PROJECT REPORT 2000-2

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Two-Dimensional Modelling of Effluent Mixing in the Athabasca River downstream of Alberta Pacific Forest Industries, Inc.

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Gordon Putz, Ifeanyi Odigboh and Daniel W. Smith

For copies of this or other SFM publications contact:

Sustainable Forest Management Network
G208 Biological Sciences Building
University of Alberta
Edmonton, Alberta, T6G 2E9
Ph: (780) 492 6659
Fax: (780) 492 8160
http://www.ualberta.ca/sfm/

ISBN 1-55261-060-8

Two-Dimensional Modelling of Effluent Mixing in the Athabasca River downstream of Alberta Pacific Forest Industries, Inc.

Development and Verification of a Two-Dimensional Hydraulic and Kinetic Model for the Prediction of Effluent Transport in Rivers

by

Gordon Putz
Department of Civil Engineering
University of Saskatchewan, Saskatoon, Saskatchewan

Ifeanyi Odigboh
Division of Environmental Engineering
University of Saskatchewan, Saskatoon, Saskatchewan

and

Daniel W. Smith
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, Alberta

April 2000

ABSTRACT

In August 1997, two tracer tests were conducted on the Athabasca River downstream of the Alberta Pacific Forest Industries pulp mill site. The tracer tests were conducted as part of a research program to further develop and verify a computer model for the prediction of effluent mixing and transport in rivers. The computer model utilizes a streamtube representation of the river and a numerical procedure employing an advection optimized grid to limit numerical errors. The computer model can predict concentrations across a stream at various distances downstream of a discharge point (i.e. within the two-dimensional mixing zone). The model also has the ability to simulate the effects of transient and steady state input conditions.

The purpose of the 1997 fieldwork was to demonstrate that a calibrated model could accurately simulate measured tracer concentrations. Once calibrated for a particular river reach the model can be used to simulate concentrations of effluent parameters. Therefore, the model can be used for efficient planning of receiving stream water quality monitoring programs, to assess the environmental impact of abnormal conditions such as spills and/or low river flow conditions, or to investigate the implications of alternative discharge locations on the receiving stream water quality.

In order to calibrate the model values of β, the transverse mixing coefficient, are selected to produce an acceptable fit of the model output to the tracer data. Data from two previous tracer tests on this portion of the Athabasca River were available in addition to data from the August 1997 tests. Model analysis of these four tracer tests allowed a rare opportunity to assess the variation in transverse mixing coefficient over a wide range of flow conditions (84 m^3/s to 960 m^3/s).

The results of the research demonstrate that the computer model was able to accurately simulate the river mixing and transport of tracer in a 30 km reach of the Athabasca River for both steady state and slug input conditions. The research also indicated that the reach-averaged transverse mixing coefficient decreased linearly with increasing flow. However, the decrease in β over the range of flows analyzed was relatively small. A sensitivity analysis indicated β averaged over the range of flow analyzed could give satisfactory model results at this location.

An important factor contributing to the successful application of the computer model is the collection of sufficient hydrometric data to adequately characterize the river reach. An overview of the hydrometric data required (cross section depths, flow velocity, river discharge etc.) and its collection at the Athabasca River study reach is presented in this report. The application of GPS technology for recording position on the river during these surveys and while sampling proved extremely useful in this study. The continued use of this technology in future river studies is highly recommended.

ACKNOWLEDGEMENTS

The authors thank Alberta Pacific Forest Industries Inc. (Mr. Keith White and Mr. Mark Spafford) for supporting these studies by providing field equipment, access to mill locations and storage facilities, and copies of reports of previous tracer and water quality studies. The authors would also like to thank the graduate students and staff of the Environmental Engineering Group, University of Alberta who participated in the 1997 field studies. Their assistance and hard work was invaluable. Special thanks to Kevin McCullum for organizing the field equipment and compiling much of the raw data. The studies were financially supported by a grant from the Sustainable Forest Management Network of Centres of Excellence, Minimum Impact Technologies Theme.

INTRODUCTION

Background

A critical component of environmental fate investigations of substances released to a receiving stream is to accurately predict where the substances will be transported to, and in what concentrations they would exist in the absence of any environmental reactions. Once this mass conservative concentration distribution is defined in space and time it can then be used as a benchmark against which the environmental fate of the substances can be judged. Without this benchmark, it is impossible to separate mixing and transport effects in the receiving stream from the effects of environmental reactions.

Several water quality models have been developed for rivers using principles of fluid mechanics, mass transport, environmental chemistry and numerical methods. The majority of these models have been developed assuming either a one-dimensional condition or a two-dimensional, steady state condition applies within the receiving stream. One-dimensional models assume rapid complete mixing of effluent within the river flow downstream of a discharge location. Therefore, one-dimensional models are limited to the prediction of channel-mean concentrations of a substance. Many one-dimensional models can simulate the effects of time varying input of effluent upon channel mean concentrations. Two-dimensional, steady state models can predict the concentration distribution of a substance across a stream, and with distance downstream of a steady input condition. However, the predicted distributions are time invariant and the model has no capability to predict the transient effects of time variations in the input condition. In other words, existing models have only been developed for simplified special case situations.

Forest materials processing industry effluents may be discharged continuously, but with variable substance concentration and flow, or intermittently, thus introducing time dependency. Effluents are commonly discharged to major rivers in which the mixing zone[1] can extend for many kilometers downstream of an outfall or diffuser location. The effluent substance concentrations resulting from an intermittent, or fluctuating continuous discharge, into such a river situation can not be satisfactorily modelled using the existing special case models. In such cases, a more comprehensive two-dimensional, unsteady source model is required.

Purpose of the Research Program

The overall purpose of the research project is to further verify and develop a two-dimensional, unsteady effluent input river mixing and transport model. Adaptations to this mixing model can provide the capability to simulate environmental reaction of water quality

[1] The mixing zone is the portion of the river, downstream of the discharge location, where significant variations in concentration occur across the stream. A common rule of thumb is the mixing zone will extent for approximately 100 to 300 river widths downstream of a near-bank discharge of effluent.

parameters, within a river, in combination with the river mixing and transport. A unique feature of the model is that unsteady input conditions can be accounted for, and that the resulting time-varying concentrations across a stream and in the downstream direction can be predicted. More popular and widely applied water quality models do not have this time-dependent, two-dimensional capability.

The model can be used to study the transport, mixing and fate of substances in forest industry effluent discharged to river systems. The first objective of the overall project involved the verification of the river mixing and transport portion of the model using tracer tests conducted at several mill locations. The second objective of the overall project is to adapt the model to predict the fate of selected mill effluent substances within the river environment. Effluent parameters such as colour, BOD, AOX and toxic compounds are possible candidates for incorporation into the model. The model can be adapted by incorporating kinetic expressions for environmental reaction of these non-conservative substances into the computer code. Substance concentrations predicted by the model will be compared to measurements taken in the river and adjustments made to the mixing and kinetic coefficients as necessary in order to calibrate the model.

A calibrated model at a particular mill site can serve as a valuable management tool for efficient planning of receiving stream water quality monitoring programs, i.e. the model will indicate where samples should to taken to document potential maximum concentrations. The model can also be used to assess the environmental impact of abnormal conditions such as spills and/or low river flow conditions on the receiving stream water quality, or to investigate the implications of alternative discharge locations on the receiving stream water quality.

1997 Field Studies

Background

In August 1997, field studies were conducted on the Athabasca River near Boyle, Alberta. The field studies consisted of hydrometric surveys and tracer tests conducted on approximately a 30 kilometre reach of the Athabasca River downstream of the Alberta Pacific Forest Industries pulp mill site. The site was chosen due to its close proximity to Edmonton and the in-kind support for the work offered by Alberta Pacific Forest Industries. Close proximity to Edmonton was considered important for the following reasons:

- This would be the first field season working with inexperienced personnel. Close proximity to Edmonton and the University of Alberta as the center of operations would allow rapid implementation of contingency plans if serious difficulties were encountered in the field.
- All the water quality and tracer samples would be analyzed at the Environmental Engineering Laboratories at the University of Alberta. Therefore, close proximity to Edmonton would minimize transport times for water quality and tracer samples.

Planning for the August field tests progressed through the spring and early summer of 1997. Air photos, maps, historical discharge data and past cross section surveys for the river reach were obtained from Alberta Environmental Protection, Water Survey of Canada and Alberta Pacific Forest Industries. In addition, engineering drawings of the effluent pipeline and diffuser structure were obtained from Alberta Pacific Forest Industries. All this information was required to plan the details of the tracer tests such as: the location of the tracer injection point, the quantities of tracer required, the tracer flow rates, the location of sampling sections, sampling schedules, numbers of boats and sampling crews, etc. The background information was also required for a preliminary assessment of the length of the two-dimensional mixing zone and to prepare an application to Alberta Environmental Protection for permission to conduct the tracer tests.

During the planning process Alberta Pacific Forest Industries also provided information on two previous tracer studies which had been conducted on the river reach for low water conditions (Beak Consultants Ltd., 1995). The results from these two tracer tests had not been analyzed or modelled to numerically characterize the river mixing. It was recognized that analysis of these previous tests and the two planned SFMNCE tests would provide a rare opportunity to characterize the mixing in a river reach over a wide range of flow conditions.

Water quality data on the mill effluent was obtained from Alberta Pacific Forest Industries as part of the planning process. It had been anticipated that parameters such a colour, BOD, and AOX could be sampled in the river and the attenuation of these parameters documented with distance downstream of the diffuser outlet. However, after reviewing the effluent data, and estimating the immediate dilution at the diffuser with the anticipated river flow for late August (approx. 300 m^3/s), it was discovered that effluent water quality parameters would be near or below limits of detection. The problem was further exacerbated by the high flow (800 to 1000 m^3/s) experienced on the Athabasca River in late August 1997. This quantity of flow combined with the level of treatment of the mill effluent made it impossible to track effluent parameters within the river.

Unfortunately at that stage of the planning it was too late to prepare for work at an alternate site in 1997. Therefore, rather than delay a year the principle investigators decided to proceed and to conduct the tracer tests only at the site. The work planned would still address the first objective of the overall project by providing a new comprehensive set of tracer test data to assess and verify the capabilities of the mixing model. The proposed tests and those previously conducted for Alberta Pacific Forest Industries would provide an opportunity to assess changes in the mixing characteristics of the Athabasca River over a range of river flows. In addition, the tracer tests would provide an opportunity to assess the effectiveness of GPS methods for river sampling and hydrometric surveys. Lastly, the tracer tests would allow field crews to gain valuable field experience for additional field surveys planned for 1998.

Objectives of the 1997 field studies

The specific objectives of the 1997 field studies on the Athabasca River downstream of the Alberta Pacific Forest Industries mill site were:

- Conduct a continuous input fluorescent tracer test to document the steady state transverse mixing occurring in a 30 km reach downstream of the diffuser structure.

- Conduct a slug input fluorescent tracer test to characterize the time dependent transverse mixing and transport occurring in a 30 km reach downstream of the diffuser structure.
- Conduct hydrometric surveys to obtain sufficient data to construct a mixing model of the river reach.
- Construct the mixing model for the study reach for each of the flow conditions represented by the two SFMNCE tracer tests and the two Beak Consultants Ltd. tests.
- Use the mixing model to characterize the transverse mixing which occurs in the study reach for the SFMNCE tests and the two previous tests conducted by Beak Consultants Ltd. The mixing is characterized by determining the numerical value of the dimensionless transverse mixing coefficient which gives the best fit to the tracer data for a particular flow condition.
- Assess the change in mixing characteristics in the river reach over the range of flows represented by the SFMNCE and the Beak Consultants Ltd. tracer tests.
- Assess the effectiveness of using GPS technology for collecting surface positioning information during hydrometric surveys and water sample collection.

TWO-DIMENSIONAL RIVER MIXING

Background

A neutrally buoyant substance discharged into a receiving stream will mix with the river water by the processes of diffusion and mixing due to differential advection. At the same time, the substance will be transported by advection in the longitudinal direction by bulk movement of the fluid. (see Figure 1 for coordinate system definition)

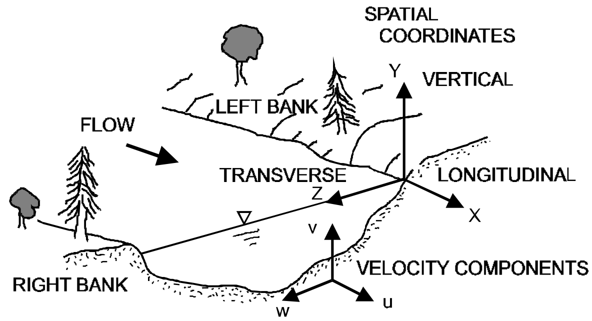

Figure 1 Coordinate system for mixing analysis.

Diffusion is substance movement within the water due to random motions in the presence of a concentration gradient. The substance moves from areas of high concentration to areas of lower concentration. The random motion may be molecular, a property of the fluid, or turbulent, a property of the fluid flow. In river flow turbulent diffusion is the dominant diffusion mechanism.

Mixing by differential advection occurs when diffusion progresses in the presence of velocity gradients in the bulk fluid flow. Rivers have significant vertical and transverse velocity gradients (see Figure 1 and Figure 2). Diffusive mass flux perpendicular to the direction of flow will result is a spreading of the substance in the direction of flow (longitudinal direction). An example is shown in Figure 3. Mixing due to differential advection is often called 'longitudinal dispersion'.

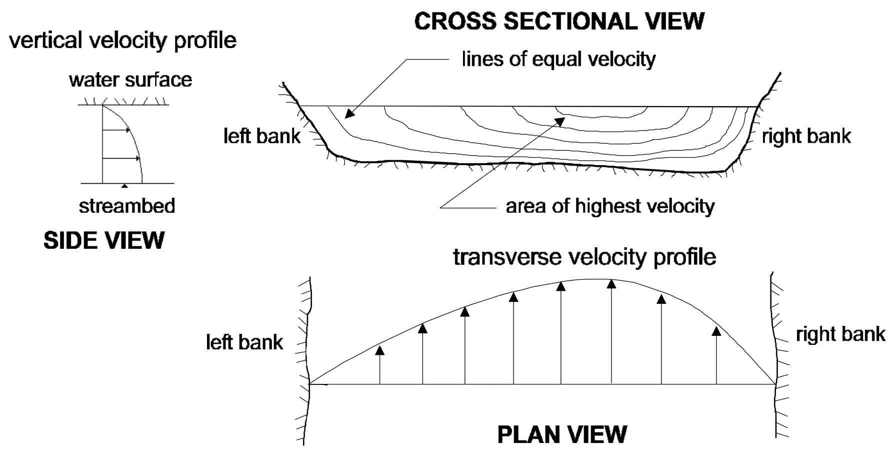

Figure 2 Typical velocity gradients in a river.

