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EFFECTS OF PULP MILL EFFLUENT ON THE TRANSPORT CHARACTERISTICS OF SUSPENDED SEDIMENTS IN THE ATHABASCA RIVER IN CANADA

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EFFECTS OF PULP MILL EFFLUENT ON THE TRANSPORT CHARACTERISTICS OF SUSPENDED SEDIMENTS IN THE ATHABASCA RIVER IN CANADA

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MANAGEMENT PERSPECTIVE

Fine grained sediments play an important role in the transport, fate and bioaccumulation of contaminants in the aquatic ecosystem and therefore, the knowledge of their transport characteristics is an essential prerequisite for modelling the impact of contaminants on the environment. This study, which was carried out using the Athabasca River sediment and the pulp mill effluent from the Weldwood Pulp Mill at Hinton, Alberta, shows that the contaminant interaction itself alters the transport characteristics of the sediment and points to a need for an improved sediment transport model that would take into account this feed back.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Les sédiments de faible granulométrie jouent un rôle important dans le transport, le devenir et la bioaccumulation des contaminants dans l'écosystème aquatique. La connaissance de leurs caractéristiques de transport est donc une condition préalable essentielle pour la modélisation des effets des contaminants sur l'environnement. La présente étude, qui a porté sur les sédiments de la rivière Athabasca et les effluents de l'usine de pâtes de Welwood à Hinton (Alberta), montre que l'interaction des contaminants modifie les caractéristiques de transport des sédiments et qu'il faut un meilleur modèle de transport des sédiments qui prendrait en compte cette rétroaction.

ABSTRACT

Field measurements of suspended sediment transport carried out in the Athabasca River near Hinton, Alberta, Canada, are described. The objective of the measurements was to examine the influence of pulp mill effluent entering the river from a nearby pulp mill, on the suspended sediment. The results of the field measurement showed that the effluent had a significant impact on the transport of the sediment. Specifically, the effluent increased the deposition rates of the sediment and caused a substantial reduction of sediment concentration in reaches downstream of the effluent outfall. The reduction in sediment concentrations and the concomitant sediment load can only be attributed to the pulp mill effluent as there were no abrupt changes in the hydraulic characteristics of the river in the reach of interest. These observations were also confirmed by a laboratory experiment conducted in a newly built circular, rotating flume at the National Water Research Institute at Burlington, Ontario, Canada. The findings of this study have implications for modelling sediment transport in rivers receiving bleached pulp mill effluent.

RÉSUMÉ

L'auteur du présent document décrit les mesures du transport des sédiments en suspension effectuées dans la rivière Athabasca près de Hinton, en Alberta (Canada). Il s'agissait d'étudier l'effet du déversement des effluents d'une usine de pâtes située à proximité sur les sédiments en suspension. Les résultats de ces mesures ont révélé que les effluents avaient un effet important sur le transport des sédiments. Plus particulièrement, les effluents augmentaient le taux de sédimentation et provoquaient une réduction importante de la concentration des sédiments dans des tronçons en aval de l'exutoire des effluents. La réduction des concentrations de sédiments et la charge en sédiments concomitante ne peuvent être attribuées qu'aux effluents de l'usine car il n'y a eu aucune modification brusque des caractéristiques hydraulique de la rivière dans le tronçon étudié. Ces observations ont également été corroborées par une expérience en laboratoire menée dans le nouveau canal rotatif circulaire de l'Institut national de recherches sur les eaux de Burlington, en Ontario (Canada). Les résultats de la présente étude ont des répercussions sur la modélisation du transport des sédiments dans les rivières recevant les effluents des usines de pâte blanchie.

INTRODUCTION:

The role of fine grained, suspended sediments in the adsorption and transport of toxic contaminants in the aquatic ecosystem has been studied extensively during the past decade (See, for example, Allan, 1986; Forstner and Wittman, 1981; Frank, 1981; Kuntz and Wary, 1983). However, to the best of the author's knowledge, there is practically no information in the literature on the effect of contaminants on the transport characteristics of sediment. Since the adsorption of contaminant onto a sediment particle is a surface phenomenon, there is a possibility that it might have an effect on the flocculation mechanism of the sediment particles and consequently on their transport characteristics. In this study, the effect of pulp mill effluent on suspended sediments of the Athabasca River near Hinton , Alberta, Canada is investigated using both field measurements and measurements in a newly built rotating circular flume in the laboratory. The details of these measurements and the results are presented in this paper.

FIELD STUDY:

The field measurements consisted of two surveys: One, during the winter of 1993 when the flow was low and ice covered and the other, during the fall of the same year under open water condition. In both surveys, the river reach covered was between the towns of Entrance and Windfall on the Athabasca river (see Fig. 1 for sampling locations) and the measurements consisted of flow field, size distribution of in-situ and primary particles and concentration of suspended particles.

River Reach:

The profile of the upper reaches of the Athabasca river is shown in Fig. 2. It shows the reach between the Towns of Entrance and Windfall as a uniform reach with an average bed slope of 0.00123. The sampling locations are also marked on this profile. The transect at Entrance is about eight kilometres upstream from the Weldwood Pulp Mill at Hinton and it is immediately

