UNDER-ICE HYDRAULICS AND MIXING IN REGULATED PEACE RIVER

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ABSTRACT

Cross-sectional surveys and a point-injection dye test were used to determine under-ice hydraulic and mixing characteristics of a 187-km length of the Peace River in northern Alberta in February 1993. The river is approximately 400 m wide, with a gradient of around 0.3 m/km and depths of up to 15 m under winter discharges of around 1700 m^3/s.

Mean velocities calculated as Q/A averaged 0.76 m/s and yielded an average Manning roughness of 0.046 as a composite of bed and ice roughness. This value includes special energy losses due to channel non-uniformity and possibly partial blockage by frazil ice. Velocities as determined from dye-cloud travel times averaged 40% higher. An alternative analysis based on dye-cloud velocities and reduced "effective" sections yielded an average roughness of 0.030.

Transverse mixing was complete about halfway along the length. Computed values of transverse mixing parameters (dimensionless diffusion factor and mixing coefficient) based on full-section hydraulics are similar to those of previous studies. The value a dimensionless linear dispersion parameter for the fully transverse-mixed length is high compared to previous studies.

INTRODUCTION

A field and analytical study was conducted in mid-winter 1993 to evaluate under-ice hydraulic characteristics, travel times and mixing parameters in a 187-km length of the Peace River in northern Alberta. The principal feature was a dye-tracking test utilizing one injection and seven sampling sites as shown in Figure 1. The study was commissioned by the Northern Rivers Basin Study, a joint Canada-Alberta-NWT project, to assist water quality modelling of the river system.

Since 1972 the Peace River in the length of interest has been strongly regulated by BC Hydro's Bennett Dam project some 400 km upstream. Regulation has increased the magnitude and variability of winter flows and altered ice conditions, particularly with respect to freeze-up dates and processes and the nature of the ice cover. The study was conducted under stable mid-winter conditions with fairly steady discharges.

Somewhat similar studies have been reported previously for various lengths of the Athabasca River in northern Alberta (Andres et al 1989; Beltaos 1979; Van Der Vinne 1992; Van Der Vinne and Andres 1992). The Athabasca, being unregulated, has relatively low winter discharges.

FIELD INVESTIGATIONS

Ice conditions

Surface ice conditions were observed by helicopter on 10 February 1993. As far downstream as Whitemud River (Figure 1) the cover was generally flat and appeared to have been formed by the juxtaposition of a single layer of ice pans. Downstream of Whitemud River the cover was generally rough and appeared to have been re-formed by sequential consolidation of an initial smoother juxtaposed cover.