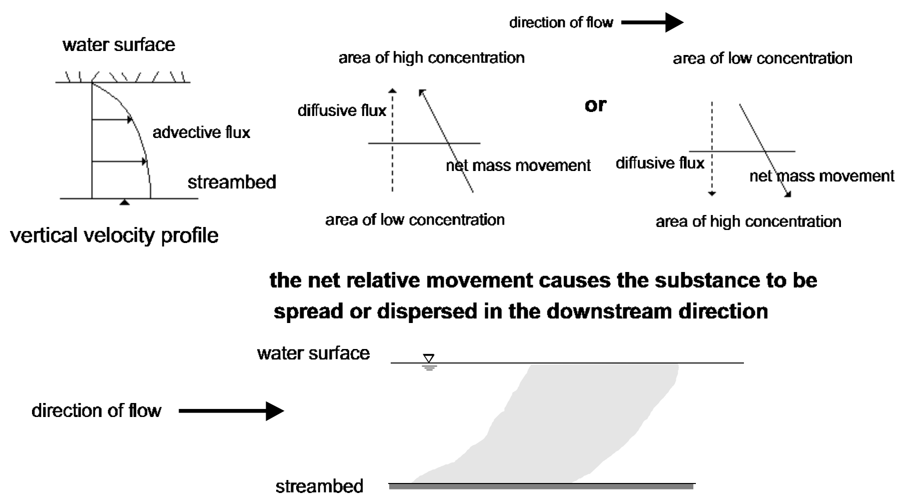

Figure 3 Mixing due to differential advection.

The interaction of diffusion, differential advection and channel geometry creates several characteristic mixing regions in a river. Beltaos (1979) described these interactions with the aid of Figure 4. At time t_0 a quantity of neutrally buoyant, mass conservative substance is instantaneously released into the river. Initially he substance mass moves downstream at the local flow velocity and uniformly mixes in all directions (primarily by diffusion) until time t_1 corresponding to distance x_1. Beyond distance x_1 the substance cloud encounters the streambed and velocities that are significantly different than the original local velocity at t_0. The substance cloud then begins to distort due to differential advection.

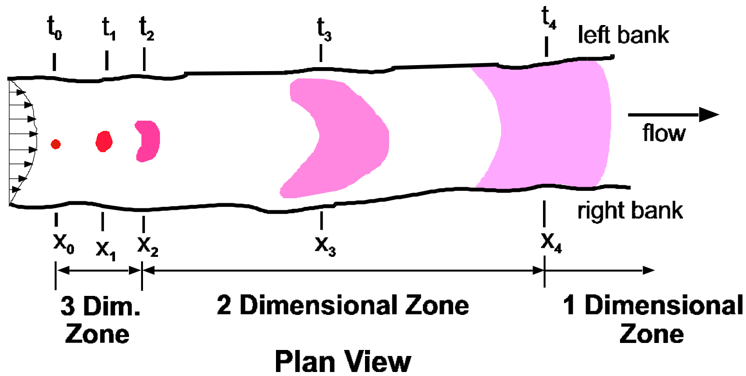

Figure 4 Typical spread of pollutant mass in each of the characteristic mixing regions.

At x_2 the main body of the substance cloud has become uniformly mixed in the vertical due to the 'no mass flux' boundary conditions of the streambed and the water surface. The cloud has become stretched into a crescent shape under the influence of longitudinal dispersion and transverse diffusion. Transverse spreading of the substance continues until the edges of the cloud encounter the stream banks at x_3. Eventually at x_4 near uniform concentration levels are established across the stream due to the 'no mass flux' boundary conditions at the stream banks. Beyond x_4 the cloud continues to stretch in the longitudinal direction.

The region x_0 to x_2 is called the three-dimensional mixing zone because concentration gradients exist in the vertical, transverse and longitudinal directions. Between x_2 and x_4 the most significant concentration gradients only exist in the transverse and longitudinal directions. This region is called the two-dimensional or transverse mixing zone because the transverse concentration gradients are dominant. Beyond x_4 the most significant concentration gradients exist in the longitudinal direction and the region is called the one-dimensional or longitudinal mixing zone.

Mathematical Representation

Mixing and transport models have been developed using principles of fluid mechanics, mass transport and numerical methods. The basis for all models is the three-dimensional mass balance equation for neutrally buoyant substances derived for steady state river flow conditions (see Putz, 1996 for details). However, rivers have a large width to depth ratio, therefore effluent discharged to the river will rapidly mix in the vertical compared to the transverse and longitudinal directions (see Figure 1 for the coordinate system definition). The distance required establishing uniform vertical concentrations is in the order of 50 to 100 river depths downstream of the source. Hence, for practical applications the general three-dimensional mass balance equation is depth-averaged resulting in the following two-dimensional equation (see Putz, 1983 for details):

$$\frac{\partial}{\partial t}(h\,c) + \frac{\partial}{\partial x}(h\,uc) + \frac{\partial}{\partial z}(h\,wc) = \frac{\partial}{\partial x}\left(h\,E_x\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial z}\left(h\,E_z\frac{\partial c}{\partial z}\right) \qquad [1]$$

where: $\frac{\partial}{\partial t}(hc)$ represents the change in concentration with time,

$\frac{\partial}{\partial x}(huc)$, $\frac{\partial}{\partial z}(hwc)$ represent changes in concentration due to advective flux,

$\frac{\partial}{\partial x}\left(hE_x\frac{\partial c}{\partial x}\right)$, $\frac{\partial}{\partial z}\left(hE_z\frac{\partial c}{\partial z}\right)$ represent changes in concentration due to diffusive flux and differential advection,

E_x and E_z are the longitudinal and transverse mixing coefficients; h is the local depth, u, and w are velocities in the x and z directions (see Figure 1) and c is concentration. Note u, w and c are time and depth-averaged quantities

River mixing models are generally based upon further simplifications of [1]. At some distance downstream of the effluent source, in what is termed the longitudinal or one-dimensional zone, the mixing has progressed to the extent that uniform concentrations have been established across the river channel (i.e. in the transverse direction). Under these conditions and assuming the channel to be prismatic [1] can be reduced to:

$$h\frac{\partial c}{\partial t} + hu\frac{\partial c}{\partial x} = h\,E_x\frac{\partial^2 c}{\partial x^2} \qquad [2]$$

Investigators have developed analytical and numerical solutions for the longitudinal mixing zone based upon [2]. However, as stated by Beltaos (1979), the distance required to establish uniform concentrations across the channel increases with the square of the channel width and therefore the practical value of these models can be limited by the channel size. Typically the distance to uniform concentration can be expected to be in the range of 100 to 350 river widths. Furthermore, in many situations the river region of primary interest is often within the transverse mixing zone where limited dilution of the effluent has occurred and large concentration gradients exist across the channel.

Within the transverse mixing zone, it can be shown using order of magnitude analysis that $\partial c/\partial z$ is much greater in magnitude than $\partial c/\partial x$. Therefore, the diffusive flux in the transverse direction is much greater than in the longitudinal direction. Applying this simplification, assuming a prismatic channel and that the advective transport in the z direction is negligible (i.e. w = 0), then [1] reduces to (see Putz, 1983 for details):

$$h\frac{\partial c}{\partial t} + hu\frac{\partial c}{\partial x} = \frac{\partial}{\partial z}(h\,E_z\frac{\partial c}{\partial z}) \qquad [3]$$

If the effluent input mass flux is steady state, a time independent concentration distribution will be established downstream of the source. For steady state conditions [3] may be further simplified by omitting the time differential.

Several mixing models have been developed for steady state conditions in the transverse mixing zone (examples are Lau and Krishnappan, 1981; McCorquodale et. al., 1983; and Gowda, 1984). Some use cartesian coordinates as in [3]. Others utilize a streamtube approach employing a transformation of the transverse coordinate z, to cumulative flow q. Cumulative flow is determined as follows:

$$q_{(z)} = \int_0^z uh\,dz \qquad [4]$$

where z = 0 represents the left bank (looking downstream) as shown in Figure 5; and u is the depth averaged velocity in the direction of flow. At the right bank z = W, the total stream width, and q = Q, the total stream discharge. Transverse coordinates are then expressed as a dimensionless q/Q ratio, where q/Q=0 is the left bank and q/Q=1 is the right bank.

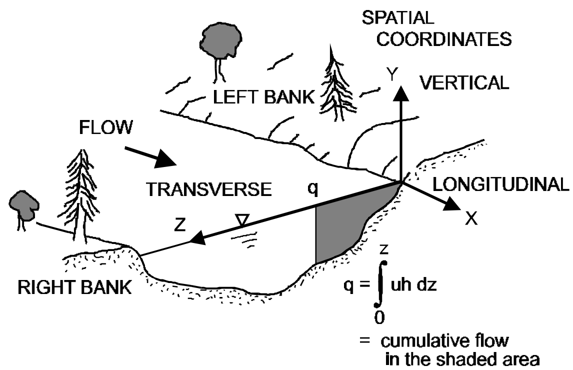

Figure 5 Transverse coordinate transformation.

The q transformation converts the plan view of a natural stream of variable width to a simple rectilinear form of constant width Q. A line of constant q along the stream represents a streamline and adjacent lines of constant q define a streamtube. There is no average flow across a streamline and therefore no depth-averaged transverse advection. The adaptation of a streamtube approach for representation of the river flow (Yotsukura and Cobb, 1972) and the use of this concept in the numerical solution of [3] further justifies not including a transverse advective term in [3].

The magnitude of the transverse mixing coefficient E_z represents the amount of mixing which occurs or how quickly an effluent plume will spread across a channel. It is generally given by an expression in the form[2]:

$$E_z = \beta L \Omega \qquad [5]$$

where L is a length scale representative of the mixing length or eddy size, Ω is a velocity scale representative of the level of turbulence, and β is the dimensionless transverse mixing coefficient. The length scale is generally taken to be the local depth h, or the channel average stream depth H. The velocity scale is generally taken to be the local shear velocity u* or the channel average U* given by the expression:

$$u^* = \sqrt{g\,r\,S} \quad \text{or} \quad U^* = \sqrt{g\,R\,S} \qquad [6]$$

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[2] See Putz (1996) for a review of the development of this expression and methods for estimating E_z.

where g is the gravitational constant, r is the local hydraulic radius, R is the channel average hydraulic radius, and S is the slope of the energy grade line (slope of the water surface for uniform flow). The dimensionless transverse mixing coefficient β is used to characterize the mixing in a river reach. If β is known, or can be estimated, then E_z can be determined with [5] using the appropriate value of the length and velocity scale for a particular location on the river.

AOG Modelling Procedure

Substance concentrations resulting from an intermittent or fluctuating discharge into a river can not be satisfactorily modelled in the two-dimensional zone using [2] (the one-dimensional situation) or the steady state versions of [1] or [3]. In such cases, a complete two-dimensional time dependent model is required.

Two-dimensional, time dependent modelling techniques have been described by Holly (1975), and Harden and Shen (1979). These methods employ elaborate implicit finite difference techniques for numerical solution of [1] at grid points superimposed at regular longitudinal spacing along the river channel. These methods are complicated and are susceptible to numerical dispersion errors. The root of the problem is associated with the grid spacing used to discretize the river channel and the selected time increment. In order to minimize numerical dispersion the grid spacing and time increment must be carefully selected to optimize the solution method. Unfortunately, with a natural channel the varying depths, velocities, and widths make it impossible to achieve this optimum over the entire channel when regular grid spacing is employed. In addition to these technical numerical problems, only steady-state field data have been presented for verification of these models.

An alternative approach for solving [3] was proposed by Fischer (1968). This approach uses a streamtube representation of the river and separates the mixing process into two substeps for each time increment. First, the advective mass flux is simulated by simple translation of the concentration by one increment down each streamtube. Second, the transverse diffusion between adjacent streamtubes is simulated using a Fickian diffusion model. Fischer's method does not solve the governing differential equation directly, however, the method is very appealing in that it seeks simplification through a physical understanding of the processes involved (Beltaos and Arora, 1988).

Fischer's approach requires near complete mass exchange between successive streamtube elements for the advective substep. This requirement is only fulfilled if the dimensionless parameter C_r (Courant No.) is equal to one for each streamtube element (i.e. $C_r = 1$). Courant No. is given by the expression:

$$C_r = u\Delta t/\Delta x \qquad [7]$$

where u is the mean flow velocity through the element, Δt is the magnitude of the time step and Δx is the length of the element. Holly (1975) demonstrated that the method is highly subject to numerical diffusion errors if this condition is not meet. This dictates that for application of Fischer's approach to rivers (with transverse and longitudinal variations in mean velocity), it is necessary to vary Δt and/or Δx to maintain Cr = 1 for each element in a grid representation of the channel. In effect, an optimized grid must be generated rather than the more customary symmetrical grid (the method was later termed the Advection Optimized Grid or AOG method). Given the complexity and the lack of adequate verification of the elaborate implicit schemes, Sobey (1981) suggested that Fischer's approach be further investigated.

Beltaos (1978), and Beltaos and Arora (1988) reported the development of a two-dimensional mixing model based upon the AOG approach. The longitudinal grid spacing employed by the model is selected based upon flow velocity in each streamtube and ensures Cr = 1 for each element. An example of the grid structure is shown in Figure 6. At each time step in the advective substep there is complete exchange from element(i,j) to element(i+1,j) which eliminates the numerical diffusion error mentioned above.

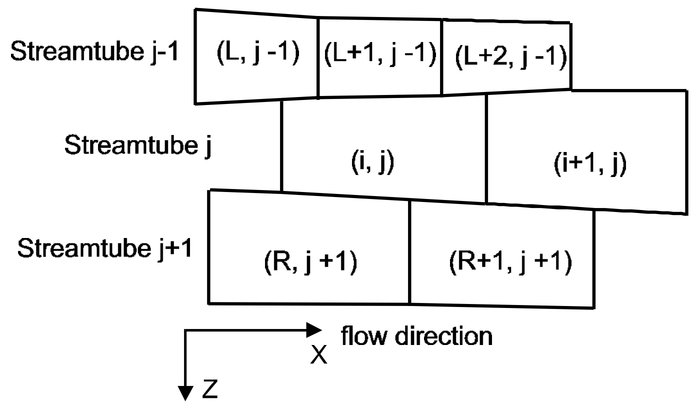


Figure 6 Asymmetrical grid space.

