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River Mixing and Mass Balance of Several Water Quality Parameters in the Wapiti River downstream of Weyerhaeuser Canada Ltd.

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River Mixing and Mass Balance of Several Water Quality Parameters in the Wapiti River downstream of Weyerhaeuser Canada Ltd.

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

by

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ABSTRACT

Field studies to determine the river mixing and potential decay in concentration of selected water quality parameters in a receiving stream downstream of a pulp mill effluent diffuser are described. The field studies were conducted on the Wapiti River downstream of Weyerhaeuser Canada Ltd. near Grande Prairie, Alberta. The river mixing in the study reach was determined based upon analysis of a steady-state fluorescent tracer test conducted at the site. Colour, adsorbable organic halide (AOX) and chemical oxygen demand (COD) samples were collected from the river on the same day as the tracer test. In this manner, the dilution effects of the river mixing are defined by the tracer test allowing an assessment of any other attenuation of these parameters within the receiving stream.

Concentrations of colour, AOX and COD were measured at seven cross sections within the study reach and compared to tracer concentrations at the same locations. A mass balance analysis is presented which compares the input of these parameters in the effluent stream to the mass flow measured in the river. Conclusions are drawn regarding whether these parameters are mass conservative and only influenced by dilution, or if other mechanisms influence their concentration within the receiving stream. AOX was found to be mass conservative over the 4.5 km study reach (approximately 2.6 hours flow time). Colour and COD levels declined in relation to the tracer in the initial portion of the reach. Following this initial decline, levels of COD and colour increased which possibly indicates resuspension of bottom sediments.

ACKNOWLEDGEMENTS

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INTRODUCTION

The overall purpose of this SFMNCE (Sustainable Forest Management Network of Centres of Excellence) 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 parameters, within a river, in combination with the river mixing and transport. Therefore, the model can be used to study the transport, mixing and fate of forest industry effluent substances discharged to river systems.

A unique feature of the model is that unsteady effluent input conditions can be accounted for, and that the resulting time-varying, effluent substance 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 need for this type of model and details regarding the numerical method used by the model are described by Putz and Smith (1996), Putz (1996) and Putz et al. (2000).

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 discharge locations. Previous verifications studies of the numerical method used in the model to simulate river mixing were described by Putz and Smith (1998). These studies were based upon tracer tests conducted on several major western Canadian rivers. However, the data available from these tracer tests was limited, as they had not been conducted with the express purpose of model verification. Additional more comprehensive field studies were conducted in August 1997 with support from the SFMNCE. Results of these studies are reported by Putz et al. (2000).

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, COD, 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 can 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. Further SFMNCE field studies were conducted in August 1998 on the Wapiti and Athabasca Rivers in order to collect data to address the second objective.

The work conducted on the Wapiti River near Grande Prairie downstream of the Weyerhaeuser Canada Ltd. mill site is described in this report. The work conducted on the Athabasca River near Hinton downstream of the Weldwood of Canada Ltd. mill site is described in a companion report (Putz and Smith, 2000).

Wapiti River 1998 Field Studies

Background

On August 5 to 7, 1998 field studies were conducted on the Wapiti River near Grande Prairie, Alberta. The field studies consisted of hydrometric surveys, a tracer test, and water quality sampling conducted on a reach of the Wapiti River downstream of the Weyerhaeuser Canada limit pulp mill site. The intent of the 1998 field studies was to simultaneously conduct a tracer test and sample for selected water quality parameters downstream of a pulp mill effluent discharge. In this manner, the attenuation of effluent parameters can be assessed against a well-defined mixing regime.

Planning for the Wapiti River field tests progressed through the spring and early summer of 1998. Air photos, maps, historical discharge data and past cross section surveys for the river reach were obtained from Alberta Environmental Protection and Water Survey of Canada. In addition, engineering drawings of the effluent pipeline and diffuser structure and previous water quality studies on the river were obtained from Weyerhaeuser Canada Ltd. All this information was required to plan the details of the tracer tests such as the location of the tracer injection point, quantities of tracer required, tracer flow rates, 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.

As part of the planning process, water quality data on the mill effluent was also obtained from Weyerhaeuser Canada Ltd. The effluent data was reviewed to select water quality parameters for sampling in the river. The intention was to pick water quality parameters that would remain above detection limits for some distance downstream of the discharge point. In addition, parameters were chosen which would potentially react within the river system and decrease in concentration in comparison to the mass conservative tracer. After reviewing the effluent data, and estimating the immediate dilution at the diffuser with the anticipated river flow for late August (approx. 90 m^3/s), colour, COD (chemical oxygen demand), and AOX (adsorbable organic halide) were selected for sampling and analysis.

Objectives of the 1998 Wapiti River field studies

The initial objectives of the 1998 field studies on the Wapiti River downstream of the Weyerhaeuser Canada Ltd. mill site were:

- Conduct a continuous input fluorescent tracer test to document the steady-state transverse mixing occurring in approximately a 20 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 20 km reach downstream of the diffuser structure.

- Conduct hydrometric surveys to obtain sufficient data to construct a mixing model of the river reach.
- Sample the river reach for colour, COD and AOX in conjunction with the continuous input tracer test.
- Assess the river concentrations of the water quality parameters in comparison to the tracer concentrations in order to identify any attenuation other than the mixing process.
- Attempt to model the water quality parameters in the reach accounting for river mixing and attenuation mechanisms.

Unfortunately, low flow conditions experienced in August 1998 on the Wapiti River prevented accomplishment of all these objectives. The anticipated flow for early August, based upon analysis of Water Survey of Canada records, was approximately 100 m^3/s. Actual flow during the fieldwork was in the range of 30 to 40 m^3/s (see the section below on Site Characterization).

River travel during the fieldwork utilizing the prop survey boats available was extremely difficult due to the low flow conditions. Travel in the upstream direction was particularly difficult and required the field crews to physically pull the boats and equipment through shallow rapid sections of the river. As result, the length of the study reach had to be restricted to approximately 4.5 km downstream of the Weyerhaeuser Canada Ltd. diffuser structure. This distance avoided the more challenging and potentially dangerous shallow sections located further downstream. In addition, the slug tracer test that was planned had to be abandoned due to restricted ability to travel on the river.

RIVER MIXING AND MASS BALANCE

Most rivers have a large width to depth ratio. Therefore, dissolved substances will rapidly become uniformly mixed in the vertical direction (over depth) in comparison to the transverse (across stream) and longitudinal (downstream) directions (see Putz et al., 2000 for a overview description of mixing processes). Hence, for most situations a two-dimensional, depth-averaged description of the mixing and transport in a river is appropriate.

The mixing, transport and in-stream reaction of a neutrally buoyant, non-conservative substance in the transverse mixing zone can be described by the following mass balance equation (see Putz, 1996 for derivation of this equation, see Figure 1 for the coordinate system definition):

$$\frac{\partial}{\partial t}(hc)+\frac{\partial}{\partial x}(huc)=\frac{\partial}{\partial z}\left(hE_z\frac{\partial c}{\partial z}\right)+hR \qquad [1]$$

in which x is the longitudinal direction, z is the transverse direction, c is depth-averaged concentration , u is local depth-averaged velocity in the longitudinal direction, h is the local depth and E_z is the transverse mixing coefficient. The second term on the left of [1] represents advective mass transport in the longitudinal direction. The first term on the right represents diffusive transport across the stream. The general term R represents an in-stream reaction rate expression. For example, if the reaction rate was first order R could be replaced by Kc where K would be a first order rate constant.

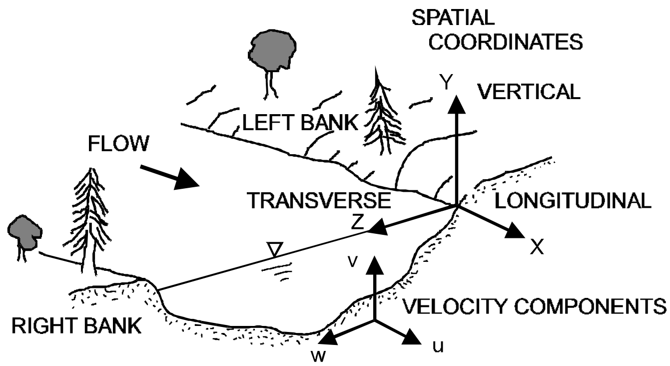


Figure 1 Coordinate system for mixing analysis.

Frequently a streamtube approach employing a transformation of the transverse coordinate z, to cumulative flow q is utilized in mixing analysis and modelling (see Yotsukura and Cobb, 1972). Cumulative flow is determined as follows:

$$q_{(z)} = \int_0^z uh\, dz \qquad [2]$$

where z = 0 represents the left bank (looking downstream) as shown in Figure 2; 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.

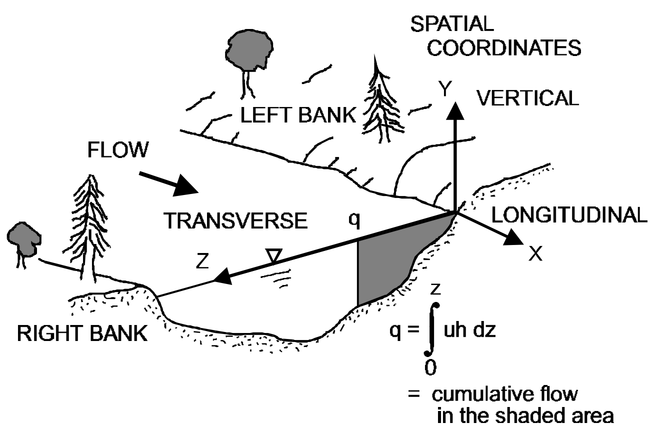


Figure 2 Transverse coordinate transformation.

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 there is no depth-averaged transverse advection across streamlines. In the derivation of [1] the term representing transverse advective transport is omitted based upon an order of magnitude argument (see derivation in Putz, 1996). The adaptation of a streamtube approach for representation of the river flow and the use of this concept in the numerical solution further justifies not including a transverse advective term in [1].

A tracer test allows accurate definition of the river mixing (i.e. dilution effects) described by the advection and diffusion terms of [1]. Analysis of tracer test results will define the transverse mixing coefficient along a river study reach. The transverse mixing coefficient combined with hydrometric survey data, allows a mathematical model of the river mixing to be constructed and utilized for mixing simulations in the reach (see Odigboh, 1999 for a description of this process for the SFMNCE tracer tests conducted in 1997).

Water quality parameter samples collected during a tracer test can be assessed relative to the tracer concentrations to determine if the parameters are non-conservative. The mass recovery of a non-conservative parameter as a function of distance or travel time downstream of a discharge point can then be used as an aid to ascertain the form of the reaction equation. Mass balance analysis for several water quality parameters in the Wapiti River is described in this report.

SITE CHARACTERIZATION

Introduction

The study reach is located downstream of the Weyerhaeuser Canada Ltd. effluent diffuser structure on the Wapiti River near Grande Prairie, Alberta. A plan view of the study reach is shown in Figure 3.

The river discharge during the field survey and tracer test was much lower than seasonal norms. Average flow for August based upon analysis of Water Survey of Canada records (1961-1995) was 98.7 m^3/s. The estimated open water and annual 7Q10 flow for the Wapiti River is 11.0 and 6.0 m^3/s respectively (Golder Associates Ltd., 1994). Because of the low flow conditions the reach consisted of a series of pool and riffle sequences (see Figure 3). Boat travel through the riffle areas, especially in the upstream direction, was extremely difficult due to the restricted depth and increased velocity. Consequently, the survey was restricted to the 4.5 km reach immediately downstream of the diffuser avoiding a number of the more challenging riffle sections located further downstream.