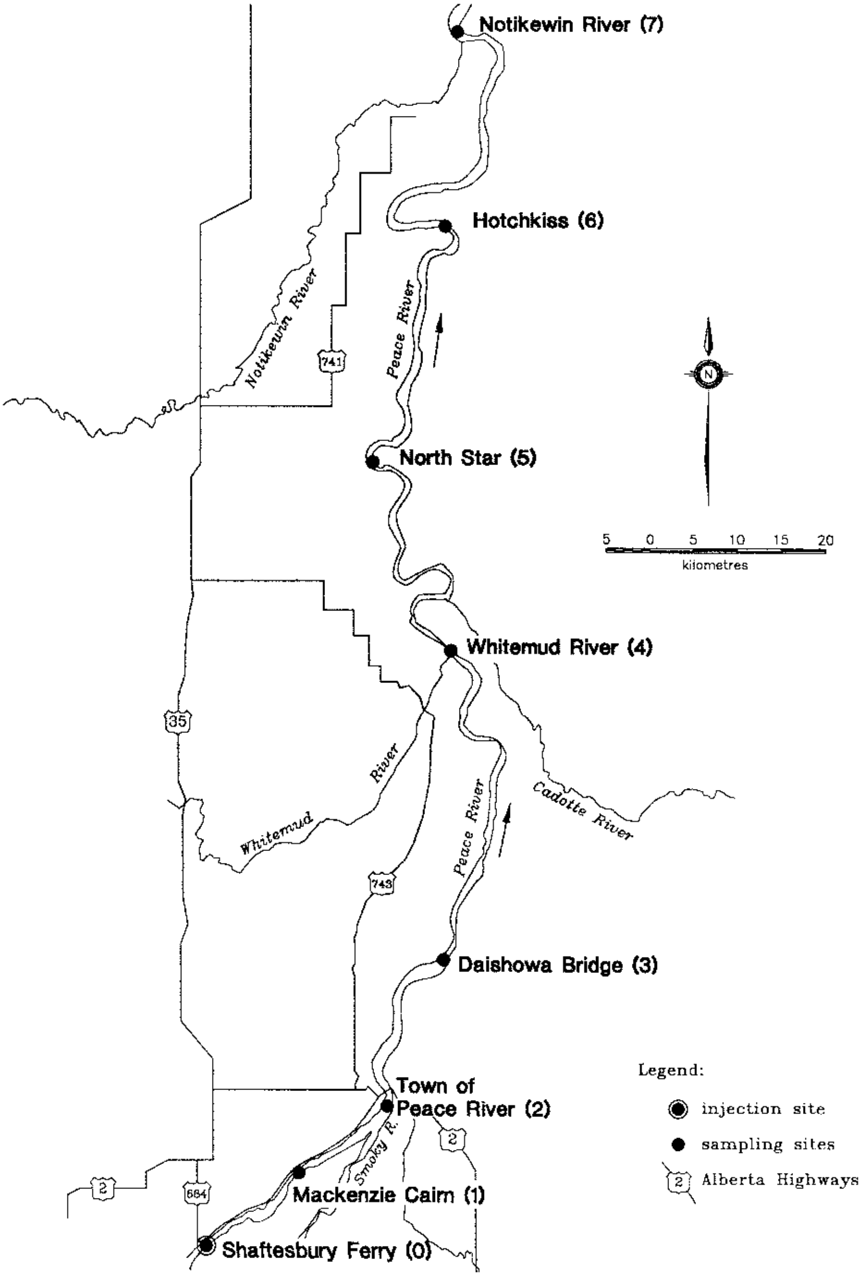


Figure 1. Peace River study length.

Cover thickness and frazil ice conditions were subsequently investigated by drilling 20 holes across each of the eight injection and sampling cross-sections. Thicknesses of solid ice and frazil slush were measured in each hole. Width-averaged total ice thicknesses ranged from 1.0 to 1.9 m. Local thicknesses were up to 2.5 m, especially at North Star where the ice was used for vehicle crossings. The thickness of frazil varied greatly from section to section and from hole to hole, ranging from zero to 1.3 m. Frazil accumulation was more pronounced downstream of Whitemud River where a rougher ice surface was also observed.

Quantities of ice "pebbles", typically 3 cm and as great as 10 cm in diameter, were encountered in holes over the main channel. These have been observed in other northern rivers (Chacho et al 1986) and are believed to represent frazil being transported by the flow.

Cross-section surveys

Cross-sections were surveyed prior to the dye test at the eight sites shown in Figure 1. The holes drilled through the ice were also used to determine piezometric water elevations, depths and velocities.

A longitudinal profile of the study length based on surveyed water elevations is shown in Figure 2. The (piezometric) water surface profile is adjusted to represent a consistent under-ice discharge of 1600 m^3/s: during the surveys, there was a certain variation in discharge from section to section.

Selected cross-sections are illustrated in Figure 3. The eight cross-sections are admittedly rather widely spaced for analysis of channel hydraulics. However, there is no reason to believe that they are biassed, because locations were chosen for reasons of spacing and access. Time and funds did not permit a more detailed survey of channel geometry.

