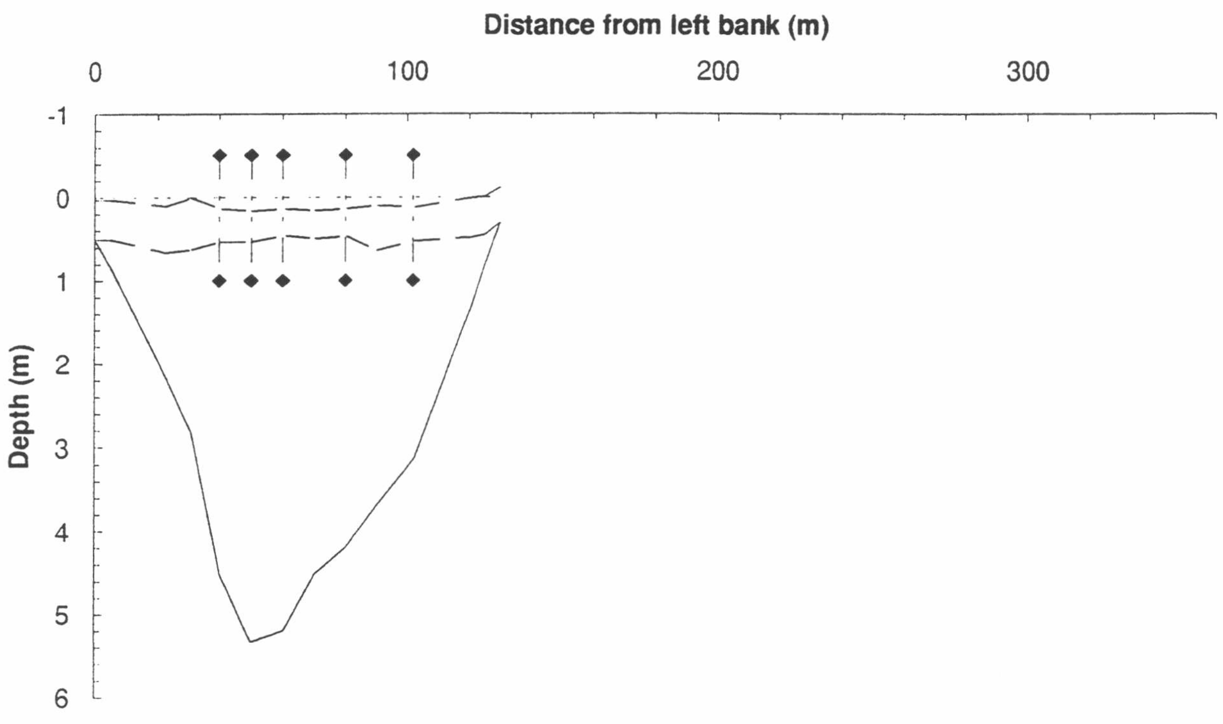


Distance from left bank (m)
0
100
200
300
-1
0
1
2
3
4
5
6
Depth (m)