The diffusive substep then distributes mass laterally between streamtubes using a Fick's law approximation. Because of the asymmetrical nature of the grid, the elements are not aligned. For element(i,j), shown in Figure 6, the diffusive exchange with each neighbouring element sharing a portion of its side boundary is simulated as follows:

[8]

$$(\Delta c_{i,j})Vol_{i,j} = E^{l}\left[\frac{c_{l,j-1} - c_{i,j}}{\Delta z_{i,l}}\right]a_{i,l}\,\Delta t + E^{l+1}\left[\frac{c_{l+1,j-1} - c_{i,j}}{\Delta z_{i,l+1}}\right]a_{i,l+1}\,\Delta t$$
$$+ E^{l+2}\left[\frac{c_{l+2,j-1} - c_{i,j}}{\Delta z_{i,l+2}}\right]a_{i,l+2}\,\Delta t + E^{r}\left[\frac{c_{r,j+1} - c_{i,j}}{\Delta z_{i,r}}\right]a_{i,r}\,\Delta t + E^{r+1}\left[\frac{c_{r+1,j+1} - c_{i,j}}{\Delta z_{i,r+1}}\right]a_{i,r+1}\,\Delta t$$

where: $\Delta c_{i,j}$ is the change in concentration of element(i,j),
$Vol_{i,j}$ is the volume of element(i,j),
$a_{i,m}$ is the side boundary area shared between element i,j and an adjacent element,
$\Delta z_{i,m}$ is the average distance between centroids of adjacent elements,
E^{m} is the local transverse mixing coefficient between adjacent elements, and
Δt is the duration of the time step.

$Vol_{i,j}$, $a_{i,m}$ and $\Delta z_{i,m}$ are calculated using the dimensions of each element. The element dimensions are calculated based upon hydrometric survey data and stored in an array by a preprocessing program. The element characteristics are recalled as required during the mixing computations. Beltaos (1978) noted that the diffusion substep might be subject to a numerical diffusion error if the $\Delta x/\Delta z$ ratio is too large. A limit of $\Delta x/\Delta z < 10$ is suggested for good results.

Beltaos used previously published results from laboratory experiments and field measurements at a single cross section during a slug tracer test on the Athabasca River to access the model. The comparison of the model output to the field tracer test gave good results although there was some minor translation in the time scales of the measured and simulated concentration vs. time curves.

Luk et al. (1990) also developed a two-dimensional unsteady effluent source model based upon the AOG approach. The model was accessed using a two-dimensional unsteady tracer test in a sinusoidal curved laboratory channel. Luk et al. also investigated the potential effect of varying the sequence of the advective, diffusive and reactive substeps within a time step but could not identify any problems.

Putz (1996) developed a microcomputer-based version of the AOG model and provided a much more extensive verification of the method using data from previously conducted slug tracer tests on the Peace, North Saskatchewan and Slave Rivers. A critical factor identified for successful application of the model is to have adequate definition of the river channel geometry in the transverse mixing zone. This requirement is much more significant for time dependent modelling than for steady state conditions. The results of these model assessments were reported by Putz and Smith (1998). A version of the AOG model developed by Putz was used for all the mixing analysis described in this report. Details of the model structure, input requirements, output options, grid construction etc. are described by Putz (1996).

The separation of the mixing process in the AOG model into substeps during each time increment allows relatively easy incorporation of reaction subroutines into the numerical scheme. For example the equation governing the mixing and first order decay of carbonaceous BOD is:

$$\frac{\partial L}{\partial t} + u\frac{\partial L}{\partial x} = u\frac{\partial}{\partial z}\left(E_z\frac{\partial L}{\partial z}\right) - K_d L \qquad [9]$$

in which L is carbonaceous BOD and K_d is a first order rate constant for decay of L. The change in BOD concentration during each time step within each element is then given by:

$$\Delta L_{i,j} = -K_d L_{i,j}\Delta t \text{ or } L_{i,j,t+\Delta t} = L_{i,j,t}e^{-K_d\Delta t} \qquad [10]$$

Similarly, more complex reaction terms can easily be incorporated, provided the kinetics of the reaction is known. Mass flux at the water-air and/or the water-bed interfaces can also be incorporated as the areal dimensions of the streamtube elements are readily available from the output of the preprocessing program used to generate the asymmetrical grid. Two applications of the AOG model for simulation of non-conservative substances are described by Putz (1996). These applications include simulation of BOD and dissolved oxygen concentrations in the South Saskatchewan River downstream of a wastewater treatment plant, and simulation of methoxychlor levels in the Athabasca River after a short duration release of the insecticide.

SITE CHARACTERIZATION

Introduction

The tracer tests were conducted on the Athabasca River near Boyle, Alberta. The study reach extends for approximately 32 km. downstream of the diffuser structure of Alberta Pacific Forest Industries pulp mill. A plan view of the study reach is shown in Figure 7. The confluence of the La Biche River and Calling River are located at approximately 17 km. and 33 km., respectively, downstream of the mill diffuser structure. Extensive hydrometric surveys of the study reach were conducted August 19 to 24, 1997. Previous surveys had been conducted in October 1994 (low flow, open water) and February 1995 (ice covered conditions) for Alberta Pacific Forest Industries (Beak Consultants Ltd., 1995).

Hydrometric Data

Cross-section Surveys

Seventeen cross sections were established in the study reach during the 1997 surveys. The location of each section in relation to the Alberta Pacific Forest Industries diffuser structure was measured using Global Positioning System (GPS) equipment. Water depths across each section were measured using echo sounding equipment. The position of the sounding boat during the depth surveys was also determined by GPS measurements. The locations of these cross sections (designated SFMNCE) are shown in Figure 7. Additional cross section information was available from the two previous surveys by Beak Consultants Ltd. The positions of these sections (designated BEAK) are also shown in Figure 7.

Cross section data tabulations and plots were then prepared for each section location for the dates on which of tracer tests were conducted. This required minor adjustments of the survey measurements to account for change in river flow between the survey date and the tracer test date. An example data tabulation and plot is shown in Table 1 and Figure 8. Odigboh (1999) presents the complete set of cross section tabulations and plots for the study reach.

Channel Slope

The average slope of the water surface through the study reach was determined to be 0.000166 m/m using elevation measurements taken using GPS equipment. Approximately 10 to 15 individual measurements of the water surface were recorded at each transect as the depth soundings were conducted. The average of these measurements at each transect was plotted versus distance and the best fit line through these points was used to approximate the slope of the water surface through the reach (Odigboh, 1999).

Velocity and Discharge

Environment Canada monitors the Athabasca River flow at the town of Athabasca approximately 40 km. upstream of the study reach. The flow time to the study reach is approximately one day. The monitored flow at the gauging station at Athabasca was used to estimate the discharge in the study reach accounting for the time lag.

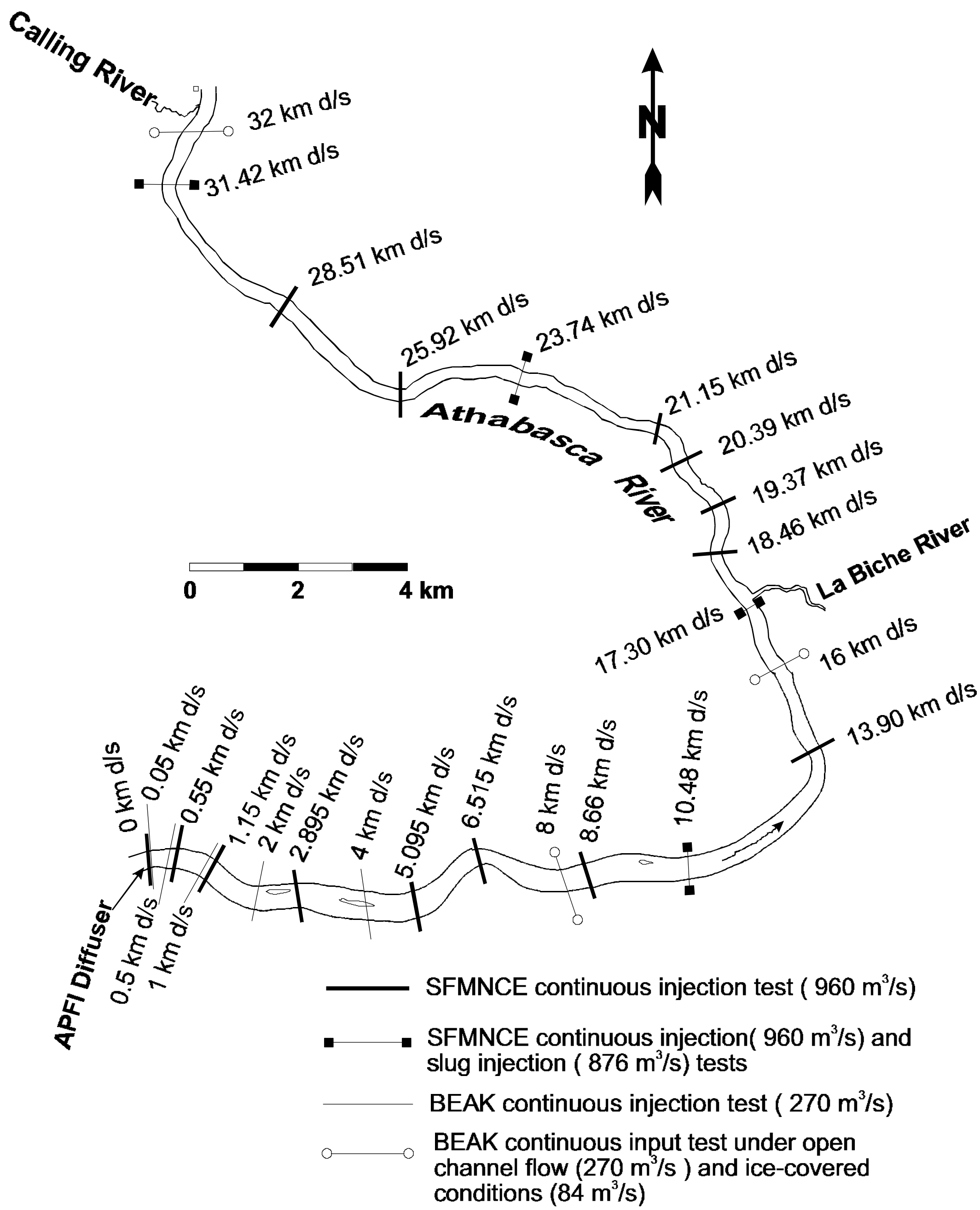
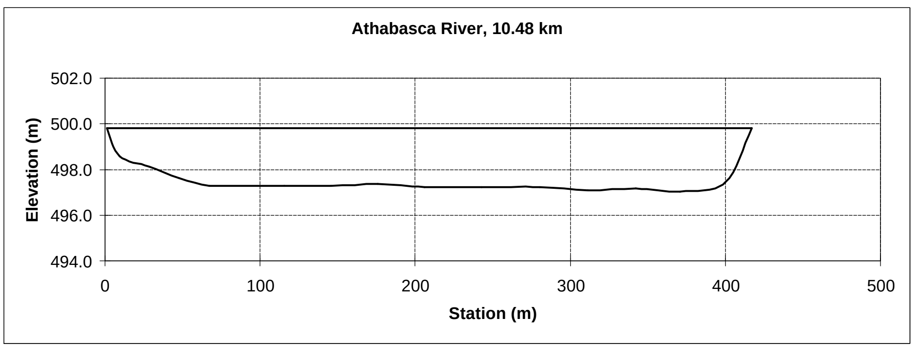


Figure 7 Athabasca River study reach downstream of the Alberta Pacific Forest Industries diffuser structure.

Table 1 Example cross section data tabulation.

X-section:	Athabasca River, 10.48 km d/s		
Date:	August 21, 1997		
Discharge (m^3/s) :	960.00	Estimated water surface elevation (m):	499.80
Width (m):	415.64	Left bank (LB) = 1.35	499.80
Mean depth (m):	2.38	Right bank (RB) = 416.99	499.80
Area (m^2):	987.63		
Mean velocity (m/s):	0.97		

Sta. (m)	Elev. (m)	h (m)	w/W	u (m/s)	DQ (m^3)	q/Q	Area (m^2)	adj. U (m/s)
1.35	499.80	0.00	0.000	0.000	0.00	0.000	0.00	0.000
9.50	498.59	1.21	0.020	0.619	1.52	0.002	4.92	0.608
28.52	498.14	1.66	0.065	0.765	18.86	0.021	32.18	0.752
48.05	497.62	2.18	0.112	0.917	31.54	0.053	69.67	0.901
67.44	497.30	2.50	0.159	1.006	43.65	0.098	115.06	0.989
86.35	497.30	2.50	0.205	1.006	47.62	0.147	162.38	0.989
115.83	497.30	2.50	0.275	1.006	74.23	0.223	236.15	0.989
145.83	497.30	2.50	0.348	1.006	75.56	0.300	311.24	0.989
176.25	497.36	2.44	0.421	0.989	74.98	0.377	386.40	0.971
206.14	497.23	2.57	0.493	1.024	75.27	0.454	461.20	1.006
242.88	497.23	2.57	0.581	1.024	96.56	0.552	555.54	1.006
280.31	497.23	2.57	0.671	1.024	98.37	0.653	651.64	1.006
311.47	497.10	2.70	0.746	1.058	85.37	0.740	733.68	1.039
342.29	497.17	2.63	0.820	1.041	86.17	0.829	815.80	1.022
370.88	497.04	2.76	0.889	1.075	81.54	0.912	892.89	1.056
399.86	497.43	2.37	0.959	0.971	76.11	0.990	967.30	0.954
416.99	499.80	0.00	1.000	0.000	9.87	1.000	987.63	0.000
			Est. total =		977.22			



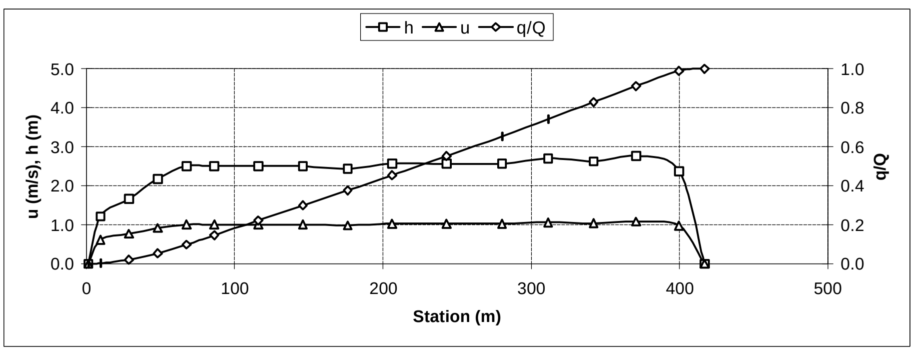


Figure 8 Example cross section plot.

A synthesized velocity distribution across each section was prepared using Manning's equation, average depth H, located depth h, and average velocity U.

$$u = \frac{1}{n} r^{2/3} S^{1/2} \quad \text{and} \quad U = \frac{1}{n} R^{2/3} S^{1/2} \quad \therefore \quad u = U\left(\frac{h}{H}\right)^{2/3} \qquad [11]$$

H and U are determined using the cross section area A and width W from hydrometric surveys and the total river flow Q. The synthesized velocity distribution and local depths were used to estimate the q distribution according [4]. Odigboh (1999) gives the details of this procedure. A tabulation and plot of local velocity u, and dimensionless cumulative flow q/Q was prepared for each cross section (an example is presented in Table 1 and Figure 8).