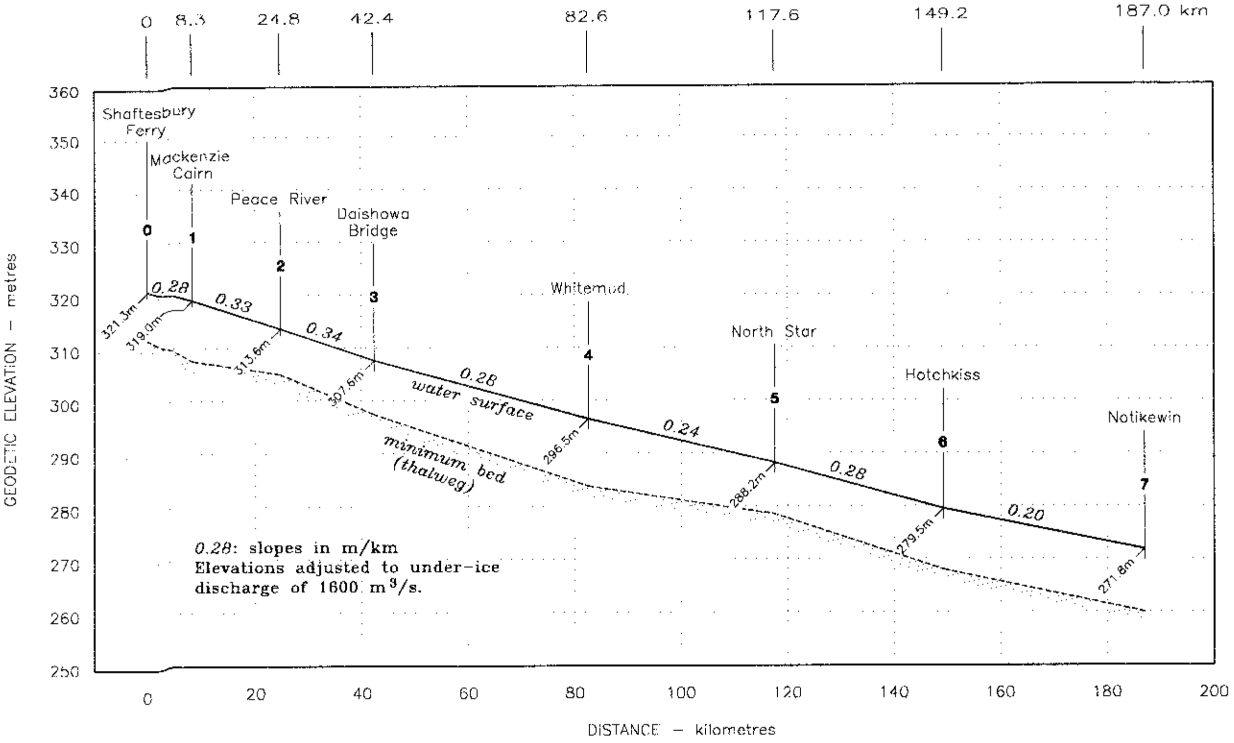


Figure 2. Longitudinal profile of study length.

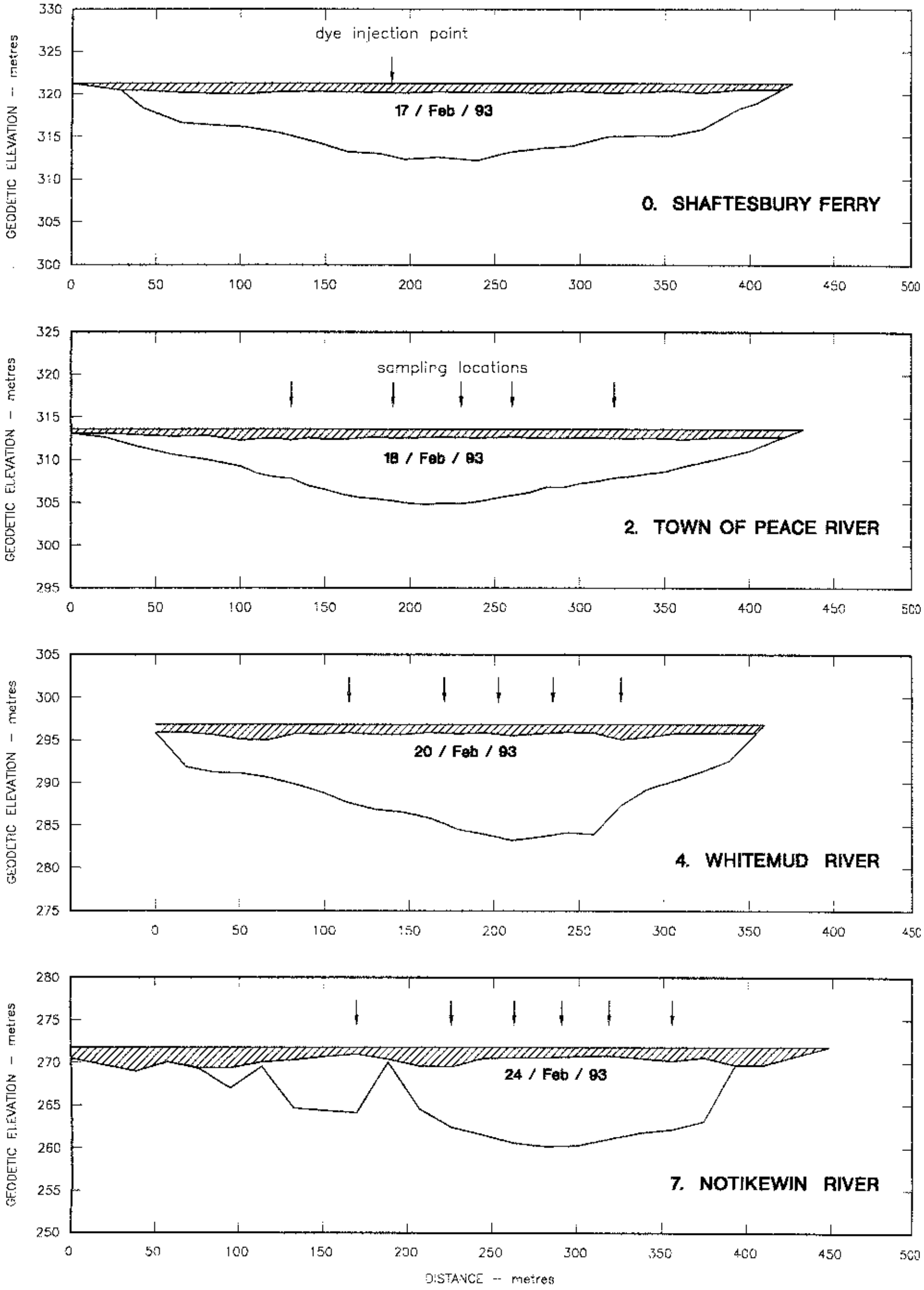


Figure 3. Selected cross-sections (looking downstream).