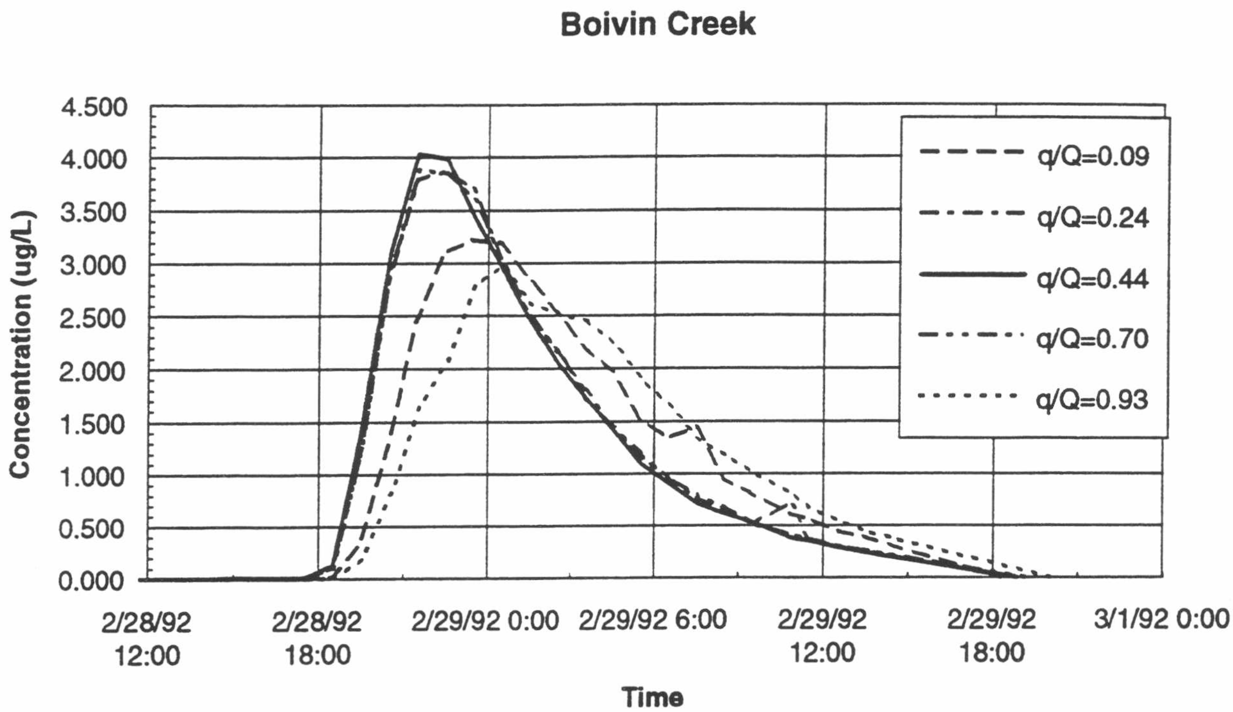
Upper Wells

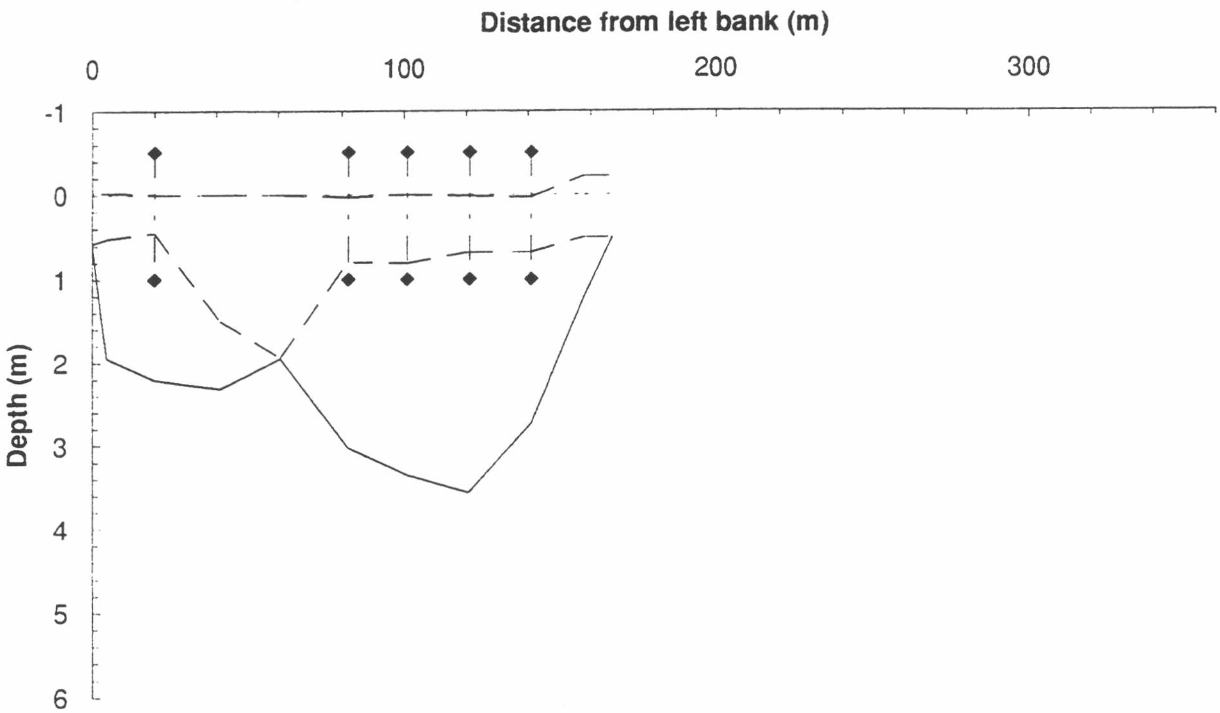


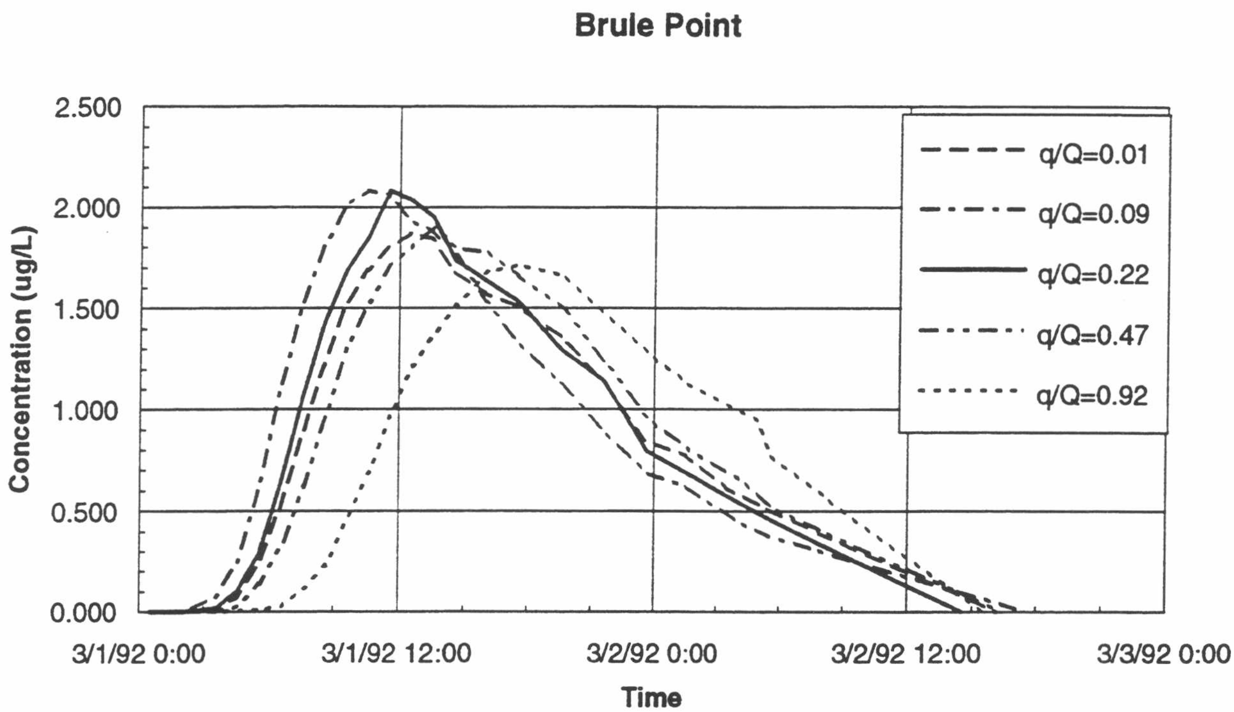
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Concentration (ug/L)
q/Q=0.14
q/Q=0.29
q/Q=0.46
q/Q=0.73
q/Q=0.93
3/15/92 12:00
3/15/92 18:00
3/16/92 0:00
3/16/92 6:00
3/16/92 12:00
3/16/92 18:00
3/17/92 0:00
3/17/92 6:00
3/17/92 12:00
Time



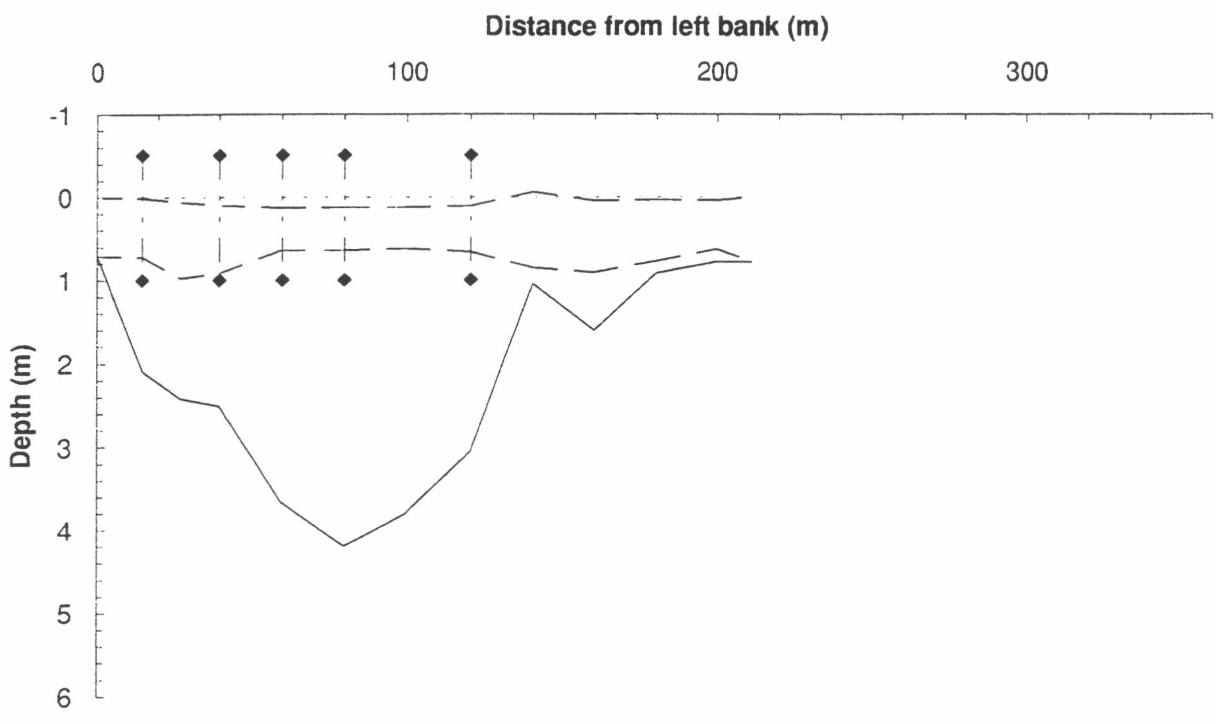
Distance from left bank (m)
0
100
200
300
-1
0
1
2
3
4
5
6
Depth (m)


Boivin Creek
Concentration (ug/L)
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
q/Q=0.09
q/Q=0.24
q/Q=0.44
q/Q=0.70
q/Q=0.93
2/28/92 12:00
2/28/92 18:00
2/29/92 0:00
2/29/92 6:00
2/29/92 12:00
2/29/92 18:00
3/1/92 0:00
Time

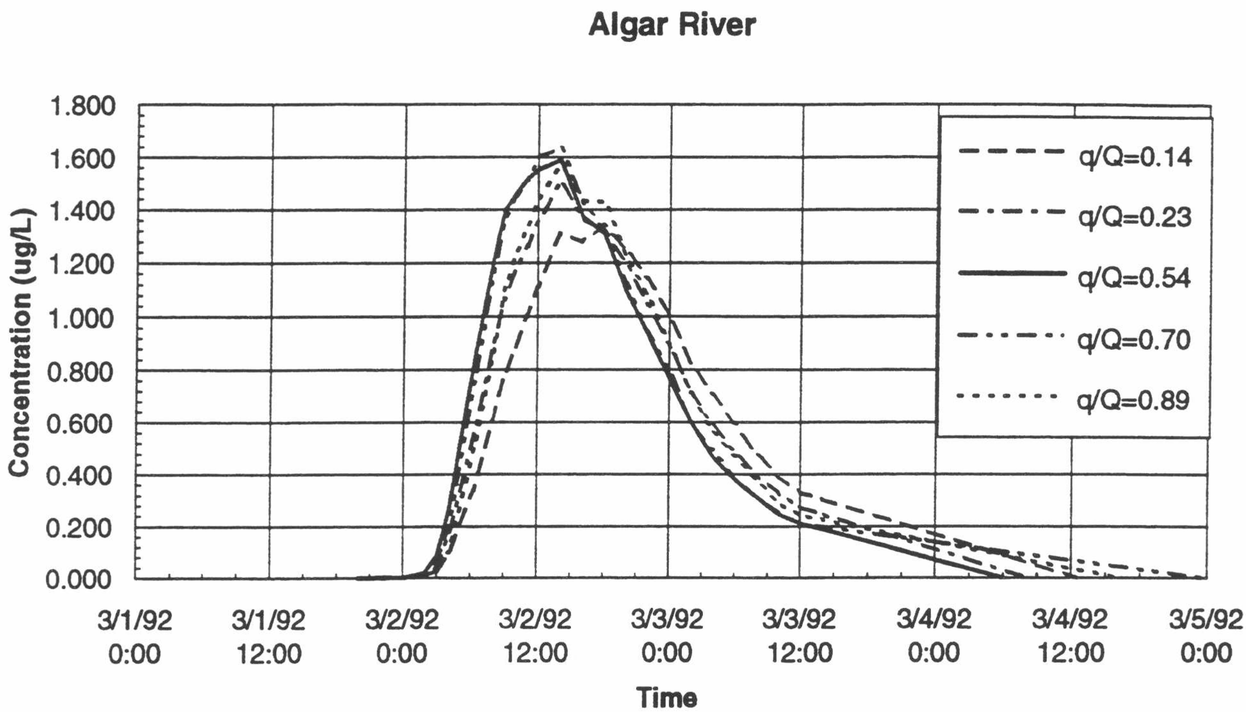

Distance from left bank (m)
0
100
200
300
Depth (m)
-1
0
1
2
3
4
5
6

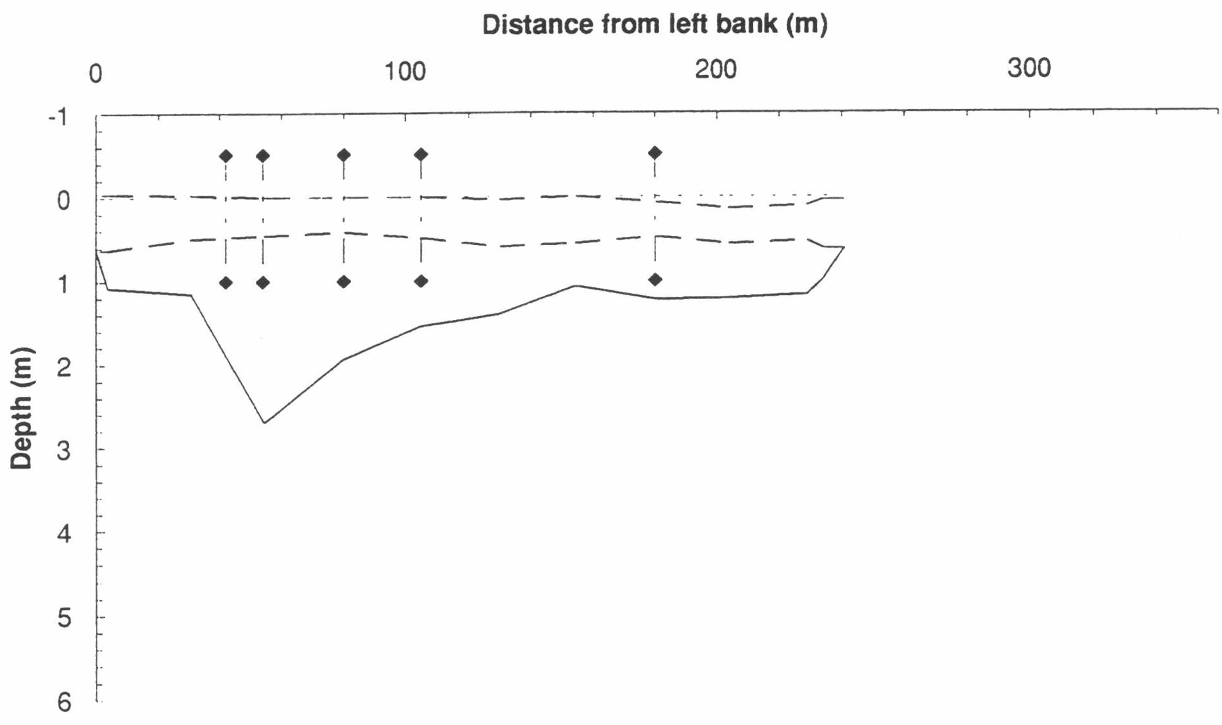


Brule Point
2.500
2.000
1.500
1.000
0.500
0.000
Concentration (ug/L)
q/Q=0.01
q/Q=0.09
q/Q=0.22
q/Q=0.47
q/Q=0.92
3/1/92 0:00
3/1/92 12:00
3/2/92 0:00
3/2/92 12:00
3/3/92 0:00
Time