Velocity and discharge measurements were taken at seven cross sections during the 1997 field surveys. These measurements were used primarily as a check against the synthesized velocity distributions, and a check of the monitored discharge. All velocity measurements were taken utilizing a Price type velocity meter suspended with a cable and weight from the survey boat (see Odigboh, 1999 for further details). A sufficient number of measurements were taken across each section to allow a reasonably accurate estimate of the discharge (10 locations in most cases). Distances to the banks from the survey boat were determined using a laser electronic distance measuring device.

River total discharge calculated based upon velocity measurements and those reported at the gauging station (accounting for the one day lag) are shown in Table 2. In all but one case, the error is less than 6%. The gauging station data were used in the preparation of velocity and flow distributions for use in the modelling procedures.

Table 2 Gauging station discharge versus discharge measurements.

Date	Transect (km)	Gauge discharge[a] (m^3/s)	Meas. discharge (m^3/s)	% diff.
Aug. 19, 1997	11.50	1049	859	-18.0
Aug. 19, 1997	28.95	1049	1027	-2.1
Aug. 20, 1997	65.15	1083	1046	-0.3
Aug. 20, 1997	10.48	1083	1035	-4.4
Aug. 23, 1997	17.30	831	802	-3.5
Aug. 24, 1997	23.74	780	826	+5.9
Aug. 23, 1997	31.42	831	822	-1.1

[a] average daily flow reported at the gauging station

The discharge measurements taken on August 23 were located upstream and downstream of the confluence with the La Biche River (~17.5 km downstream). The difference in these flow measurements indicates the La Biche River discharge is approximately 20 m^3/s.

An example comparison plot of measured and synthesized velocities across a section is shown in Figure 9. Odigboh (1999) presents a complete set of these comparisons. For the majority of the sections, the measured and synthesized velocities demonstrate reasonable agreement. Therefore, synthesized velocities were used for the preparation of data files used in the modelling procedures.

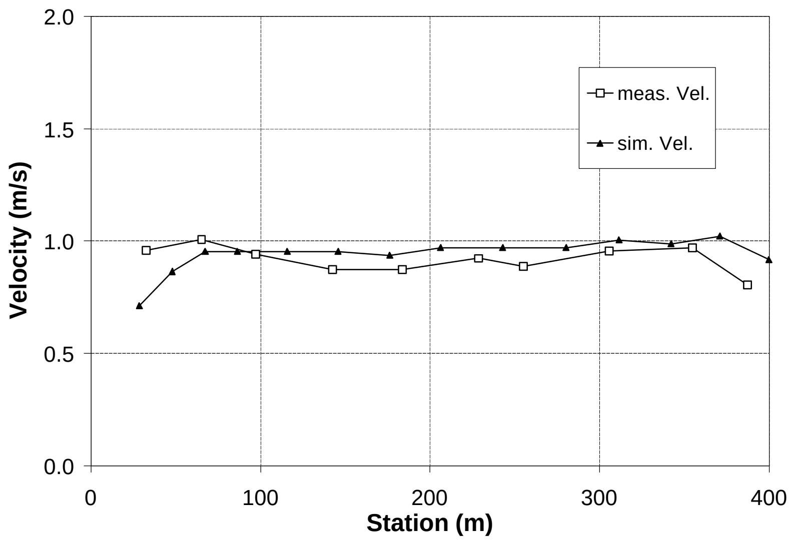


Figure 9 Measured and synthesized velocity distribution at 10.48 km. downstream.

Summary

A summary of the study reach characteristics compiled from the 1997 SFMNCE surveys and from surveys reported by Beak Consultants Ltd. (1995) is presented in Table 1. The data shown are reach characteristics for the days upon which tracer tests were conducted.

Table 3 Summary of Athabasca River study reach characteristics.

Parameter	Feb., 1995[a]	Oct., 1994[a]	Aug., 1997[b]
Flow , m^3/s	84 (ice-covered)	270 (open water)	960 (open water)
Sections surveyed	4	8	17
Avg. width (range), m	250 (187 to 326)	283 (203 to 350)	302 (209 to 467)
Avg. depth (range), m	1.1 (1.0 to 1.3)	1.5 (1.2 to 2.0)	2.92 (2.1 to 3.4)
Avg. velocity (range), m/s	0.3 (0.3 to 0.4)	0.7 (0.6 to 1.0)	1.2 (1.0 to 1.4)

notes: [a] Characteristics are based upon cross section surveys reported by Beak Consultants Ltd. (1995)
[b] Characteristics are based upon SFMNCE surveys. Tracer tests were conducted at flows of 960 m^3/s and 876 m^3/s. Characteristics for each were very similar therefore, only the 960 m^3/s data are shown here.

TRACER TESTS

Introduction

Two tracer tests were conducted in August 1997 downstream of the Alberta Pacific Forest Industries effluent diffuser. While compiling background information in order to plan these SFMNCE tracer tests it was discovered that two previous tracer tests had been conducted at this location for Alberta Pacific. The four tracer tests cover a range of flow and input conditions as outlined below:

- 84 m^3/s, ice cover, February 1995, continuous tracer input,
- 270 m^3/s, open water, October 1994, continuous tracer input,
- 960 m^3/s, open water, August 1997, continuous tracer input, and
- 876 m^3/s, open water, August 1997, slug input of tracer.

Odigboh (1999) presents the methodologies for the SFMNCE tests. Beak Consultants Ltd. (1995) describe the methodologies for the October 1994 and February 1995. A brief summary of input conditions and sampling for the four tests are presented in this report.

Input Conditions

For each of the continuous input tests Rhodamine WT fluorescent dye was injected at a constant mass flow rate into the mill treated effluent pipeline. The tracer entered the river with the treated mill effluent via the submerged diffuser structure located below the river bed. The diffuser is 52 m long with 25 outlet ports (20 of which were in operation in August 1997), oriented approximately perpendicular to the river flow, and located close to the right bank (looking downstream) of the river.

A sufficiently long period of continuous injection was maintained during each test to establish steady-state concentration conditions at each section in the river. A summary of the input conditions for each of the continuous input tests is presented in Table 4.

Table 4 Summary of input conditions for continuous input tests.

Date	q_{in} (mL/min)	C_o (μg/L)	Q (m^3/s)	Duration (hours)	C_∞ ((μg/L)
August 21, 1997	74	2.4×10^8	960	7	0.31
Feb. 26 to Mar. 1, 1995	17	2.4×10^8	84	24	0.80
Oct. 16 to 17, 1994	15	2.4×10^8	270	48	0.22

note: Sample concentrations reported by Beak Consultants Ltd. (1995) were based upon an assumed feed solution concentration of 100%, however dye is supplied at a maximum concentration of 20% active ingredient. The fully mixed concentrations shown above are based upon input of 20% active ingredient.

In Table 4 C_∞ represents the fully mixed tracer concentration in the river (in excess of background levels). C_∞ is given by the expression:

$$C_\infty = q_{in} C_o / (Q + q_{in}) \approx q_{in} C_o / Q \quad \text{for } q_{in} << Q \qquad [12]$$

where q_{in} is the tracer input flow, C_o is the tracer input concentration and Q is the total river flow.

The slug input test consisted of a rapid direct injection of 17 litres of 20% solution of Rhodamine WT dye (4.05 Kg. fluorescent component). The dye was dumped at approximately the mid-point along the length of the diffuser. The dump time was 9:07 a.m. on August 22, 1997. The dump time was selected to allow sampling crews to be on station when the dye plume arrived at sampling sections and to be completed at most distant cross section before night fall.

Sampling Procedures and Analysis

For the open water continuous input tests samples were taken at each cross section during the steady-state period. The position of each sampling point across each section was recorded using GPS equipment. During the ice-covered test the samples were withdrawn from holes drilled through the ice which had been used to measure position, river depth and ice thickness (Beak Consultants Ltd., 1995).

During the slug test the passage of the dye plume was sampled at four cross sections. Each section was traversed and sampled approximately ten times during the passage of the dye plume. The sampling period was scheduled to begin before the plume arrived and was continued until the extent of the plume had passed (Odigboh, 1999).

Samples were taken at two depths (approximately 0.3 and 1.5m) during the SFMNCE continuous input test. Subsequent analysis of the samples showed that concentration readings at the two depths were equivalent as expected. The concentrations reported here for the SFMNCE continuous input test are an average of the readings at the two depths. Samples for the 1994 and 1995 continuous input tests ((Beak Consultants Ltd., 1995) and for the 1997 slug input test were taken from one depth only.

Tracer Measurement Results

Continuous Input Tests

The results of the tracer measurements for the continuous input tests are shown in Figure 10 to Figure 12. The horizontal axis on each of these plots represents dimensionless cumulative flow, q/Q, where q is the flow accumulated from the left bank (looking downstream) and Q is the total stream flow. The vertical axis for the continuous input test results represents non-dimensional concentration C' given by:

$$C' = c/C_\infty \qquad [13]$$

where, c is a normalized measured concentration and C_∞ is the fully mixed concentration of the tracer mass within the river flow. Note that the fully mixed condition expressed in terms of dimensionless concentration is C' = 1.

The tracer concentrations were normalized to account for incomplete mass recovery at individual transects. Normalized concentrations are required for comparison to the modelling results. Individual tracer measurements are normalized by dividing them by the mass recovery ratio at a section. The mass recovery of tracer at each transect was determined by integrating the measured tracer concentration versus cumulative flow curve. The mass recovery ratio is designated M_r and is given in the upper left-hand corner of the individual plots in Figure 10 to Figure 12. The average mass recovery ratios for the 1994, 1995 and 1997 continuous input tests were 0.75, 0.76 and 0.88 respectively.

The progression of the transverse mixing which occurred in the study reach during the SFMNCE continuous input test is well illustrated in Figure 13. As the effluent mixes with the river flow the plume spreads across the channel and the concentration distribution begins to approach a uniform fully mixed condition. For the August 1997 test, a distance of approximately 22 km. was required for the edge of the effluent plume to spread to the bank opposite the diffuser.

Slug Input Test

The results of the tracer measurements for the 1997 slug test are plotted using two different approaches. The first approach is shown in Figure 14. The vertical axis in these plots represents dimensionless dosage. Analysis of slug input tests using the dosage concept was developed by Beltaos (1975). Plots of dimensionless dosage versus cumulative flow are analogous to plots of c' versus q/Q for the continuous input tests. Measured dimensionless dosage and normalized dimensionless dosage are both shown in the plot. Note the dimensionless dosage distributions are similar to the dimensionless concentration distributions for the August 1997 test (see Figure 10 and Figure 14). However the peak dimensionless dosage at a several sections is slightly greater than the corresponding dimensionless concentration peak because the tracer enters the river as a point source in the slug test (e.g. see 10.48 km). The effect of the point source disappears as distance from the discharge point increases (e.g. see 31.42 km).

The mass recovery ratio for each section sampled during the slug test is given in the upper left-hand corner of the individual plots shown in Figure 14. The average mass recovery for the four transects is 0.72. Note the average mass recovery is lower that for the continuous input tests. In the continuous input tests the steady-state conditions likely allow saturation of tracer adsorption sites on the bottom sediments of the river. Hence, when the samples are taken from the water column there is near complete mass recovery. In the slug test the exposure of the tracer to the bottom sediments is transient and it likely some tracer is lost to bottom sediments.

The second approach is to plot the tracer measurements as a concentration versus time series (c-t curves) for selected q/Q locations across each transect. The concentrations series at a particular q/Q location is interpolated from the aggregate sample measurements using the GPS position and time stamp information. The q/Q locations were chosen to correspond with output locations for the modelling procedure. This facilitates comparison of the measurements and the model results. Concentration versus time curves for each of the sections sampled during the slug test are presented in Figure 15 to Figure 18.

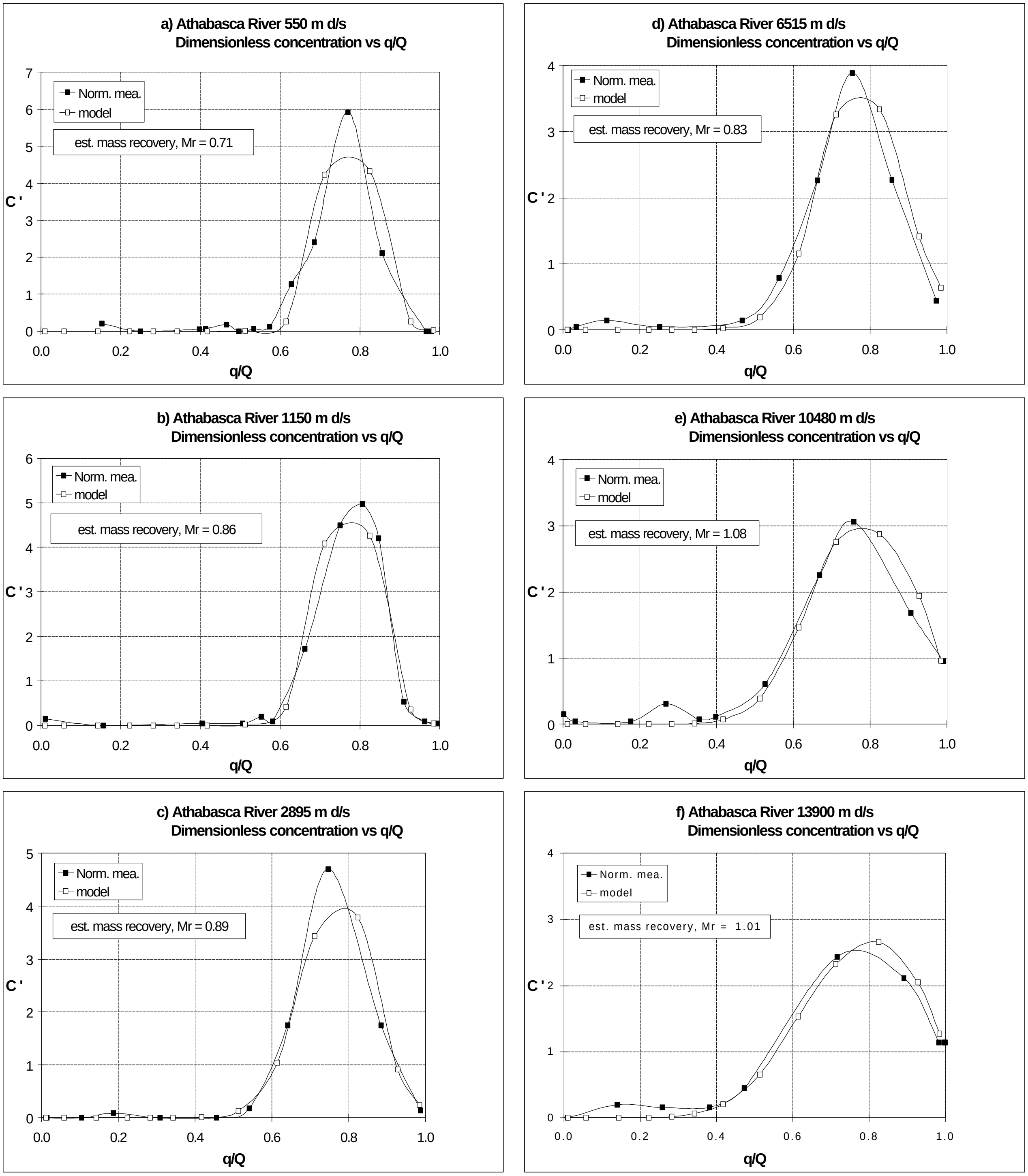


Figure 10 Tracer dimensionless concentrations and model results, 960 m^3/s, open water, continuous input.