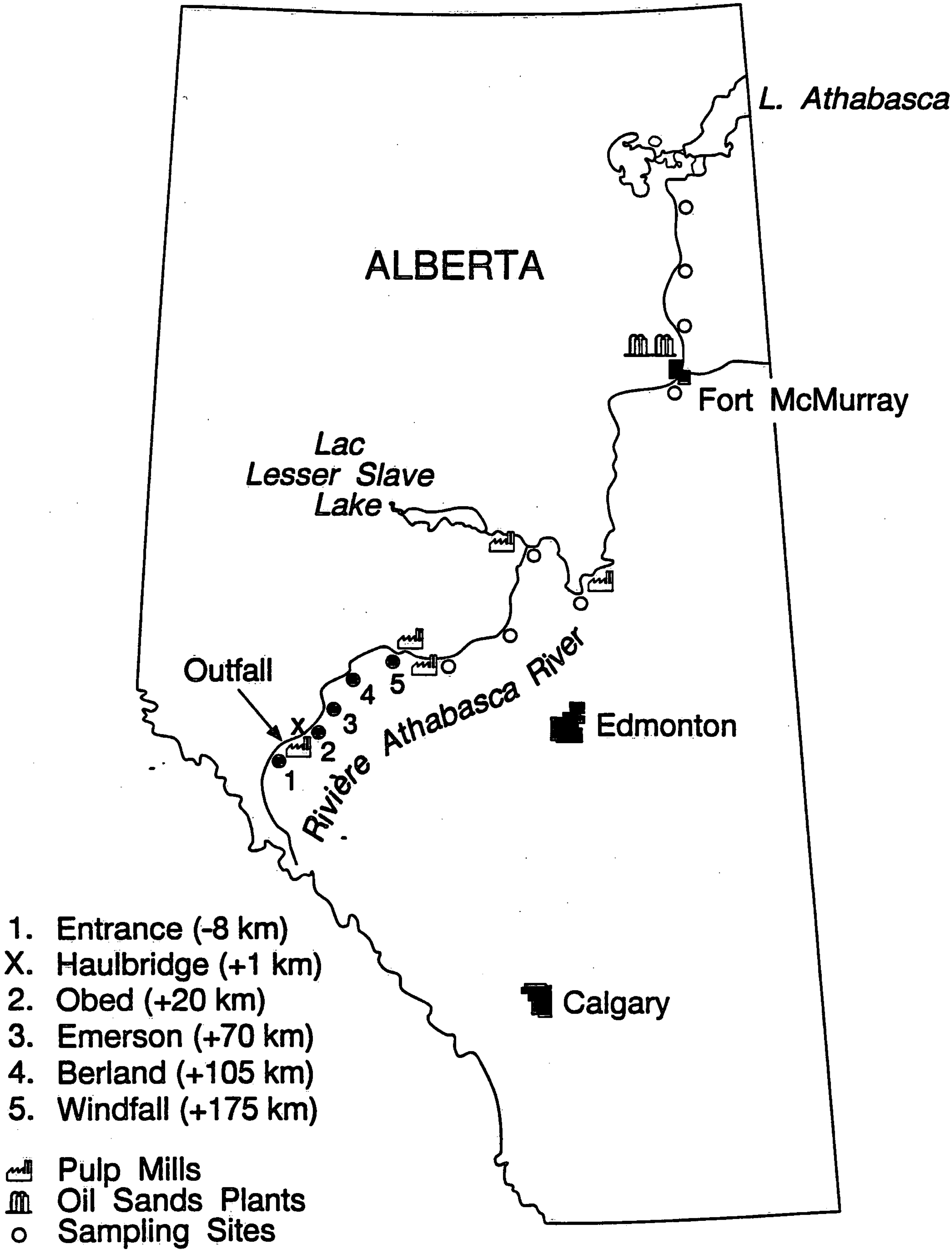
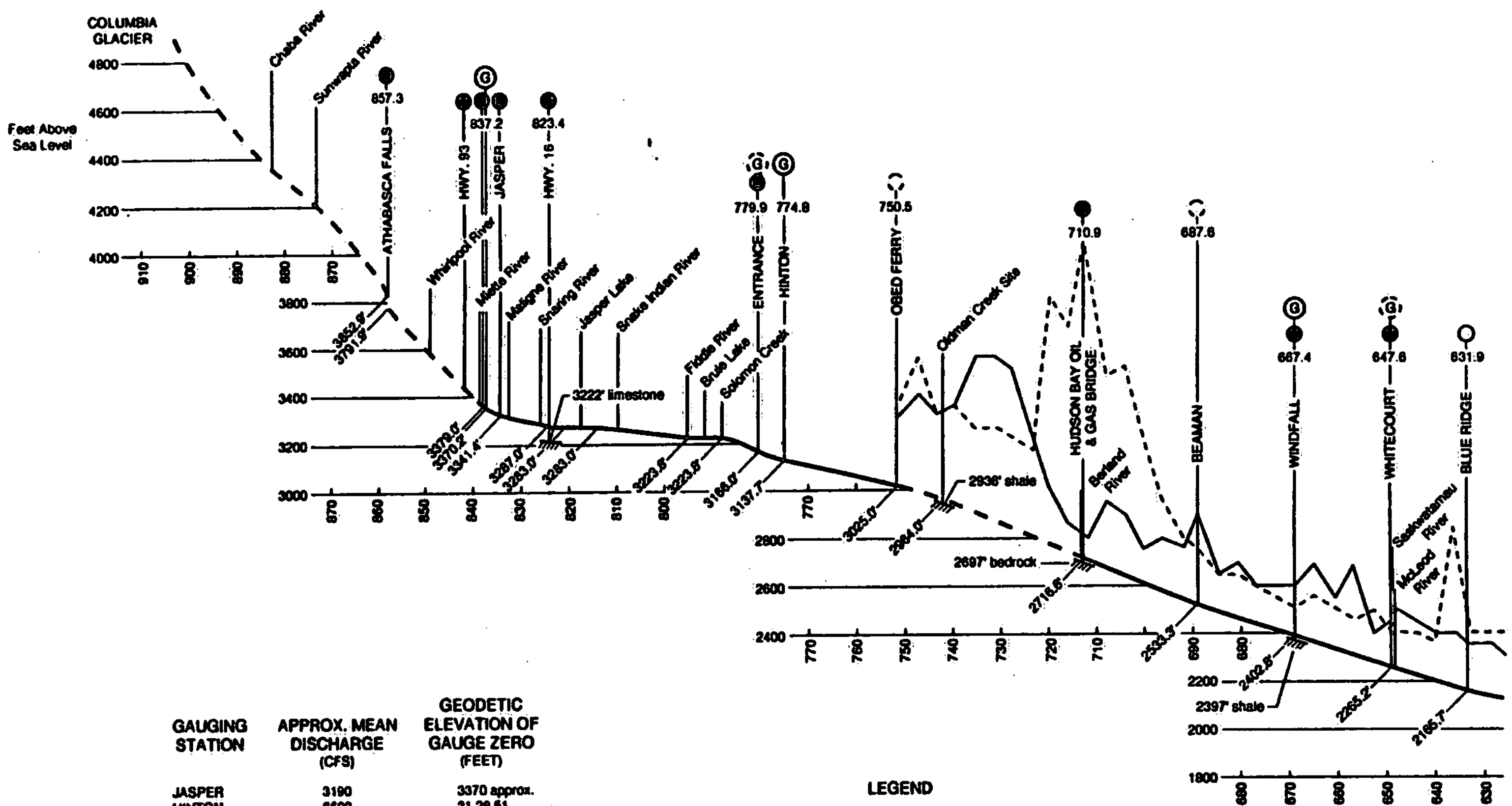


Figure 1. Map of sampling locations



GAUGING STATION	APPROX. MEAN DISCHARGE (CFS)	GEODETIC ELEVATION OF GAUGE ZERO (FEET)
JASPER	3190	3370 approx.
HINTON	6600	31.26.51
WHITECOURT	9730	2255.67

TABLE OF AVERAGE SLOPES

	DISTANCE (MILES)	FALL (FEET)	SLOPE (FT. / MILE)	SLOPE (PER 1000)
COLUMBIA GLACIER - ATHABASCA FALLS (top)	44.5	1047.1	23.53	4.456
ATHABASCA FALLS top - bottom	0.1	61.0	610.00	115.000
ATHABASCA FALLS bottom - JASPER	20.5	421.7	20.57	3.896
JASPER - HINTON	62.4	232.5	3.73	0.706
HINTON - HUDSON BAY OIL & GAS BRIDGE	63.4	421.1	6.64	1.258
HUDSON BAY OIL & GAS BRIDGE - WINDFALL	43.3	313.8	7.25	1.372
WINDFALL - WHITECOURT	19.8	137.6	6.95	1.316
WHITECOURT - BLUERIDGE FERR	15.7	99.5	6.34	1.200

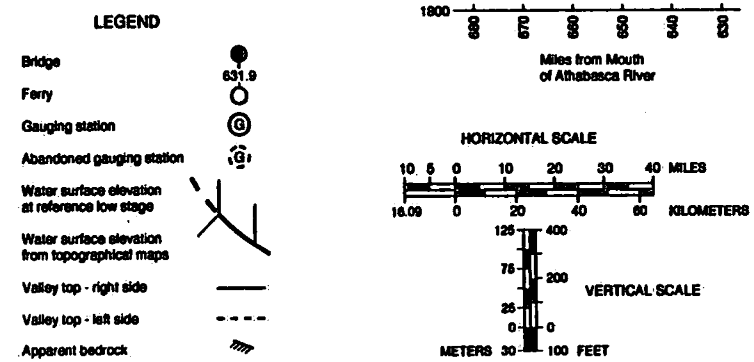


Fig. 2. Profile of the Athabasca River near Hinton, Alberta.

downstream from a Water Survey of Canada gauging station. The transect at the Obed coal mines bridge is 20 kilometres downstream from the pulp mill. Other transects sampled include the Emerson bridge, the Berland bridge and the Windfall bridge at 70 Km, 105 Km and 175 Km, respectively from Hinton. There are two other Water Survey of Canada gauging stations within the sampled reach: One at Obed and the other at Windfall. The profile in Fig. 2 shows a break in the bed slope at Solomon Creek upstream from the Entrance transect. The slope changes from a milder slope to a steeper slope at this location. This implies that the flow velocity and the stream power to transport sediment in the downstream reach (i.e. the reach containing the sampling transects) are higher than those in the upstream reach. In other words, the sediment delivered to the downstream reach from upstream is not likely to be deposited in the sampled reach. Limited information on the bed characteristics shows that the river bed in the study reach consists of shale and bedrock.