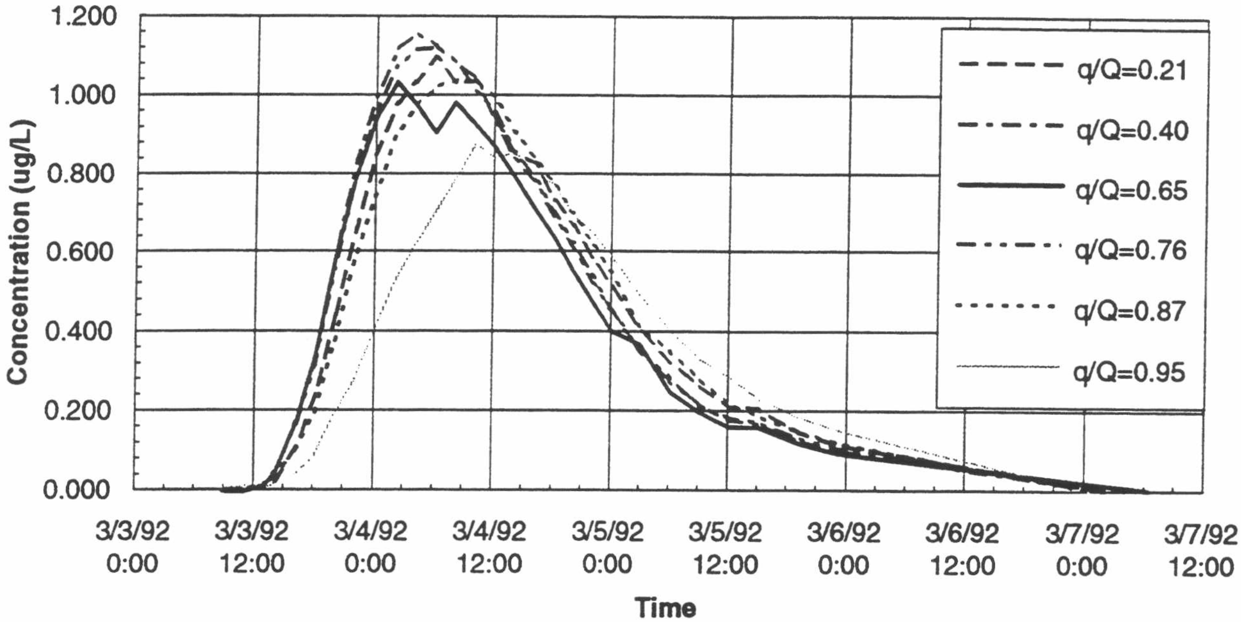


Distance from left bank (m)
0
100
200
300
-1
0
1
2
3
4
5
6
Depth (m)

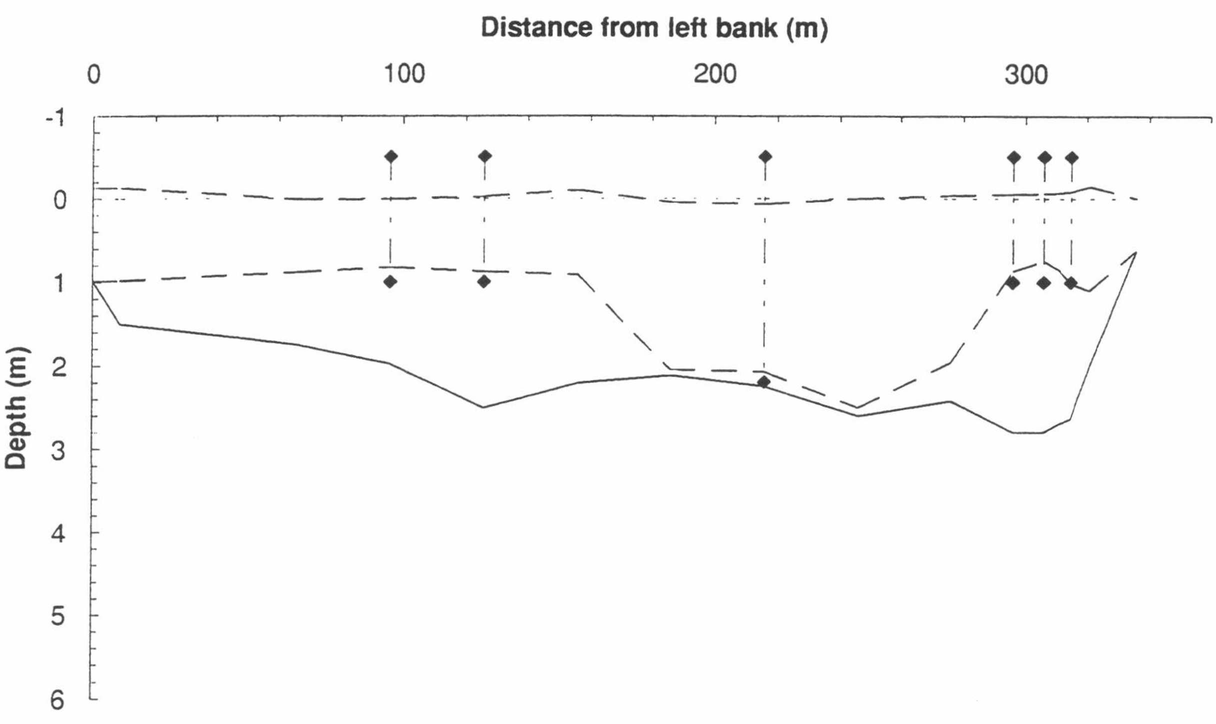

Algar River
Concentration (ug/L)
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
q/Q=0.14
q/Q=0.23
q/Q=0.54
q/Q=0.70
q/Q=0.89
3/1/92 0:00
3/1/92 12:00
3/2/92 0:00
3/2/92 12:00
3/3/92 0:00
3/3/92 12:00
3/4/92 0:00
3/4/92 12:00
3/5/92 0:00
Time