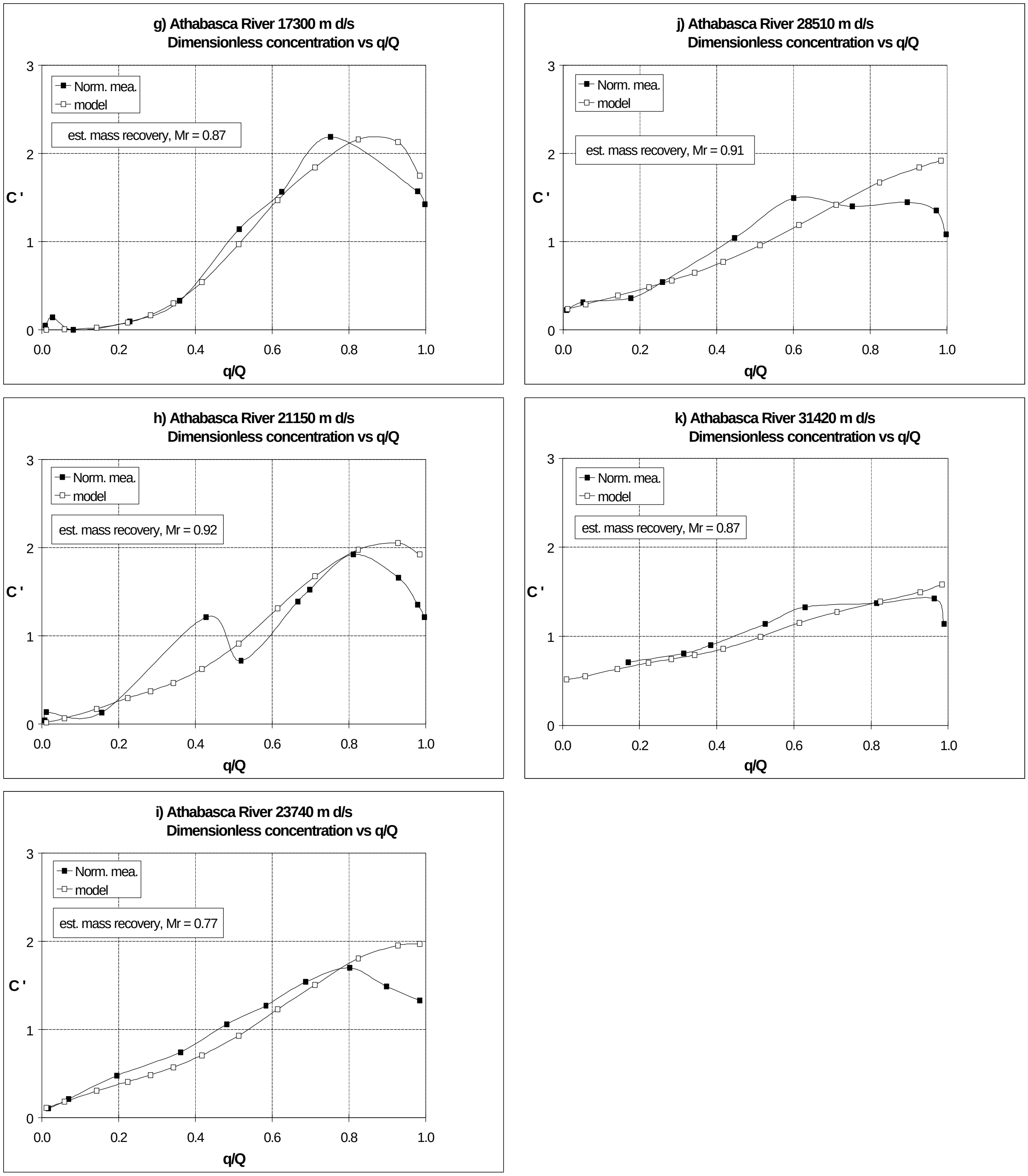


Figure 10 Tracer dimensionless concentrations and model results, 960 m^3/s, open water, continuous input - *Continued*.

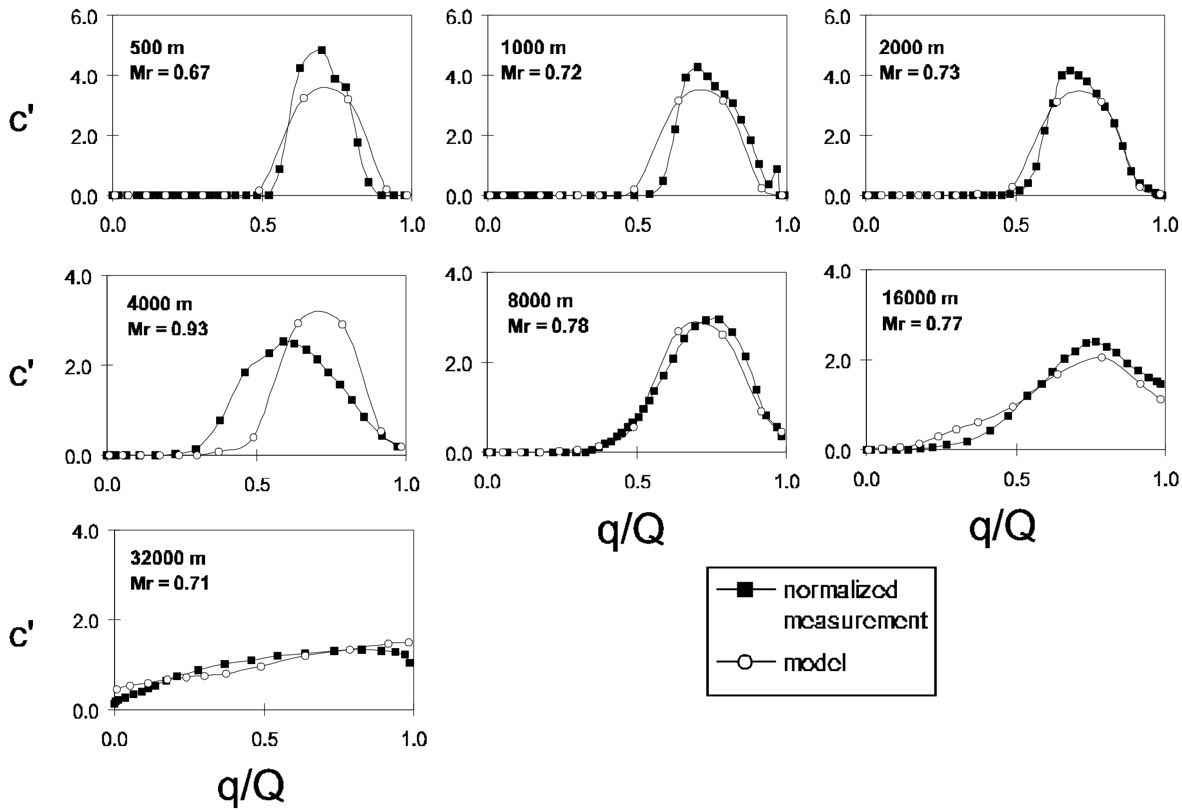


Figure 11 Tracer dimensionless concentrations and model results, 270 m^3/s, open water, continuous input.

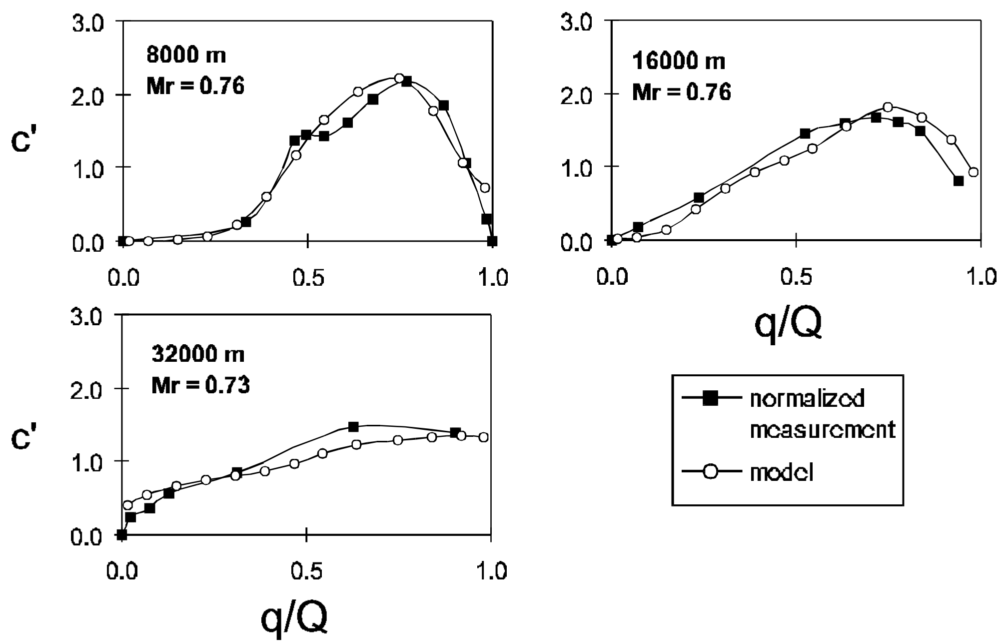


Figure 12 Tracer dimensionless concentrations and model results, 84 m^3/s, ice-covered, continuous input.

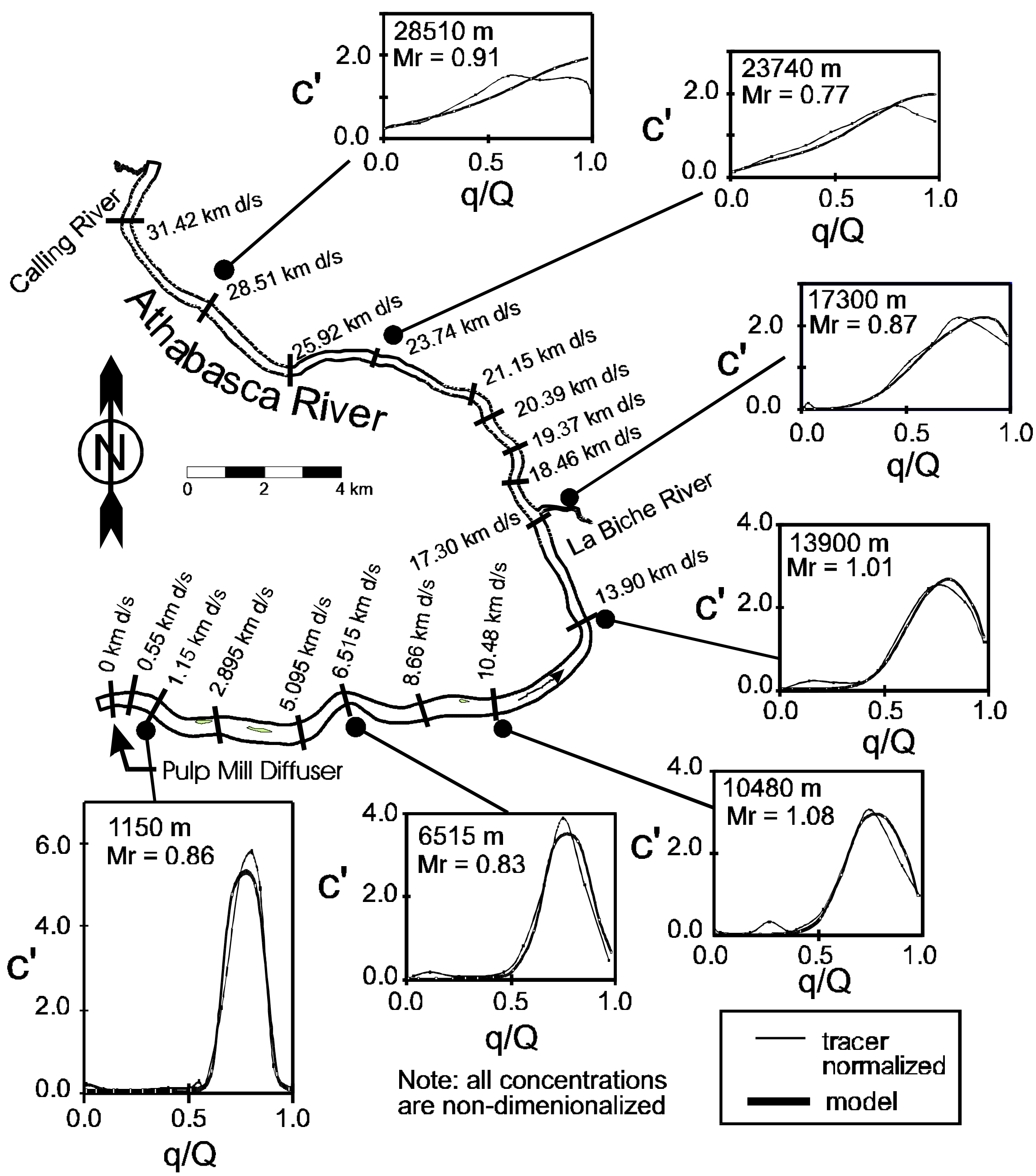


Figure 13 Athabasca River study reach, dimensionless tracer concentrations and model results, 960 m^3/s, open water, continuous input.