Hydrometric Data

Cross-section Surveys

Hydrometric surveys of the study reach were conducted on August 7, 1998. Ten cross sections were established and surveyed. The section locations in relation to the Weyerhaeuser diffuser structure were measured using Global Positioning System (GPS) equipment. Depths across each section were measured using echo sounding equipment. The depth measurement positions were determined by simultaneous GPS measurement of the sounding boat location. The location of each of the sections is shown in Figure 3. A summary of the reach characteristics measured on August 7, 1999 is given in Table 1.

Table 1 Summary of measured reach characteristics and flow.

Cross Section (distance d/s) (m)	River Width (m)	Avg. Depth (m)	Avg. Velocity (m/s)	Measured Discharge (m^3/s)
0	67.0	0.69	0.72	-
110	77.0	1.06	0.41	-
610	69.0	0.91	0.53	33.2
1230	82.4	0.87	0.47	30.7
1610	76.4	1.58	0.28	34.3
2155	73.0	0.80	0.57	-
2915	73.0	0.80	0.57	36.4
3600	66.1	0.77	0.65	-
4115	91.3	1.16	0.32	-
4525	72.7	1.11	0.41	32.6
Average	74.8	0.98	0.49	33.4

Note: The reach characteristics shown are for August 7, 1998 (the day hydrometric surveys were conducted). All characteristics were adjusted to the estimated flow of 36 m^3/s for August 6, 1998 (the day the tracer and water quality sampling was conducted).

Detailed cross section tabulations and plots were prepared for each section for the date on which the tracer test was conducted (August 6, 1998). This required minor adjustments of the survey measurements to account for the change in river flow between August 6 and 7. An example detailed tabulation and plot is shown in Table 2 and Figure 4. A complete set of cross section tabulations and plots for the study reach is presented in Appendix A.

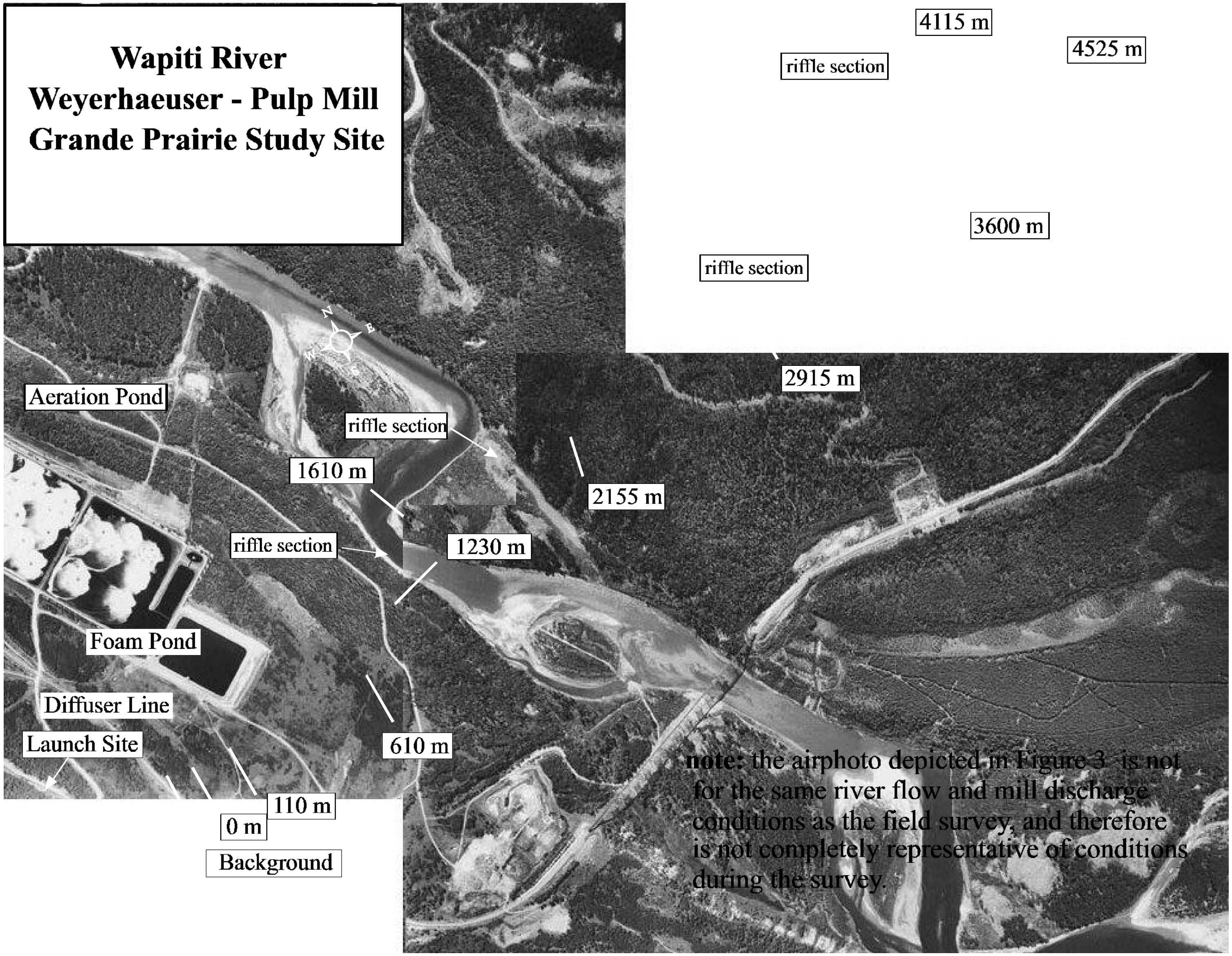
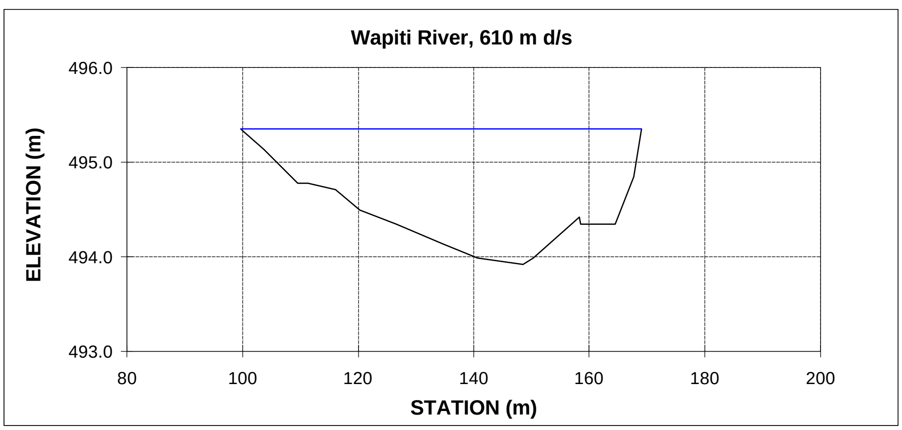


Figure 3 Wapiti River study reach downstream of the Weyerhaeuser Canada diffuser.

Table 2 Example cross section tabulation.

X-SECTION   Wapiti River, 610 m d/s
DATE   August 6, 1998
DISCHARGE m^3/s 36.00
WIDTH m   69.33   Est. Water Surf. Elev.   495.35
MEAN DEPTH m   0.92   LB   99.72   495.35
AREA m^2 64.10   RB   169.05   495.35
MEAN VELOCITY m/s   0.562

Sta. m	Elev. m	h m	w/W	u m/s	dq est. m^3	norm. q/Q	Area m^2	adj. U m/s
99.72	495.35	0.00	0.000	0.000	0.00	0.00000	0.0	0.000
100.00	495.33	0.02	0.004	0.048	0.00	0.00000	0.0	0.044
103.76	495.13	0.22	0.058	0.22	0.06	0.00154	0.5	0.20
109.51	494.78	0.57	0.141	0.41	0.71	0.01973	2.7	0.37
111.38	494.78	0.57	0.168	0.41	0.44	0.03091	3.8	0.37
116.13	494.71	0.65	0.237	0.44	1.24	0.06236	6.7	0.41
120.24	494.49	0.86	0.296	0.54	1.51	0.10090	9.8	0.49
126.58	494.35	1.00	0.388	0.59	3.34	0.18602	15.7	0.54
134.66	494.13	1.22	0.504	0.68	5.70	0.33116	24.7	0.62
140.70	493.99	1.36	0.591	0.73	5.47	0.47057	32.5	0.67
148.54	493.92	1.43	0.704	0.75	8.12	0.67722	43.5	0.69
150.27	493.99	1.36	0.729	0.73	1.79	0.72268	45.9	0.67
158.30	494.42	0.93	0.845	0.57	5.96	0.87450	55.1	0.52
158.52	494.35	1.00	0.848	0.59	0.12	0.87764	55.3	0.54
164.51	494.35	1.00	0.935	0.59	3.57	0.96857	61.4	0.54
167.71	494.85	0.50	0.981	0.37	1.17	0.99829	63.8	0.34
169.01	495.34	0.01	0.999	0.03	0.07	1.00000	64.1	0.02
169.05	495.35	0.00	1.000	0.000	0.00	1.00000	64.1	0.000
Last Line				Est. Total	39.27			



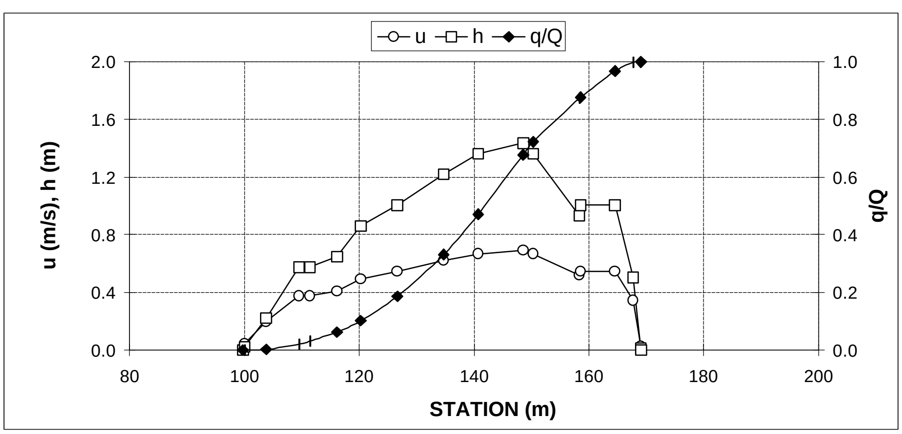


Figure 4 Example cross section plot.

Channel Slope

The slope of the water surface through the study reach was determined using elevation measurements taken using GPS equipment. Approximately 12 to 15 individual measurements of the water surface were recorded at each section as the depth soundings were conducted. The average of these measurements at each section versus distance is plotted in Figure 5. The breaks in channel slope shown in the plot are an indication of the pool and riffle nature of the flow.

