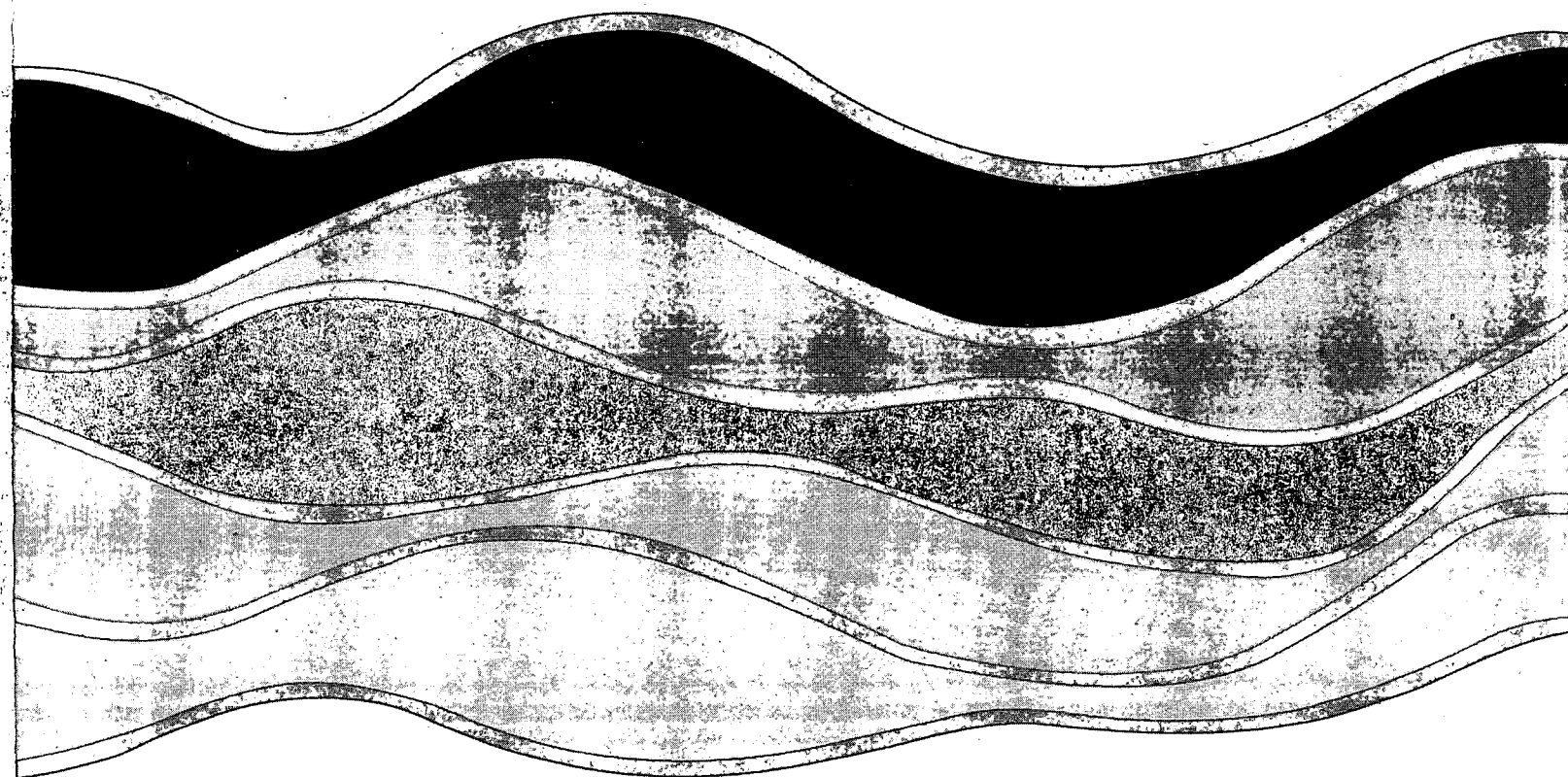
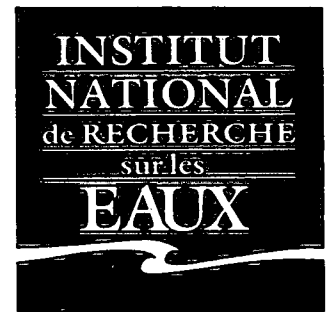
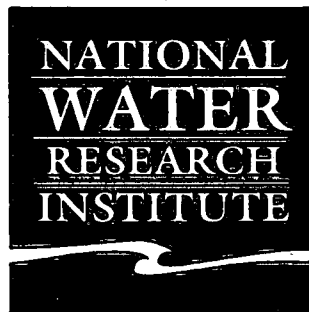