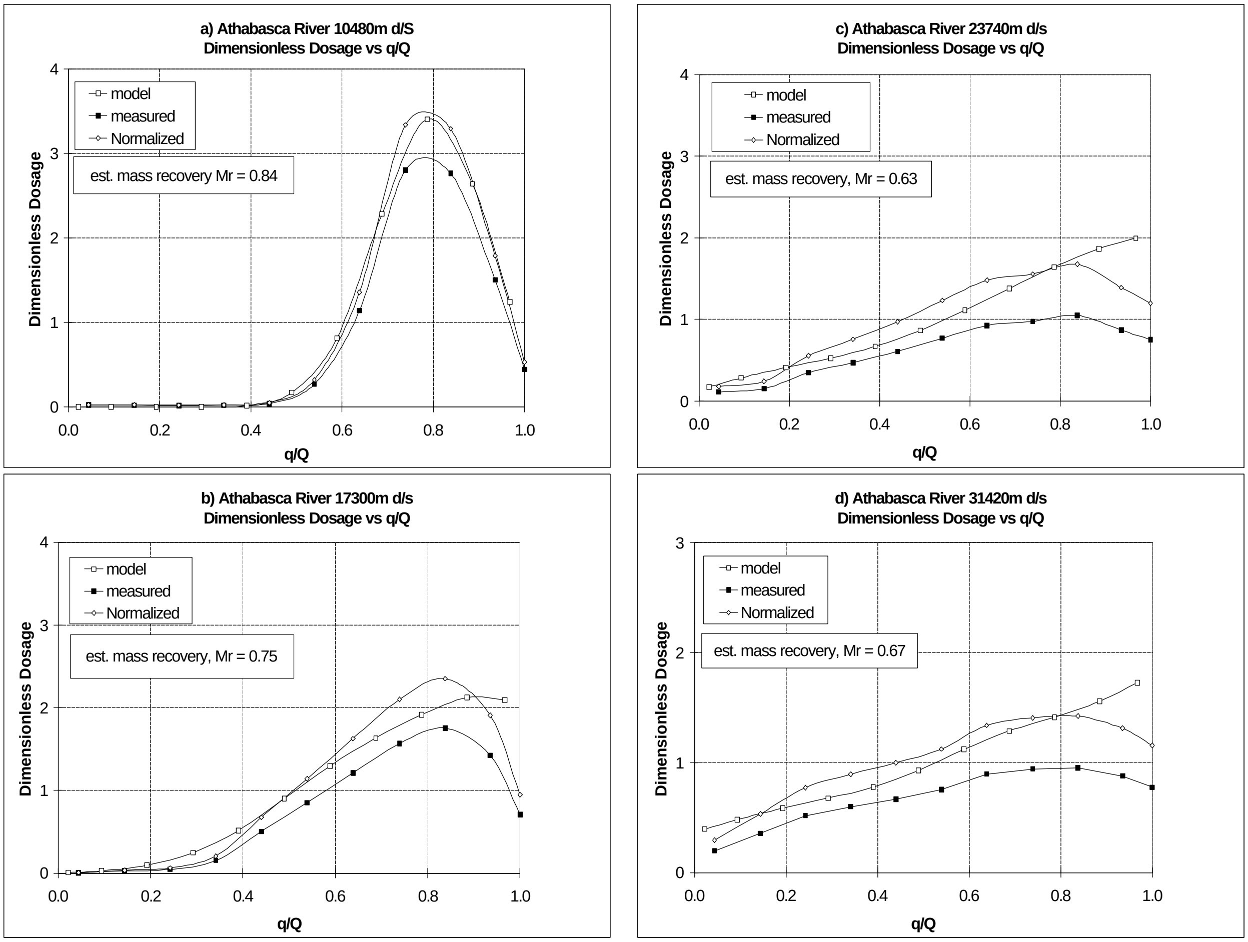


Figure 14 Tracer dimensionless dosage and model results, 876 m^3/s, open water, slug input.

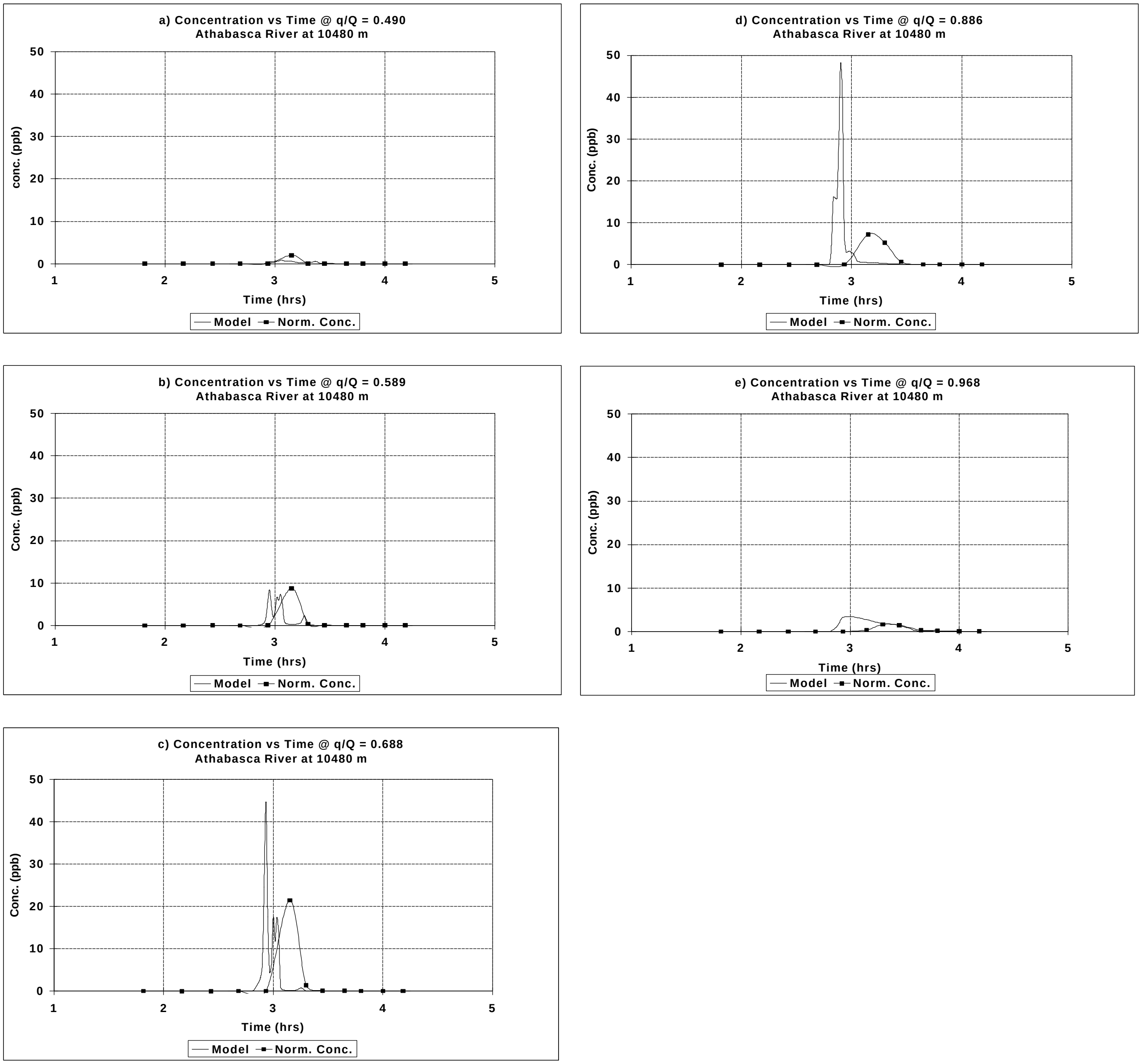


Figure 15 Athabasca River, c-t curves at 10480 m, 876 m^3/s, open water, slug input.

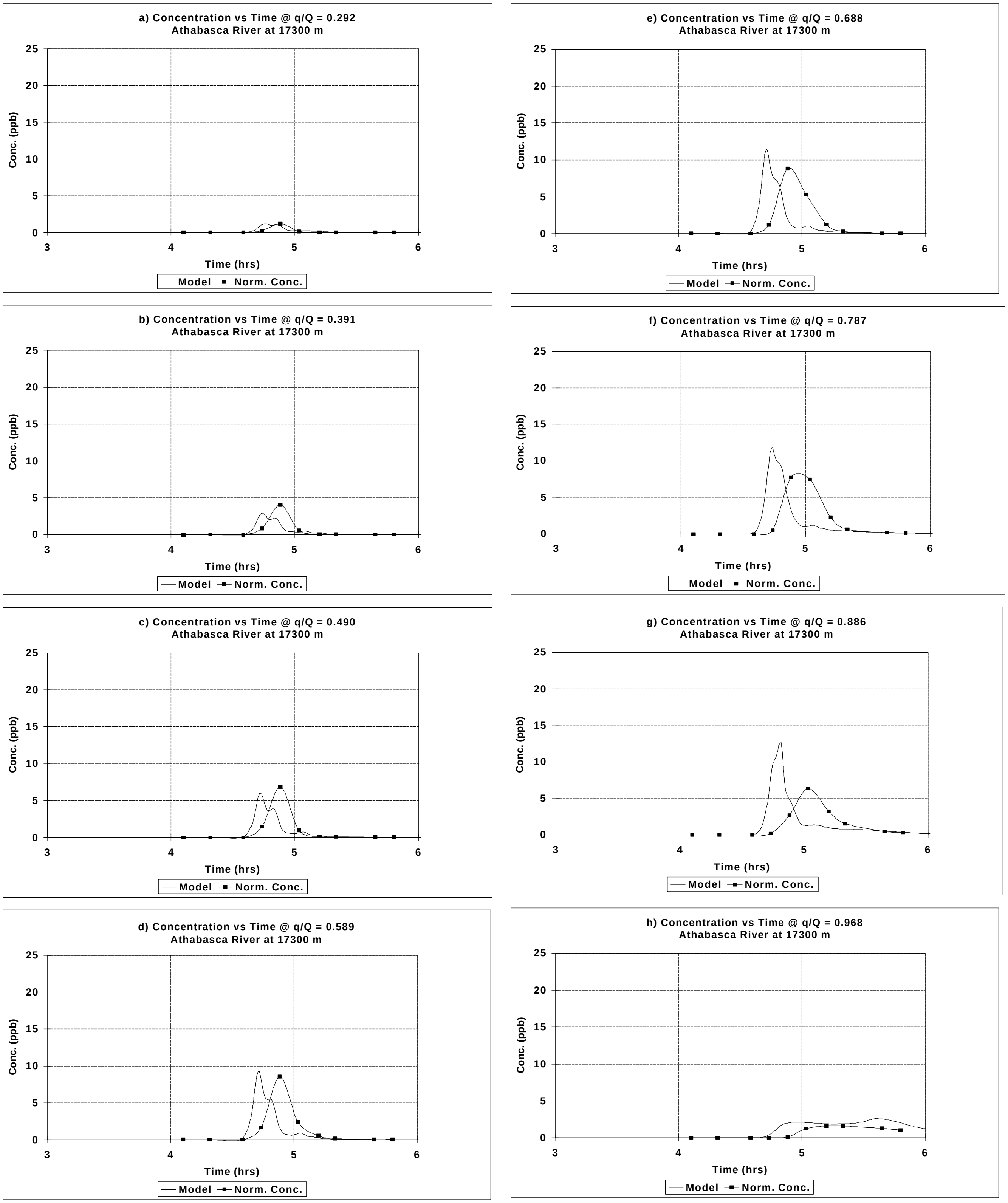


Figure 16 Athabasca River, c-t curves at 17300 m, 876 m^3/s, open water, slug input.

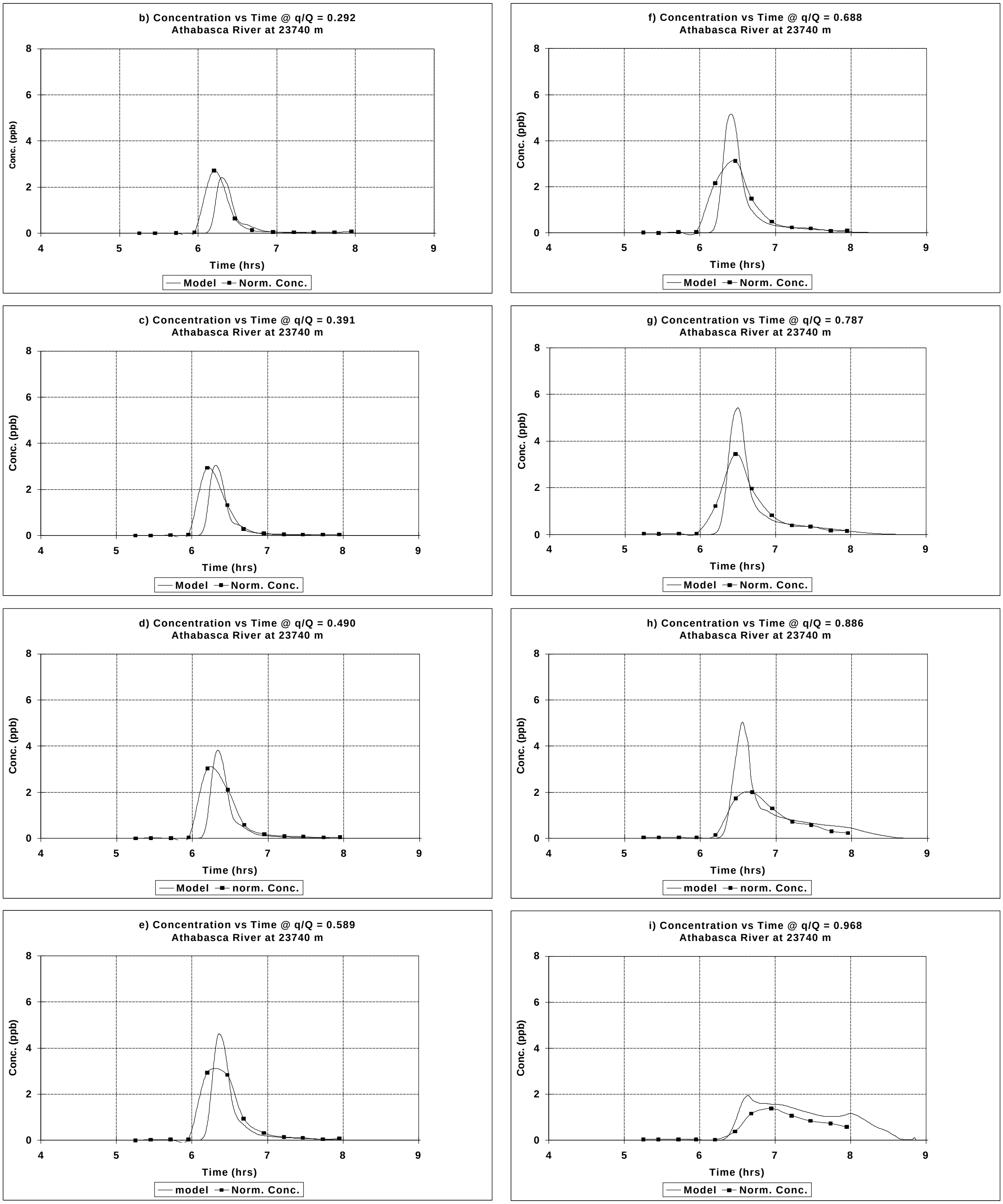


Figure 17 Athabasca River, c-t curves at 23740 m, 876 m^3/s, open water, slug input.