Distance from left bank (m)
0
100
200
300
Depth (m)
-1
0
1
2
3
4
5
6

Ft. McMurray

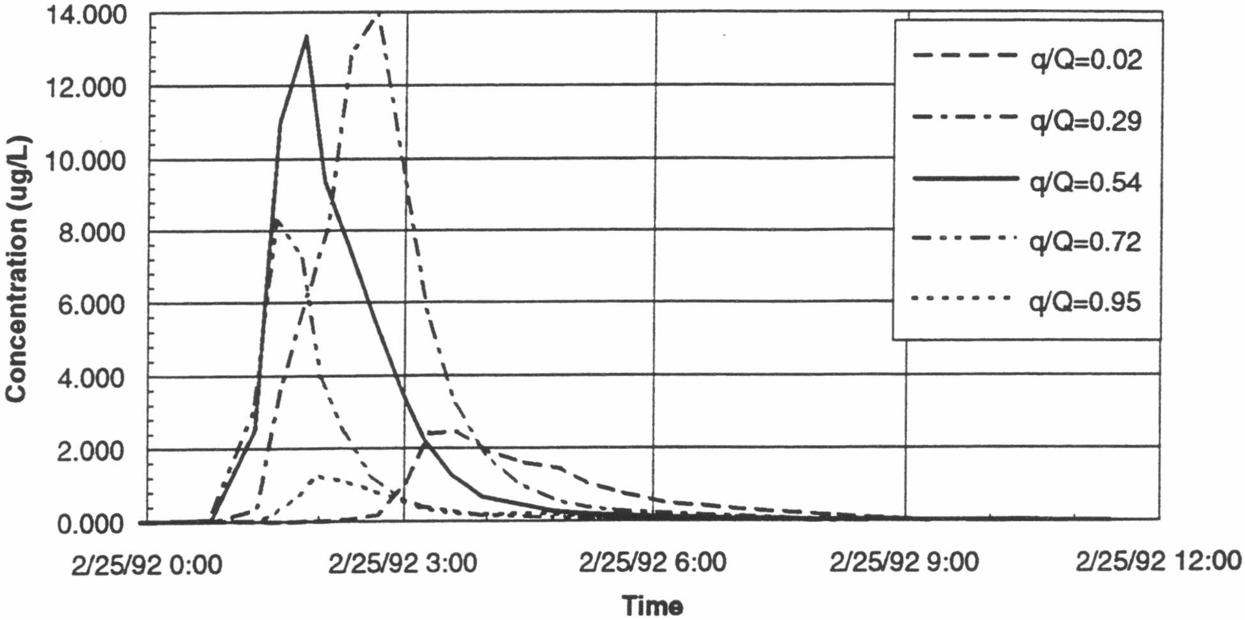


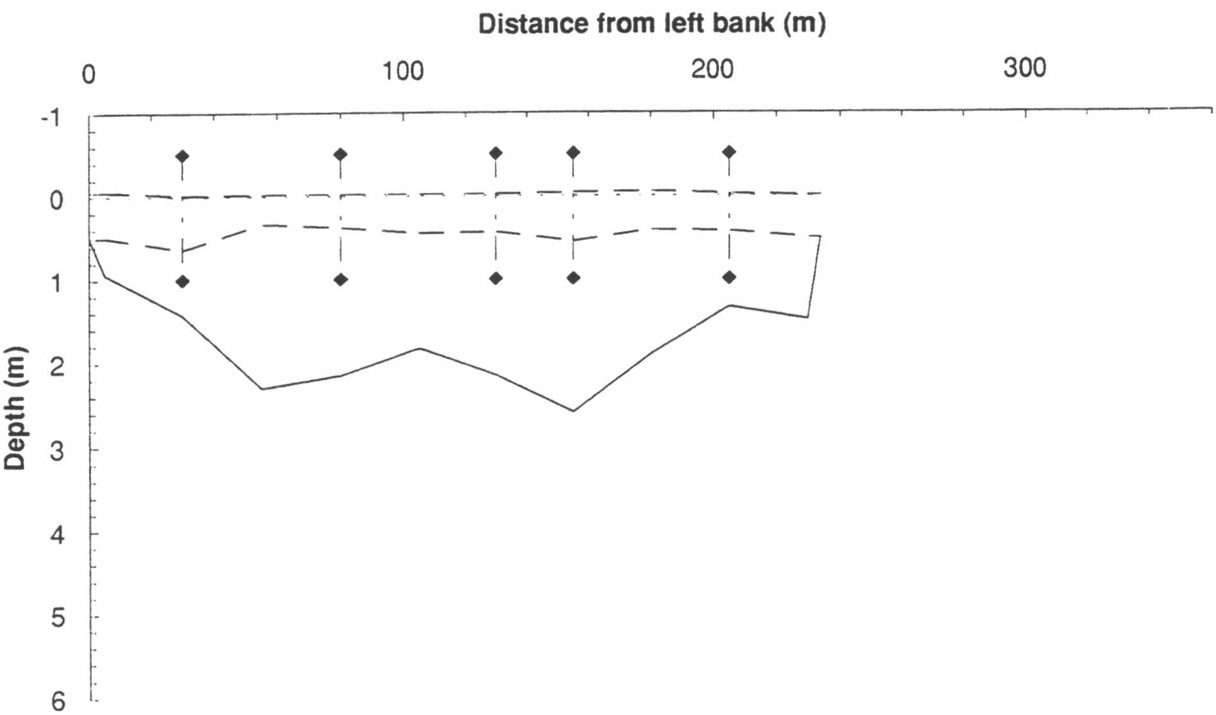
Concentration (ug/L)
1.200
1.000
0.800
0.600
0.400
0.200
0.000
3/3/92 0:00
3/3/92 12:00
3/4/92 0:00
3/4/92 12:00
3/5/92 0:00
3/5/92 12:00
3/6/92 0:00
3/6/92 12:00
3/7/92 0:00
3/7/92 12:00
Time
q/Q=0.21
q/Q=0.40
q/Q=0.65
q/Q=0.76
q/Q=0.87
q/Q=0.95

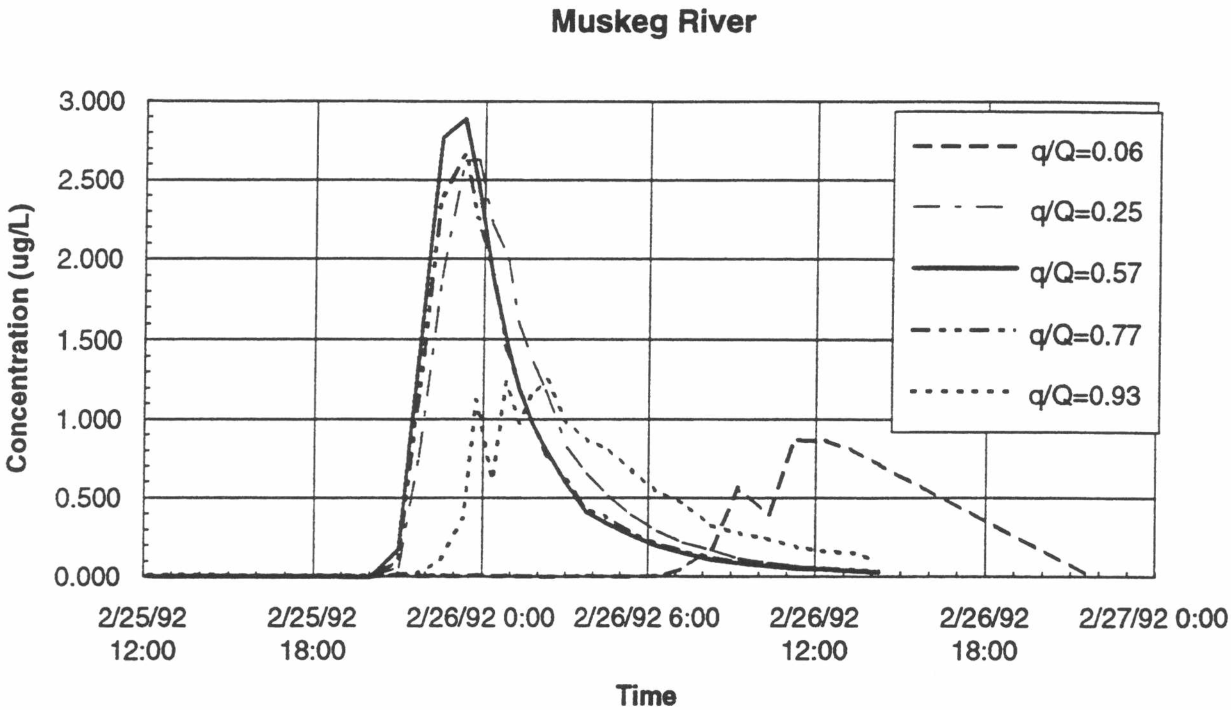


Distance from left bank (m)
0
100
200
300
Depth (m)
-1
0
1
2
3
4
5
6

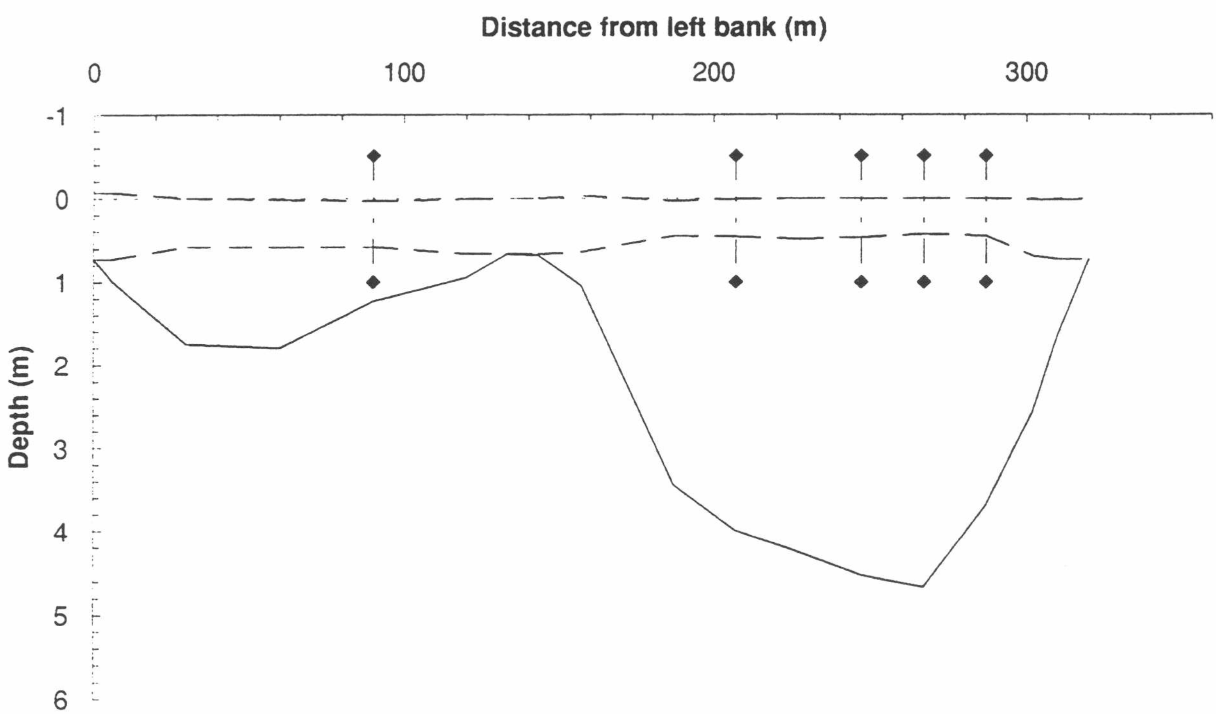
McLean Creek





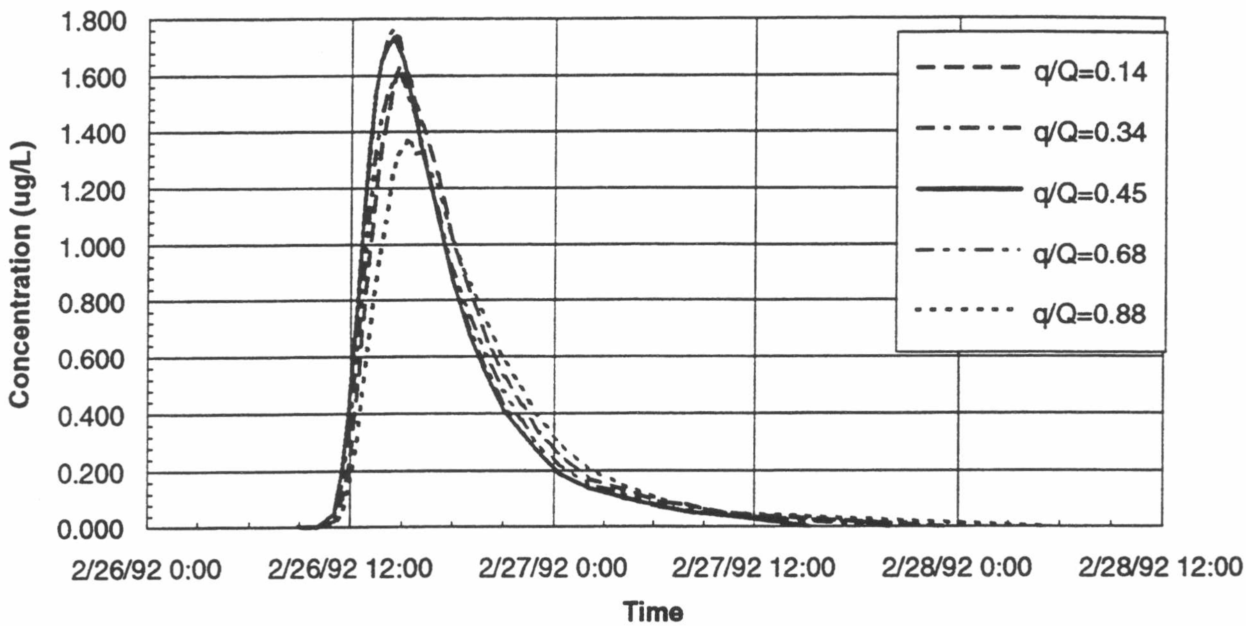


Muskeg River
Concentration (ug/L)
3.000
2.500
2.000
1.500
1.000
0.500
0.000
2/25/92 12:00
2/25/92 18:00
2/26/92 0:00
2/26/92 6:00
2/26/92 12:00
2/26/92 18:00
2/27/92 0:00
Time
q/Q=0.06
q/Q=0.25
q/Q=0.57
q/Q=0.77
q/Q=0.93