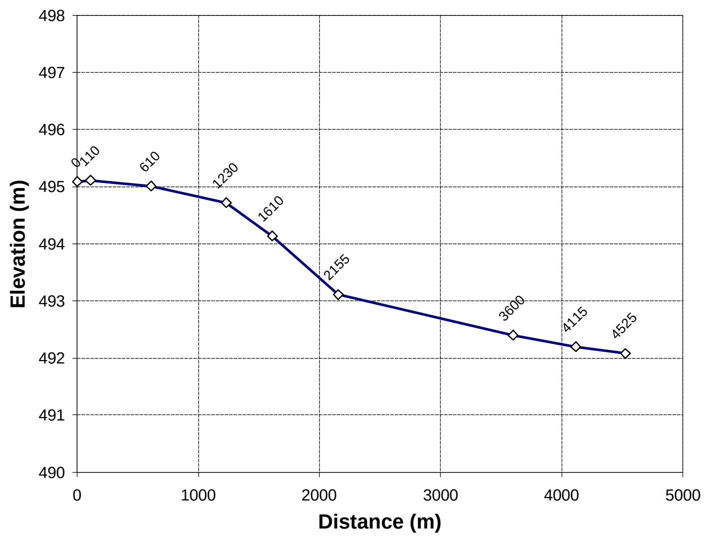


Figure 5 Water surface versus distance.

Velocity and Discharge

Environment Canada monitors flow and water level in the Wapiti River at a gauging station located several kilometers upstream of the study reach. As part of the hydrometric surveys conducted on August 7, 1998 river discharge was measured at five sections. Velocity measurements were taken across each of these sections using a standard Price type current meter suspended with a cable and weight from the anchored survey boat. A sufficient number of measurements were taken across each section to allow a reasonably accurate estimate of the discharge (10 locations in most cases). The position of the boat was determined by GPS measurement. The results of these discharge measurements are shown in Table 1.

The average gauge reading reported during the flow measurements was 27.1 m^3/s. The discrepancy between the gauge reading and the field measurements is due to tributary inflow between the gauge and the study reach (note the tributary opposite the launch site in the lower left corner of Figure 3). Consequently, the mean of the flow measurements (33.4 m^3/s) was used to represent the flow on August 7. An adjustment of this flow was required for analysis of the tracer test conducted on August 6. The adjustment was based upon the proportional change in flow recorded at the gauge between August 6 and 7. The resulting estimate of river flow during the tracer test and water quality sampling was 36 m^3/s.

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

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

H and U are determined utilizing the cross section area A and width W from hydrometric surveys and the total river flow Q. An example plot comparing measured and synthesized velocities across a section is shown in Figure 6. For most of the sections the measured and synthesized velocities demonstrate reasonable agreement.

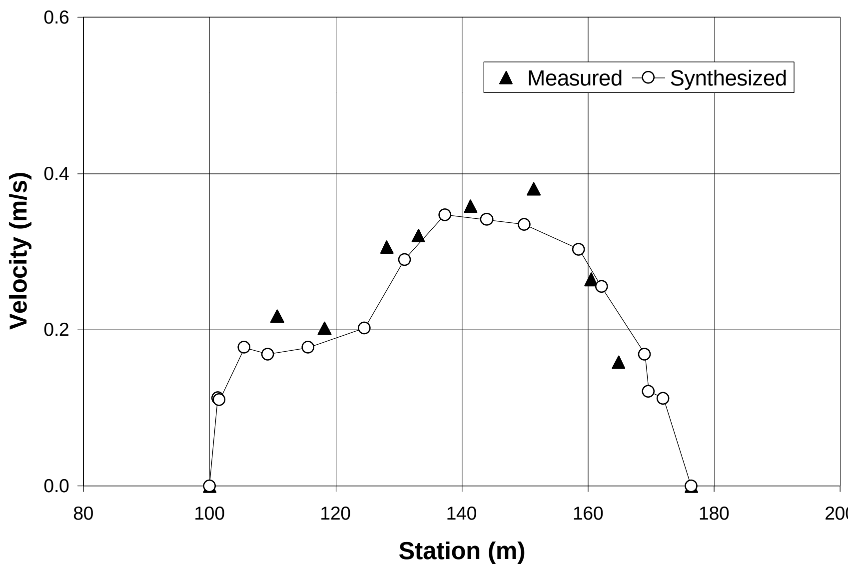


Figure 6 Measured and synthesized velocity distribution at 1610 m downstream.

Synthesized velocities and local depths were used to estimate the q distribution at each section according to [2] (see Putz, 1983 or Odigboh, 1999 for details of this procedure). A tabulation and plot of local velocity u, and dimensionless cumulative flow q/Q was prepared for each cross section for the day of the tracer test (see Table 2 and Figure 4, and Appendix A).

TRACER TEST

Introduction

A continuous input, fluorescent tracer test was conducted on August 6 1998 downstream of the Weyerhaeuser Canada effluent diffuser structure. The tracer was injected into the mill effluent stream in order to delineate the effluent plume. Samples were collected at each of the cross sections established along the river reach. The samples were later analyzed for tracer content using a Turner Designs fluorometer. A summary of the tracer input conditions, sampling procedures and analysis results is presented in this section of the report.

Input Conditions

The continuous input of tracer consisted of injection of 20% Rhodamine WT fluorescent dye into the mill effluent stream at a volumetric flow rate of 30 mL/minute. The tracer was pumped into the effluent pipeline through a manhole located downstream of the foam pond (see Figure 3). The tracer entered the river with the mill effluent via Weyerhaeuser's submerged diffuser structure. The diffuser is about 58 m long, oriented approximately perpendicular to the river flow, and extends into the flow from the north bank of the river. The effluent is discharged approximately two metres below the riverbed surface. It then percolates up through a layer of granular materials to mix with the river flow. The effluent initially mixed with approximately 55% of the river flow over 60% of the channel width for the prevailing flow conditions.

A sufficiently long period of continuous injection was maintained in order to establish a 'window' of steady-state concentration conditions at each cross section. A summary of the input conditions for the continuous input tracer test is presented in Table 3.

Table 3 Summary of input conditions for continuous input tracer test.

q_{in} (m^3/s)	C_o ($\mu g/L$)	Duration (hours)	Q (m^3/s)	C_{back} ($\mu g/L$)	C_∞ ($\mu g/L$)
5.0×10^{-7}	2.3×10^{8}	3.5	36	0.05	3.2

In Table 3 C_∞ represents the fully mixed tracer concentration in the river flow (in excess of background levels). C_∞ is given by the expression:

$$C_\infty = q_{in} C_o / (Q + q_{in}) \quad \approx \quad q_{in} C_o / Q \quad \text{for } q_{in} << Q \qquad [4]$$

where q_{in} is the tracer input flow, C_o is the tracer input concentration and Q is the total river flow. The background concentration in the river was determined based upon samples taken from upstream of the diffuser structure.

Sampling Procedure and Analysis

Tracer samples were taken at each river cross section during the steady-state concentration 'window'. The position of each sample was recorded using GPS equipment as the boat traversed across a section. Samples were taken approximately 0.3 metres below the water surface and collected in 150 mL plastic bottles. The sample bottles were immediately placed in a cooler container to isolate them from sunlight. The samples were transported to Edmonton the following day for analysis using a Turner Designs fluorometer.

Tracer Sample Results

The results of the tracer measurements are shown in Figure 7. The horizontal axis of each plot 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 represents non-dimensional concentration C' given by:

$$C' = c/C_\infty \qquad [5]$$

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. Both c and C_∞ represent concentrations in excess of background readings. The background and fully mixed tracer concentration are given in Table 3.

The tracer concentrations are normalized to adjust for small inaccuracies in tracer mass recovery at individual sections. The normalized curves act as a benchmark indicating the concentration distribution of a completely mass conservative substance at each section. Individual tracer measurements are normalized by dividing them by the mass recovery ratio at a section. The mass recovery ratio at each section was determined by integrating the measured dimensionless tracer concentration versus cumulative flow curve. The tracer mass recovery ratio at each transect is given in Table 4. Note a value of 1.0 represents 100% mass recovery.

Table 4 Mass recovery ratios for tracer.

Cross Section (m)	Ratio
110	0.84
610	1.06
1230	1.11
1610	1.05
2155	1.05
2915	0.93
3600	0.96
4115	1.02
4525	1.02
Average[a]	1.02

[a] average excludes recovery at transect 110 m

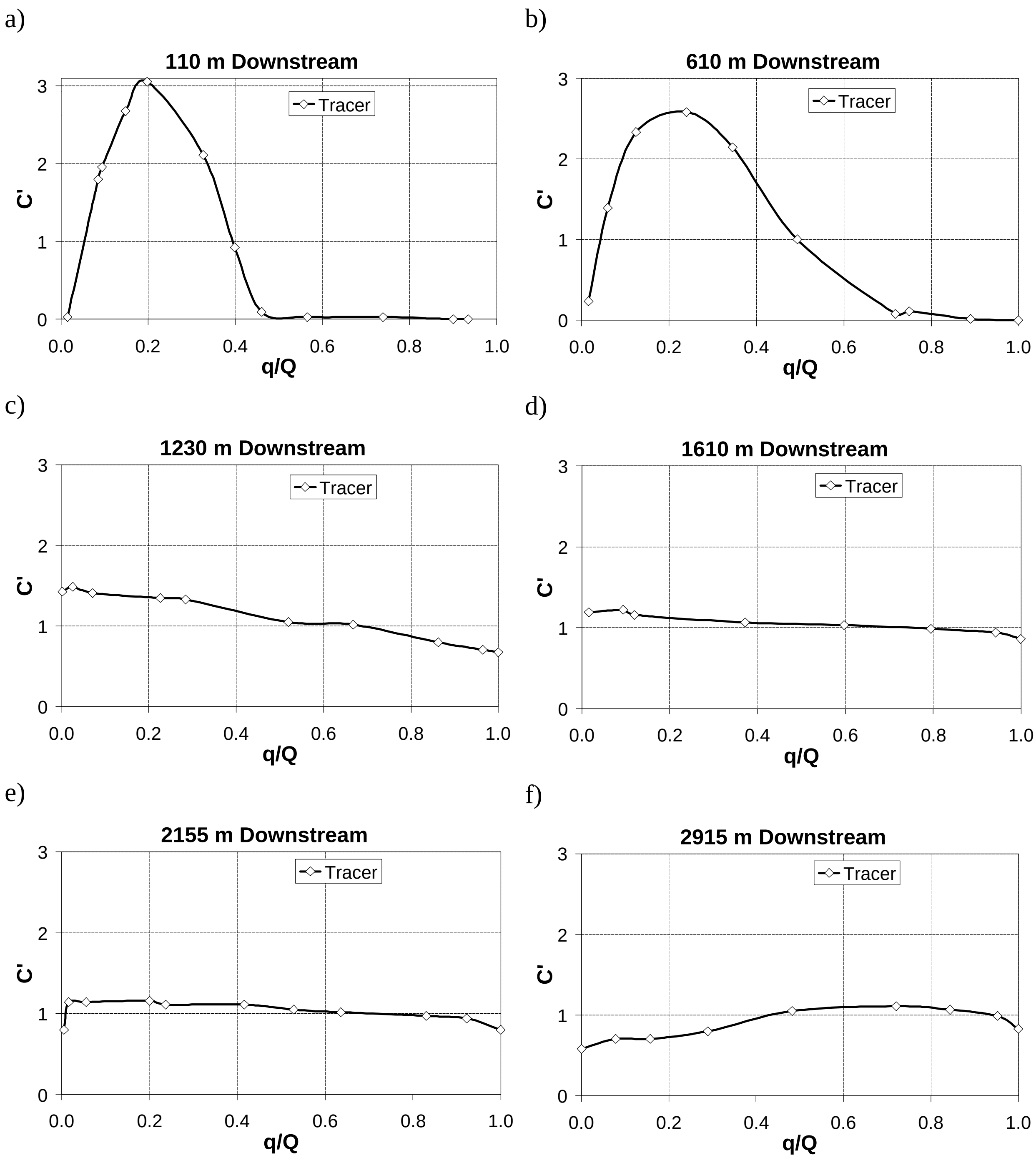


Figure 7 Normalized Dimensionless Tracer Concentrations.