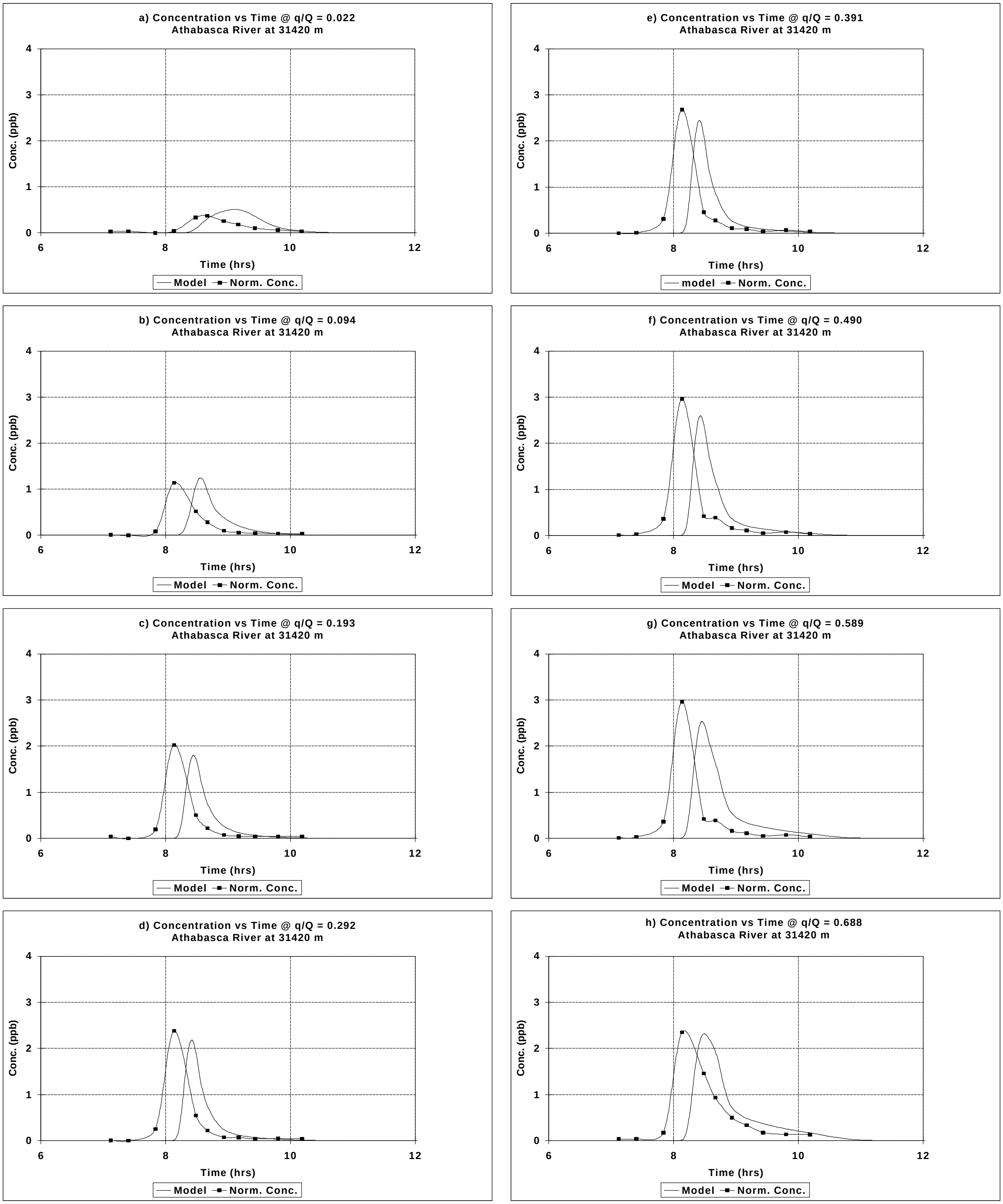


Figure 18 Athabasca River, C-t curves at 31420 m, 876 m^3/s, open water, slug input.

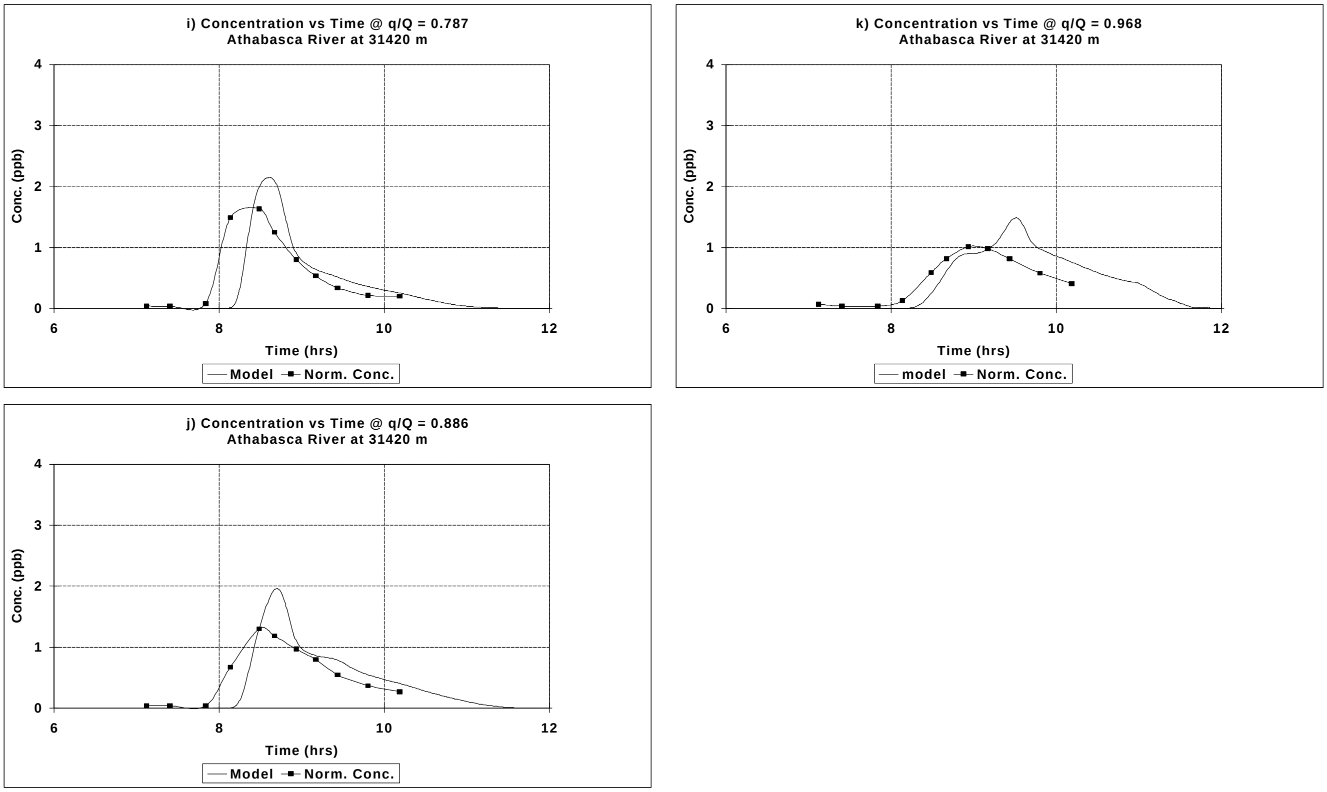


Figure 18 Athabasca River, C-t curves at 31420 m, 876 m^3/s, open water, slug input - *Continued*.

MODELLING RESULTS

Details regarding division of the study reach into streamtubes and sub-reaches, grid file construction, input data file construction, and the modelling procedures are given by Odigboh (1999). The data contained within the grid file is required to conduct the numerical calculations of the mixing simulation. This data is derived from the hydrometric surveys conducted on the river by incorporating water level and flow adjustments between the survey date and the date of the tracer test. Sufficient hydrometric data must be available for accurate representation of the reach characteristics.

Once the input and grid files are constructed (for a particular flow and input condition) successive runs of the model are executed varying β for each sub-reach until an optimum[3] match is obtained compared to the measured tracer data. In this manner, the model is calibrated for a particular flow condition. This procedure was repeated for each of the continuous input tracer tests. The same procedure was used for the slug test simulation but comparisons were made to the dosage plots.

Continuous Input Tests

Modelling results compared to normalized tracer measurements for the three continuous input tests are shown in Figure 10 to Figure 12. Overall, the Advection Optimized Grid (AOG) model provides very reliable representation of the transverse mixing in the reach for each of the flow conditions. In Figure 10 downstream of the La Biche River (approx. 17.5 km) there is evidence of a dilution effect in sample measurements compared to the model output near the left bank (i.e. $q/Q = 1$). This effect continues to approximately 31 km. Presumably, the La Biche River water mixing with the Athabasca River causes the effect.

Slug Input Test

Modelling results for the slug test are presented in Figure 14 using the dosage approach. Comparison of the model output to tracer dosage was used to select optimum values for β in the slug test simulation. As for the continuous tests, the AOG model provides reliable representation of the transverse mixing of the slug input of tracer.

The c-t curves generated by the model for the optimum β values are shown in Figure 15 through Figure 18 with the normalized c-t distributions measured at each sampling location. In general, there is a good agreement between the time base of the modelled and measured waveforms (i.e. the time between tracer arrival and departure at a section). However, there are commonly minor discrepancies between the measured and simulated elapsed time to peak concentration. These discrepancies are small compared to the elapsed time to peak (in the range of 3 to 10%). This error is well within the accuracy of stream flow measurements and the subsequent generation of the velocity and flow distribution at each cross section based upon

[3] In all cases the optimum fit was judged by visually comparing the model results to normalized measurements

these measurements. The model also appears to over estimate the peak at several of the sample points. However, this may simply be because the actual peak concentration may not have been captured in the sampling. Note for example at 10.48 km, q/Q = 0.688 and 0.886 the passage of the tracer plume occurs in approximately 10 minutes. This short duration permitted only one or two samples to be collected and hence the peak concentration could easily have been missed. A more complete discussion of the c-t model results in presented by Odigboh (1999).

Dimensionless Transverse Mixing Coefficient

The transverse mixing occurring in a river reach at a particular discharge is quantified by determining E_z (the transverse mixing coefficient). The transverse mixing can also be characterized by expressing the transverse mixing coefficient in non-dimensional form. In this manner E_z at other flow conditions can be estimated (see [5]) provided estimates of the length and velocity scales are available. However little field data is available to verify the reliability of this procedure, which assumes β does not vary significantly with flow. The tracer test results described above provide an opportunity to assess the consistency of the dimensionless transverse mixing coefficient for a river reach over a reasonably wide range of flow conditions.

A plot of β values used in the mixing simulations versus distance is shown in Figure 19. The reach-averaged value of β for each test is shown in the plot legend. The reach averages were calculated using a weighting approach based upon sub-reach lengths.

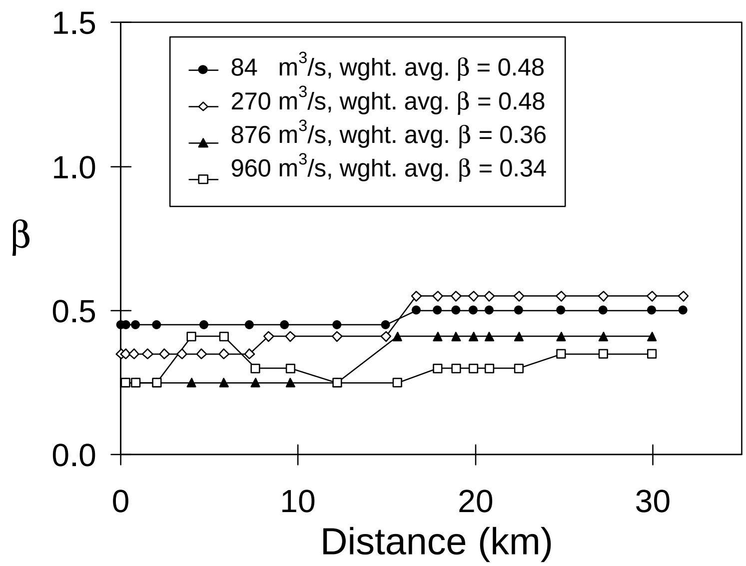


Figure 19 β versus distance downstream.

The plot of β versus distance indicates there are minor variations in the dimensionless mixing coefficient with distance. For instance, there appears to be a consistent step up in β values near the La Biche River confluence at about 17 km. downstream. There also appears to be a linear relationship between the reach average β and flow. Figure 20 illustrates this trend. As flow decreases the transverse mixing in the reach is enhanced.