Instrumentation:

The size distribution of suspended particles was measured using a new submersible laser particle size analyzer developed at the National Water Research Institute, Burlington, Ontario, Canada. This instrument can measure the size distribution of sediment flocs directly in the flow and overcome the problem of floc breakage that is normally encountered in the traditional method of size measurement involving collection of sediment samples and analysis using laboratory instruments. Complete details of the instrument are given in Krishnappan et al. (1992). Here, a brief description is given for the sake of completeness.

The instrument operates on the principle of laser diffraction and it consists of a 2mW laser, a receiving lens, a detector plate, an electronic interface and a microcomputer. The laser, the detector plate and the electronic circuitry are attached to an aluminum chassis mounted inside a watertight canister. The laser beam emerges out through a glass window and passes through a laser path tube, which is attached to a Dow prism that deflects the laser beam by 180 degrees. The deflected beam passes through the sensing volume and enters the canister through a second glass window. The receiving lens focuses the diffracted light on the detector plate. From the measured distribution of the diffracted light, the size distribution of the particles in the sensing volume is calculated using the Fraunhofer diffraction theory. The computer and a generator are placed on the boat and the instrument is lowered into the flow. A Colombus type sounding weight is attached to the lifting cage of the instrument to align the sensing volume to the direction of flow.

Concentration of suspended particles was measured by collecting samples using a P-72 suspended sediment sampler and analyzing the samples using the filtration method in the laboratory. The flow velocity was measured using a Price current metre according to the Water Survey of Canada procedures.

Measurement Procedure:

1. Winter survey:

The winter survey was carried out in February 1993. The study reach was predominantly ice-covered except in few locations near the Weldwood Pulp Mill outfall. The effluent entered the river at approximately 20°C and melted the ice cover in the immediate vicinity. The ice cover reestablished itself within a short distance downstream. All the selected transects were ice covered. At each transect, holes were drilled through the ice using an ice-auger at 10 metre intervals from bank to bank. Ice cover thickness and the water depth in each hole were measured. Velocity measurements were carried out in each hole at 10 cm intervals along the depth.

Four to five slush-free holes in the middle section of the river were selected for particle size measurements. These holes had to be enlarged to about 60 cm square for the particle size instrument to fit. This was done by drilling several holes side by side and cutting out a square section using an ice-saw. A tent was built to house the computer and protect it from the wind and cold. Two small, ceramic heaters were used to heat the tent. The temperature inside the tent was around 5°C when the outside temperature was about -30°C. The particle size analyzer was lowered into the hole using a tripod with a small rope block and tackle. The size distributions of the suspended particles were measured over the vertical in 20 cm intervals. Two 1-litre water samples were collected to measure the size distribution of the suspended particles in the dispersed state using a laboratory particle size analyzer that operates on the same principle as the field instrument. By comparing the two size distributions, conclusions can be drawn regarding the extent of flocculation of the suspended particles. Samples of effluent from the Weldwood Pulp Mill were collected for particle concentration measurements; effluent discharge rates and temperatures were obtained from the Mill authorities.

2. Fall survey:

The fall survey was carried out in September 1993. The reach sampled was the same as in the winter survey. During this survey, the river was ice free and sampling had to be done from a boat and from bridges. The transects selected for this survey are shown in Fig. 1. The transect at Haulbridge was a new one and the transects at Emerson and Berland were omitted because of poor access. The transects at Entrance and Haulbridge were sampled from a boat. The transects at Obed and Windfall were sampled from bridges. The procedure used for the boat survey was as follows:

1. A tag line was strung across the river and measurement locations were marked at every 10 metre intervals.

2. Current meter measurements were made from the boat held in place by running the engines to counteract the current speed at measurement locations. Three point velocities were measured at each vertical. These were at 0.2h, 0.6h and 0.8h from the water surface where h is the local flow depth. The average velocity over the vertical was then computed as the average of 0.2h and 0.8h values and was compared with that measured at 0.6h. The average velocity will be close to 0.6h value if the flow is nearly two-dimensional.

3. Measurement of particle sizes was made using the particle size analyzer at selected verticals in the middle section of the river. The point of measurement was around the mid depth.

4. The suspended sediment samples were collected using the P-72 sampler at the same locations where the current meter measurements were made.

The sampling from bridges was similar to boat sampling. In this operation, the sampling locations were marked on the bridge and a cart carrying the particle sizer, the computer and the generator was moved along the bridge to sampling locations. The instruments were lowered into the flow from the bridge on the upstream side of the bridge to reduce the influence of the bridge piers on the measurement.

Results and Discussion:

1. Winter survey:

1a. Flow distribution:

From the vertical distribution of velocity, a depth average velocity was computed for each vertical in a transect. Knowing the depth of water under the ice, the flow rate was calculated assuming linear variation of depth averaged velocities and water depths between measurement verticals. The flow rate so calculated for the Entrance transect was 29.3 m^3/s. This value compares well with the data (27.7 m^3/s) supplied by the Water Survey of Canada. For Obed and Emerson, such a calculation of flow rate was not possible because some measurement holes contained slush ice that prevented the velocity measurements. The flow rates for these transects were assumed to be the same as the Entrance transect because there was no significant tributary inflow in this reach and the flow was fairly steady. For Berland and Windfall transects, the flow rate data is not available because the Berland River flow was not measured during this survey. The other data such as the lateral distribution of ice cover thickness, depth of water under ice-cover, depth averaged velocities for slush-ice-free holes are listed in a tabular form for all the transects in a data report (Krishnappan et al., 1994).

1b. Concentration distribution:

As indicated earlier, the concentration of the suspended particles (in mg/L) was measured