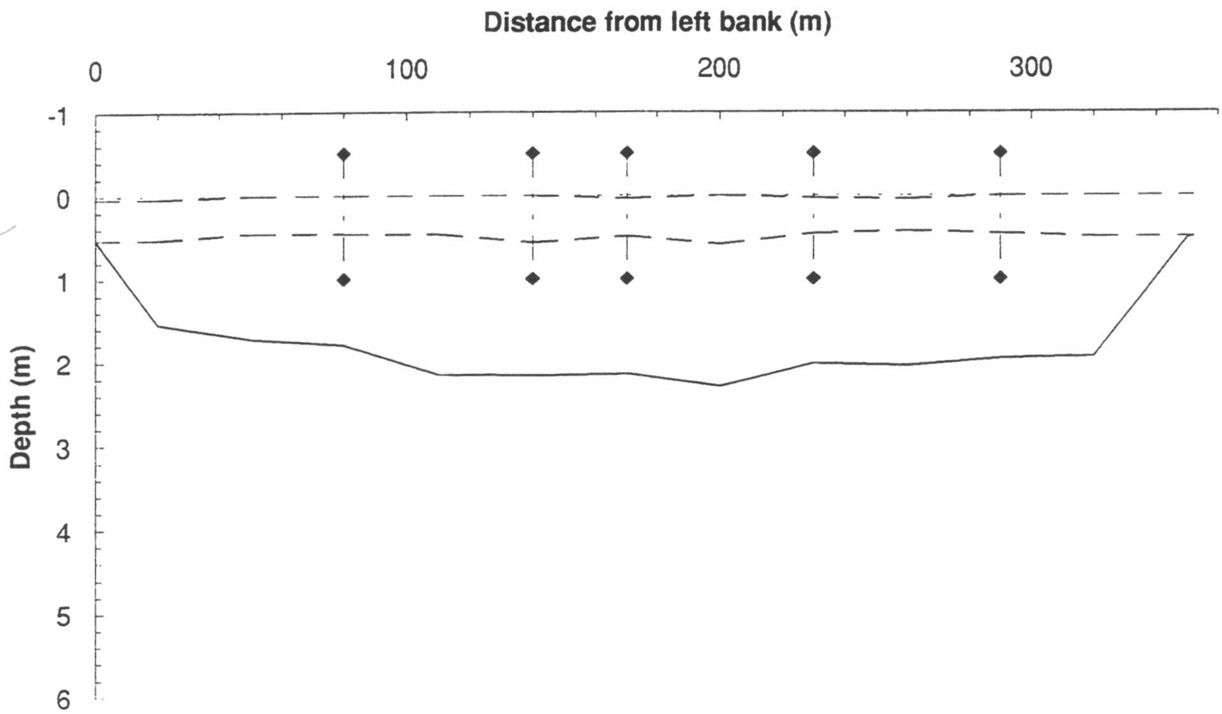


Distance from left bank (m)
0
100
200
300
Depth (m)
-1
0
1
2
3
4
5
6

Ells River



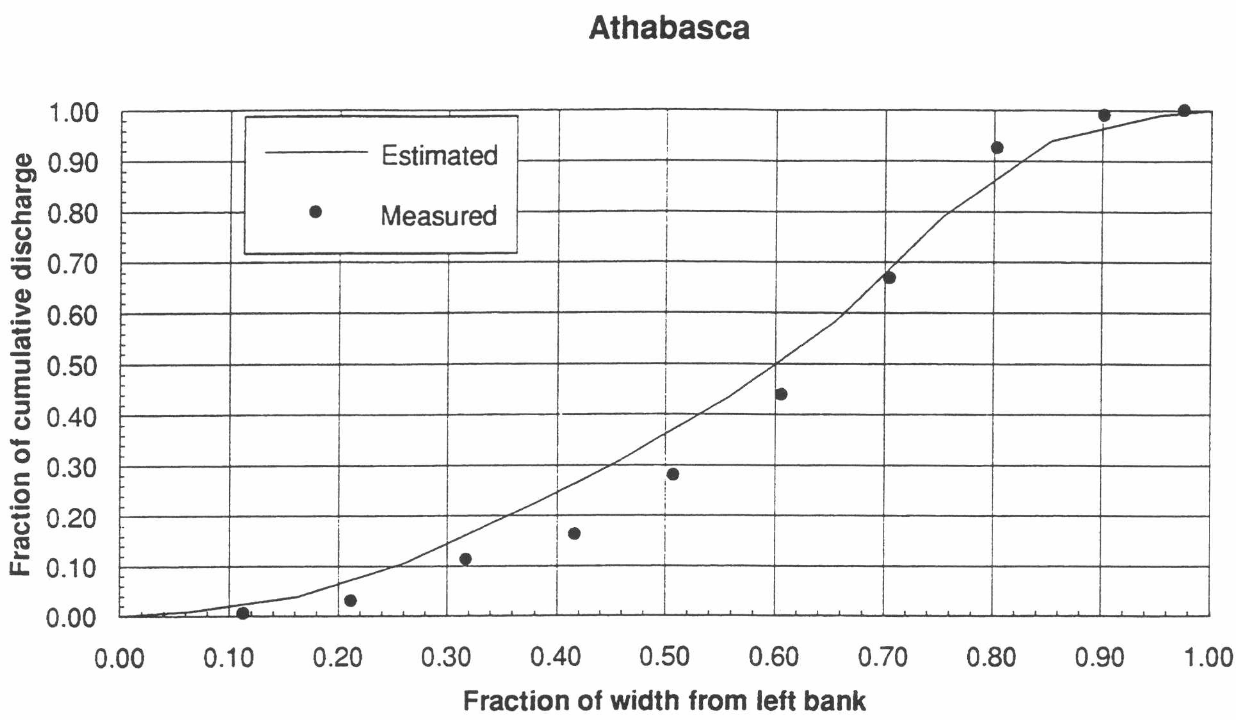
1.800
1.600
1.400
1.200
1.000
0.800
0.600
0.400
0.200
0.000
Concentration (ug/L)
q/Q=0.14
q/Q=0.34
q/Q=0.45
q/Q=0.68
q/Q=0.88
2/26/92 0:00
2/26/92 12:00
2/27/92 0:00
2/27/92 12:00
2/28/92 0:00
2/28/92 12:00
Time



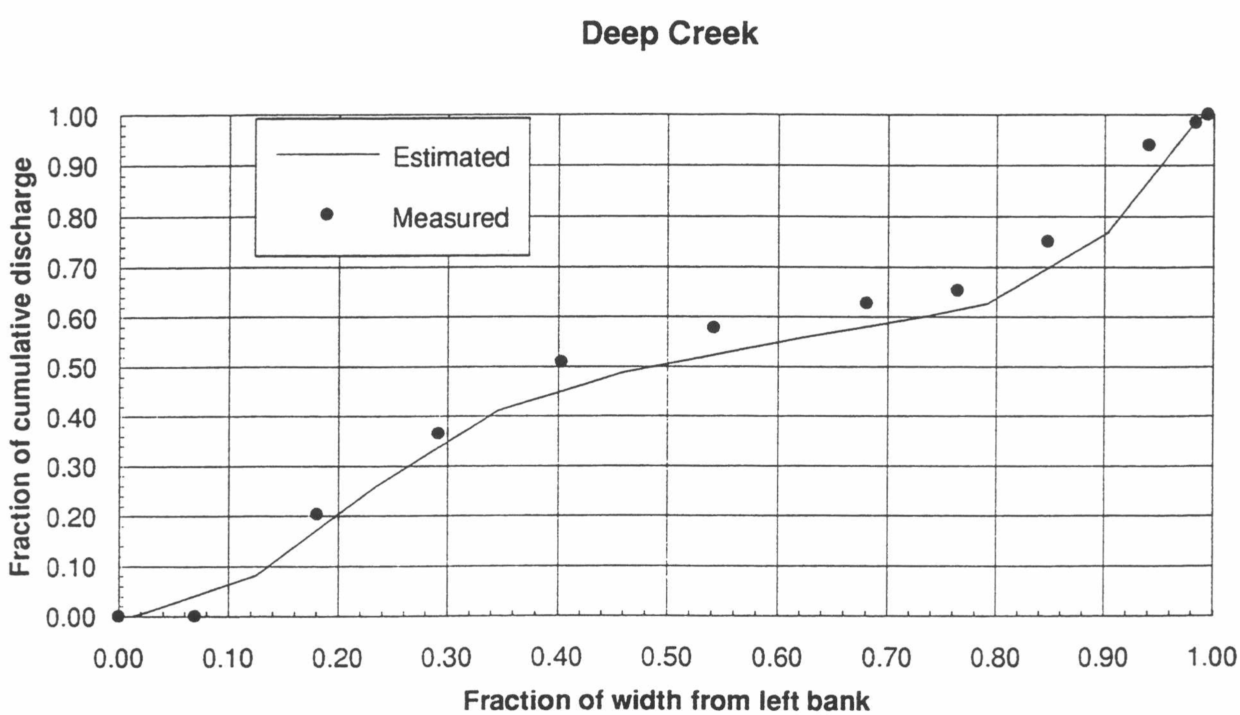
Distance from left bank (m)
0
100
200
300
-1
0
1
2
3
4
5
6
Depth (m)