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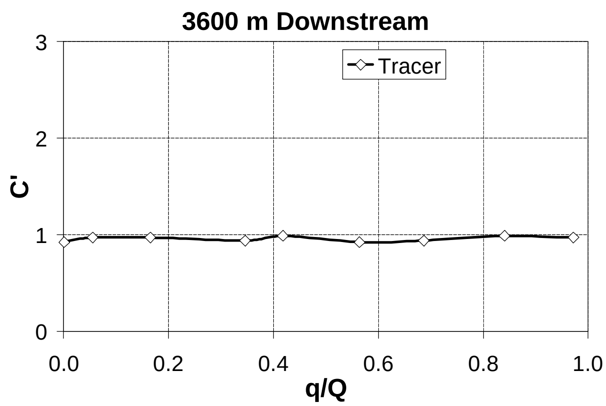

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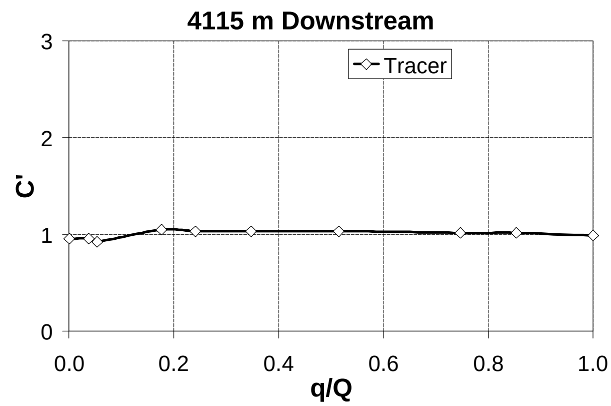

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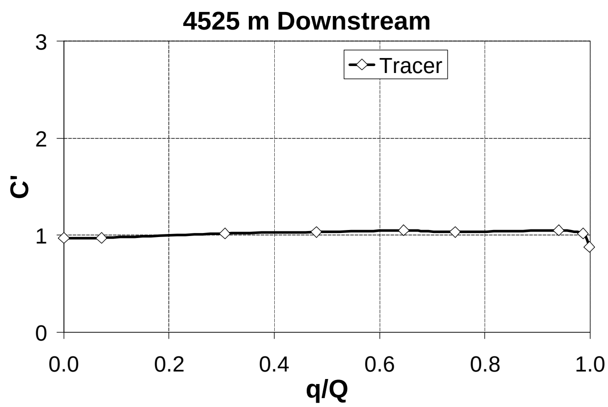


Figure 7 cont. Normalized Dimensionless Tracer Concentrations.

Complete vertical mixing of effluent is generally assumed to occur within a short distance (approximately 100 river depths) downstream of a discharge point. All the tracer samples were collected approximately 0.3 m below the water surface. Therefore, tracer recovery significantly less than 100% at the first section is an indication of incomplete vertical mixing.

The tracer recovery at 110 m is 84%, but increases to 106% at 610 m (see Table 4). Apparently a distance greater than 100 depths is required for complete vertical mixing at this site, possibly due to the discharge and percolation of the effluent up through the granular material of the river bed.

Excluding the first section, the tracer recoveries range from 93 to 111% along the rest of the reach (see Table 4). The majority of the tracer mass recoveries are within 5 to 6% of the injected mass flow. This small percentage error indicates reasonable accuracy in the estimated total river flow and the synthesized flow distribution at each section as these parameters are utilized in the mass recovery calculations.

The transverse mixing downstream of the effluent diffuser progresses relatively slowly (see Figure 7a and Figure 7b) until the first bend in the river is encountered at approximately 1 km. The increased turbulence and secondary currents induced by this sharp bend greatly enhance the transverse mixing. The tracer plot at 1.2 km shows the effect of this enhanced mixing (see Figure 7c). At this point the concentrations are already close to uniform across the channel, and by 1.6 km the transverse mixing is virtually complete. The rapid transverse mixing of the effluent plume in the first bend downstream of the diffuser is also evident in Figure 3.

The observations outlined above indicate complete transverse mixing occurs within approximately 1.5 km of the discharge location for the prevailing low flow conditions. Beyond this distance, one-dimensional mixing conditions are applicable. Therefore, due to the very limited extent of the two-dimensional mixing zone modelling of the river mixing and transport was not conducted.

WATER QUALITY PARAMETERS

Introduction

Water quality samples were collected during the same time period as the tracer samples. The position of each sample was recorded using GPS equipment. Samples were taken approximately 0.3 metres below the water surface and collected in glass bottles or vials (which ever was appropriate for the analysis to be conducted). The sample bottles were immediately placed in a cooler container to isolate them from sunlight. The samples were transported to Edmonton the following day for analysis using standard laboratory procedures.

Water samples were also taken from the effluent pipeline immediately before and after the tracer injection test. These undiluted effluent samples and the flow reported by the mill were used to estimate the mass flow rate of each effluent parameter into the river. The background, effluent and fully mixed concentrations for each water quality parameter are given in Table 5.

Water Quality Sample Results

The results of the water quality measurements are shown in Figure 8. In Figure 8 the primary and secondary vertical axes represent dimensional concentrations (COD in mg/L as O_2, Colour in true colour units[1], and AOX in μg/L). The results of the water quality measurements are also shown in Figure 9 plotted on the same axis as the tracer concentrations. The vertical axis here represents non-dimensional concentration C'. Therefore, the figure illustrates the recovery of each water quality parameter compared to the mass conservative tracer results.

Mass recovery of the water quality parameters was determined using the same procedure as outlined for the tracer. The recovery at each section, is presented in Table 6. The recoveries given in Table 6 and the dimensionless plots presented in Figure 9 indicate that colour and COD results are more variable than for AOX. The AOX recoveries closely parallel the tracer results. At several locations, the tracer and AOX curves are almost identical. Hence, there is no

[1] One true colour unit equals one mg/L platinum-cobalt colour standard

evidence of any significant reduction in total mass of AOX over the approximately 2.6 hours of flow time to 4.5 km downstream.

As noted above the colour and COD recoveries are quite variable. There is evidence of initial decay in these two parameters over the first 1.2 km of the reach (see Figure 9 and Table 6). After the river passes through the riffle section immediately upstream of 1.6 km the COD recoveries rise to what appears to be unreasonable levels (over twice the input mass). The colour levels beyond 1.6 km also rise significantly. These increases are consistent across the channel (see Figure 9(d) and Figure 9(e)) and therefore cannot be the result of one or two erroneous analysis results. Beyond 2.2 km the colour levels steadily decline to approximately 100% of input and the COD levels rapidly fall back below input levels.

One plausible explanation for this behaviour may be resuspension and dissolution of previously deposited sediments in the region immediately downstream of the riffle section near 1.4 km. COD can originate from suspended as well as dissolved materials. Whereas, colour measurements are conducted on filtered samples to obtain true colour readings. Hence, resuspension could rapidly increase COD readings but may not immediately increase colour readings. This finding is consistent with the work of Krishnappan et al. (1995), and Yang and Smith (1999), which show that the formation of floc in discharged pulp mill effluent influences river water quality. The drop in COD and colour at the 0.6 and 1.2 km cross-sections followed by a significant increase in COD and colour below the riffle at 1.4 km are consistent with this phenomena.

Table 5 Input and fully mixed conditions for water quality parameters.

Parameter	Background Conc.[a]	Input Conc.[b]	Volumetric Flow [c]	Fully Mixed Conc.[d]
Tracer	0.05 μg/L	0.23×10^9 μg/L	5.0×10^{-7} m^3/s	3.2 μg/L
Colour	6.0 CU	791 CU	0.74 m^3/s	16 CU
AOX	0.95 μg/L	8288 μg/L	0.74 m^3/s	170 μg/L
COD	10 mg O_2/L	550 mg O_2/L	0.74 m^3/s	11 mg O_2/L

[a] based upon samples taken outside the plume region

[b] tracer feed 20% by weight, S.G. 1.15; average concentration of colour, AOX and COD measured in the effluent flow

[c] tracer feed rate 30 mL/minute; average effluent flow reported by the mill for August 6th and 7th was used for water quality parameters because the river samples were taken the morning of August 7th.

[d] fully mixed river concentration in excess of background (combined river and effluent flow of 36 m^3/s)

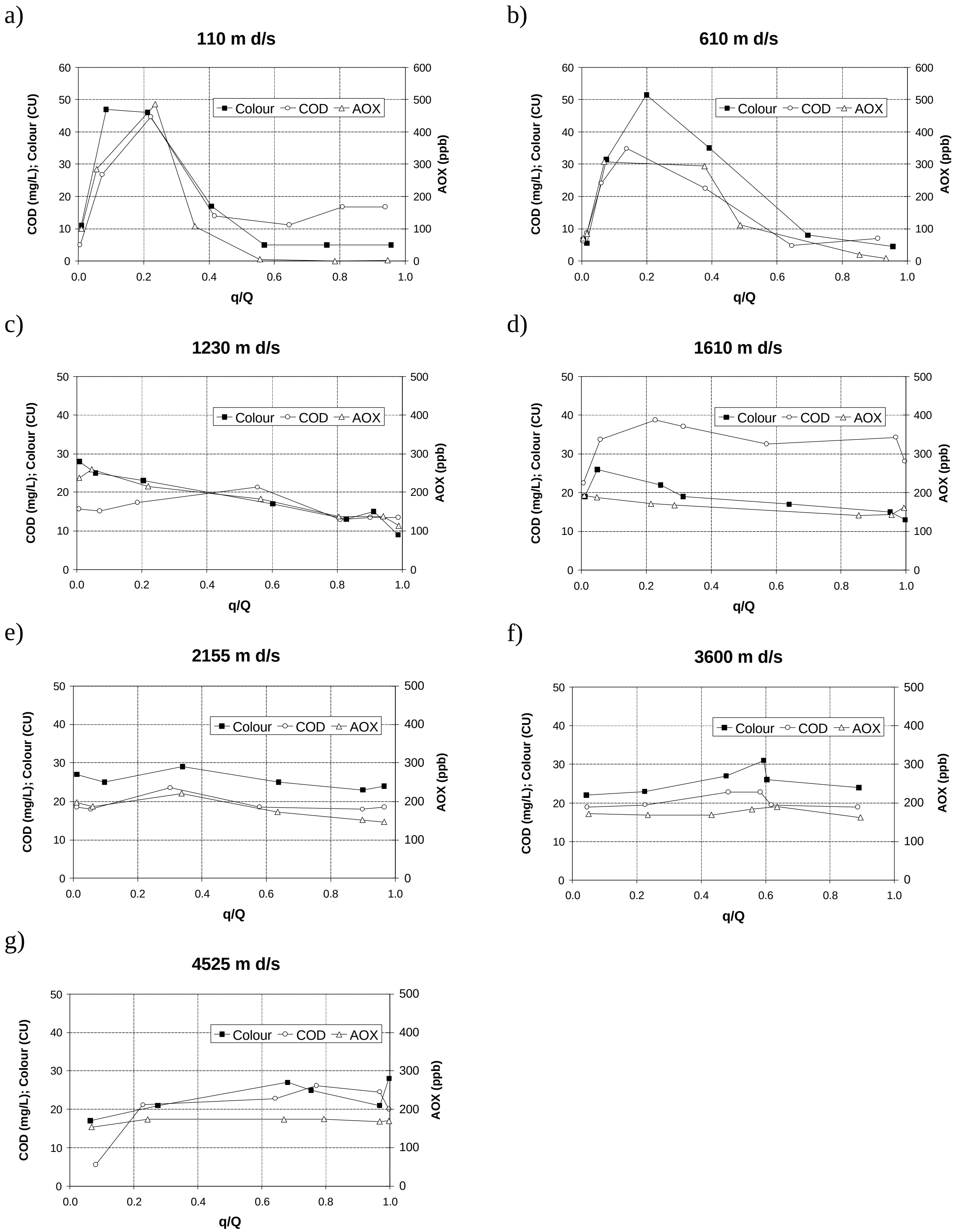


Figure 8 Water Quality Parameter Concentrations.