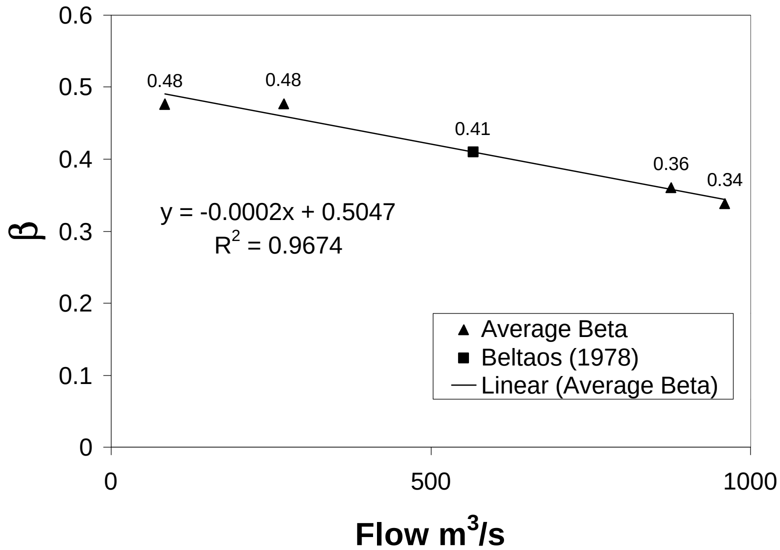
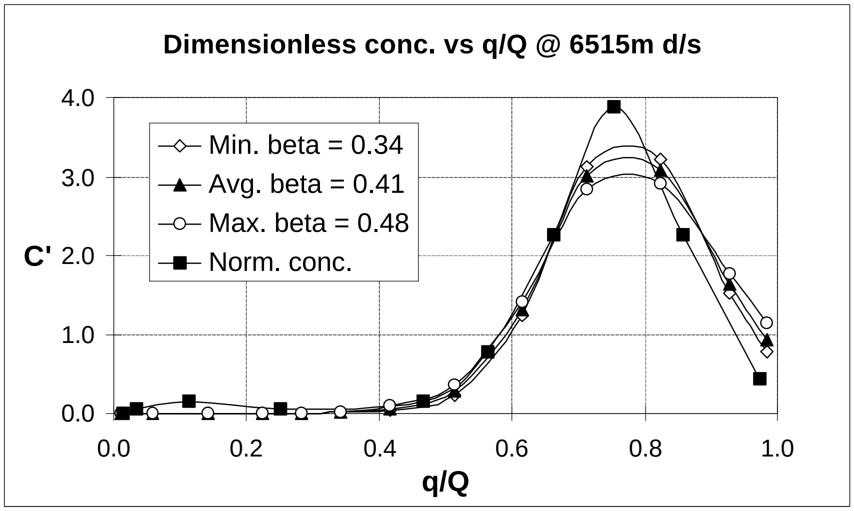


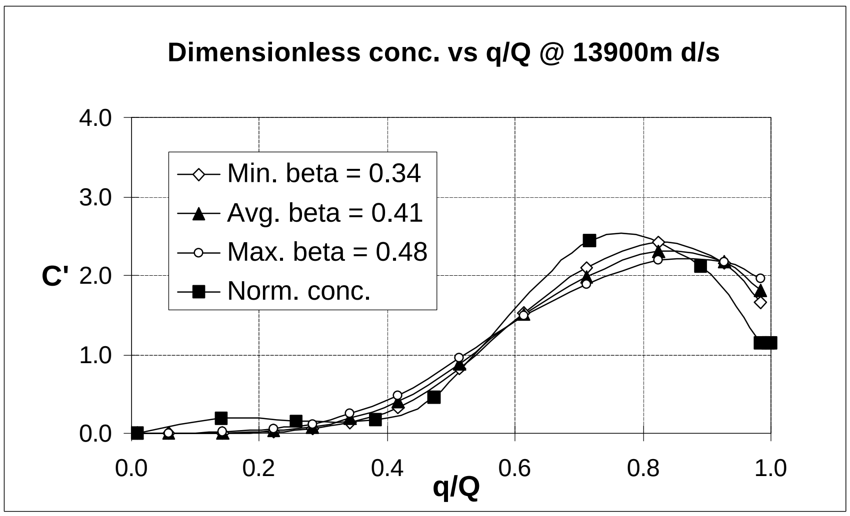
Figure 20 Average β versus discharge for the study reach.

The range of β values determined this reach of the Athabasca River fall well within the range of reported values of β from studies at other locations. For example, compilations prepared by Elhadi et al. (1984) and Rutherford (1994) report a range of 0.22 to 3.3 and 0.12 to 3.4, respectively. In particular β obtained in this study agrees very closely with a reported reach-averaged value of β = 0.41 (Q = 566 m^3/s) for the 40 km stretch of the Athabasca River immediately downstream of the town of Athabasca (Beltaos, 1978). This portion of the river is immediately upstream of the reach investigated in this study and very similar in characteristics. The Beltaos (1978) study result is plotted in Figure 20. It closely matches the linear trend versus flow.

A series of mixing simulations was run for Q = 960 m^3/s to investigate the sensitivity of the output to change in β. β was varied over the range 0.34 to 0.48 obtained for the reach averages. Selected results of these sensitivity tests are shown in Figure 21. The results indicate the mixing simulations are not overly sensitive to a change in B of that magnitude. Simulation using an overall average of 0.41 can provide satisfactory results (see Figure 21).

The sensitivity analysis indicates that for this reach of the Athabasca River β determined from a single tracer test (i.e. at a single river flow) can provide reasonable results when applied to other flows. However this observation may be site specific and is probably a function of how dramatically the channel shape and boundary characteristics change with discharge. If data are available over a range of flows, then improved estimates of β can be obtained by developing a relationship similar to that shown in Figure 20.





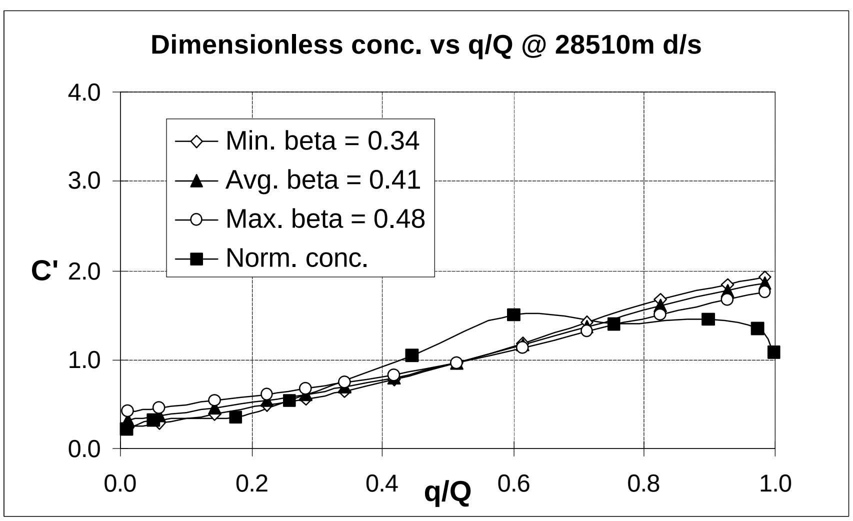


Figure 21 Effect of β upon mixing, Q = 960 m^3/s.

MANAGEMENT APPLICATIONS

As noted earlier a calibrated river mixing model at a particular mill site can serve as a valuable management tool for efficient planning of receiving stream water quality monitoring programs. The mixing model can also be used to assess the environmental impact of abnormal conditions such as spills and/or low river flow conditions on receiving stream water quality. These applications are in reference to existing diffuser structures. An additional application of the model is to predict the effects upon mixing of the location and configuration of a new diffuser or of altering an existing structure. Once the receiving stream characteristics are defined within the model the effects of input location and configuration are simply handled by altering the input file.

Several specific applications of the model are outlined below utilizing the mixing model results presented in this report. All examples are given for the cross section 10.48 km downstream of the diffuser location and apply only to the input conditions corresponding to those specified in this report.

1) Position of peak concentration and delineation of effluent plume

   Continuous input conditions, $Q = 960\ m^3/s$, see Figure 10 e)

      Peak concentration occurs at $q/Q \approx 0.78$
      Left edge of the plume occurs at $q/Q \approx 0.50$
      Right edge of the plume occurs at $q/Q = 1.0$.

   To convert q/Q to distances refer to Table 1 and Figure 8

      Peak at $q/Q \approx 0.78$ corresponds to $z \approx 325$ m from left bank (looking downstream)
      Left edge at $q/Q \approx 0.50$ corresponds to $z \approx 225$ m from left bank (looking downstream)
      Right edge at q/Q corresponds to $z = 417$ m from left bank i.e. the right bank

   Similarly, peak location and plume edges can be determined for a slug input using Figure 14(a). Reference would have to be made to a section tabulation for Q = 876 m3/s similar to Table 1.

2) Concentration at a specified transverse location for continuous input

   Continuous input conditions, Q = 960 m3/s, see Figure 10 e)

      Peak dimensionless concentration is $C' \approx 3.0$

   To convert C' to actual concentration refer to [13]

      For the fluorescent tracer test $C_\infty = 0.31\ \mu g/L$ (see Table 4), therefore
         $c = C' C_\infty = (3.0)(0.31) = 0.93\ \mu g/L$

   For effluent parameters determine C_∞ for the input and flow condition (see [12]),

      For example given $q_{in} = 1\ m^3/s$, $C_o = 500\ \mu g/L$ for parameter A, then[4]
         $C_\infty = C_o\, q_{in} / Q = 500*(1)/960 = 0.52\ \mu g/L$;
         $c = C' C_\infty = (3.0)(0.52) = 1.56\ \mu g/L$

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[4] Note parameter A is a fictitious component used for illustrative purposes only.

3) Time to peak concentration at a specified transverse location following a slug(transient) input

   Slug input condition, Q = 876 m^3/s, q/Q = 0.886, see Figure 15 d)

   The model predicts the peak concentration arrives approx. 2.9 hrs. after the slug injection for this location, consult other plots for time to peak at other q/Q locations for this section.

4) Time of passage at a specified transverse location following a slug(transient) input

   Slug input condition, Q = 876 m^3/s, q/Q = 0.886, see Figure 15 d)

   The model predicts the arrival and departure of the plume at approx. 2.8 hrs. and 3.2 hrs. after the slug injection for this location, consult other plots for times of arrival and departure at other q/Q locations for this section.

5) Concentration at a specified transverse location and time following a slug(transient) input

   Slug input condition, Q = 876 m^3/s, q/Q = 0.886, see Figure 15 d)

   Using peak concentration as an example, the model predicts a peak tracer concentration of approximately 48 μg/L at 2.9 hrs.

   This concentration results from input of 4.05 Kg. of fluorescent component. To make predictions for other quantities of mass input the model can be rerun for the new input conditions or a ratio calculation can be used.

   For example if 50 Kg. of neutrally buoyant mass conservative substance was spilled into the river at the midpoint of the diffuser the estimated peak concentration at 10.48 km., at q/Q= 0.886 would be:

   $c_2 = c_1$ (mass input 1)/(mass input 2) = 48(50)/(4.05) = 593 μg/L.

The examples given above utilize plots for field survey locations shown in the report. However once a simulation has been run the model can generate output at any desired location downstream of the outfall within the defined reach. In addition simulations can be prepared for any desired river discharge provided there is sufficient hydrometric survey data to allow adjustment of water levels and flow characteristics at surveyed sections to the desired flow condition.

CONCLUSIONS AND RECOMMENDATIONS

The following may be concluded from the tracer tests and modelling analyses conducted on the Athabasca River downstream of the Alberta Pacific Forest Industries mill site:

- In order to successfully apply the AOG model a study reach must be characterized by a significant number of cross section surveys and flow characterization measurements. The application of GPS technology to these hydrometric surveys allowed rapid collection of a very large database of positioning data associated with these surveys. The GPS technology was also ideally suited to collection of positioning data and times during sampling.
- The mixing model utilizing the Advection Optimized Grid (AOG) method can accurately simulate the transverse mixing of neutrally buoyant mass conservative parameters input to the river via a continuous or slug injection.
- The AOG mixing model can also simulate with reasonable accuracy the longitudinal dispersion of neutrally buoyant, mass conservative parameters instantaneously discharged to the river. Minor discrepancies in the time to peak concentration are evident between the model and samples. However these discrepancies are small (< 7%) and are likely the result of inaccuracies in measurements of channel and flow parameters.
- The reach-averaged transverse mixing coefficient β varied from 0.34 to 0.48 over the range of flow conditions (84 m^3/s ice-covered to 960 m^3/s open water) represented by the four tracer tests analyzed. Model simulations using β ranging from 0.34 to 0.48 indicated limited sensitivity. These results demonstrate that for this river reach β measured at one flow condition could be used with the appropriate flow parameters to estimate E_z for other flows without significant error.
- Reach-averaged β for this study location increased linearly with decreasing river discharge. A previous β measurement of 0.41 for the Athabasca River downstream of the town of Athabasca is very closely predicted by this relationship.

The following is recommended as a result of the 1997 field studies:

- Additional surveys are required at mill sites where water quality parameters can be tracked for some distance in the receiving waters. These surveys will assist the development and verification of additional subroutines for simulation of environmental reaction of non-conservative water quality parameters.
- GPS technology should continue to be used for all field surveys. The ease of collection and compilation of position and elevation data, and its accuracy, far outweigh the costs associated with renting the equipment.

REFERENCES

Beak Consultants Ltd. 1995. Effluent plume delineation study for Alberta Pacific Forest Industries Inc. Beak Consultants Ltd., Reference 7.10610.1, Brampton, Ontario.

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

Beltaos, S. 1978. Transverse mixing in natural streams. Alberta Research Council, Report SWE 78-1, Edmonton, Alberta.

Beltaos, S. 1979. Transverse mixing in natural streams. Canadian Journal of Civil Engineering, CSCE, 6(4):575-591.

Beltaos, S., and Arora, V.K. 1988. An explicit algorithm to simulate transient transverse mixing in rivers. Canadian Journal of Civil Engineering, 15(6):964-976.

Elhadi, N., Harrington, A., Hill, I., Lau, Y.L., and Krishnappan, B.G. 1984. River mixing - A state of the art report. Canadian Journal of Civil Engineering, 11(3):585-609.

Fischer, H. B. 1968. Methods for predicting dispersion coefficients in natural streams with applications to the lower reaches of the Green and Duwamish Rivers, Washington. United States Geological Survey, Professional paper, 582-A, Washington, D.C.

Gowda, T.P.H. 1984. Water quality prediction in mixing zones of rivers. ASCE Journal of Environmental Engineering Division, 110(EE4):751-769.

Harden, T.O. and Shen, H.T. 1979. Numerical simulation of mixing in natural rivers. Journal of the Hydraulics Division, ASCE, 105(HY4):393-408.

Holly, F.M. 1975. Two-dimensional mass dispersion in rivers. Hydrology papers, No. 78 Colorado State University, Fort Collins, Colorado.

Lau, Y. L. and Krishnappan, B.G. 1981. Modelling transverse mixing in natural streams. ASCE Journal of the Hydraulics Division, 107(HY2):209-226.

Luk, G.Y.K., Lau, Y.L., and Watt, W.E. 1990. Two-dimensional mixing in rivers with unsteady pollutant source. Journal of Environmental Engineering, 116(1):125-143.

McCorquodale, J.A., Iman, E.H., Bewtra, J.K., Hamdy, Y.S., and Kinkead, J.K. 1983. Transport of pollutants in natural streams. Canadian Journal of Civil Engineering, CSCE, 10(1), pp. 9-17.

Odigboh, I. 1999. Characterization and modelling of the mixing in the Athabasca River downstream of a pulp mill. M.Sc. thesis, Division of Environmental Engineering, University of Saskatchewan, Saskatoon, Saskatchewan.

Putz, G. 1996. Dynamic two-dimensional river quality modeling, Ph.D. thesis, Department of Civil Engineering, University of Alberta, Edmonton, Alberta.

Putz, G. 1983. Mixing and microorganism survival, Slave River, N.W.T. M.Sc. thesis, Department of Civil Engineering, University of Alberta, Edmonton, Alberta.

Putz, G., and Smith, D. W. 1998. Verification of a transient input, two-dimensional, river mixing model. Canadian journal of Civil Engineering, 25(1):51-66.

Rutherford, J.C. 1994. River Mixing. John Wiley and Sons, New York, New York.

Sobey, R.J. 1984. Numerical alternatives in transient stream response. ASCE Journal of the Hydraulics Division, 110(HY6):749-772.

Yotsukura, N., and Cobb, E.D. 1972. Transverse diffusion of solutes in natural streams. United States Geological Survey, Professional Paper, 582-C, pp. c1-c19.