APPENDIX B

Cumulative discharge distributions
across the channel
at each sample site

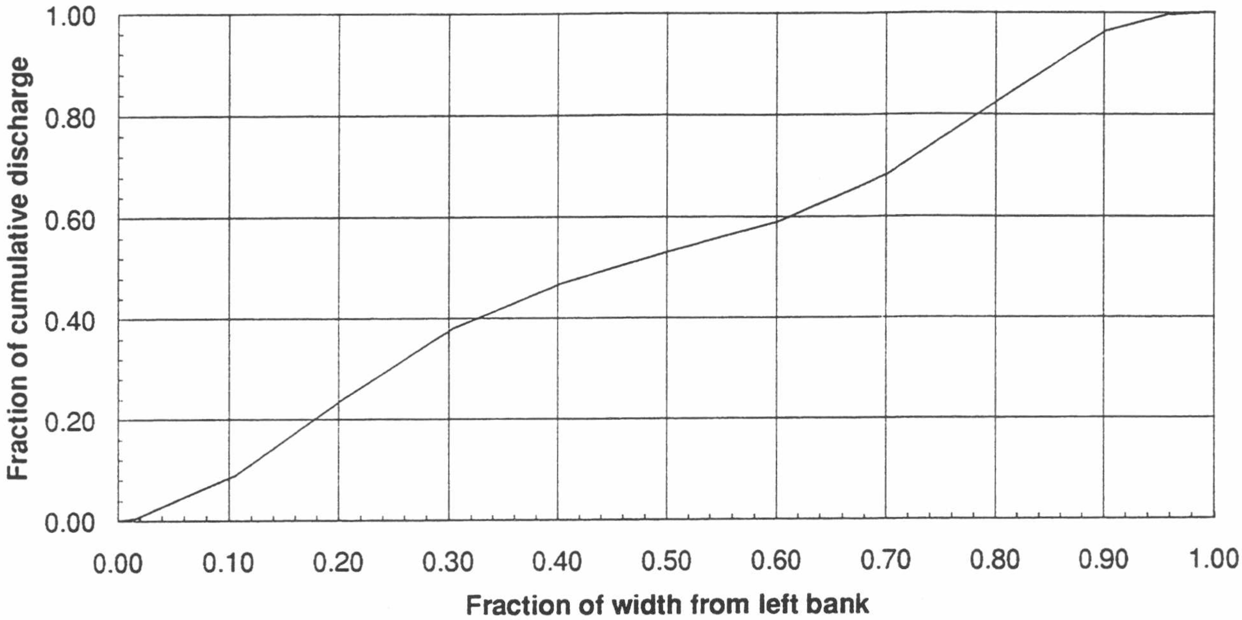


Athabasca
Estimated
Measured
Fraction of cumulative discharge
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Fraction of width from left bank

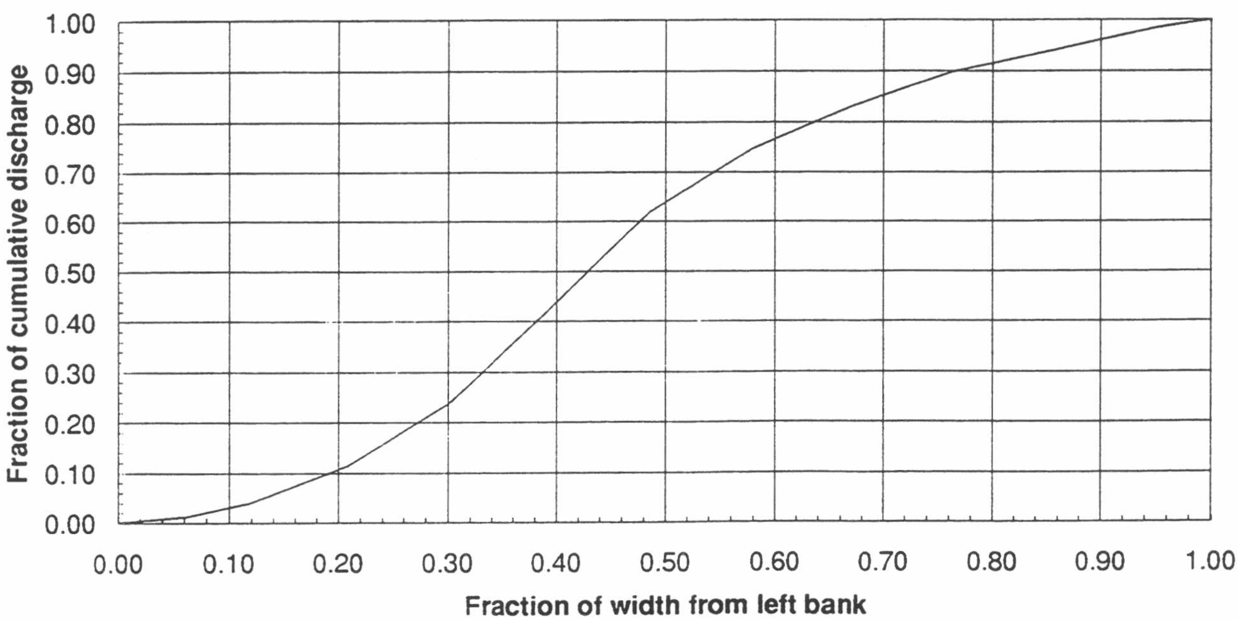


Deep Creek
Estimated
Measured
Fraction of cumulative discharge
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Fraction of width from left bank