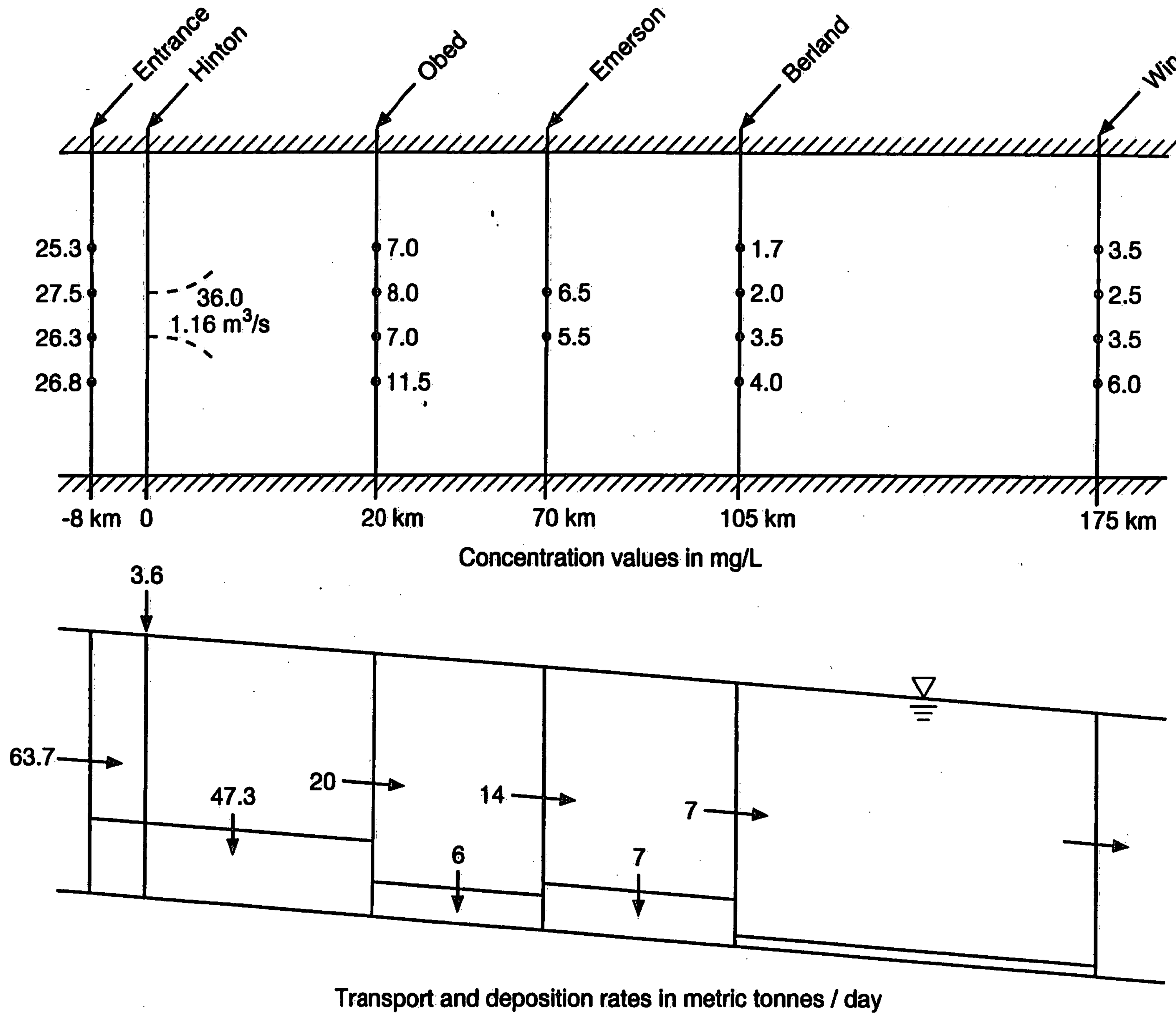


Figure 3. Concentration distribution and suspendend particle mass balance from the winter survey.

using the filtration technique in the laboratory. Three samples were analyzed for each vertical and a depth averaged value was calculated. The depth average values for all the transects are given in Krishnappan et al. 1994.

1c. Suspended particle transport rate:

Knowing the depth average values of flow velocity and concentration of the suspended particles, the transport rate can be calculated as a product of the two and can be integrated across the transect to obtain the total suspended particle transport rate in metric tonne per day. Such a calculation was carried out for the Entrance transect and transport rate was computed as 63.7 metric tonne per day. For Obed and Emerson transects, the transport rates were calculated as a product of the cross-sectional average concentration and the total flow rate of $29.3 m^3/s$ as the depth average flow velocity was not available for all the verticals. The values calculated for these two transects are 20 metric tonnes per day and 14 metric tonnes per day respectively. Such low values in comparison to that at Entrance imply that the reach below Entrance is a depositional reach. The depth average concentration values and the suspended particle mass balance including the effluent mass are shown schematically in Fig. 3. The ratio of the effluent discharge to the flow discharge is about 0.04 and the ratio of the effluent solids discharge to the ambient sediment discharge is about 0.08. From Fig. 3, it can be seen that 70% of the incoming sediment has deposited in the reach between the outfall and Obed. The deposition continues in the reach between Obed and Emerson also, but at a slower rate. In this reach, 30% of the material entering Obed transect has deposited. Since Berland River contributions of flow and suspended particles were not measured, it is not possible to extend the mass balance analysis downstream from Emerson transect. Only 20% of the material entering the reach at Entrance is leaving the Emerson transect.

1d. Particle Size Distribution:

The size distribution of the suspended particles, measured using the submersible size analyzer in one of the verticals of the Entrance transect, is shown in Fig. 4. In the same figure, the size distribution of the dispersed particles, measured using the laboratory size analyzer by sonicating the samples, is shown for comparison. From this figure, it can be seen that the