Tracer dye test

A single slug consisting of 250 kg of 20% solution Rhodamine WT was injected in midstream at Shaftesbury Ferry at 9.30 a.m. on 27 February 1993, and tracked downstream over the next 80 hours. Precautions were taken to ensure virtually instantaneous injection and to avoid under-ice trapping of dye at the injection point.

Water samples were taken in 5 to 10 holes at each section at intervals of 5 minutes to 2 hours depending on the transit time of the dye cloud, so that at least 20 to 30 samples were obtained at each hole. Prior samples were also taken to establish background. Sampling was done with a 125 mL bottle attached to a 4-metre pole, plunged as deeply as possible into the flow, and samples were analyzed immediately for fluorescence in a mobile laboratory. Fluorescence values were converted to dye concentrations using calibration regressions with corrections for temperature and background.

The mass balance of the dye tracer was checked by integrating concentration profiles with respect to time and discharge across the channel at each site, and comparing the integrated dye mass with the injected mass. Apparent recovery ratios at individual sites varied somewhat erratically from 87% to 52%, with an average of 71%. The apparent deficiency in dye recovery is believed to be due to a combination of measurement errors and dye losses. The true loss discounting errors was estimated to be from 20% to 25% over the study length, of which about half is believed due to long-term retention of dye in the interstitial water of frazil ice masses.

HYDRAULIC ANALYSIS

River flow conditions

Discharges in the river during the study varied between 1600 and 1900 m^3/s, fairly close to long-term regulated averages for the time of year. During the dye test the discharge was almost constant at 1740 m^3/s. Daily discharges as gauged at Peace River town were routed to sampling sites by proportioning lag times of discharge fluctuations as observed between Peace River town and another gauge 265 km downstream. The overall lag time over the study length was approximately 48 hours.

Channel geometry

Hydraulic gradients between sampling points, adjusted to a constant discharge, ranged from a maximum of 0.34 m/km just downstream of Peace River town to a minimum of 0.20 m/km in the farthest downstream reach.

Properties of surveyed cross-sections at the injection and sampling sites are listed in Table 1. Under-ice surface widths vary from 315 to 480 m, and mean under-ice depths (2 x listed hydraulic radius) from 4.6 to 7.5 m.

These sections and gradients were used for approximate hydraulic analysis of the study length. Over the upstream 30% of the study length a certain amount of previous cross-sectional information was used to check the representativeness of the sampling sections. Over the downstream 70% the only feasible check was against map widths. These checks indicated that six of the eight sections were reasonably representative of local reaches. North Star (5) was too wide and Notikewin (7) was too narrow, but their representativeness in terms of area could not be determined.

Velocities and roughness

For each reach, hydraulic mean velocity was calculated as discharge divided by under-ice area averaged from end sections. A composite roughness coefficient was then calculated by applying Manning's equation using the reach gradient and averaged hydraulic radius. Results are shown in Table 1. Mean velocities range from 0.57 to 0.88 m/s with an average of 0.74 m/s. Apparent composite n values range from 0.039 to 0.059 with an average of 0.046. These n values include the effects of river

Table 1. Measured and computed geometric and hydraulic data

Site	Av. total ice thickness (m)	Under-ice surface width B (m)	Under-ice area A (m^2)	Est'd. local discharge Q on date of survey (m^3/s)	Hydraulic mean velocity $U = Q/A$ (m/s)	Hydraulic radius $R = A/2B$ (m)	Reach-averaged values			Apparent composite roughness
							U (m/s)	R (m)	S	$n = R^{2/3}S^{1/2}/U$
0. Shaftesbury	1.0	385	2010	1600	0.80	2.61				
							0.835	2.76	.00028	0.039
1. Mackenzie Cairn	1.3	315	1840	1600	0.87	2.92				
							0.875	2.60	.00033	0.039
2. Peace River	1.0	400	1820	1600	0.88	2.28				
							0.845	2.52	.00034	0.040
3. Daishowa	1.1	400	2210	1800	0.81	2.76				
							0.765	3.26	.00028	0.048
4. Whitemud River	1.2	350	2640	1900	0.72	3.77				
							0.645	3.26	.00024	0.053
5. North Star	1.9	580	3180	1800	0.57	2.74				
							0.595	3.01	.00028	0.059
6. Hotchkiss	1.0	430	2830	1750	0.62	3.29				
							0.735	3.43	.00020	0.044
7. Notikewin River	1.8	280	2000	1700	0.85	3.57				
Averages	1.3	390	2320	1720	(0.74)	(2.97)			(.00026)	(0.046)

bed and ice underside roughness, energy losses due to channel non-uniformity and curvature, and possibly partial blockage of sections by frazil ice. The roughness is noticeably greater in the downstream part of the study length, consistent with observed thicker and rougher ice.

Dye-cloud velocities were calculated by dividing each reach length by the observed travel time of the dye cloud, as determined from width-averaged concentration distributions developed from measured point concentrations. Calculated velocities for dye-cloud peak and centroid are listed in Table 2. For all but the farthest downstream reach, peak velocities are slightly higher than centroid velocities, with an average difference of about 5%. Averages of the two measures were used in subsequent calculations.