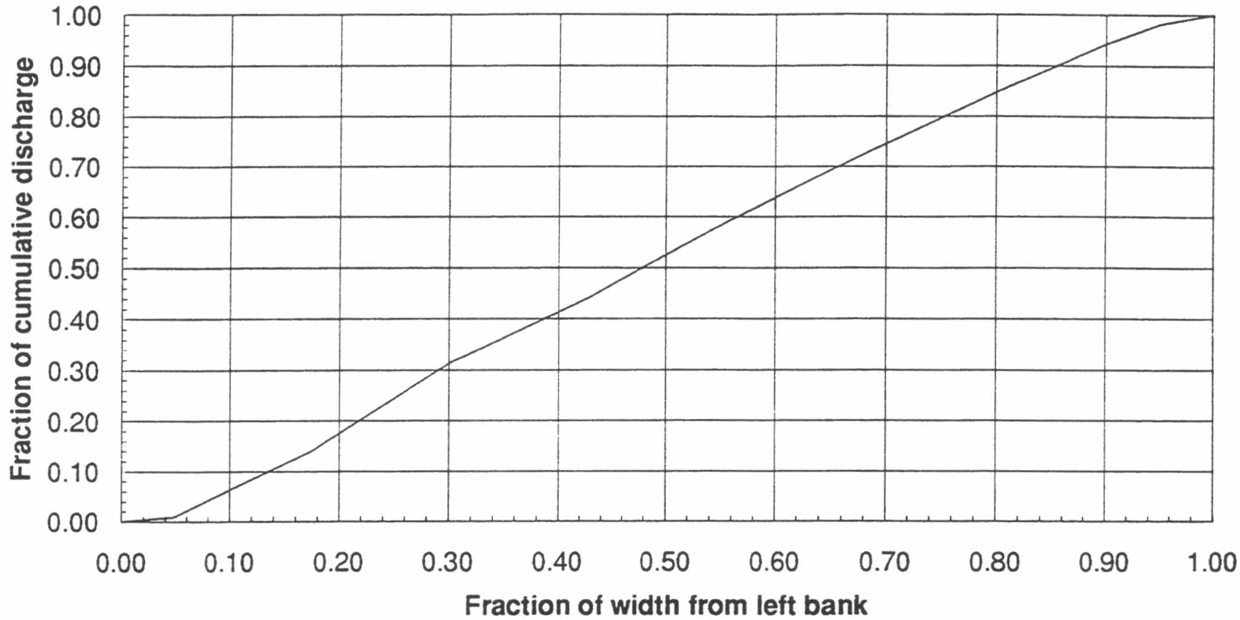
ALPAC Diffuser



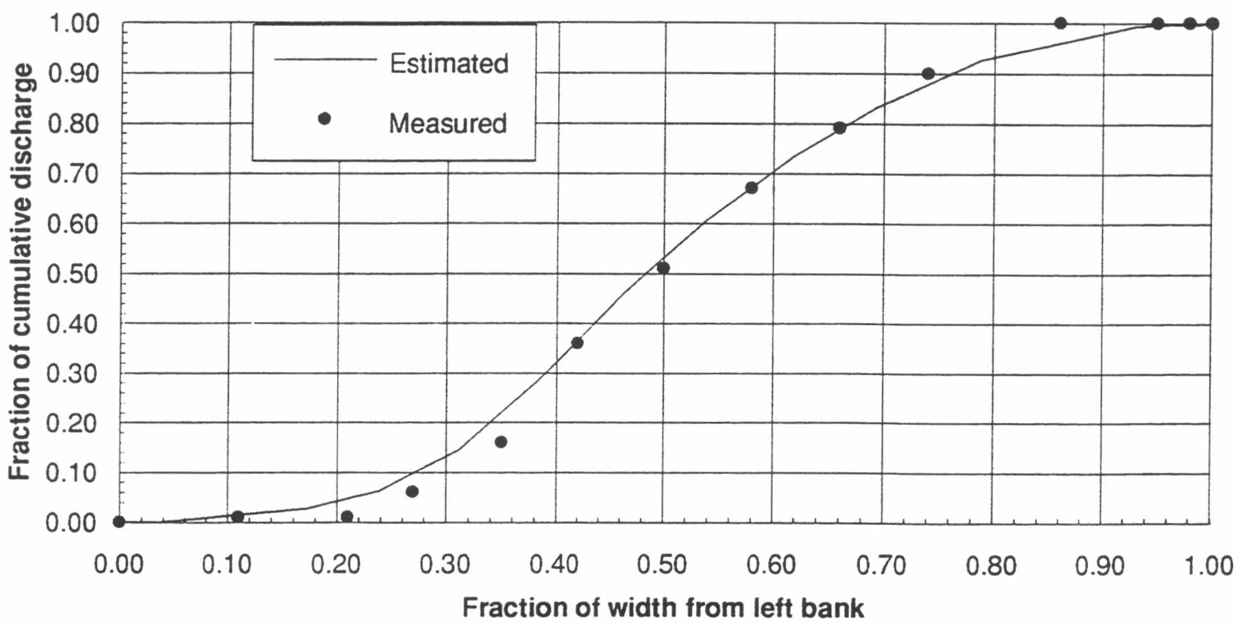
Calling River



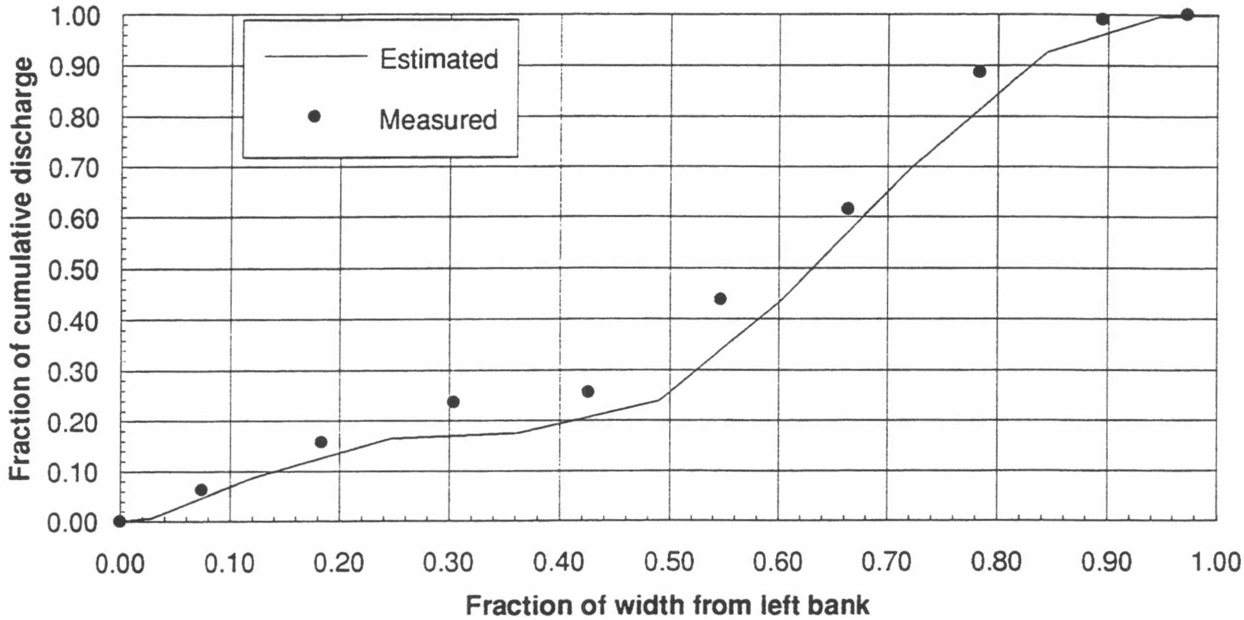
Iron Point



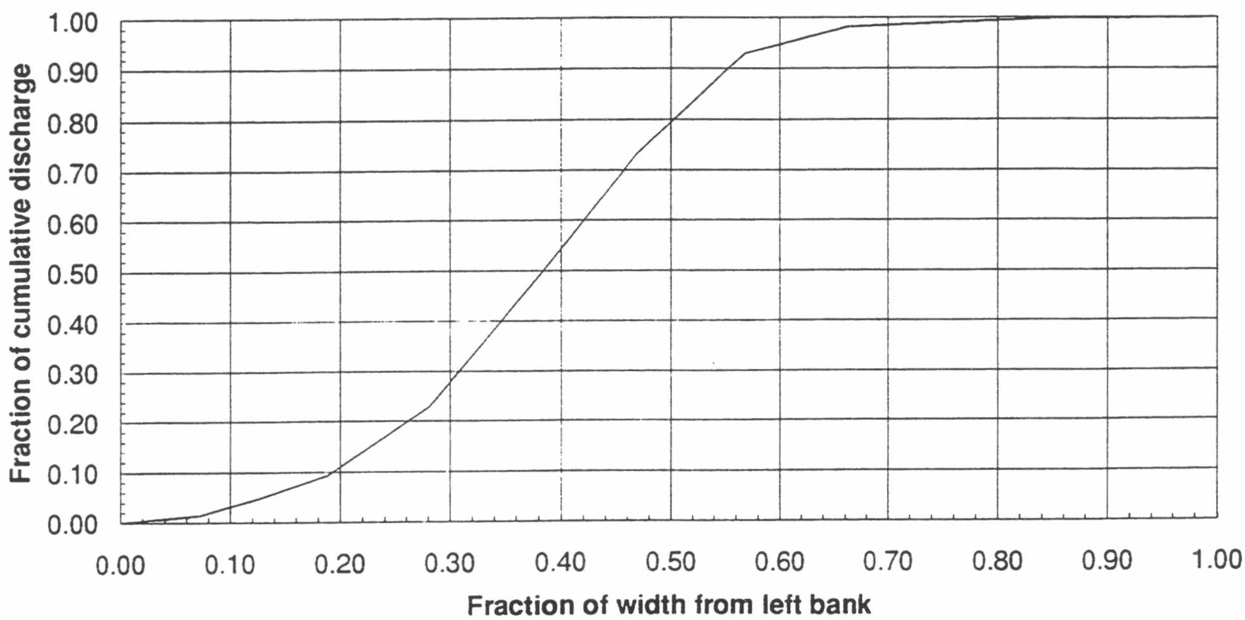
Upper Wells

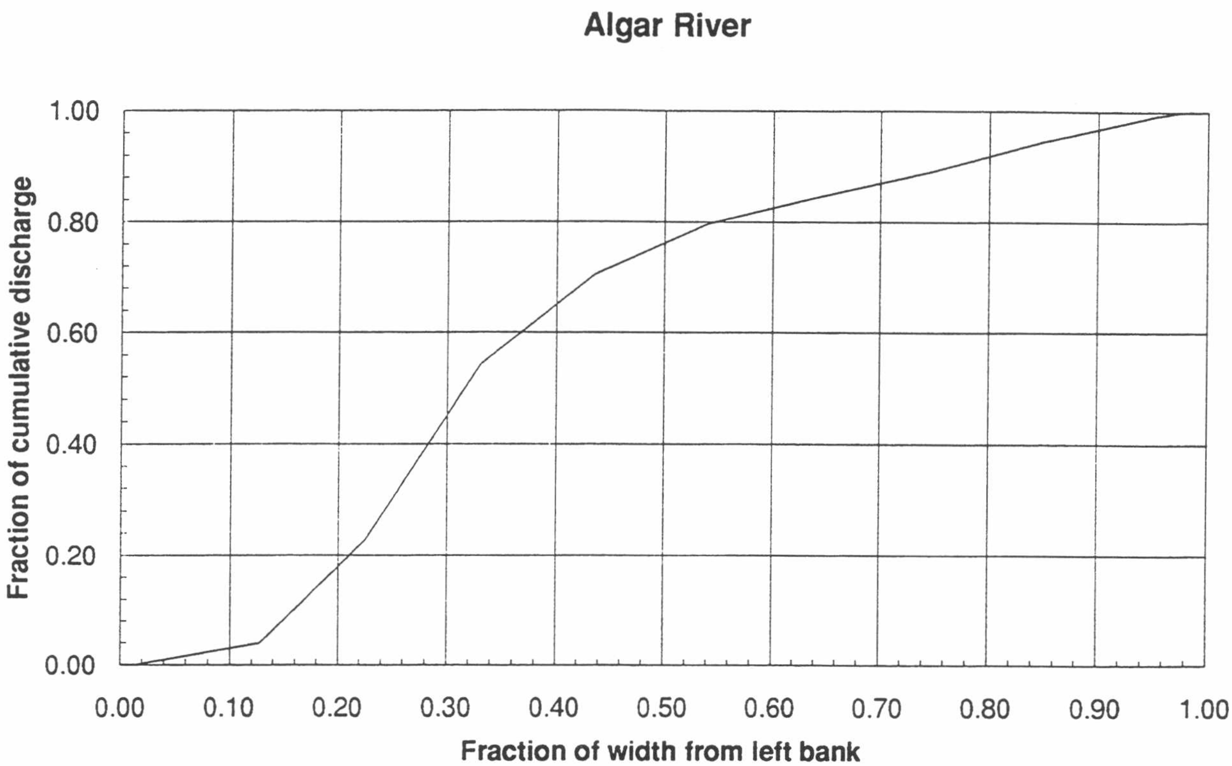


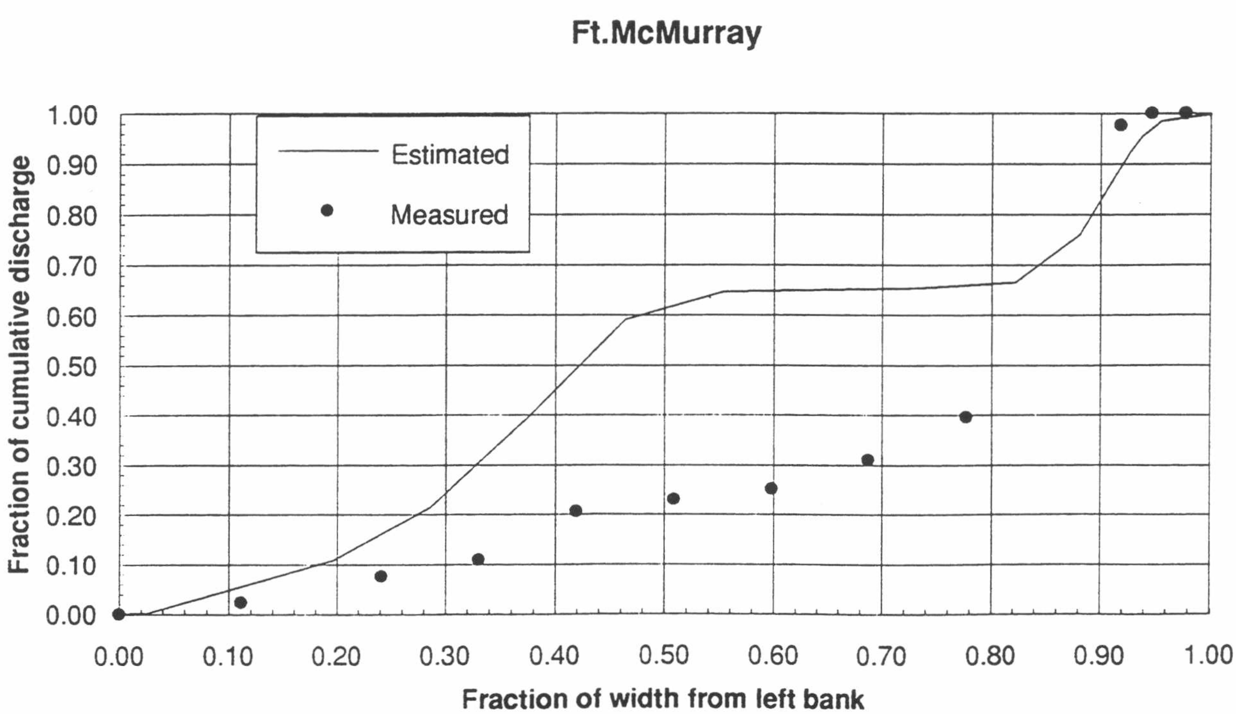
Boivin Creek



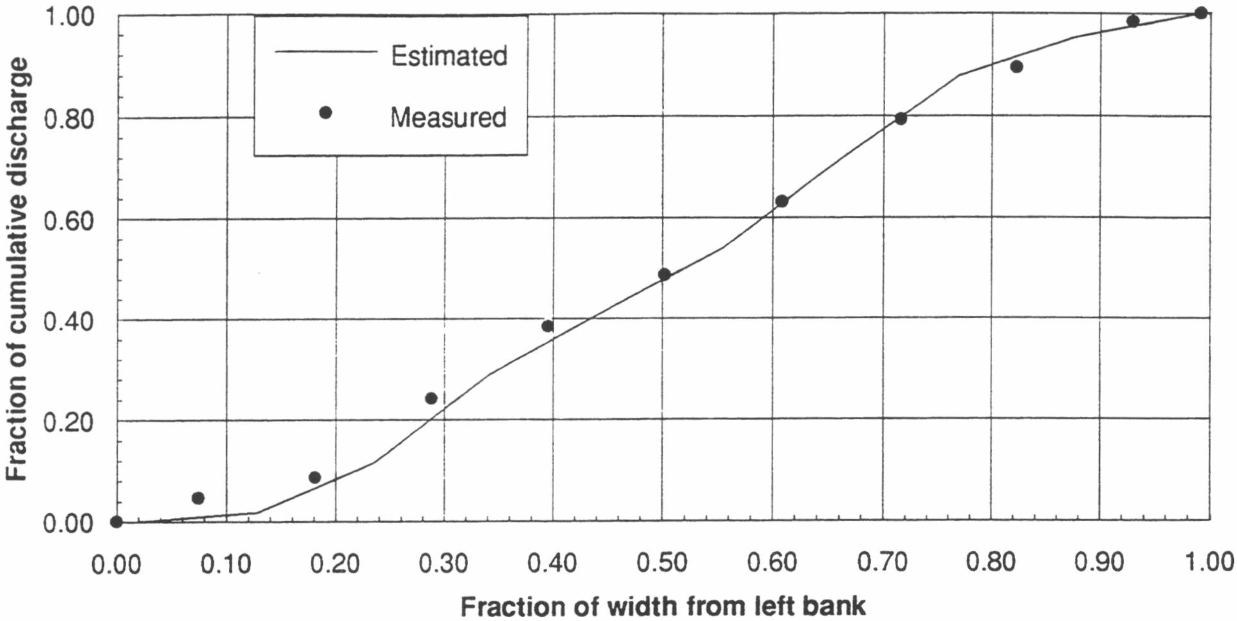
Brule Point



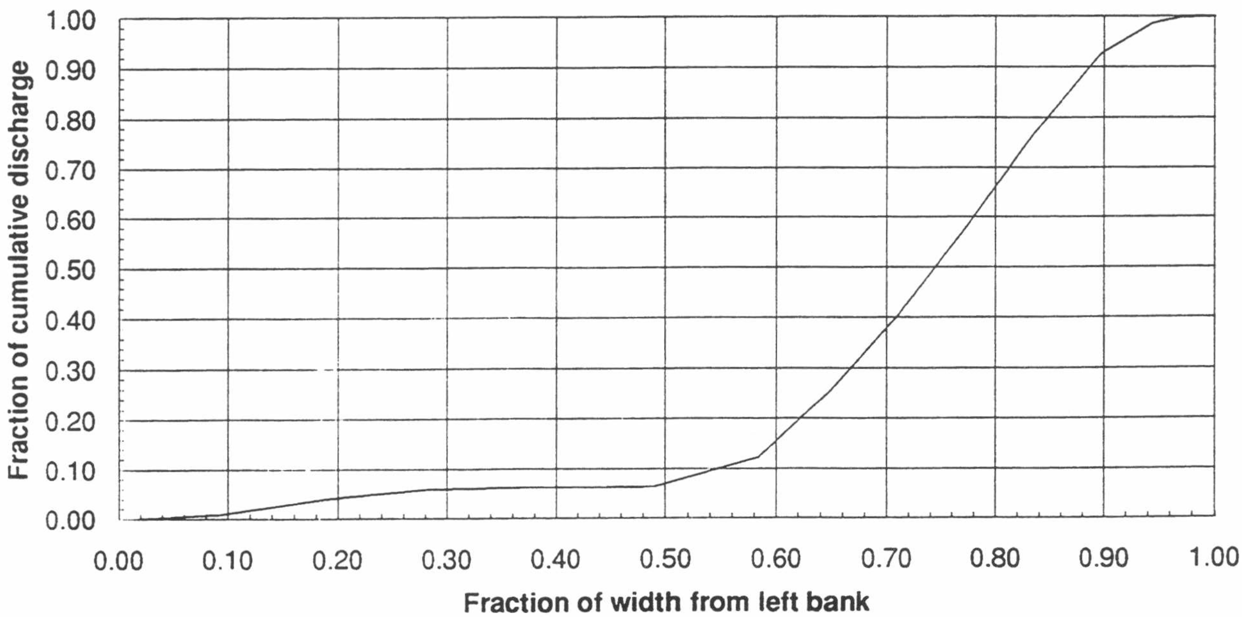

Algar River
1.00
0.80
0.60
0.40
0.20
0.00
Fraction of cumulative discharge