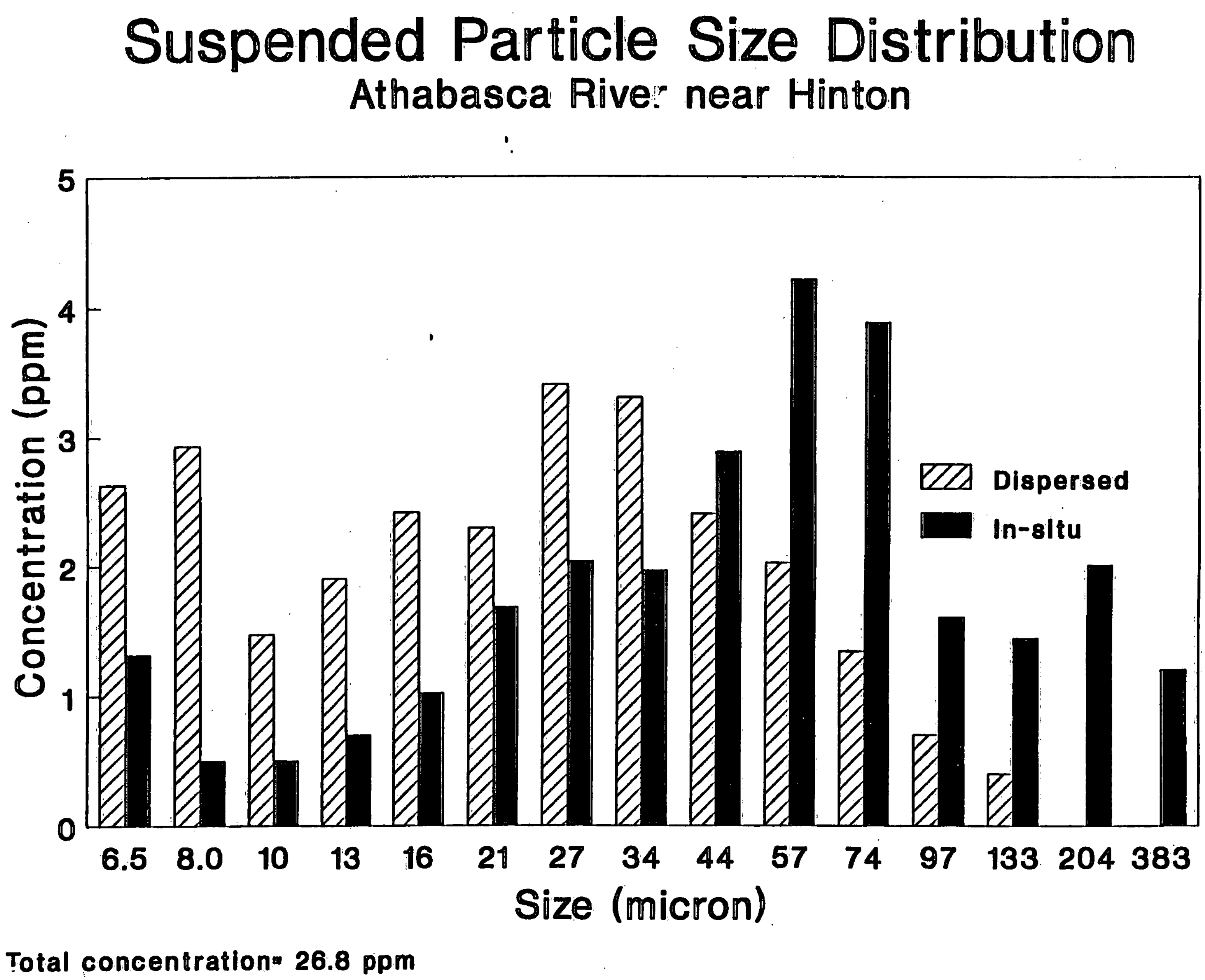


Fig. 4 Size distribution of in-situ and dispersed particles at the Entrance transect.

suspended particles are transported in a flocculated form at this transect. The in-situ distribution contains particles in size classes 204 and 383 microns whereas the dispersed particles are totally absent in these size classes. The sonication has broken up the flocs and has increased the number of particles in the smaller size classes.

A similar comparison was made for the Obed transect and the distributions of in-situ and dispersed particles are shown in Fig.5. This figure also shows evidence of flocculated particles in suspension. In addition, it shows that the concentration of particles in every size class has diminished during their transport from Entrance to Obed. This implies that the particles have settled to the river bed and the settling has been promoted by flocculation, i.e. the smaller particles attaching themselves to larger particles and settling.

From the consideration of flow hydrodynamics and sediment transport alone it is not possible to explain the deposition of suspended particles in this reach. The sediment transporting capacity of the flow at Obed is about the same as that at Entrance and if there is no change in the sediment properties (size and density and consequently the settling velocity), then the transport rate at Obed should be equal to that at Entrance. The fact that we observe sediment deposition is an indication that the sediment properties have been altered. This is a real possibility because of the presence of the pulp mill effluent in the reach. The pulp mill effluent contains organic fibers and bacteria that have affinity for ambient inorganic sediment. Sediment particles of different sizes can attach themselves to the organic material and settle as larger units and resist the hydrodynamic drag and lift forces.

The deposition of the incoming sediment and the solid fraction of the pulp mill effluent is likely to continue during the low flow periods. At freshet, it is possible that the bed shear stress will exceed the critical shear stress for erosion and the resuspension of the deposited material will occur resulting in transport of the material further downstream. When the flow rate decreases, the deposition cycle will repeat. The purpose of the fall survey was to examine if the deposition cycle has begun.

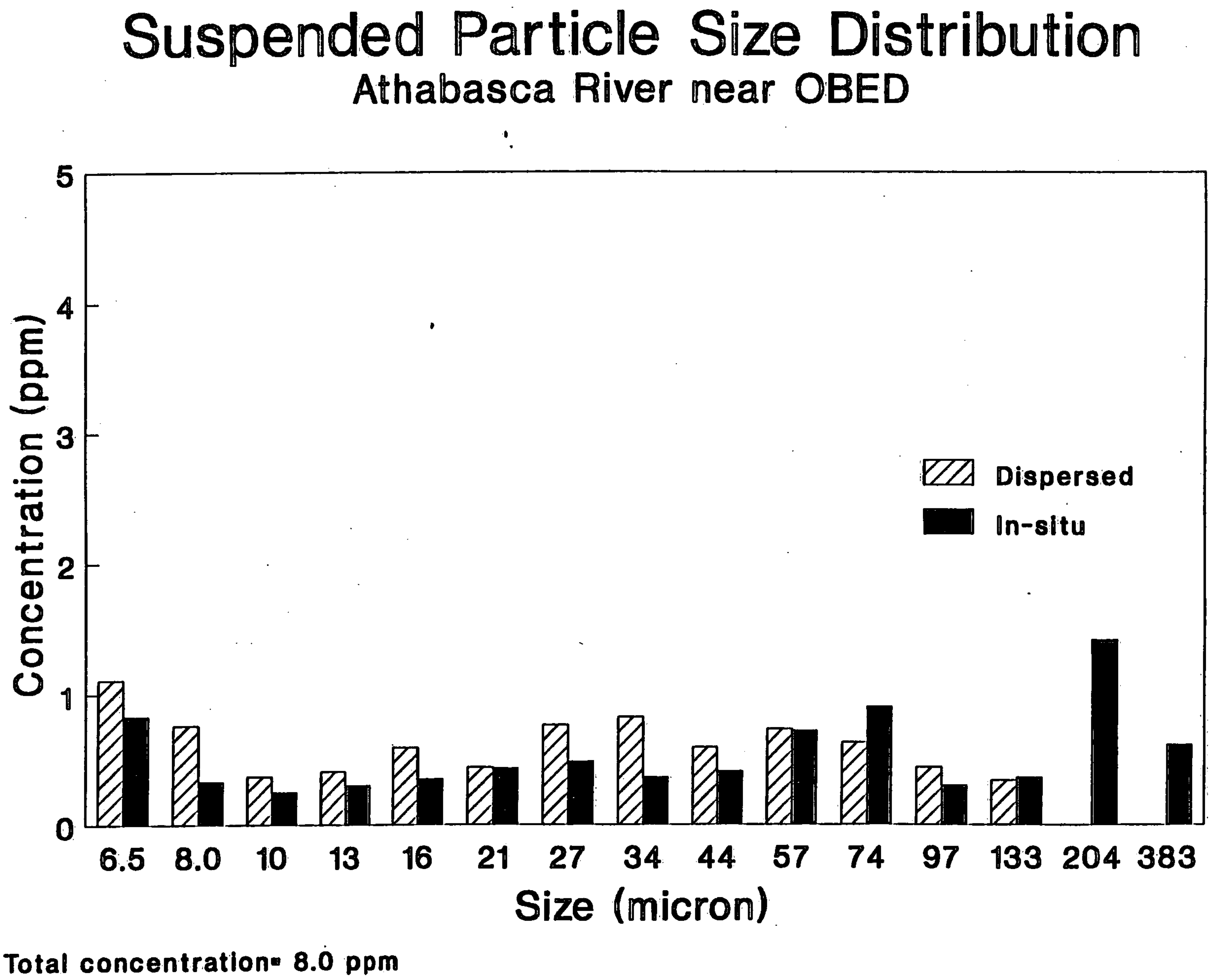


Fig. 5 Size distribution of in-situ and dispersed particles at the Obed transect.

2. Fall survey:

2a. Flow Distribution:

The depth averaged velocity at a vertical was calculated as the average value of velocities at 0.2 and 0.8 depths from the free surface. Knowing the depth and the depth averaged velocity, the flow rate across the transect was computed assuming linear variations of both depth and depth averaged velocity, between the measured verticals. The flow rates calculated for all transects compared well with the data of the Water Survey of Canada. The flow rate measured for the transect at Entrance was 149 m^3/s, which is almost five times the flow rate measured during the Winter survey at this transect.

2b. Suspended Sediment Concentration:

Suspended sediment samples collected during the fall survey were analyzed in the same way as for those collected during the winter survey and the depth average concentration for each vertical was determined.