Comparison of hydraulic and dye-cloud velocities

Table 3 compares hydraulic and tracer dye-cloud velocities as calculated for the seven reaches as double averages over the cross-section and the reach length. Dye-cloud velocities exceed hydraulic velocities by 40% on average and by from 14% to 60% for individual reaches. Factors responsible for these discrepancies may include the following:

1. **Incomplete transverse mixing.** In the four upstream reaches, transverse mixing of the dye was incomplete. As a result, the dye tended to move in the central, higher-velocity zone of the flow. This would explain why the average discrepancy is greater in the four upstream reaches than in the three downstream ones.

2. **Unrepresentativeness of surveyed sections.** The surveyed sections may have been larger than true reach averages. Against this, it seems unlikely that sampling errors would be all one way.

Table 2. Dye-test travel times and velocities

Reach	Reach Length (km)	Travel Times (hrs)		Associated Dye-cloud velocities (m/s)	
		Peak	Centroid	Peak	Centroid
Shaftesbury - Mackenzie Cairn	8.3	2.1	2.1	1.10	1.08
Mackenzie Cairn - Peace River	16.5	3.2	3.3	1.43	1.39
Peace River - Daishowa	17.6	3.8	4.0	1.29	1.22
Daishowa - Whitemud	40.2	9.2	9.8	1.21	1.14
Whitemud - North Star	35.0	11.5	11.7	0.85	0.83
North Star - Hotchkiss	31.6	8.9	11.1	0.99	0.79
Hotchkiss - Notikewin	37.8	12.9	12.0	0.81	0.88

Table 3. Comparison of hydraulic and dye-cloud velocities

Reach	Hydraulic mean velocity from Table 1 m/s	Dye-cloud mean velocity[1] from Table 2 m/s	Ratio dye-cloud/ hydraulic
Shaftesbury - Mackenzie Cairn	0.84	1.10	1.31
Mackenzie Cairn - Peace River	0.88	1.41	1.60
Peace River - Daishowa	0.85	1.25	1.47
Daishowa - Whitemud	0.77	1.17	1.52
Whitemud - North Star	0.65	0.84	1.29
North Star - Hotchkiss	0.60	0.89	1.48
Hotchkiss - Notikewin	0.74	0.84	1.14
averages	0.76	1.07	1.40

[1] Average of peak and centroid values

3. **Frazil blockage.** Field observation suggested that frazil ice, although present, was insufficient to have a large effect on channel hydraulics. However, little is known of frazil conditions between sections. It is therefore possible that blockage by static frazil was generally more significant than it appeared. The effective waterway areas would then be less than assumed, resulting in greater hydraulic velocities and lower roughness coefficients than shown in Table 1.

4. **Non-contributing flow area.** Parts of the cross-section may not have contributed significantly to discharge. Measured transverse discharge distributions indicated than on average 90% of the discharge was conveyed by the central 70% of the width: partial discharges in shallow near-bank zones were considerably less than those calculated by applying the Manning formula to local depths.

Alternative Manning roughness values to those of Table 1 were calculated by dividing the dye-test discharge by the dye-cloud velocities of Table 3 to yield "effective" cross-sectional areas, and then dividing those by reduced under-ice widths to yield "effective" mean depths. Table 4 compares the original and alternative values. On average the alternative values are about one-third lower. However, the re-calculation ignores other factors affecting discrepancies between hydraulic and dye-cloud velocities, as described in paragraphs 1 through 3 above, and therefore probably under-estimates true roughnesses.

MIXING ANALYSIS

Transverse Mixing

The basic partial differential equation for mass transport in 2-D steady-state mixing is presented by Yotsukura and Sayre (1976). When this equation is made dimensionless and modified to account for transient concentrations, the following equation is obtained:

Table 4. Comparison of composite hydraulic roughness values

Reach	Composite Manning roughness n	
	Table 1 values using full cross-sections	Alternative values using reduced cross-sections
Shaftesbury - Mackenzie Cairn	0.039	0.036
Mackenzie Cairn - Peace River	0.039	0.025
Peace River - Daishowa	0.040	0.027
Daishowa - Whitemud	0.048	0.028
Whitemud - North Star	0.053	0.038
North Star - Hotchkiss	0.059	0.030
Hotchkiss - Notikewin	0.044	0.027
Averages	0.046	0.030

$$\frac{\partial\phi}{\partial\chi} = \beta_z \frac{\partial^2\phi}{\partial\eta^2} \qquad [1]$$

where $\eta = q_c/Q$ is the dimensionless cumulative discharge across the channel (in this case from the left bank), $\chi = x/B$ is the ratio distance along the river to river width, $\phi = \theta Q/M_o$ is the dimensionless dosage (the time-integration of concentration θ non-dimensionalized using discharge **Q** and injected mass M_o). A dimensionless diffusion factor β_z can be defined in terms of the diffusion factor D_z (Gowda, 1984) or the transverse mixing coefficient e_z as follows:

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

where U, m_x and e_z are cross-section average values of velocity, curvature, and transverse mixing coefficient and ψ is an integration factor, generally between 1.0 and 3.2 for natural channels (Beltaos, 1978a), resulting from the use of these average values. Values of ψ calculated from the Peace River cross-sections range between 1.7 and 3.2.