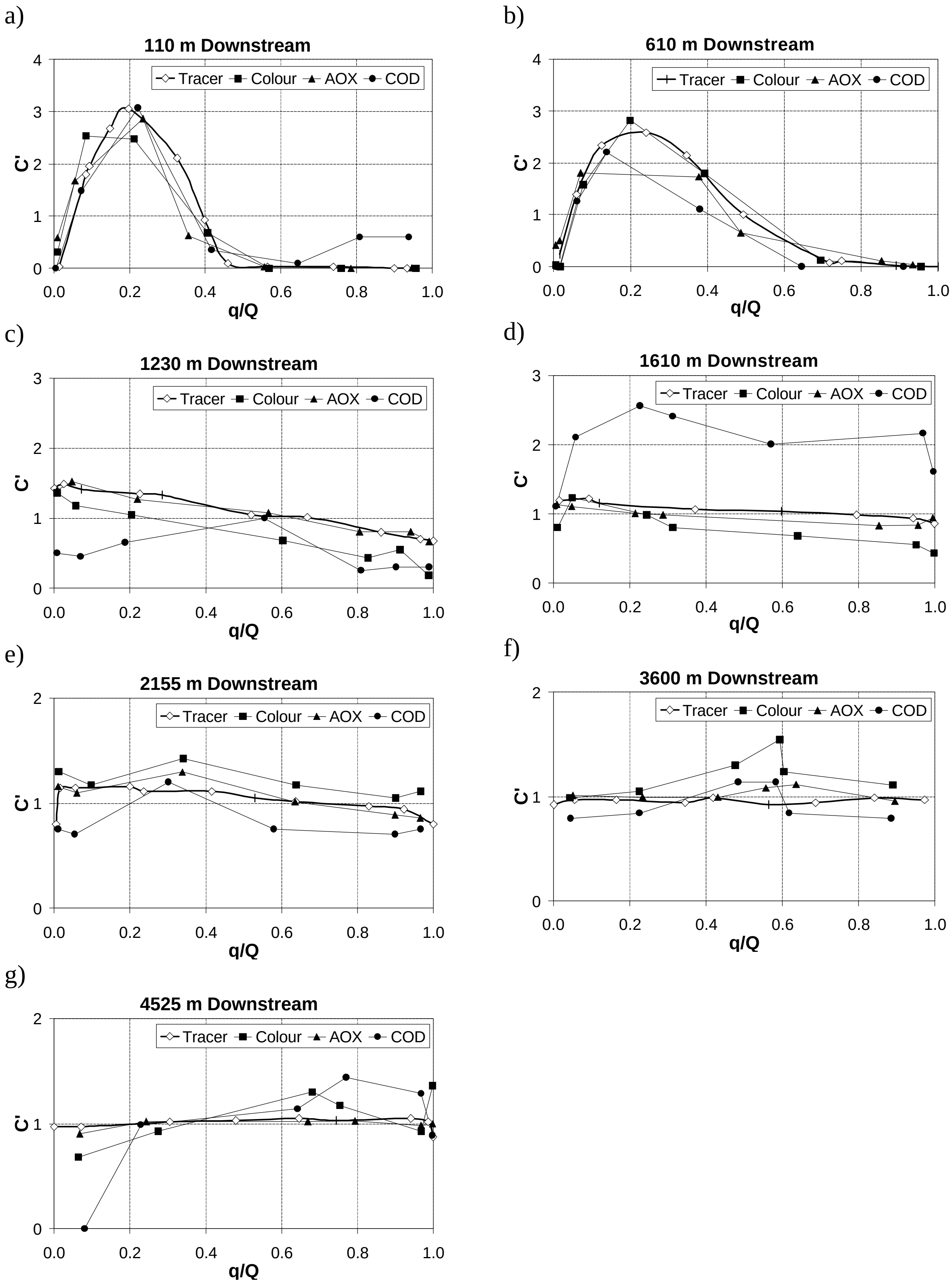


Figure 9 Tracer and Water Quality Parameter Dimensionless Concentrations.

Table 6 Mass recovery ratios for tracer and effluent parameters.

Cross Section Downstream (m)	Tracer	Colour	AOX	COD
110	0.84	0.79	0.75	0.94
610	1.06	1.07	0.89	0.71
1230	1.11	0.78	1.09	0.62
1610	1.05	0.79	0.94	2.15
2155	1.05	1.22	1.08	0.85
2915	0.93	-	-	-
3600	0.96	1.16	1.02	0.90
4115	1.02	-	-	-
4525	1.02	1.02	1.00	0.98
Average[a]	1.02	1.01	1.00	1.04

[a] averages exclude recovery at transect 110 m downstream

MANAGEMENT APPLICATIONS

The results of the fluorescent tracer test described in this report indicate that the length of the two-dimensional mixing zone in the Wapiti River downstream of Weyerhaeuser Canada Ltd. is limited during low flow conditions (<36 m^3/s). The two-dimensional mixing zone extended only 1.5 kilometers downstream of the diffuser structure during the tracer test. Beyond this distance, the mill effluent is fully mixed with the river flow. Therefore, for low flow conditions a simple one-dimensional mass balance calculation can be used to predict concentrations of mass conservative effluent parameters in the river.

Rapid establishment of a fully mixed condition has implications for receiving water quality monitoring programs conducted at this site. For low flow conditions (for example 7Q10 flow) consideration of transverse variations in concentration is not required beyond approximately 1.5 km. Beyond this distance samples taken from any mid channel location should be representative of the channel mean. One-dimensional steady state water quality modelling packages such as USEPA QUAL2E should therefore give representative results for the river reach.

The results of the water quality sampling program described in this report indicated the following within the 4.5 km river reach sampled:

- AOX discharged to the river remains in the water column and behaves as a mass conservative parameter similar to the tracer.
- The behaviour of colour and COD is erratic. Both parameters initially attenuated in the river in comparison to the tracer. However, local increases in COD and colour levels were measured at approximately 1.6 and 2.1 kilometers respectively downstream.

These results imply that it may be possible to model AOX as a mass conservative parameter. They also imply it would be impossible to model colour and COD using a simple decay function. However, these results may only apply to the specific antecedent and low flow conditions experienced in 1998. Further water quality sampling in conjunction with tracer tests should be conducted before any general conclusions can be formulated. Specifically the source of the localized increase in COD and colour should be investigated during low flow. Also the existence of this localized increase in COD and colour should be investigated at normal flow conditions earlier in the year.

CONCLUSIONS AND RECOMMENDATIONS

The following may be concluded from the Wapiti River field study:

1. Vertical mixing of the effluent is complete between 0.1 and 0.6 km downstream of the diffuser for the prevailing flow conditions.
2. Transverse mixing of the effluent is rapid after encountering the first bend in the river for the prevailing flow conditions. The transverse mixing is virtually complete 1.6 km downstream of the diffuser.
3. The steady-state tracer test combined with hydrometric surveys provides an accurate definition of the river mixing and dilution. Water quality sampling in conjunction with the tracer test provides a means of assessing attenuation of parameters by mechanisms other than dilution effects.
4. No significant reduction in total mass of AOX was evident over the 4.5 km river reach.
5. Assessment of the attenuation of colour and COD was confounded due to a localized increase in mass recovery to levels significantly greater than the effluent input rate. The local increase is suspected to be the result of resuspension of sediment materials. However, no specific evidence is currently available to support this hypothesis.

The following actions are recommended as follow up to the field study:

1. Additional field surveys extending over a longer reach of the river should be conducted to further investigate attenuation of effluent parameters in the river. Sampling at higher river flows is recommended to facilitate travel on the river.
2. An additional tracer study should be conducted to delineate the extent of the two-dimensional mixing zone at higher river flow. If the extent of the mixing zone is significant then a computer model of the river mixing should be constructed for use in assessing effluent impact upon the river.
3. Specific detailed sampling in the region of the observed local increases in colour and COD is recommended to determine the source of the additional material.

REFERENCES

Golder Associates Ltd. 1994. Environmental effects monitoring pre-design study report for Weyerhaeuser Canada Ltd. Grande Prairie. Golder Associates Ltd. Calgary, Alberta.

Krishnappan, D.G., Stephens, R., Kraft, J.A. and Moore, B.H. 1995. Size distribution and transport of suspended particles: Athabasca River, February and September 1993. Northern River Basin Study Report 1-30, Alberta Environmental Protection, Edmonton.

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. 2000. Two-dimensional modelling of effluent mixing in the Athabasca River downstream of Weldwood of Canada Ltd., Hinton, Alberta. SFMNCE Research Project Report, Edmonton, Alberta, (*in press*).

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.

Putz, G. and Smith, D.W. 1996. Two-dimensional modelling of unsteady effluent discharges to rivers. Proceedings, Conference on Sustainable Forestry Partnerships: Forging a Network of Excellence, Sustainable Forest Management Network of Centres of Excellence, March 8-10, 1996, Edmonton, pp. 46-53.

Putz, G., Odigboh, I. and Smith, D.W. 2000. Two-dimensional modelling of effluent mixing in the Athabasca River downstream of Alberta Pacific Forest Industries, Inc. SFMNCE Research Project Report, Edmonton, Alberta, 37p.

Putz, G., Smith, D.W. and Odigboh, I. 1999. Characterization and modelling of transverse mixing in the Athabasca River downstream of a pulp mill. Proceedings, Sustainable Forest Management Network Conference, Edmonton, Alberta, pp. 668-673.

Yang, X. and Smith, D.W. 1999. Pulp mill effluent induced coagulation and flocculation in receiving waters. Proceedings, Sustainable Forest Management Network Conference, Edmonton, Alberta, pp. 320-326.

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.