2c. Suspended Sediment Transport rate:

Knowing the flow distribution and the suspended particle concentration distribution, the transport rate of suspended particles were calculated according to the method outlined for the winter survey and the values are used to construct the mass balance diagram as shown in Fig. 6. The ratio of the effluent discharge to the flow discharge during the fall survey is about 0.008 while that of effluent solids and ambient sediment is around 0.02. From Fig.6, it can be seen that there is evidence of sediment deposition even during this period. But, the rate of deposition is comparatively slower. Between Haulbridge and Obed, there is a small drop in sediment transport rate (about 13%). Between Obed and Windfall the drop is as high as 40%. In the mass balance shown in Fig. 6, the sediment load coming from the Berland River was not considered. If it were included, then the deposition would be even larger.

The data from the two surveys show that the pulp mill effluent has affected the physical transport characteristics of the ambient sediment in the Athabasca River downstream from the

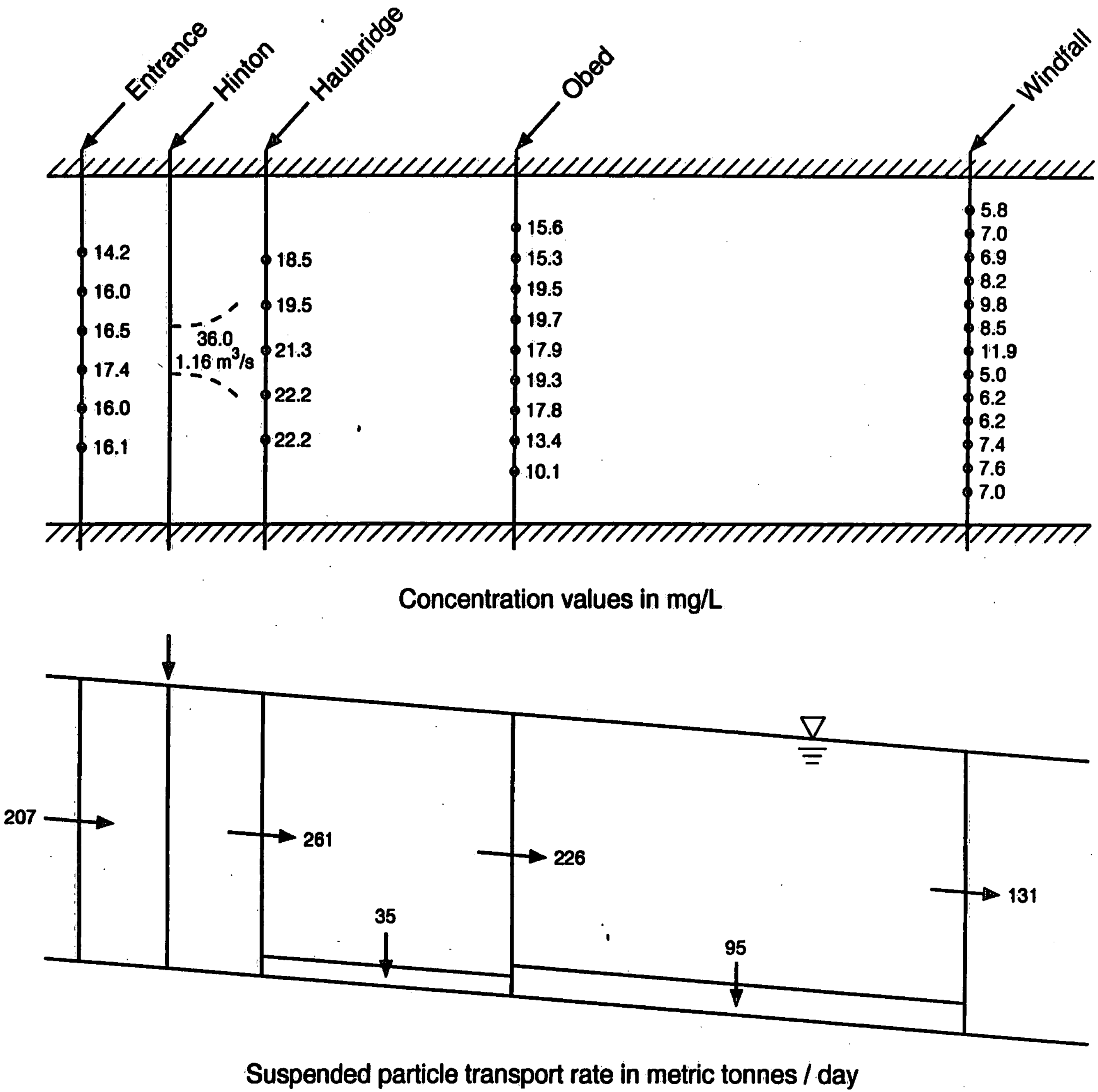


Figure 6. Concentration distribution and suspendend particle mass balance from the fall survey.