97-51 Master C1



**A NEW MODEL OF FINE SEDIMENT TRANSPORT
FOR THE FRASER RIVER**

B.G. Krishnappan

NWRI Contribution No. 97-51

A NEW MODEL OF FINE SEDIMENT TRANSPORT FOR THE FRASER RIVER

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MANAGEMENT PERSPECTIVE

Fine sediments of the Fraser River play an important rôle in the transportation of contaminants and hence form an essential component of the modelling system that is being developed for the prediction of transport, fate and bio-accumulation of contaminants in the Fraser River system under the FRASER RIVER ACTION PLAN. The existing models of fine sediment transport assume that the fine sediments behave in the same manner as the coarse-grained sediment and use transport theories developed for the coarse sediment to treat the fine sediment. But, recent research has shown that there are fundamental differences in the transport characteristics of the two types of sediments. The new model proposed in this paper is based on experimental observations of deposition and erosion of Fraser River sediment in a laboratory flume and hence it can be considered as a realistic model of fine sediment of the Fraser River.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Les sédiments fins du Fraser jouent un rôle important dans le transport des contaminants; ils sont donc un élément essentiel du système de modélisation mis au point pour la prévision du transport, du devenir et de la bioaccumulation des contaminants dans le réseau du fleuve Fraser dans le cadre du PLAN D'ACTION DU FRASER. Les modèles existants de transport des sédiments fins posent l'hypothèse que les sédiments fins se comportent de la même façon que les sédiments plus gros et ils font appel aux théories sur le transport élaborées pour les sédiments grossiers pour traiter les sédiments fins. Toutefois, des recherches récentes ont montré qu'il existe des différences fondamentales dans les caractéristiques du transport des deux types de sédiments. Le nouveau modèle proposé dans le présent article est basé sur des observations expérimentales sur le dépôt et l'érosion des sédiments du Fraser dans un canal en laboratoire; il peut donc être considéré comme un modèle réaliste de transport des sédiments fin du Fraser.

ABSTRACT

A new model is proposed for the transport of fine sediment in the Fraser River. The model is based on empirical relationships developed from laboratory experiments in a rotating circular flume using Fraser River sediment. The model takes into account the differences in the critical conditions for erosion and deposition of fine sediment and allows simultaneous erosion and deposition to occur only for a limited range of bed shear stresses. For bed shear stresses outside of this range, either erosion or deposition is allowed reflecting the cohesive nature of the Fraser River sediment. The model can easily be incorporated into existing models of contaminant transport, fate and bioaccumulation.

RÉSUMÉ

On propose un nouveau modèle pour le transport des sédiments fins dans le Fraser. Le modèle est basé sur des relations empiriques élaborées dans le cadre d'expériences de laboratoire dans un canal rotatif utilisant des sédiments du Fraser. Le modèle tient compte des différences dans les conditions critiques d'érosion et de dépôt des sédiments fins et permet simultanément le dépôt et l'érosion seulement pour une fourchette limitée de contraintes de cisaillement dans le lit. Dans le cas des contraintes de cisaillement à l'extérieur de cette fourchette, soit l'érosion ou le dépôt peut rendre compte de la nature cohésive des sédiments du Fraser. Le modèle peut facilement être incorporé à des modèles existants de transport, de devenir et de bioaccumulation des contaminants.

A NEW MODEL OF FINE SEDIMENT TRANSPORT FOR THE FRASER RIVER

by

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INTRODUCTION

Many of the existing models of transport, fate and bioaccumulation of toxic substances in surface waters assume that the transport characteristics of fine sediment are analogous to that of the coarse sediment and adopt sediment transport theories that were developed for the latter to treat the former. Among the many differences between the two types of sediments, the most crucial is the difference in the critical condition for initiation and cessation of sediment motion in a flowing medium. In the case of coarse grained sediment, the critical conditions for initiation and cessation merge into a single criterion, which means that the coarse sediments undergo simultaneous erosion and deposition while being transported under a constant bed shear stress. In the case of fine sediment, on the other hand, two distinct critical conditions were identified in the literature; one for erosion and a different one for deposition (see, e.g. Partheniades and Kennedy, 1966; Partheniades et al., 1968; Mehta and Partheniades, 1975; Lau and Krishnappan, 1994). Therefore, for fine sediments, the simultaneous erosion and deposition is possible only for a certain range of bed shear stresses. For shear stresses outside of this range, there could only be sediment deposition or sediment erosion, but not both simultaneously.

A true representation of the erosion and deposition of fine sediment is important for the contaminant transport models. If the simultaneous erosion and deposition is assumed, then the model will predict an enhanced dispersion of the contaminants whereas a mutually exclusive erosion and deposition will result in the preservation of comparatively high concentration of sediment bound contaminants over long distances from the source. In this paper, a new sediment transport algorithm, which allows the treatment of erosion and deposition processes as mutually exclusive ones for certain range of shear stresses is proposed. The new algorithm is based on the erosion and deposition experiments that were carried out in a rotating, circular flume at the National Water Research Institute at Burlington, Ontario, Canada using sediments from the Fraser River. The work was carried out as part of the Fraser River Action Plan, which is a Government of Canada's initiative to clean up the Fraser River system.

BASIS OF NEW ALGORITHM

The deposition and erosion experiments carried out in the rotating, circular flume for the Fraser River sediment were described in Krishnappan and Engel (1994). The deposition results of Krishnappan and Engel (1994) are reproduced here as Figs. 1 and 2 for easy reference. Fig. 1 shows the variation of concentration of sediment in suspension as a function of time during deposition under different bed-shear stresses. This figure shows that after an initial 20 minute period during which the flume was operated at high speed to break up the flocs and provide the same initial start up condition for all the runs, the sediment concentration drops gradually and reaches a steady state value for all runs. The figure also shows that the steady state concentration is a function of the bed shear stress. When the bed shear stress is higher, the sediment concentration of the suspension is also higher. For the lowest shear stress tested, the steady state concentration was only $1/20^{\text{th}}$ of the initial concentration and a slightly lower shear stress would have produced a nil concentration in suspension. The shear stress at which the concentration in suspension becomes zero is termed the critical shear stress for deposition. From the experiments of