The diffusion factor, D_z can be evaluated from the change in variance of the dosage distribution with distance along the channel, allowing for the confining effect of the river banks. This technique is described in detail by Beltaos (1978a). The dimensionless diffusion factor β_z can then be evaluated from the diffusion factor D_z using the first part of Equation **[2]**.

Fischer et al. (1979) proposed an alternative parameter, the dimensionless transverse mixing coefficient, $k_t = e_z/U_*H$, where U_* is the shear velocity, **H** is the mean depth, and the transverse mixing coefficient e_z is evaluated from the second part of Equation **[2]**.

Two sets of dimensionless diffusion factors and transverse mixing coefficients derived from the diffusion factor and the Peace River hydraulic characteristics are listed in Table 5. The first set is based on full under-ice widths and the second set on reduced "effective" widths. Figure 4 plots the results for the Peace and other rivers against a composite hydraulic parameter (Elhadi et al. 1984). It is difficult to discern any systematic distinction between the ice-covered and open-water data.

The mixing parameter values obtained using full widths are similar to those of previous studies, but the reduced width analysis produced values below the usual range. Values from previous studies would also decrease if re-calculated using reduced widths, but the more trapezoidal cross-sections of the rivers in most previous studies, in contrast to the sub-triangular shape of the Peace River sections, would tend to yield less difference between the two approaches.

Longitudinal Mixing

Longitudinal mixing becomes dominant once transverse mixing is completed. In the dye test, transverse mixing was virtually complete at Whitemud River, 83 km downstream from the injection point. Longitudinal mixing can be described in terms of either a linear dispersion or a storage-and-release process. Both approaches were used to analyze the Peace River data, but only the first is presented here.

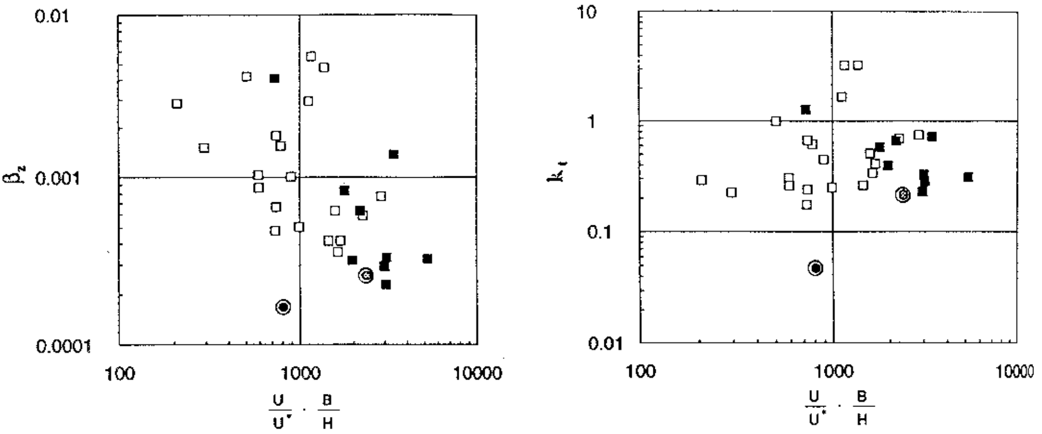
Beltaos (1978b) proposed the following equation:

$$C=\frac{M_oU}{Qx\sqrt{2\pi\beta_x}}\left[\frac{Ut}{x}\exp\left(1-\frac{Ut}{x}\right)\right]^{\frac{1}{\beta_x}} \qquad [3]$$

where **C** is the mean concentration in the section, $\mathbf{M_o}$ is the initial mass, **t** and **x** are the time and distance from injection and β_x is a dimensionless linear dispersion parameter defined by:

Table 5. Transverse mixing parameters for upstream reaches

Reach	**Diffusion Factor** D_z $(m/^5s^2)$	**Transverse mixing coefficient** e_z (m^2/s)		**Dimensionless diffusion factor** β_z		**Dimensionless transverse mixing coefficient** k_t	
		reduced width	**full width**	**reduced width**	**full width**	**reduced width**	**full width**
Shaftesbury - Mackenzie Cairn	2.49	0.028	0.069	0.00022	0.00035	0.051	0.25
Mackenzie Cairn - Peace River	1.84	0.021	0.053	0.00016	0.00026	0.053	0.27
Peace River - Daishowa	1.25	0.016	0.039	0.00012	0.00019	0.044	0.21
Daishowa - Whitemud	1.91	0.020	0.045	0.00017	0.00026	0.047	0.19
Average Shaftesbury to Whitemud	1.81	0.020	0.048	0.00017	0.00026	0.047	0.21