APPENDIX A CROSS SECTION TABULATIONS AND PLOTS

Table A1 Cross section 0 m downstream

X-SECTION Wapiti River, 0 m d/s
DATE August 6, 1998
DISCHARGE m^3/s 36.00
WIDTH m 68.61
MEAN DEPTH m 0.70
AREA m^2 47.81
MEAN VELOCITY m/s 0.753

Est. Water Surf. Elev.		495.51
LB	98.65	495.51
RB	167.26	495.51

Sta.	Elev.	h	w/W	u	dq est.	norm. q/Q	Area	adj. u
m	m	m		m/s	m^3		m^2	m/s
98.65	495.51	0.00	0.000	0.00	0.00	0.00000	0.0	0.00
100.00	495.49	0.02	0.020	0.08	0.00	0.00002	0.0	0.07
107.24	495.18	0.33	0.125	0.46	0.35	0.00873	1.3	0.42
111.15	494.79	0.73	0.182	0.77	1.28	0.04084	3.4	0.70
112.18	495.00	0.51	0.197	0.61	0.45	0.05207	4.0	0.56
115.75	494.79	0.73	0.249	0.77	1.54	0.09069	6.2	0.70
119.11	494.64	0.87	0.298	0.87	2.21	0.14622	8.9	0.79
125.18	494.71	0.80	0.387	0.82	4.30	0.25437	14.0	0.75
127.20	494.64	0.87	0.416	0.87	1.43	0.29042	15.7	0.79
133.66	494.36	1.16	0.510	1.06	6.32	0.44931	22.2	0.96
135.04	494.64	0.87	0.530	0.87	1.35	0.48333	23.6	0.79
144.26	494.64	0.87	0.665	0.87	7.01	0.65958	31.6	0.79
145.63	494.64	0.87	0.685	0.87	1.04	0.68583	32.8	0.79
156.29	494.57	0.94	0.840	0.92	8.67	0.90371	42.5	0.83
156.50	494.57	0.94	0.843	0.92	0.18	0.90835	42.7	0.83
161.10	494.86	0.66	0.910	0.723	3.02	0.98437	46.4	0.654
161.94	495.13	0.39	0.922	0.509	0.27	0.99116	46.8	0.460
164.99	495.36	0.15	0.967	0.272	0.32	0.99921	47.6	0.246
166.93	495.49	0.03	0.995	0.088	0.03	0.99999	47.8	0.080
167.26	495.51	0.00	1.000	0.000	0.00	1.00000	47.8	0.000
Last Line				Est. Total	39.77			

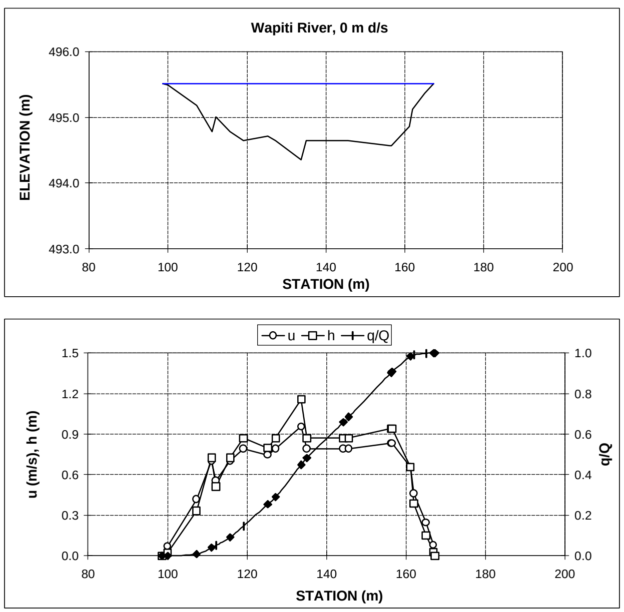


Figure A1 Cross section 0 m downstream

Table A2 Cross section 110 m downstream

X-SECTION Wapiti River, 110 m d/s
DATE August 6, 1998
DISCHARGE m^3/s 36.0
WIDTH m 77.57
MEAN DEPTH m 1.08
AREA m^2 83.70
MEAN VELOCITY m/s 0.430

Est. Water Surf. Elev.		495.52
LB	99.50	495.52
RB	177.07	495.52

Sta.	Elev.	h	w/W	u	dq est.	norm. q/Q	Area	adj. u
m	m	m		m/s	m^3		m^2	m/s
99.50	495.52	0.00	0.000	0.000	0.00	0.00000	0.0	0.000
100.00	495.49	0.02	0.006	0.03	0.00	0.00000	0.0	0.03
103.09	495.22	0.30	0.046	0.18	0.05	0.00136	0.5	0.17
106.84	495.01	0.50	0.095	0.26	0.33	0.00976	2.0	0.23
111.61	494.87	0.65	0.156	0.31	0.77	0.02926	4.7	0.28
112.07	494.73	0.79	0.162	0.35	0.11	0.03203	5.1	0.32
120.30	494.44	1.08	0.268	0.43	2.99	0.10743	12.8	0.39
122.13	494.44	1.08	0.292	0.43	0.85	0.12884	14.7	0.39
132.19	494.01	1.51	0.421	0.54	6.28	0.28733	27.7	0.49
135.41	493.94	1.58	0.463	0.55	2.72	0.35591	32.7	0.50
148.03	493.80	1.72	0.626	0.59	11.88	0.65600	53.5	0.53
151.16	493.87	1.65	0.666	0.57	3.05	0.73308	58.8	0.52
160.85	494.44	1.08	0.791	0.43	6.60	0.89986	72.0	0.39
162.05	494.66	0.86	0.806	0.37	0.47	0.91160	73.1	0.34
169.15	494.73	0.79	0.898	0.35	2.11	0.96485	79.0	0.32
175.61	494.98	0.54	0.981	0.27	1.34	0.99858	83.3	0.25
177.03	495.51	0.01	0.999	0.018	0.06	1.00000	83.7	0.016
177.07	495.52	0.00	1.000	0.000	0.00	1.00000	83.7	0.000
Last Line				Est. Total	39.60			

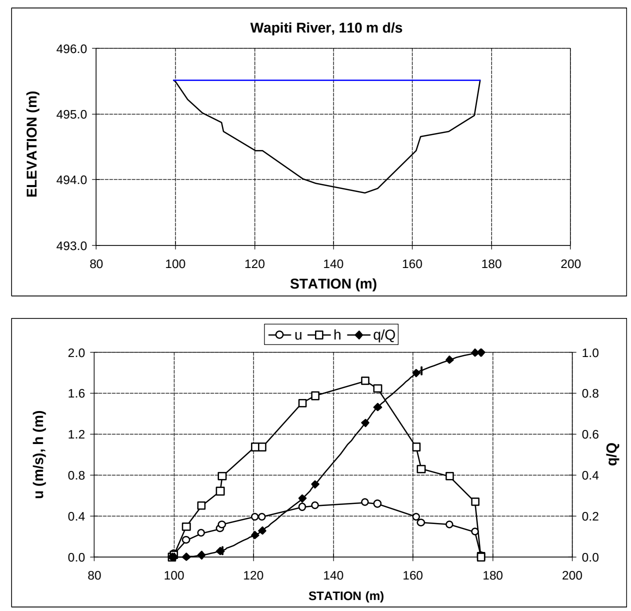
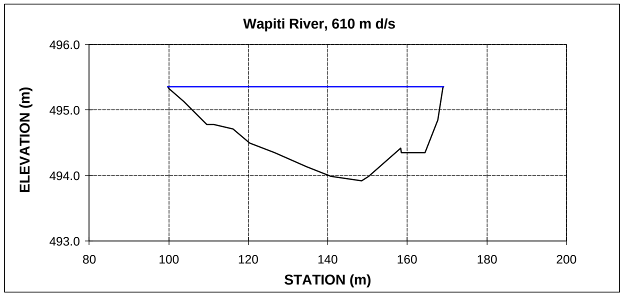


Figure A2 Cross section 110 m downstream

Table A3 Cross section 610 m downstream

X-SECTION Wapiti River, 610 m d/s
DATE August 6, 1998
DISCHARGE m^3/s 36.00
WIDTH m 69.33 Est. Water Surf. Elev. 495.35
MEAN DEPTH m 0.92 LB 99.72 495.35
AREA m^2 64.10 RB 169.05 495.35
MEAN VELOCITY m/s 0.562

Sta.	Elev.	h	w/W	u	dq est.	norm. q/Q	Area	adj. U
m	m	m		m/s	m^3		m^2	m/s
99.72	495.35	0.00	0.000	0.000	0.00	0.00000	0.0	0.000
100.00	495.33	0.02	0.004	0.048	0.00	0.00000	0.0	0.044
103.76	495.13	0.22	0.058	0.22	0.06	0.00154	0.5	0.20
109.51	494.78	0.57	0.141	0.41	0.71	0.01973	2.7	0.37
111.38	494.78	0.57	0.168	0.41	0.44	0.03091	3.8	0.37
116.13	494.71	0.65	0.237	0.44	1.24	0.06236	6.7	0.41
120.24	494.49	0.86	0.296	0.54	1.51	0.10090	9.8	0.49
126.58	494.35	1.00	0.388	0.59	3.34	0.18602	15.7	0.54
134.66	494.13	1.22	0.504	0.68	5.70	0.33116	24.7	0.62
140.70	493.99	1.36	0.591	0.73	5.47	0.47057	32.5	0.67
148.54	493.92	1.43	0.704	0.75	8.12	0.67722	43.5	0.69
150.27	493.99	1.36	0.729	0.73	1.79	0.72268	45.9	0.67
158.30	494.42	0.93	0.845	0.57	5.96	0.87450	55.1	0.52
158.52	494.35	1.00	0.848	0.59	0.12	0.87764	55.3	0.54
164.51	494.35	1.00	0.935	0.59	3.57	0.96857	61.4	0.54
167.71	494.85	0.50	0.981	0.37	1.17	0.99829	63.8	0.34
169.01	495.34	0.01	0.999	0.03	0.07	1.00000	64.1	0.02
169.05	495.35	0.00	1.000	0.000	0.00	1.00000	64.1	0.000
Last Line				Est. Total	39.27			



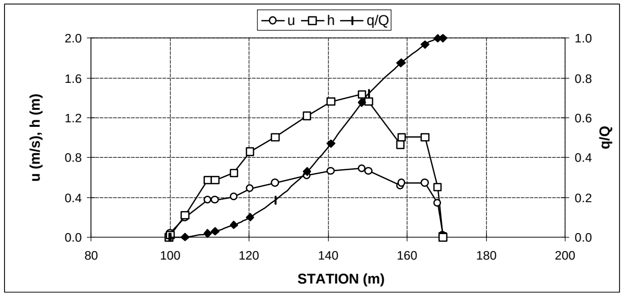
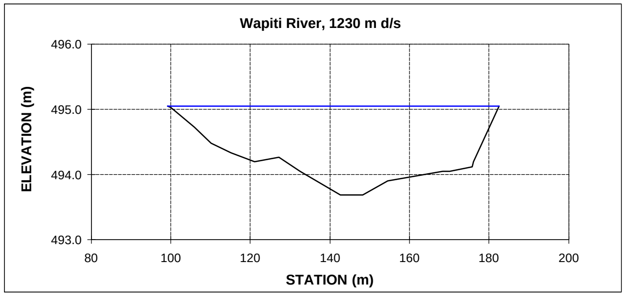


Figure A3 Cross section 610 m downstream

Table A4 Cross section 1230 m downstream

X-SECTION Wapiti River, 1230 m d/s
DATE August 6, 1998
DISCHARGE m^3/s 36.00
WIDTH m 83.33 Est. Water Surf. Elev. 495.05
MEAN DEPTH m 0.88 LB 99.24 495.05
AREA m^2 73.19 RB 182.57 495.05
MEAN VELOCITY m/s 0.492