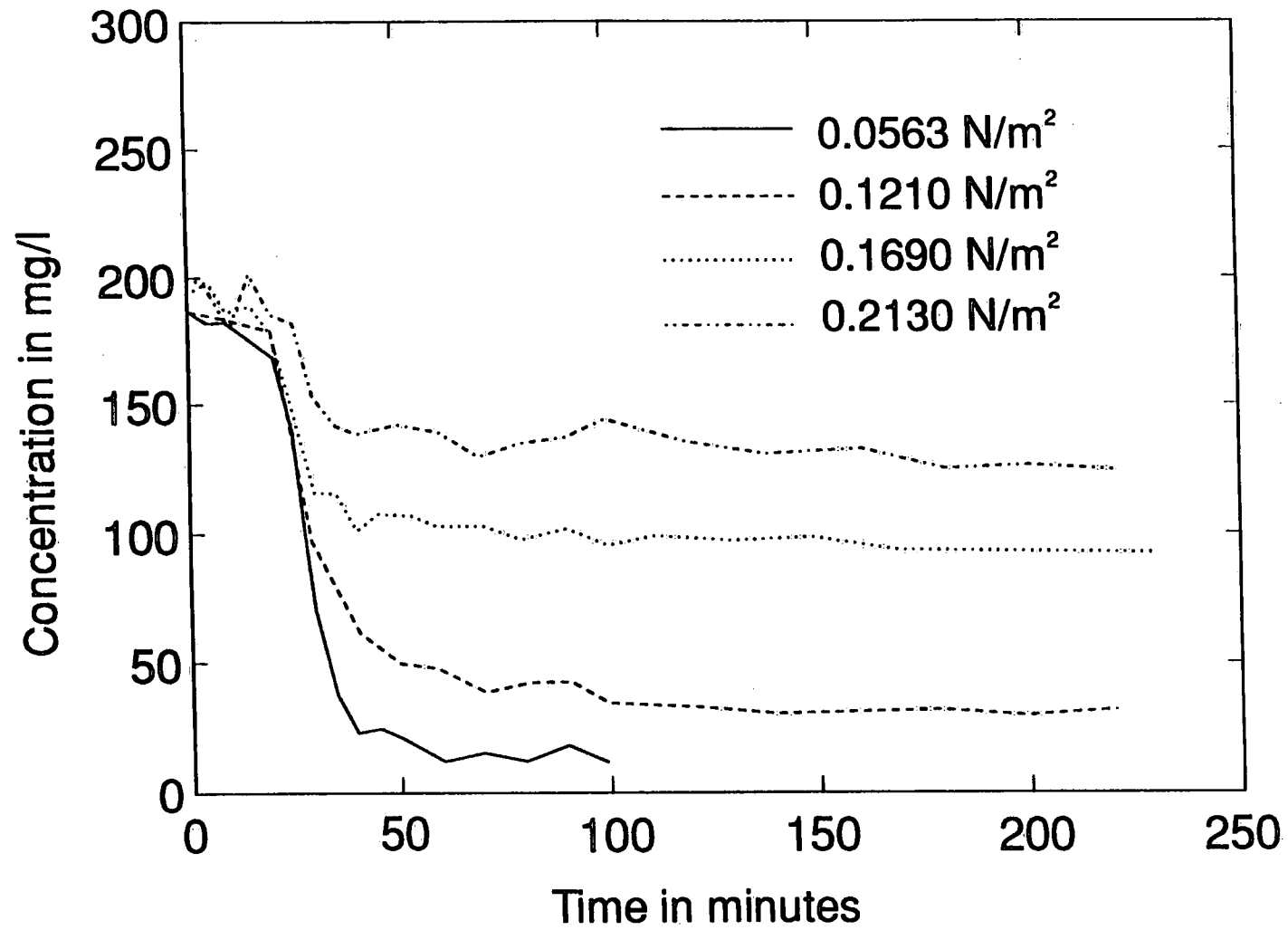


Figure 1. Variation of concentration for different shear stresses

Krishnappan and Engel, the critical shear stress for deposition of Fraser River sediment was estimated to be 0.05 N/m^2 .

Fig. 2 shows the depositional characteristics of the sediment under constant bed shear stress but with different initial concentrations. It can be seen from this figure that the steady state concentration that results during deposition is a function of the initial concentration. Such a behaviour is peculiar to fine grained cohesive sediments and conforms to earlier studies on cohesive sediment transport (See Partheniades and Kennedy (1966), Mehta and Partheniades (1975) and Lick (1982)). From Fig. 2, it can also be seen that the ratio between the steady state concentration and the initial concentration is a constant for a particular shear stress. For the tests shown in this figure, the ratio is about 0.5. For a given sediment, the ratio was found to vary only as a function of the bed shear stress. In other words, in deposition process of fine sediment, the amount of sediment that would deposit under a particular bed shear stress is a function of the amount of sediment introduced to the system initially, and the fraction of the sediment that would deposit is constant as long as the bed shear stress is held constant. Such a conclusion allows one to establish a relationship between the fraction of the sediment that would deposit and the bed shear stress. The relationship established for the Fraser River sediment is shown in Fig. 3.

In this figure, the bed shear stress is expressed in terms of the critical shear stress for deposition (i.e. the shear stress below which all the initially suspended sediment would eventually deposit). From this figure, it can be seen that when the bed shear stress is at or below the critical shear stress for deposition, the fraction that would deposit takes a value of unity and the fraction deposited decreases as the bed shear stress increases and when the bed shear stress is about ten times the critical shear stress for deposition, the fraction deposited becomes zero and all the initially suspended sediment stays in suspension. A power law relationship between the fraction deposited and the ratio of bed shear stress to the critical shear stress for deposition was fitted and is shown as solid line in Fig.3. The relationship takes the following analytical form:

$$\begin{aligned} f_d &= 1.0 - 0.26(\tau_0 / \tau_{cd} - 1)^{0.60} \text{ for } \{1 < \tau_0 / \tau_{cd} < 10.5\} \\ f_d &= 1.0 \text{ for } \{\tau_0 / \tau_{cd} < 1\} \\ f_d &= 0 \text{ for } \{\tau_0 / \tau_{cd} > 10.5\} \end{aligned} \quad (1)$$

where f_d is the fraction deposited, τ_0 is bed shear stress and τ_{cd} is the critical shear stress for deposition.