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Fraction of width from left bank

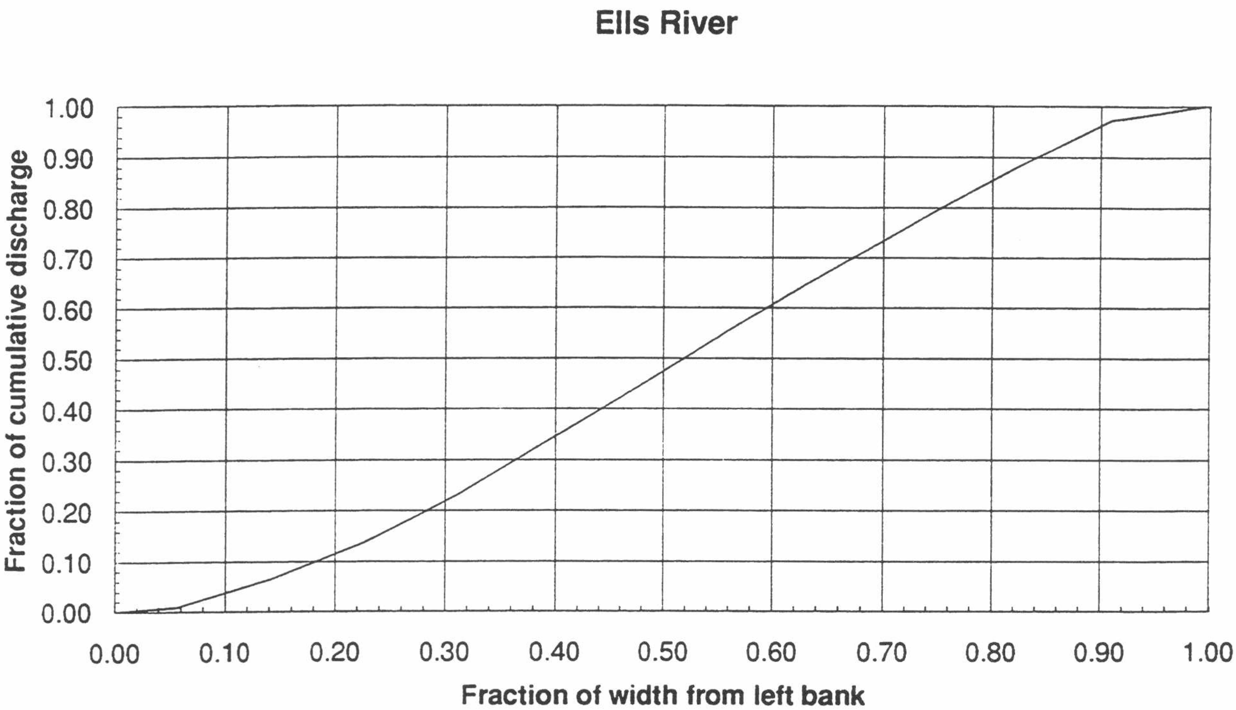

Ft.McMurray
Estimated
Measured
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Fraction of cumulative discharge
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Fraction of width from left bank

McLean Creek



Muskeg River




Ells River
Fraction of cumulative discharge
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
Fraction of width from left bank