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ENVIRONMENTAL ASPECTS OF RIVER ICE
SECTION 1.4. TRANSPORT AND MIXING PROCESSES

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ABSTRACT

This report is intended to become a part of a state-of-the-art report on environmental aspects of river ice. The river ice cover acts as a second boundary for the flow thus increasing hydraulic resistance and changing the velocity profile. The effects of the ice cover in the transport and mixing processes are discussed, in light of the altered flow field. The conventional concept of the two-layer, composite flow under an upper boundary provides good approximations if used judiciously. Major gaps in current knowledge exist with respect to scour caused by ice jams and to transport of coarse and fine sediments under an ice cover.

RÉSUMÉ

Le présent rapport constitue une portion d'un rapport sur l'état actuel portant sur les aspects environnementaux de la glace de rivière. La couverture de glace agit comme deuxième barrière à l'écoulement, augmentant ainsi la résistance hydraulique et modifiant le profil des vitesses. Les effets de la couverture de glace sur les processus de transport et de mélange, à la lumière des modifications du champs d'écoulement observé sont traités. Le concept classique de l'écoulement à deux couches sous une limite supérieure permet d'obtenir de bonnes approximations, là où on l'utilise avec soin. Les connaissances actuelles sont limitées dans le domaine de l'affouillement causé par les embâcles et celui du transport des sédiments grossiers et fins sous une couverture de glace.

MANAGEMENT PERSPECTIVE

In its 1987 meeting, the NRCC Subcommittee on Hydraulics of Ice Covered Rivers, identified a need to address environmental aspects of river ice, a subject that has received little attention in the past and is poorly understood. Consequently, a Task Force was initiated in 1988. One of its objectives is to prepare a state-of-the-art report and formulate research needs in all three areas of concern, physical, chemical, and biological. This report discusses transport and mixing processes and is intended to become a part of the Chapter on Physical Processes. It is concluded that major gaps in current knowledge exist in the area of sediment transport for both coarse and fine sediments. Closely related to sediment transport are gaps pertaining to scour under ice jams or to scour caused by surging flow velocities upon the release of an ice jam.

PERSPECTIVES GESTION

Lors de sa réunion de 1987, le Sous-comité de l'hydraulique des rivières recouvertes de glace de la CNRC a décidé de s'intéresser aux aspects environnementaux de la glace de rivière, domaine encore peu étudié et assez mal connu. Un Groupe de travail a donc été créé en 1988. L'un des objectifs de ce groupe est de préparer un rapport sur l'état actuel et de déterminer les besoins en recherche dans les trois domaines d'intérêt : aspects physiques, chimiques et biologiques. Le présent rapport traite des processus de transport et de mélange et constitue une partie du chapitre portant sur les processus physiques. Les auteurs concluent que les connaissances actuelles manquent surtout dans le domaine du transport des sédiments fins et grossiers. De plus, on connaît mal l'affouillement qui se produit sous les embâcles de glace ou qui est causé par des écoulements soudains lors de débâcles.

INTRODUCTION

The presence of ice in a river significantly alters the transport and mixing characteristics of the flow. Such effects are most pronounced where the ice is in the form of a stationary cover which creates an additional flow boundary. Except for some infrequent and short-lived conditions, the ice cover, along with any snow load that may be present, is in a state of flotation so that it can generally move up or down with the water level. As in the open-water case, the flow is essentially driven by gravity.

The effects of an ice cover on transport and mixing processes are considered in this section. A comprehensive, quantitative treatment of riverine transport and mixing is beyond the scope of this report and there are several texts and articles containing detailed information (e.g. see Henderson, 1966; Yalin, 1972; Ashton, 1986; Fischer et al., 1979; Beltaos, 1978; Elhadi et al., 1984). Instead, emphasis is placed on the underlying physical mechanisms so as to illustrate the effects of the ice cover and identify knowledge gaps that require investigation.

VELOCITY AND SHEAR STRESS

For open-water flow in a very wide rectangular channel, the well known logarithmic and linear distributions respectively describe the velocity and shear stress (Fig. 1). The average velocity, V, and the bottom shear stress, τ_0, are related by a flow resistance equation, i.e.

$$\tau_0 = (f/8)\rho V^2 \qquad (1)$$

in which ρ = density of water; and f = friction factor of the bed which, for "fully rough turbulent" flow, as is the usual case in natural streams, increases with relative roughness. The latter is defined as the ratio of absolute roughness, K_b, to flow depth, Y_0.