The results of the erosion experiment that was carried out by Krishnappan and Engel are also reproduced here for ease of reference as Fig.4. In this figure the concentration of eroded sediment and the applied shear stress are shown as a function of time. For the erosion test, the sediment was allowed to deposit and consolidate for a known period of time and then the shear stress was applied in steps as shown in Fig. 4. The sediment deposit was fully stable until the bed shear stress of 0.121 N/m^2 was established. At this bed shear stress, the sediment concentration began to increase and attained a steady state value of about 5 mg/l . Therefore, the critical shear stress for erosion is slightly lower than this shear stress. A value of 0.12 N/m^2 was selected as the critical shear stress for erosion for the sediment that deposited at the critical shear stress for deposition. Note that the critical shear stress for erosion is almost two and a half times the critical shear stress for deposition, confirming the earlier result that the fine sediments of the Fraser River behave in a manner similar to that of the cohesive sediment.

From Fig. 4, it can be seen that at each shear stress step, the variation of sediment concentration with time was similar: a steep increase as the shear stress was applied followed by a gradual increase towards a steady state concentration. The magnitude of the steady state concentration at a particular shear stress step was lower than the steady state concentration during the deposition experiment with the same bed shear stress. For the maximum shear stress (0.462 N/m^2) tested, not all the deposited sediment was resuspended. The maximum concentration reached was only about 60% of the total concentration that