A. DIFFUSION FACTOR

B. TRANSVERSE MIXING COEFFICIENT

LEGEND:

◎ Peace River (Full width)
◉ Peace River (Reduced width)
■ Ice cover data, other rivers
□ Open water data, other rivers

Figure 4. Transverse mixing parameters vs. hydraulic parameter (various rivers).

$$\beta_x = 0.18\left(\frac{\Delta T}{t_p}\right)^2 \qquad [4]$$

where the half-duration ΔT is defined as the time during which the concentration exceeds 50% of the peak, the time to peak t_p is defined as U/x, and other symbols are as defined previously. The values of half-duration and time-to-peak for the present study are given in Table 6, along with other parameters which characterize the time-distribution of the cross-sectionally averaged concentrations.

Average values of the linear dispersion parameter β_x can be obtained from the slope of a best-fit line through the half-duration versus time-to-peak data shown in Figure 5. Incomplete transverse mixing was probably responsible for reduced values of β_x in the three upstream reaches. The most appropriate value is therefore indicated by the data between Daishowa and Notikewin. This value is presented in Table 7 along with two sets of hydraulic characteristics calculated using full widths and reduced "effective" widths respectively. The full width basis is considered more appropriate for comparison with other rivers.

DISCUSSION

Hydraulics

Table 3 shows that dye-cloud velocities were on average 40% higher than mean hydraulic velocities based on surveyed under-ice areas. In the upper half of the study length, part of the discrepancy can be explained by incomplete transverse mixing of the central-point dye injection. The difference is substantial, however, even in the downstream half, suggesting that effective areas were considerably smaller than surveyed areas. If 5% of the theoretical discharge is discounted near each bank on the basis of dead zones, effective under-ice widths and areas are reduced by

Table 6. Linear dispersion parameters at all cross-sections

			Distribution parameters			
Location	**Distance (km)**	**Time to Peak (hrs)**	**Half-duration ΔT (hrs)**	**Variance σ_t^2 (hrs^2)**	**Peak Concentration[1] ($\mu g/L$)**	**Apparent Mass Recovery Ratio**
Shaftesbury	0.0	0.0	0.00	0.00	--	1.00
Mackenzie Cairn	8.3	2.0	0.18	0.01	35.18	0.87
Peace River	24.8	5.1	0.26	0.08	17.38	0.75
Daishowa	42.4	8.9	0.80	0.64	5.65	0.72
Whitemud	82.6	18.8	2.66	7.49	1.78	0.78
North Star	117.6	29.4	6.382	2.43	0.63	0.58
Hotchkiss	149.2	38.4	8.144	2.41	0.60	0.77
Notikewin	187.0	49.21	2.107	3.88	0.30	0.52

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[1] Peak, with respect to time, of cross-sectional average

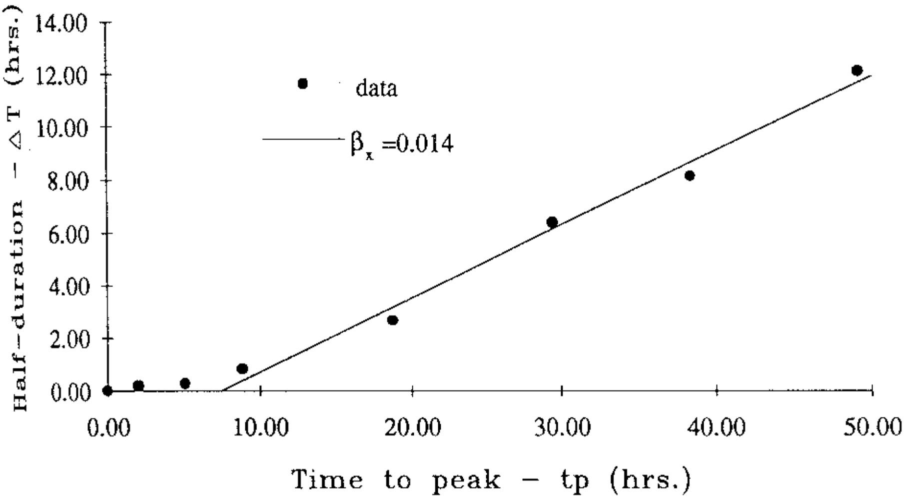

Figure 5. Half-duration vs. time to peak (Peace River).

Table 7. Average hydraulic and linear dispersion parameters, Daishowa to Notikewin

Method of Analysis	Width (m)	Depth (m)	Velocity (m/s)	Shear Velocity (m/s)	Linear Dispersion Parameter (β_x)
Full width basis	437	4.10	0.97	0.070	0.014
Reduced width basis	310	5.77	0.97	0.084	0.014

approximately 30% and 20% respectively. Downstream of Whitemud, this would account for much of the velocity discrepancy.