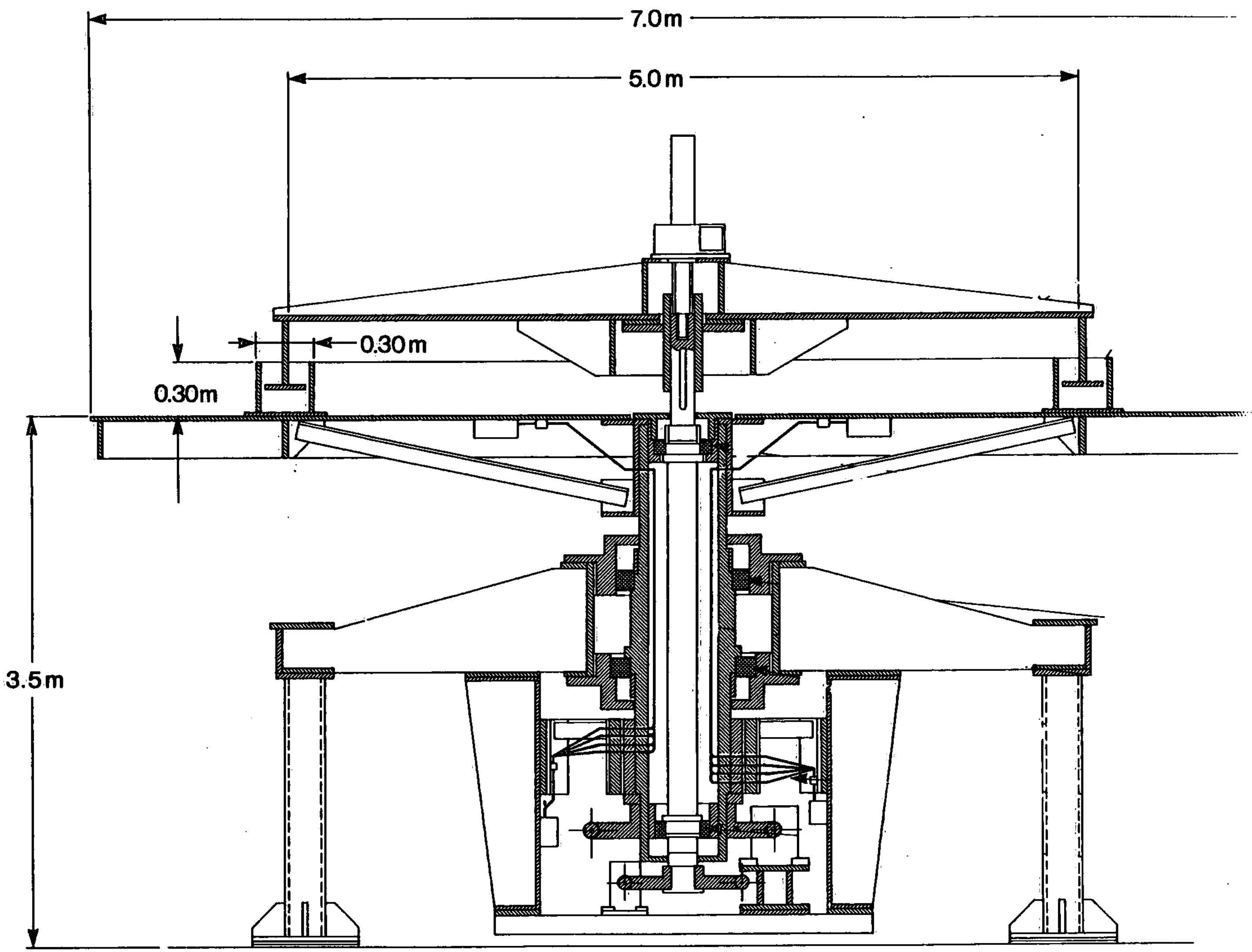


Fig.7 A sectional view of NWRI's rotating circular flume

Weldwood Pulp Mill at Hinton. The effluent appears to have promoted the flocculation of the incoming sediments and increased their deposition rate. The effects are pronounced during low flow periods when the ratio of the effluent discharge to the flow discharge is the highest (about 4%). During moderate flows (flows in the order of five times the base flow), there is still evidence of sediment deposition. But, the deposition rate is slower and the deposition zone is shifted further downstream. This leads one to speculate that the deposition of the effluent solids and the ambient sediment could persist over a period of almost eight months in a year when the flow rate is lower than the fall survey value. The deposited sediment could be resuspended during the high flows that normally start in June in the Athabasca River.

LABORATORY STUDY:

The laboratory investigation was carried out to verify the field observation that the pulp mill effluent enhanced the flocculation of the ambient sediment in the Athabasca River. The tests were carried out in a newly built rotating circular flume at the National Water Research Institute in Burlington, Ontario, Canada. The details of this investigation are described in the following sections.

The Flume:

The flume is 5.0 m in mean diameter, 0.30 m in width and 0.30 m in depth. It rests on a rotating platform, which is 7.0 m in diameter. A counter rotating top cover, called the ring, fits inside the flume with close tolerance (1.5mm on either side) and makes contact with the surface of the sediment-water mixture in the flume. By rotating the platform and the ring assembly in opposite directions, it is possible to generate turbulent shear flows and to study the behavior of fine sediment under different flow conditions. The flume and the ring can each be rotated up to a maximum rate of three revolutions per minute. A sectional view of the flume is shown in Fig. 7 and the complete details of the flume can be found in Krishnappan (1993).

Instrumentation:

The flume is instrumented with a Laser Doppler Anemometer to measure the flow field,

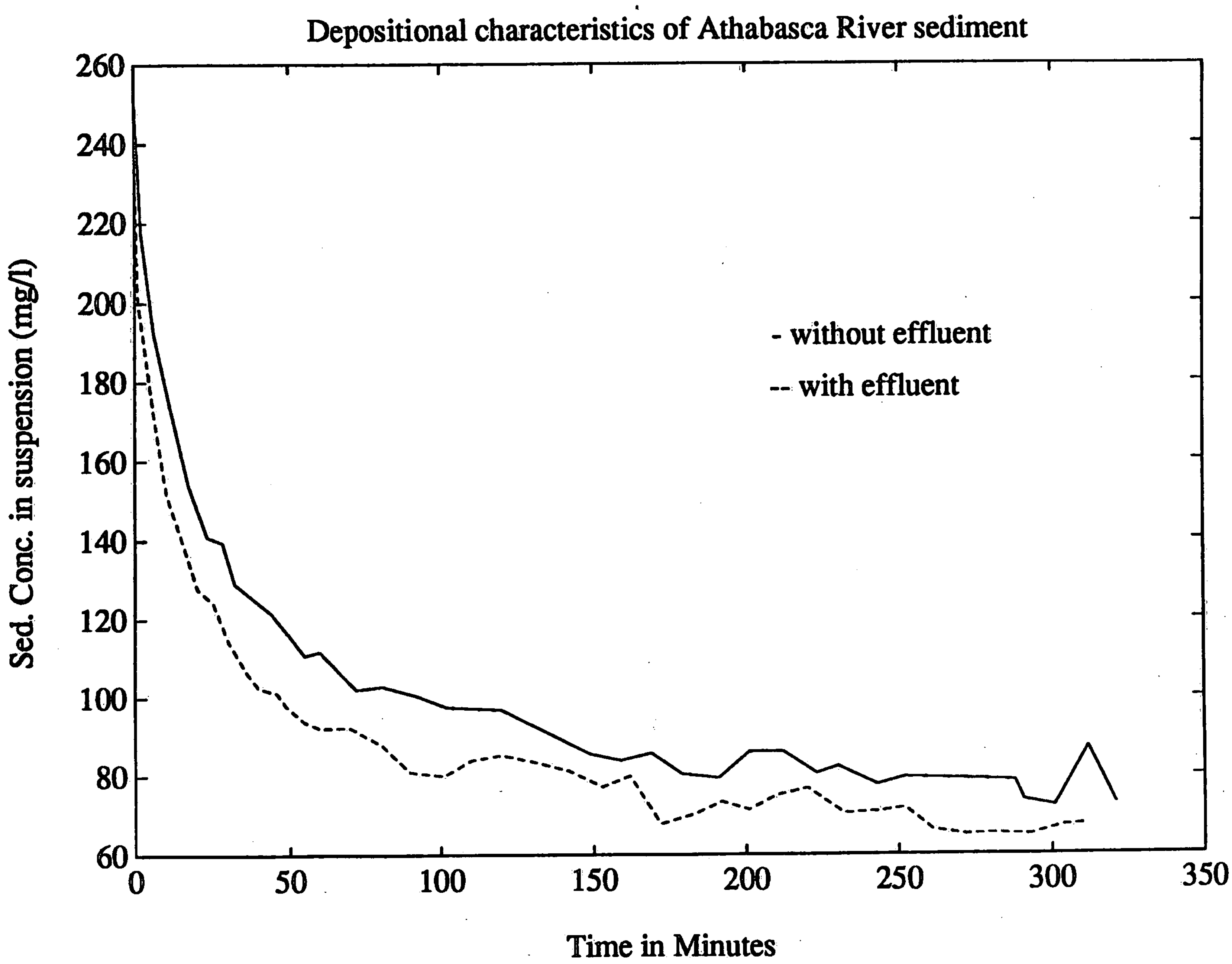


Fig. 8 Sediment concentration vs time during deposition at a constant shear stress

a Preston tube to measure the bed shear stress, a Malvern Particle Size Analyzer to measure the in situ floc size distribution and an optical turbidity sensor to measure the suspended particle concentration. For the present measurements all the instruments except the Laser Doppler Anemometer were activated.

Sample Collection and Preparation:

Sediment and river water samples were collected at the Entrance transect upstream of the pulp mill. A pumping system, similar to the one used for cleaning swimming pools, was used to vacuum the sediment deposited on the gravel bed and pump river water into 100 l plastic containers that could be sealed tightly for shipping. Eight such containers were filled and shipped to Burlington in trucks with cold storage. In addition, an effluent sample of about 50 l was collected from the pulp mill outfall. The sediment -water mixture was placed in the flume to give a prescribed flow depth of 12.0 cm and an initial sediment concentration (under fully mixed condition) of 250 mg/l. The sediment-water mixture was then tested for depositional characteristics with and without the pulp mill effluent.