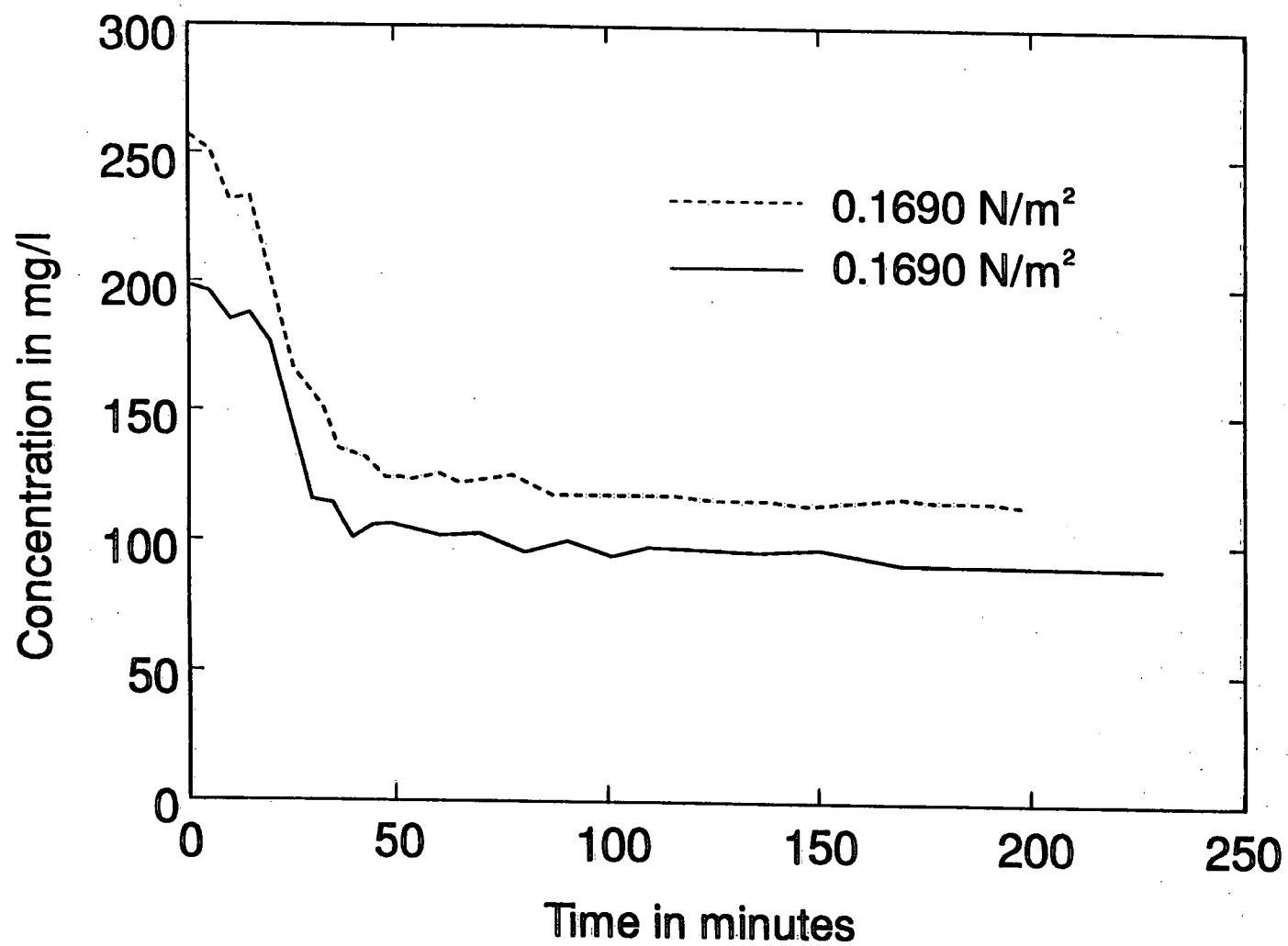


Figure 2. Variation of concentration for different initial concentrations

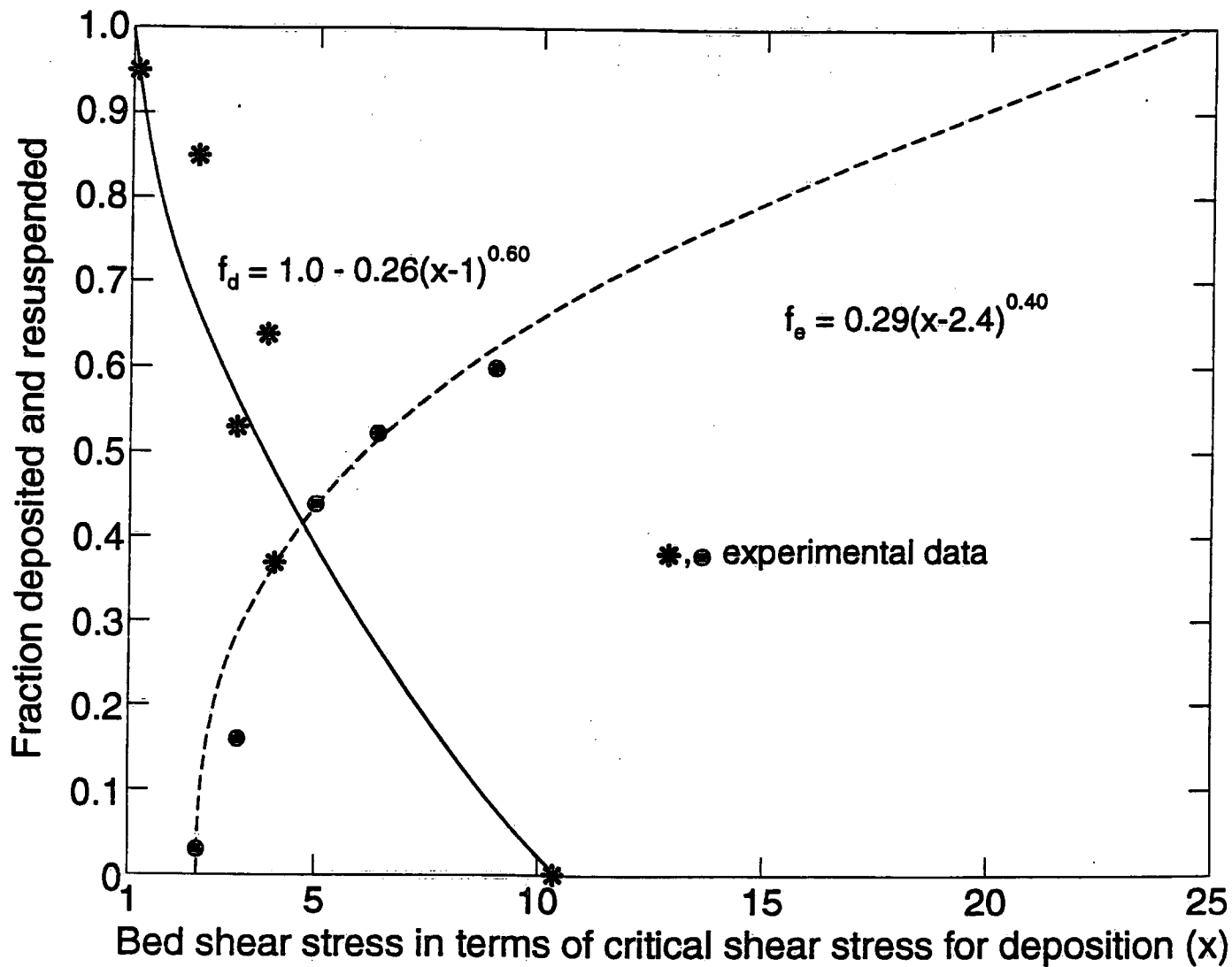


Figure 3. Transport functions for Fraser River sediment

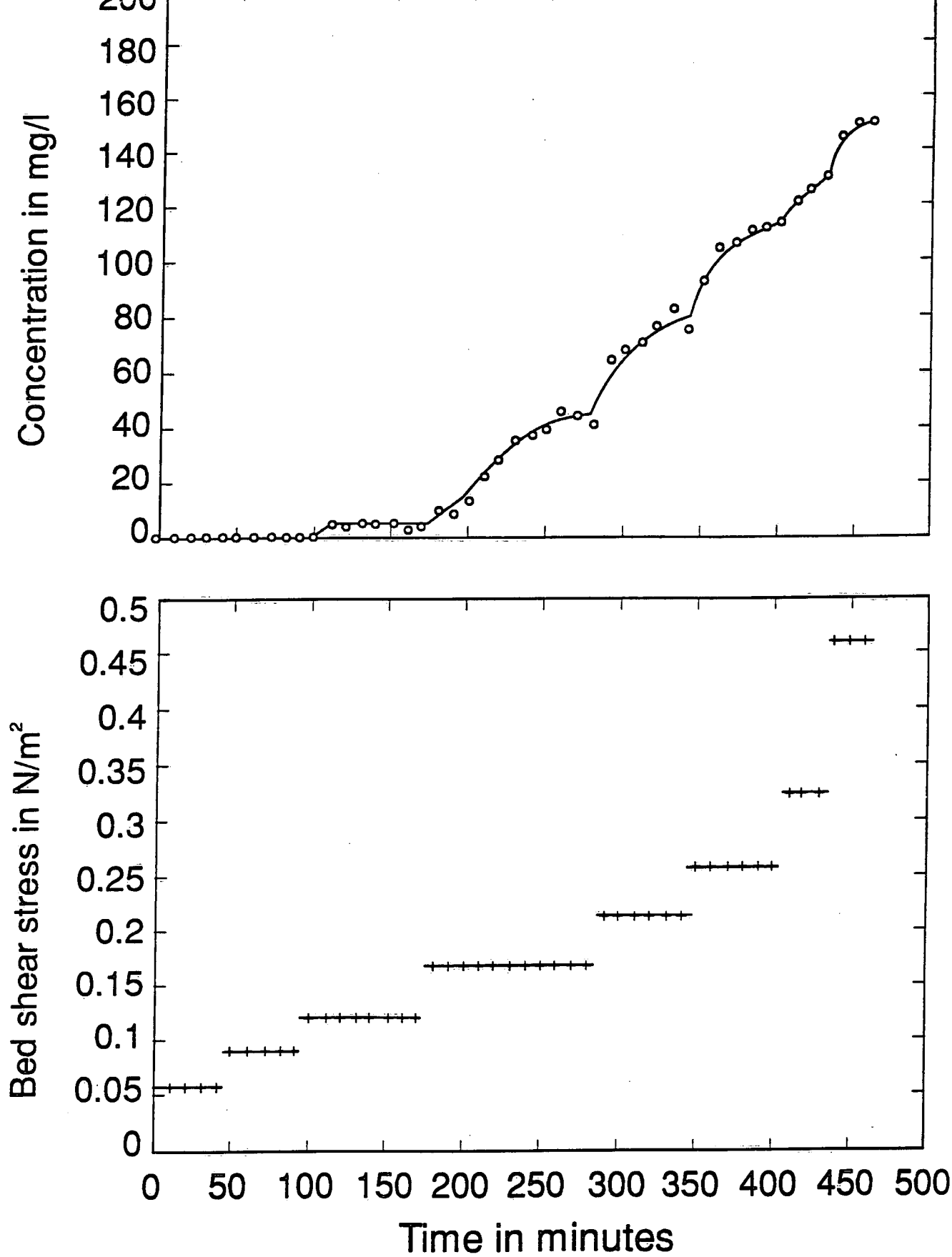


Figure 4. Erosion characteristics of the Fraser River sediment

would have resulted from complete resuspension. For complete resuspension a shear stress 25 times larger than the critical shear stress for deposition would have been required. From the erosion experiments, the fraction of resuspension was determined for various bed shear stresses and plotted in Fig. 3 as circles. A power law relationship was fitted through the experimental points. The form of the power law is shown below:

$$\begin{aligned} f_s &= 0.29(\tau_0 / \tau_{cd} - 2.4)^{0.4} \text{ for } \{2.4 < \tau_0 / \tau_{cd} < 25\} \\ f_s &= 0 \text{ for } \{\tau_0 / \tau_{cd} < 2.4\} \\ f_s &= 1 \text{ for } \{\tau_0 / \tau_{cd} > 25\} \end{aligned} \quad (2)$$

where f_s is the fraction of sediment re-suspended. For a sediment fraction that is deposited at a shear stress different from the critical shear stress for deposition, the above function can still be used with the following modifications: a) the critical shear stress term has to be replaced by the shear stress at which the deposition occurred and b) the upper limit of the shear stress has to be maintained at the original value of 25 times the critical shear stress for deposition. Using the two functions given by equations (1) and (2), a new model is proposed for the transport of fine sediments of the Fraser River. The details of the model are outlined in the next Section.

DETAILS OF THE NEW MODEL:

Basic information:

The river reach is divided into a number of river segments as shown schematically in Fig.5. The flow rate in each segment is considered to be steady. Let the flow rate of the control segment be Q (m^3/s). For a varying flow, a quasi-steady state is assumed and the flow hydrograph is approximated by a step function. The average bed shear stress (τ_0) has to be determined for each segment as a function of the flow rate. This can be done by employing friction factor relationships developed for uniform flows. There are numerous friction factor relationships in the literature. The choice of the relationship would depend on the available flow and river geometry data. The relationship proposed for the Fraser River is outlined in the Appendix-A.

For each segment, the range of the flow rates over an average year is established and the corresponding boundary-shear stress range is calculated. This shear stress range is then divided into a fixed number of flow stages. Each flow stage is identified with its own average boundary-shear stress which is the mean value of the shear stresses bounding the range. To be consistent with the sediment transport functions given by equations 1 and 2, the boundary shear stress is normalized using the critical shear stress for deposition.

Mass Balance of sediment in a control segment:

1. Sediment inflow:

The mass balance of the sediment in a control segment is calculated as follows: Sediment entering the control segment can be 1) from the upstream segment and 2) from tributary inflows. The amount of sediment (q_{su}) entering the control segment during a time interval of Δt can be expressed as follows:

$$q_{su} = QC_{i-1}\Delta t + Q_t C_t \Delta t \quad (3)$$

where C_{i-1} is the sediment concentration in the upstream segment, C_t is the concentration of sediment in the tributary inflow to the control segment and Q_t is the tributary inflow rate.