Sta.	Elev.	h	w/W	u	dq est.	norm. q/Q	Area	adj. u
m	m	m		m/s	m^3		m^2	m/s
99.24	495.05	0.00	0.000	0.000	0.00	0.00000	0.0	0.000
100.00	495.03	0.02	0.009	0.043	0.00	0.00000	0.0	0.040
105.90	494.73	0.33	0.080	0.254	0.15	0.00393	1.0	0.235
110.15	494.48	0.57	0.131	0.369	0.59	0.01920	2.9	0.341
115.13	494.34	0.71	0.191	0.429	1.28	0.05201	6.1	0.396
121.10	494.19	0.86	0.262	0.48	2.14	0.10710	10.8	0.45
127.19	494.27	0.79	0.335	0.46	2.36	0.16762	15.9	0.42
132.52	494.05	1.00	0.399	0.54	2.37	0.22840	20.6	0.50
142.57	493.69	1.36	0.520	0.66	7.09	0.41059	32.5	0.61
148.28	493.69	1.36	0.589	0.66	5.12	0.54200	40.3	0.61
154.50	493.91	1.14	0.663	0.59	4.84	0.66642	48.0	0.54
168.37	494.05	1.00	0.830	0.54	8.37	0.88136	62.9	0.50
170.18	494.05	1.00	0.851	0.54	0.97	0.90638	64.7	0.50
175.71	494.12	0.93	0.918	0.51	2.80	0.97820	70.1	0.47
176.06	494.19	0.86	0.922	0.48	0.16	0.98221	70.4	0.45
182.56	495.05	0.00	1.000	0.01	0.69	1.00000	73.2	0.01
182.57	495.05	0.00	1.000	0.00	0.00	1.00000	73.2	0.00
Last Line				Est. Total	38.94			



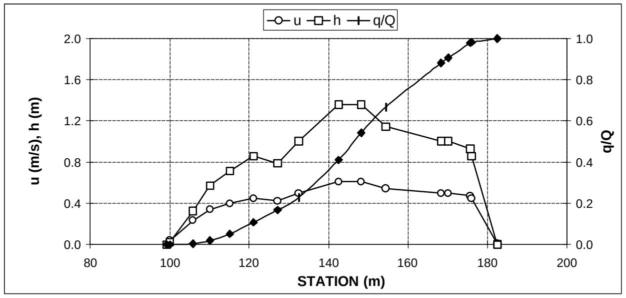


Figure A4 Cross section 1230 m downstream

Table A5 Cross section 1610 m downstream

X-SECTION	Wapiti River,1610 m d/s		
DATE	August 6, 1998		
DISCHARGE m^3/s	36.0		
WIDTH m	77.01	Est. Water Surf. Elev.	494.44
MEAN DEPTH m	1.59	LB 99.89	494.44
AREA m^2	122.78	RB 176.90	494.44
MEAN VELOCITY m/s	0.293		

Sta. m	Elev. m	h m	w/W	u m/s	dq est. m^3	norm. q/Q	Area m^2	adj. u m/s
99.89	494.44	0.00	0.000	0.000	0.00	0.00000	0.0	0.000
100.00	494.42	0.02	0.001	0.017	0.00	0.00000	0.0	0.015
101.31	493.92	0.52	0.019	0.139	0.03	0.00068	0.4	0.122
101.55	493.93	0.51	0.022	0.137	0.02	0.00110	0.5	0.120
105.51	493.43	1.01	0.073	0.22	0.53	0.01404	3.5	0.19
109.30	493.50	0.94	0.122	0.21	0.78	0.03308	7.2	0.18
115.61	493.43	1.01	0.204	0.22	1.30	0.06473	13.3	0.19
124.58	493.22	1.23	0.321	0.25	2.32	0.12128	23.4	0.22
130.95	492.36	2.09	0.403	0.35	3.15	0.19803	33.9	0.31
137.36	491.71	2.73	0.487	0.42	5.95	0.34303	49.3	0.37
144.01	491.78	2.66	0.573	0.41	7.46	0.52490	67.3	0.36
149.89	491.85	2.59	0.649	0.41	6.31	0.67881	82.7	0.36
158.54	492.21	2.23	0.762	0.37	8.04	0.87484	103.5	0.32
162.16	492.71	1.73	0.809	0.31	2.42	0.93385	110.7	0.27
169.01	493.50	0.94	0.898	0.21	2.35	0.99120	119.8	0.18
169.66	493.86	0.58	0.906	0.15	0.09	0.99333	120.3	0.13
171.94	493.92	0.52	0.936	0.14	0.18	0.99773	121.6	0.12
176.37	494.42	0.02	0.993	0.02	0.09	1.00000	122.8	0.01
176.90	494.44	0.00	1.000	0.00	0.00	1.00000	122.8	0.00
Last Line				Est. Total	41.01			

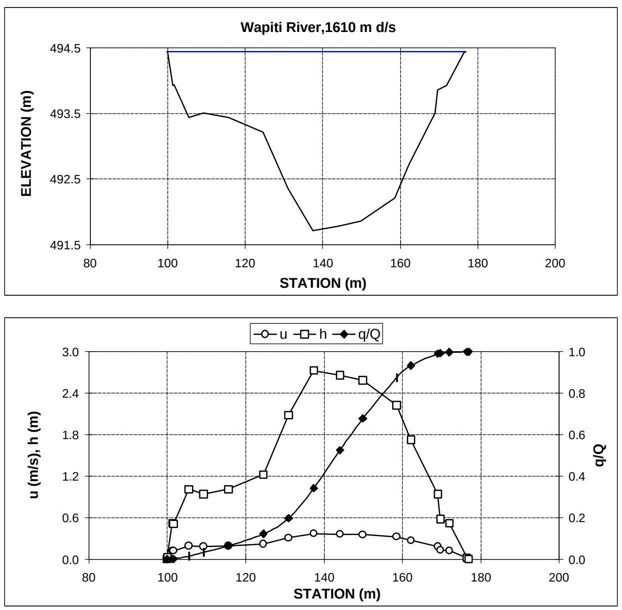


Figure A5 Cross section 1610 m downstream

Table A6 Cross section 2155 m downstream

X-SECTION	Wapiti River, 2155 m d/s		
DATE	August 6, 1998		
DISCHARGE m^3/s	36.0		
WIDTH m	73.13	Est. Water Surf. Elev.	493.70
MEAN DEPTH m	0.82	LB 100.00	493.70
AREA m^2	60.22	RB 173.13	493.70
MEAN VELOCITY m/s	0.598		

Sta. m	Elev. m	h m	w/W	u m/s	dq est. m^3	norm. q/Q	Area m^2	adj. u m/s
100.00	493.70	0.00	0.000	0.00	0.00	0.00000	0.0	0.00
109.51	493.12	0.58	0.130	0.47	0.65	0.01731	2.7	0.45
111.08	493.12	0.58	0.151	0.47	0.43	0.02875	3.7	0.45
111.66	493.27	0.43	0.159	0.39	0.13	0.03213	3.9	0.37
115.04	493.12	0.58	0.206	0.47	0.73	0.05157	5.6	0.45
117.13	492.90	0.79	0.234	0.58	0.75	0.07171	7.1	0.56
123.86	492.69	1.01	0.326	0.68	3.84	0.17436	13.1	0.66
124.72	492.76	0.94	0.338	0.65	0.55	0.18917	14.0	0.63
134.67	492.47	1.22	0.474	0.78	7.68	0.39432	24.7	0.75
137.60	492.62	1.08	0.514	0.72	2.52	0.46152	28.1	0.69
149.33	492.47	1.22	0.675	0.78	10.10	0.73109	41.6	0.75
151.07	492.55	1.15	0.698	0.75	1.58	0.77320	43.7	0.72
155.01	492.40	1.29	0.752	0.81	3.75	0.87338	48.5	0.78
173.13	493.70	0.00	1.000	0.000	4.74	1.00000	60.2	0.000
Last Line				Est. Total	37.45			

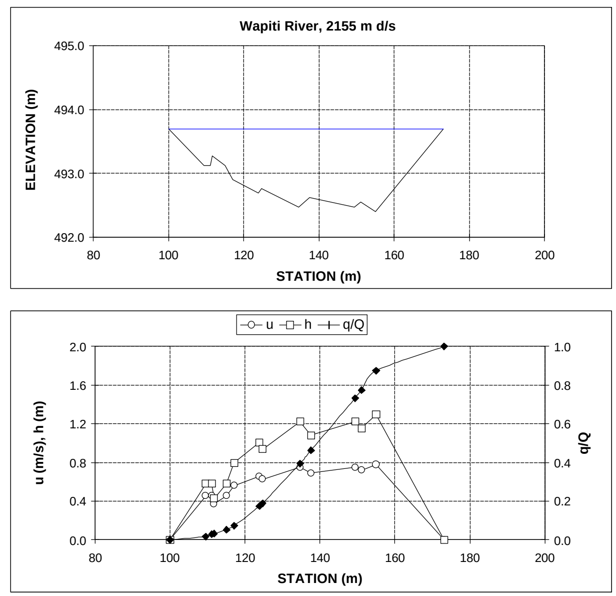
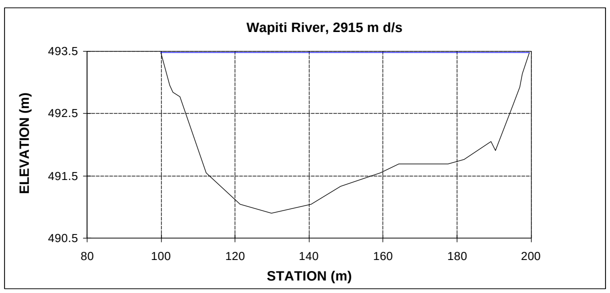


Figure A6 Cross section 2155 m downstream

Table A7 Cross section 2915 m downstream

X-SECTION	Wapiti River, 2915 m d/s		
DATE	August 6, 1998		
DISCHARGE m^3/s	36.0		
WIDTH m	99.62	Est. Water Surf. Elev.	493.48
MEAN DEPTH m	1.82	LB 99.92	493.48
AREA m^2	181.07	RB 199.54	493.48
MEAN VELOCITY m/s	0.199		

Sta. m	Elev. m	h m	w/W	u m/s	dq est. m^3	norm. q/Q	Area m^2	adj. u m/s
99.92	493.48	0.00	0.000	0.000	0.00	0.00000	0.0	0.000
100.00	493.45	0.02	0.001	0.011	0.00	0.00000	0.0	0.010
102.29	492.95	0.52	0.024	0.09	0.03	0.00080	0.6	0.08
103.11	492.84	0.64	0.032	0.10	0.04	0.00195	1.1	0.09
105.11	492.77	0.71	0.052	0.11	0.14	0.00555	2.4	0.10
112.22	491.55	1.93	0.123	0.21	1.46	0.04388	11.8	0.19
121.40	491.05	2.43	0.216	0.24	4.47	0.16103	31.8	0.23
129.80	490.90	2.57	0.300	0.25	5.17	0.29638	52.8	0.24
140.55	491.05	2.43	0.408	0.24	6.61	0.46944	79.7	0.23
148.53	491.33	2.14	0.488	0.22	4.22	0.57984	97.9	0.21
159.17	491.55	1.93	0.595	0.21	4.64	0.70130	119.5	0.19
164.21	491.69	1.78	0.645	0.20	1.88	0.75066	128.9	0.19
177.59	491.69	1.78	0.780	0.20	4.68	0.87332	152.8	0.19
181.88	491.76	1.71	0.823	0.19	1.45	0.91127	160.2	0.18
189.20	492.05	1.42	0.896	0.17	2.07	0.96539	171.7	0.16
190.35	491.91	1.57	0.908	0.18	0.30	0.97326	173.4	0.17
194.96	492.62	0.85	0.954	0.12	0.84	0.99516	179.0	0.11
197.02	492.92	0.56	0.975	0.090	0.15	0.99914	180.5	0.085
197.69	493.14	0.33	0.981	0.064	0.02	0.99974	180.8	0.060
199.54	493.48	0.00	1.000	0.000	0.01	1.00000	181.1	0.000
Last Line				Est. Total	38.19			