Experimental Procedure:

Before starting the test, the sediment- water suspension was thoroughly mixed in the flume with a mechanical mixer to break up existing flocs. The ring was then lowered until it contacted the water surface. The flume and the ring were rotated at desired speeds to establish a certain bed shear stress and periodic measurements of suspended sediment concentration and size distribution of suspended sediment flocs started. Measurements continued until the suspended sediment concentration reached a steady state value. This took about 300 minutes from the start of the experiment. The experiment was then repeated with pulp mill effluent added to the flume.

Results and discussion:

The variation of suspended sediment concentration as a function of time for the two tests is shown in Fig. 8. It can be seen from this figure that for both runs, the concentration drops at a faster rate initially and it reaches a steady state value after a period of about 200 minutes or

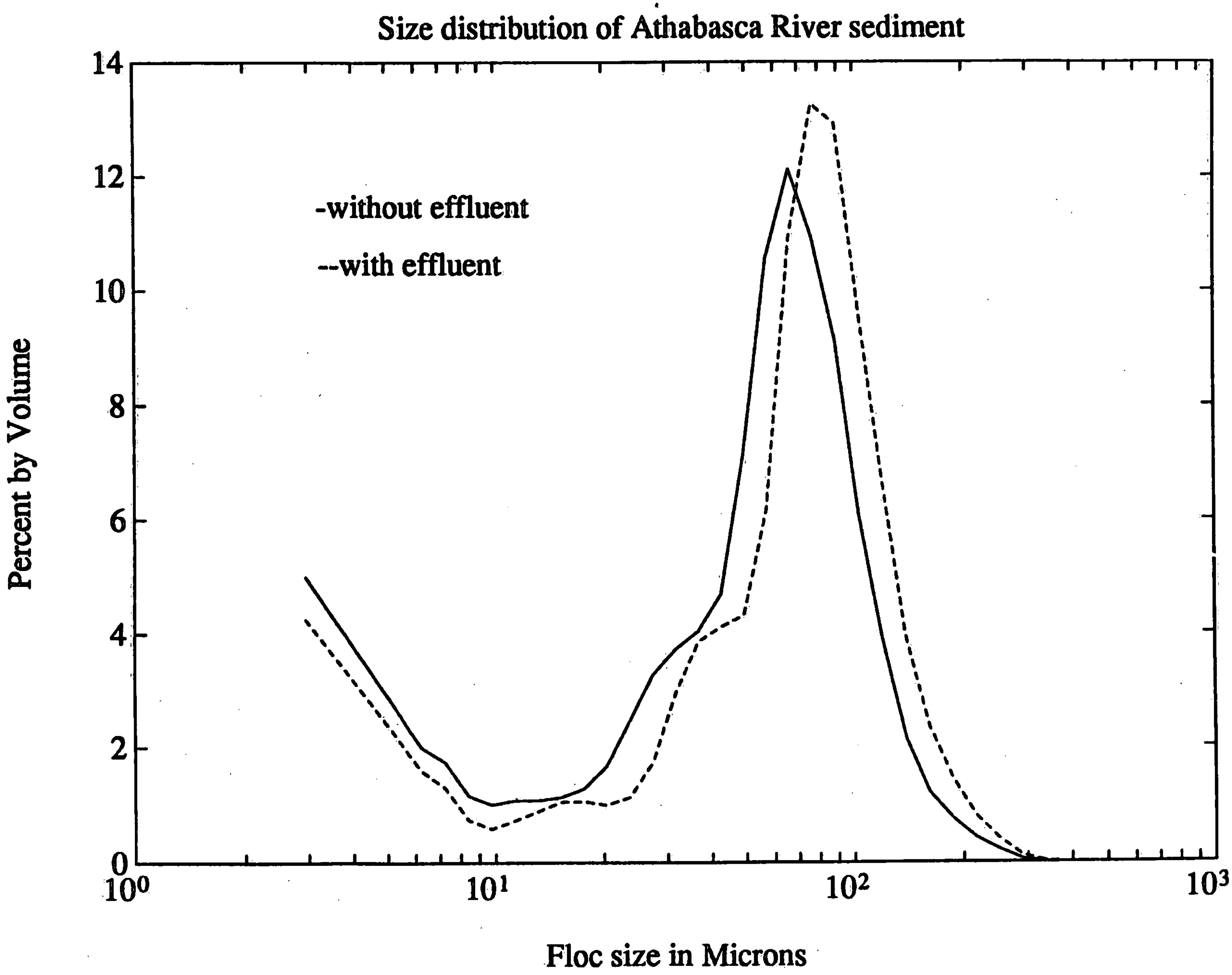


Fig. 9 Size distribution of sediment flocs with and without pulp mill effluent

so. But, for the run with effluent, the rate of initial drop is faster and steady state concentration is lower. This result is in accordance with the field measurement and suggests that the pulp mill effluent has indeed enhanced the deposition rate of the ambient sediment.

The size distribution of the suspended sediment floc measured at 200 minutes for the two runs are shown in Fig. 9. It can be seen from this figure that for the run with the effluent, the size distribution has shifted to the right indicating that the flocs formed in the presence of effluent are larger. The modal value of the distribution without the effluent is about 70 microns whereas the same with the effluent is about 90 microns. This result suggests that the pulp mill effluent has enhanced the flocculation of the river sediment.

SUMMARY AND CONCLUSIONS:

The influence of the bleached pulp mill effluent on the transport characteristics of riverine suspended sediment was studied using field measurements and laboratory investigations. The field measurements were carried out in the Athabasca River near Hinton in the vicinity of a Bleached Kraft Pulp Mill. Measurements of flow, suspended sediment concentration, size distribution of suspended sediment flocs and the primary particles upstream and downstream of the pulp mill outfall showed that the presence of pulp mill effluent modified the transport characteristics of the river sediment. It increased the deposition rate of the sediment by enhancing the flocculation of the suspended particles under low flow conditions. These observations were verified by conducting controlled experiments in the laboratory using a rotating circular flume.

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REFERENCES

Allan, R. J. 1986. The role of particulate matter in the fate of contaminants in aquatic ecosystems. Scientific Series No. 142, Inland Waters Directorate, Environment Canada, Burlington, Ontario. 128 pages.

Frank, R. 1981. Pesticides and PCBs in the Grand and Saugeen River basins. Journal of Great Lakes Research 7:440-454.

Forstner, U. and Wittman, G. T. W. 1981. Metal Pollution in Aquatic Environment, Springer -Verlag, New York.

Krishnappan, B. G. 1993. Rotating Circular Flume. Journal of Hydraulic Engineering, Vol. 119, No. 6, ASCE.

Krishnappan, B.G. , Madsen, N.,Stephens, R. and Ongley, E.D. 1992. Field instrument for size distribution of flocculated sediment. NWRI Contribution No. 92-117, NWRI, CCIW, Burlington, Ontario, Canada.

Krishnappan, B. G., Stephens, R., Kraft, J. A., and Moore, B. H. 1994. Size distribution and transport of suspended particles in the Athabasca River near Hinton. Report submitted to the Northern River Basins Study, Edmonton, Alberta, Canada.

Kuntz, K. W. and Warry, N. D. 1983. Chlorinated organic contaminants in water and suspended sediments of the lower Niagra River. Journal of Great Lakes Research. 9:241-248.

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