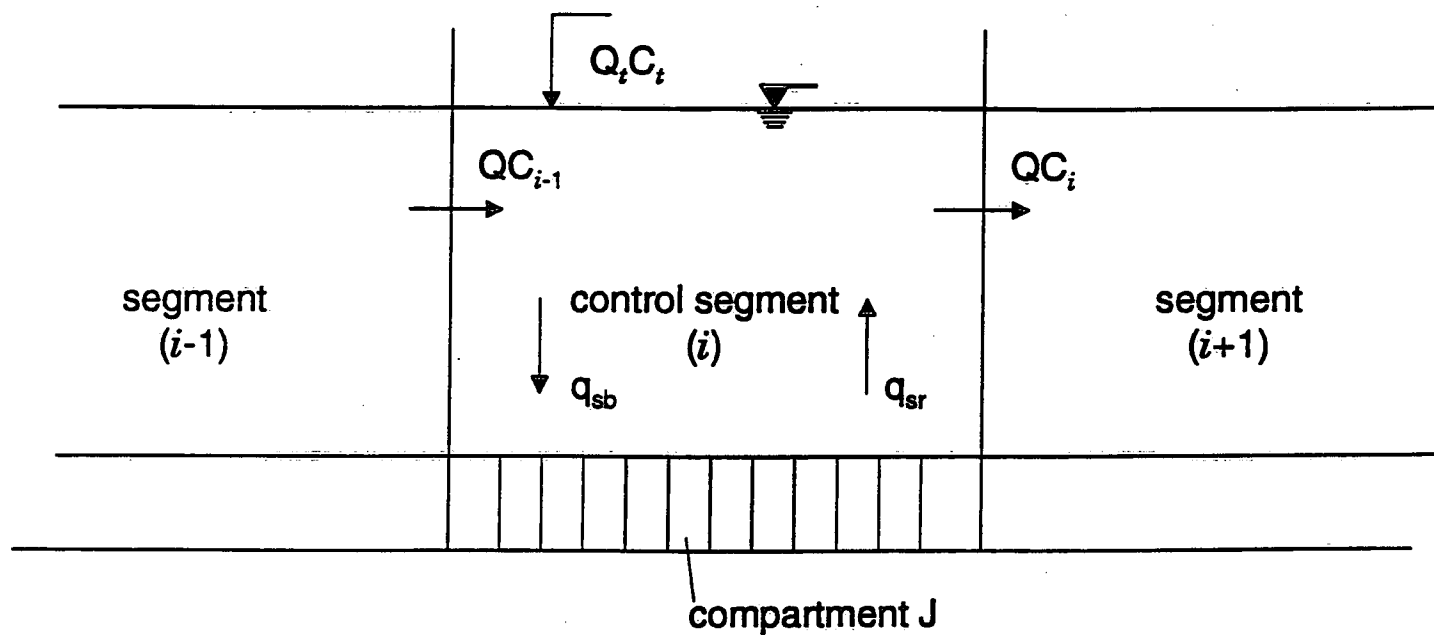


Figure 5. schematic representation of sediment mass balance

2. Sediment depositing to the bed:

Out of the incoming sediment, q_{in} , a portion will deposit depending on the prevailing flow conditions. The sediment quantity coming from the upstream segment will be subjected to the deposition only when the shear stress in the control segment is lower than that in the upstream segment. If the shear stress in the control segment is equal to or greater than that of the upstream segment, then the sediment arriving from the upstream segment would have gone through the deposition process already and would have reached the steady state concentration. Therefore, this sediment has to be routed straight through the control segment. The amount that would deposit in the control segment, therefore, can be calculated as:

$$\begin{aligned} q_{sd} &= (QC_{i-1}\Delta t)f_d + (Q_iC_i\Delta t)f_d & \text{if } \tau_i \leq \tau_{i-1} \\ q_{sd} &= (Q_iC_i\Delta t)f_d & \text{if } \tau_i > \tau_{i-1} \end{aligned} \quad (4)$$

where q_{sd} is the amount deposited during the current time step.

The amount remaining in suspension (q_{ss}) becomes:

$$\begin{aligned} q_{ss} &= (QC_{i-1}\Delta t + Q_iC_i\Delta t)(1 - f_d) & \text{if } \tau_i \leq \tau_{i-1} \\ q_{ss} &= Q_iC_i\Delta t(1 - f_d) & \text{if } \tau_i > \tau_{i-1} \end{aligned} \quad (5)$$

3. Sediment resuspension:

Sediment can also be resuspended from deposits that occurred in previous time steps. This resuspended amount can be calculated by keeping track of the amounts of deposited sediment and the shear stresses at which these depositions took place. This can be done by schematizing the river bed to consist of different compartments and assuming that each compartment holds sediment deposited at a particular shear stress. For example, let us assume that there are N compartments in the control segment and each compartment is identified with an index, say, J . Therefore, J varies from 1 to N . Compartment 1 is assumed to collect sediment deposited at shear stress equal to or less than the critical shear stress for deposition, τ_{cd} , and compartment 2 collects sediment deposited at shear stresses between τ_{cd} and $2\tau_{cd}$ and so on. Let the sediment deposited in each of the compartments from the previous time steps be P_J . For a given shear stress, the sediment resuspended from various compartments can be calculated by applying equation 2 for each compartment with the appropriate τ_{cd} value as follows:

$$q_{sr} = \sum_{J=1}^N q_{srJ} = \sum_{J=1}^N P_J f_{dJ} \quad (6)$$

where q_{sr} is the total amount of resuspended sediment and f_{dJ} is the erosion function for the compartment J .

Knowing the amounts of sediment resuspending from and depositing to the bed, the concentration of the suspended sediment and the amount of sediment in the various compartments in the bed of the control segment at the end of the current time step can be calculated as follows:

4. *Sediment concentration at the end of the current time step:*

The suspended sediment concentration in the control segment at the end of the current time step is:

$$C(i) = \frac{(q_{ss} + q_{sr})}{(Q\Delta t)} \quad (7)$$

5. *The amount of sediment in various bed compartments at the end of the current time step:*

The amount of sediment left behind in the control segment at the end of the current time step is:

$$\sum_{J=1}^N P_J^* = \sum_{J=1}^N P_J (1 - f_{dJ}) + \delta(J, K) * q_{sd} \quad (8)$$

where P_J^* is the updated value of P_J at the end of the current time step. The function $\delta(J, K)$ takes a value of unity, when $J=K$, and zero when $J \neq K$. K denotes the compartment which receives the deposited sediment during the current time step.