The average values of composite Manning roughness (Table 4) derived using (1) hydraulic mean velocities and surveyed sections, and (2) dye-cloud velocities and reduced sections, probably represent upper and lower bounds of reasonable values. A compromise average for the study length would be 0.038. Reach values derived by both methods tend to be higher in the downstream part of the length, where the ice was thicker and rougher. In a previous study of ice conditions at Peace River town in 1982, Neill and Andres (1984) reported a value of 0.043, but there is reason to believe this may have been over-estimated due to unreliable discharge data.

In most previous studies of under-ice mixing, reliable discharge and cross-sectional information has not been available to enable comparison of mean hydraulic and dye-cloud velocities, so that discrepancies were not apparent. Also, in many cases the channel cross-sections were approximately trapezoidal or semi-elliptical, so that wide shallow areas near the banks, so evident in the Peace River, were largely absent.

Mixing

Some of the scatter in the transverse mixing data in Figure 4 may be due to errors in estimating hydraulic characteristics. For example, mean velocities determined from peak dye travel times are likely to be over-estimated in upstream reaches because of incomplete transverse mixing. Also, under-ice widths used in many studies were probably too large: closer correspondence with present study results would be obtained using "effective" widths. Some of the scatter in previous results has been attributed to river sinuosity (Lau and Krishnappan, 1981).

Errors in determination of the dimensionless diffusion factor β_z are probably less than in the dimensionless transverse mixing coefficient $\mathbf{k}_t$, because β_z is calculated directly from the measured parameters of top width and discharge rather than depending on the cube of estimated mean depth. According to Equation [2], β_z should be independent of hydraulic characteristics; however Figure 4 appears to exhibit a slight dependence. On the other hand, it suggests that k_t may be independent of these factors. The overall scatter and uncertainty in the data make it difficult to predict the transverse mixing characteristics of a given river without actual field tests. The data do not conclusively indicate which dimensionless parameter is more appropriate or how their values vary with hydraulic characteristics.

The calculated value of the linear dispersion parameter β_x for the present study is high compared to previously studied rivers, especially relative to U^*/U as shown in Figure 6. The use of different river widths does not significantly affect the comparison. The high value of β_x for the Peace River can be explained on the basis of the sub-triangular cross-sectional shape, which tends to have greater transverse velocity gradients than a trapezoidal shape. Differential advection, a major cause of linear dispersion, is therefore enhanced.

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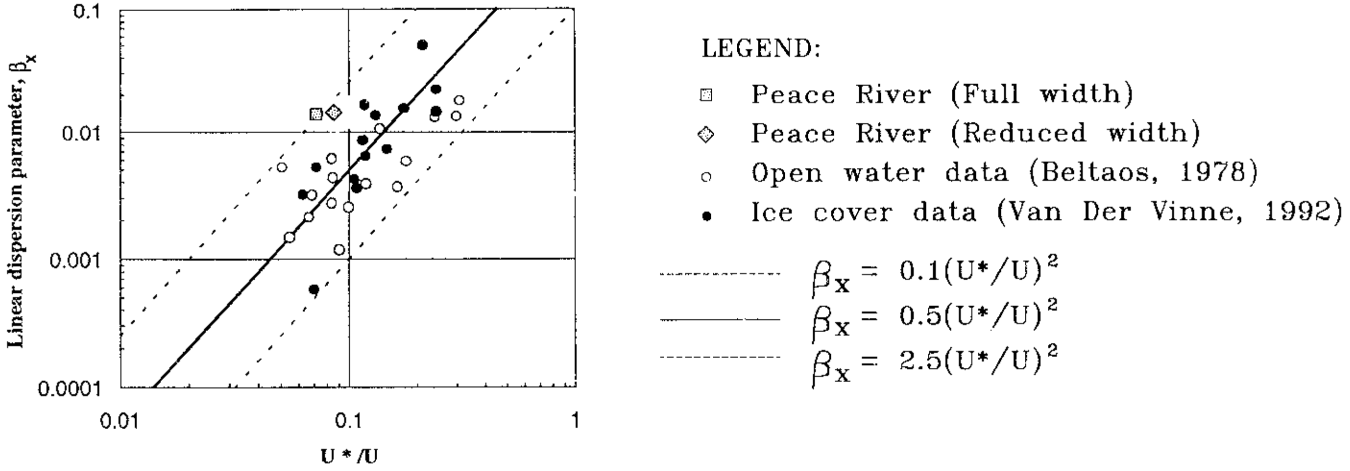

Figure 6. Linear dispersion parameter vs. hydraulic parameter (various rivers).

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DISCUSSION QUESTIONS

Kate White (CRREL): Did you store dye samples for later testing. If not, how did you account for differences in DO and temperature as compared to the standards? Also, how was dye introduced into the river, as a point source or a line source?

Gary Van Der Vinne (Trillium Engineering): The dye was introduced as a point source so that transverse mixing could be evaluated. Samples were analyzed on site in a mobile laboratory. Sample temperatures were taken before analysis. A laboratory standard was analyzed at various temperatures to establish a relationship between temperature and sample fluorescence. No attempt was made to account for differences in dissolved oxygen.