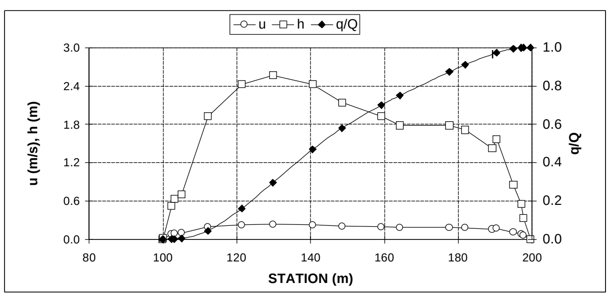
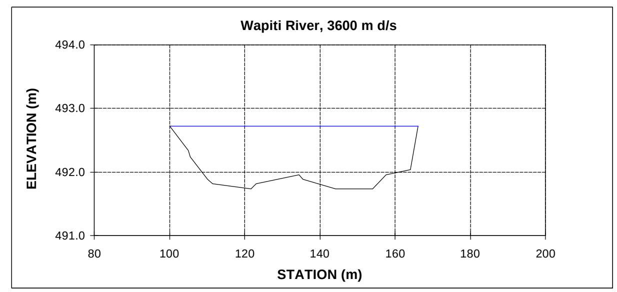


Figure A7 Cross section 2915 m downstream

Table A8 Cross section 3600 m downstream

X-SECTION	Wapiti River, 3600 m d/s		
DATE	August 6, 1998		
DISCHARGE m^3/s	36.0		
WIDTH m	66.12	Est. Water Surface Elev.	492.72
MEAN DEPTH m	0.80	LB 100.00	492.72
AREA m^2	52.65	RB 166.12	492.72
MEAN VELOCITY m/s	0.684		

Sta. m	Elev. m	h m	w/W	u m/s	dq est. m^3	norm. q/Q	Area m^2	adj. u m/s
100.00	492.72	0.00	0.000	0.00	0.00	0.00000	0.0	0.00
105.00	492.34	0.38	0.076	0.42	0.20	0.00525	0.9	0.40
105.42	492.24	0.48	0.082	0.49	0.08	0.00740	1.1	0.47
110.06	491.88	0.84	0.152	0.71	1.81	0.05571	4.2	0.68
111.43	491.81	0.91	0.173	0.75	0.87	0.07883	5.4	0.72
121.64	491.74	0.98	0.327	0.78	7.36	0.27513	15.0	0.75
123.08	491.81	0.91	0.349	0.75	1.04	0.30282	16.3	0.72
134.33	491.96	0.76	0.519	0.66	6.63	0.47962	25.7	0.64
135.42	491.88	0.84	0.536	0.71	0.60	0.49550	26.6	0.68
144.03	491.74	0.98	0.666	0.78	5.82	0.65072	34.4	0.75
153.94	491.74	0.98	0.816	0.78	7.61	0.85355	44.1	0.75
157.53	491.96	0.76	0.870	0.66	2.27	0.91395	47.2	0.64
164.08	492.04	0.68	0.969	0.61	3.01	0.99434	52.0	0.59
166.12	492.72	0.00	1.000	0.000	0.21	1.00000	52.6	0.000
Last Line				Est. Total	37.50			



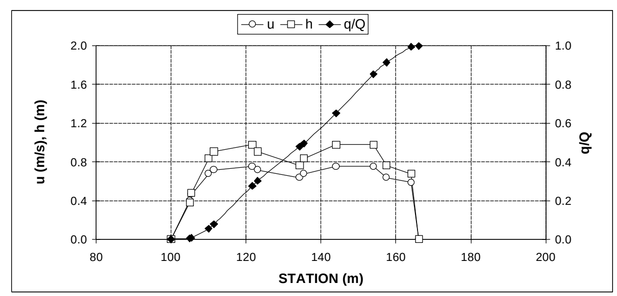


Figure A8 Cross section 3600 m downstream

Table A9 Cross section 4115 m downstream

X-SECTION	Wapiti River, 4115 m d/s			
DATE	August 6, 1998			
DISCHARGE m^3/s	36.00			
WIDTH m	91.42	Est. Water Surf. Elev.		492.51
MEAN DEPTH m	1.18	LB	100.00	492.51
AREA m^2	107.57	RB	191.42	492.51
MEAN VELOCITY m/s	0.335			

Sta. m	Elev. m	h m	w/W	u m/s	dq est. m^3	norm. q/Q	Area m^2	adj. u m/s
100.00	492.51	0.00	0.000	0.00	0.00	0.00000	0.0	0.00
103.55	491.92	0.58	0.039	0.21	0.11	0.00290	1.0	0.20
106.45	491.85	0.66	0.071	0.23	0.39	0.01337	2.8	0.22
109.76	491.49	1.01	0.107	0.30	0.73	0.03296	5.6	0.29
114.45	491.06	1.44	0.158	0.38	1.98	0.08588	11.4	0.37
124.24	491.13	1.37	0.265	0.37	5.20	0.22496	25.1	0.36
126.84	491.13	1.37	0.294	0.37	1.32	0.26033	28.7	0.36
138.47	491.21	1.30	0.421	0.36	5.66	0.41178	44.2	0.34
145.60	490.78	1.73	0.499	0.43	4.27	0.52602	55.0	0.42
150.91	490.92	1.59	0.557	0.41	3.70	0.62513	63.9	0.39
162.54	491.92	0.58	0.684	0.21	3.90	0.72953	76.5	0.20
169.06	491.64	0.87	0.755	0.27	1.15	0.76018	81.2	0.26
172.80	491.35	1.16	0.796	0.33	1.14	0.79079	85.0	0.32
180.58	490.99	1.52	0.881	0.40	3.78	0.89195	95.4	0.38
182.17	490.63	1.87	0.899	0.46	1.15	0.92269	98.1	0.44
190.34	492.11	0.40	0.988	0.162	2.87	0.99949	107.4	0.156
191.28	492.48	0.03	0.998	0.027	0.02	1.00000	107.6	0.026
191.42	492.51	0.00	1.000	0.000	0.00	1.00000	107.6	0.000
Last Line				Est. Total	37.37			

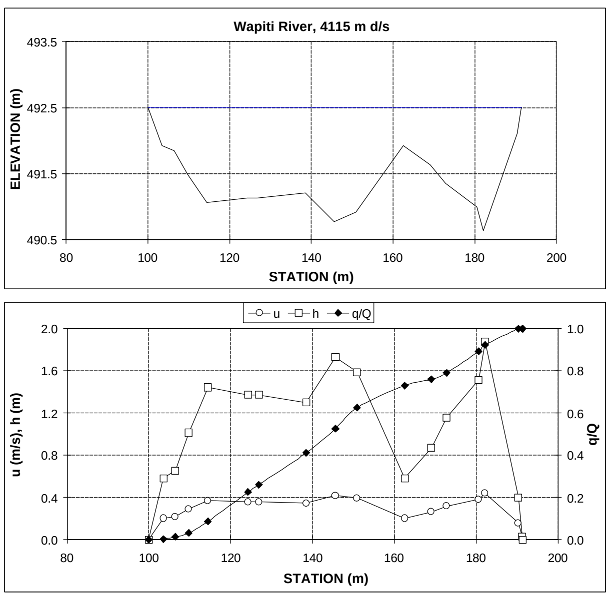


Figure A9 Cross section 4115 m downstream

Table A10 Cross section 4525 m downstream

X-SECTION	Wapiti River, 4525 m d/s			
DATE	August 6, 1998			
DISCHARGE m^3/s	36.0			
WIDTH m	73.72	Est. Water Surf. Elev.		492.45
MEAN DEPTH m	1.12	LB	99.95	492.45
AREA m^2	82.40	RB	173.67	492.45
MEAN VELOCITY m/s	0.437			

Sta. m	Elev. m	h m	w/W	u m/s	dq est. m^3	norm. q/Q	Area m^2	adj. u m/s
99.95	492.45	0.00	0.000	0.000	0.00	0.00000	0.0	0.000
100.00	492.42	0.02	0.001	0.033	0.00	0.00000	0.0	0.028
101.28	491.95	0.49	0.018	0.253	0.05	0.00114	0.3	0.219
103.83	491.13	1.32	0.053	0.49	0.85	0.02161	2.6	0.42
106.70	491.06	1.39	0.092	0.50	1.92	0.06763	6.5	0.44
112.02	490.48	1.96	0.164	0.64	5.08	0.18947	15.4	0.55
118.62	490.34	2.10	0.253	0.67	8.73	0.39891	28.8	0.58
124.51	490.77	1.67	0.333	0.57	6.89	0.56419	40.0	0.49
129.72	491.13	1.32	0.404	0.49	4.13	0.66318	47.8	0.42
134.77	491.13	1.32	0.472	0.49	3.23	0.74069	54.4	0.42
141.49	491.13	1.32	0.564	0.49	4.31	0.84414	63.2	0.42
149.70	491.63	0.81	0.675	0.35	3.67	0.93218	72.0	0.31
150.22	491.63	0.81	0.682	0.35	0.15	0.93579	72.4	0.31
155.57	491.85	0.60	0.754	0.29	1.21	0.96489	76.2	0.25
159.84	491.85	0.60	0.812	0.29	0.74	0.98258	78.7	0.25
161.44	491.99	0.46	0.834	0.24	0.22	0.98796	79.6	0.21
167.06	492.18	0.27	0.910	0.17	0.42	0.99802	81.6	0.15
171.35	492.39	0.06	0.969	0.06	0.08	0.99995	82.3	0.05
173.67	492.45	0.00	1.000	0.000	0.00	1.00000	82.4	0.000
Last Line				Est. Total	41.69			

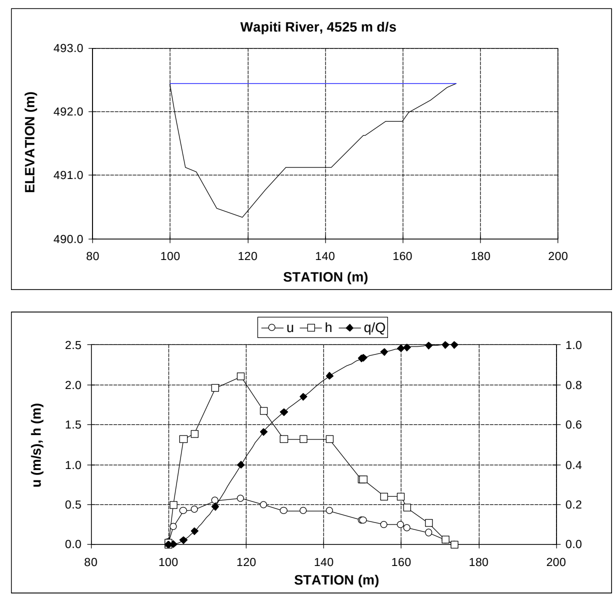


Figure A10 Cross section 4525 m downstream