The concentration $C(i)$, as calculated by equation (7), is routed to the downstream segment and the calculations outlined above for the control segment are repeated for the downstream segment. The process is continued until all the segments are encountered. The calculations are then repeated for the next time step until the simulation period is covered.

SUMMARY

A new algorithm for the transport of fine sediments of the Fraser River is formulated based on laboratory experiments in a rotating circular flume. The algorithm is formulated for steady flows and may be used for gradually varied flow by considering the flow rate as quasi-steady. This algorithm is an improvement over the existing sediment transport models as it accounts for the differences in the critical conditions for erosion and deposition processes of fine sediment transport.

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APPENDIX-A

CALCULATION OF BED SHEAR STRESS:

Assuming that the hydraulic parameters such as the flow rate Q (m^3/s), the flow cross-sectional area A (m^2), the wetted perimeter, P (m) and the representative bed material size D_{65} (m) are known, we can calculate the bed shear stress using the logarithmic friction factor relation as follows:

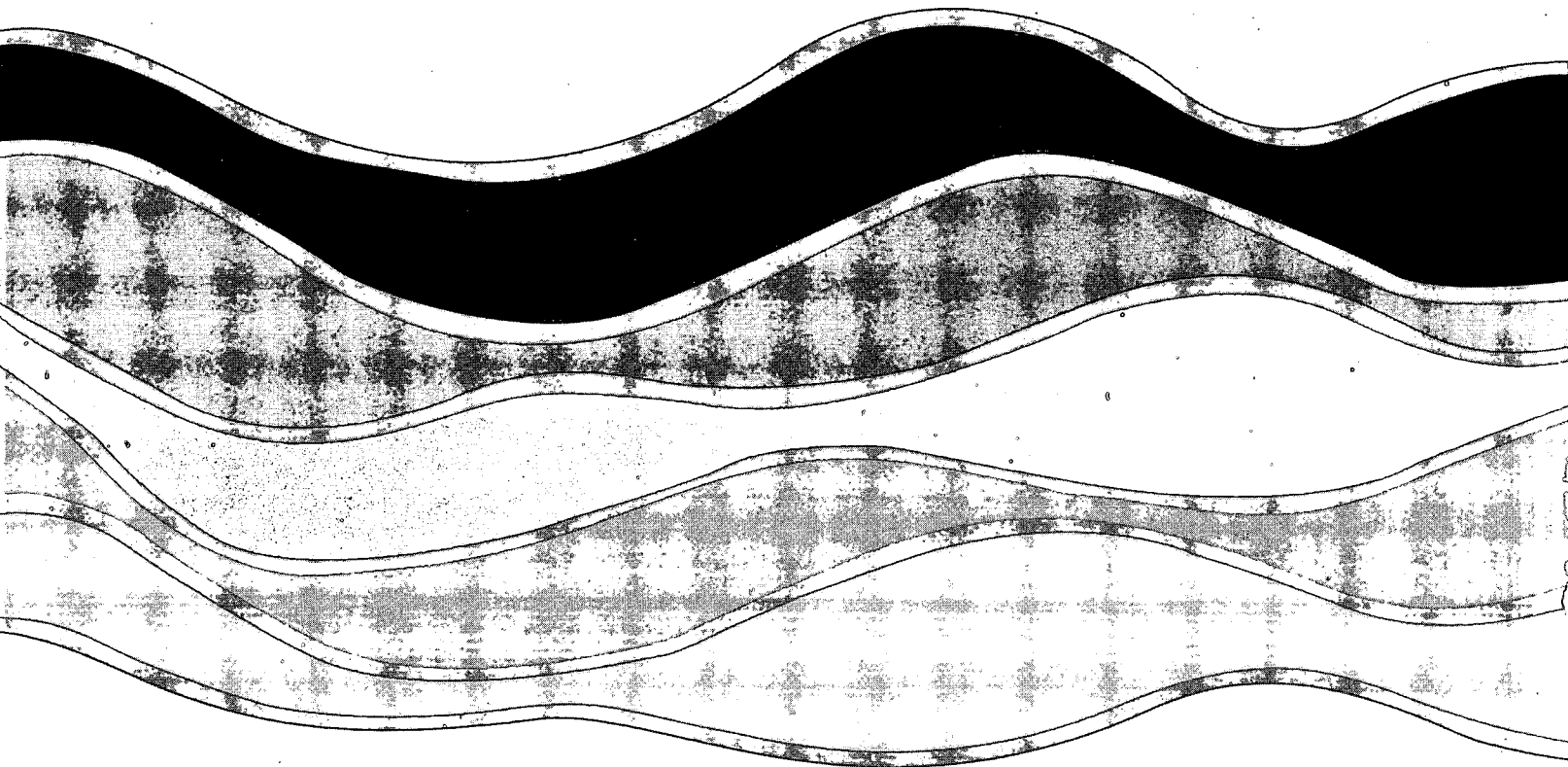
$$U_* = \frac{(Q / A)}{2.50 \ln [1.10(A / P) / (2.50 D_{65})]} \quad (\text{A1})$$

where U_* is the shear velocity in m/s.

Knowing U_* , the bed shear stress τ_0 in N/m^2 can be calculated using the following conversion:

$$\tau_0 = 1000 U_*^2 \quad (\text{A2})$$

The equation (A1) assumes that the flow is in rough turbulent regime which may be a reasonable assumption for the Fraser River. When the flow is ice-covered, a 50% reduction in U_* values can be assumed as a first approximation. Further refinement can be carried out if it is warranted.



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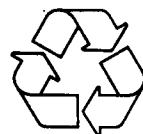


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