For ice-covered flow, the shear stress remains linear, becoming zero at a depth dictated by the two roughnesses K_i (ice cover) and K_b (bed). The flow velocity is zero at the top and bottom of the profile and has a maximum at a depth that nearly coincides with that of zero shear stress.* A common, though only partially correct, approximation is to view the composite, ice-covered flow as a superposition of two open-water layers, the upper one being inverted (Fig. 1). Using this concept, simple equations can be derived to calculate the shear stresses τ_0 and τ_b and the average velocity of the composite flow. It should be kept in mind that we are discussing flow in a straight, very wide channel of constant depth. In natural streams, where various irregularities and bends are present, vertical velocity distributions are occasionally very different from the idealized forms of Fig. 1. Consequently, flow resistance equations in both open-water and ice covered river flows are only meaningful in a reach-averaged sense.

The additional resistance to flow caused by the ice cover reduces the velocity so that, to pass the same discharge, an ice-covered, unregulated channel has to be deeper than when it is open. The increase in flow depth depends, among other things, on the roughness of the ice cover. If this roughness is equal to that of the bed, then the increase in depth will be ~30%; it can be much more severe (100% or more) under an ice jam, i.e. a porous and characteristically rough accumulation of ice floes that forms during freezeup or breakup. Considering that the water level must rise to also accommodate some nine-tenths of the jam's thickness - could be several metres - explains the frequent flooding caused by ice jams. This is the main consequence for which ice jams are known but they cause additional problems, as will be discussed later.

VERTICAL DIFFUSIVITY

In rivers, the main diffusive mechanism responsible for vertical

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* Lack of symmetry, occuring when $K_i \neq K_b$, is the cause of non-coincidence between these two points (e.g. see Hanjalic and Launder, 1972).

spreading of dissolved or suspended substances is the turbulence of the flow. It is commonly assumed that momentum and mass transfer processes are analogous, so that the vertical diffusivity, ϵ_y is calculated from:

$$\epsilon_y = (\tau/\rho)\Big/\left(\frac{du}{dy}\right) \tag{2}$$

in which τ = shear stress at depth y; u = velocity at depth y; and du/dy = vertical gradient of u at depth y. Equation 2 describes a parabola (Fig. 2a), so that the depth-averaged diffusivity $\overline{\epsilon_y}$ amounts to $0.07\ u_* Y_0$ ($u_* \equiv \sqrt{\tau_0/\rho}$).

This concept breaks down when applied to the two-layer, ice-covered flow representation because it gives an unrealistic distribution of ϵ_y (Fig. 2a); for example, it requires $\epsilon_y = 0$ at the point of zero τ implying no transfer of mass across this plane. Figure 2b, reproduced from Lau and Krishnappan (1981), shows distributions of ϵ_y calculated using the "kappa-epsilon" turbulence model, known to give very good results in many types of turbulent flow. It is clear that ϵ_y does not vanish near mid-depth under an ice cover. On the whole, the vertical diffusive capacity of a stream is reduced in the presence of an ice cover.

TRANSVERSE MIXING

In purely two-dimensional, open-channel flow, the transverse spreading of a pollutant is mostly accomplished by turbulence, the corresponding diffusivity being proportional to $u_* Y_0$. In natural streams, however, additional spreading mechanisms are at work, caused by secondary currents. These arise from vertical and transverse components of velocity so that individual fluid particles move along helical paths.

There are two kinds of secondary currents. The first kind is produced by an imbalance in the normal Reynolds stresses, in turn caused by the fact that turbulence is not identical in all directions.* Such currents are normally very weak but may become significant if the aspect ratio of the stream is less than about 10.

River bends give rise to a much stronger type of secondary current, driven by radial accelerations. Figure 3 illustrates this kind of circulation for both open-water and ice-covered flows. In the latter case, two "cells" are present which is consistent with the two-layer, composite flow concept. Measurements (Zufelt, 1988; Urroz, 1988) indicate that the magnitude of the radial (transverse) velocity component, relative to the tangential (longitudinal) component, is about the same for both open-water and ice-covered conditions (~0.1). Because the radial velocity distribution is not uniform, a dissolved or suspended contaminant would be radially advected at different rates, depending on its vertical position. This "differential advection" causes "dispersion", a term that has been adopted to describe spreading of aquatic substances due to non-diffusive mechanisms.

Transverse dispersion is commonly quantified by using an augmented, or apparent diffusivity, called the transverse mixing coefficient. This assumption, by-and-large empirically based, greatly simplifies mixing calculations by focusing on the depth-averaged concentration. The transverse mixing coefficient, E_Z, is obtained by comparing measurements with solutions of the depth-averaged continuity equation for the spreading substance. Field data indicate that E_Z scales on shear velocity, u_*, and flow depth, Y, for both open-water and ice-covered streams**. It is not known why this is so, as very little work has been done to elucidate the effects of secondary currents on transverse mixing. An empirical relationship between K_Z ($=E_Z/u_*Y$) and river sinuosity has been obtained by

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*"Normal Reynolds stresses" are time-averages or ensemble-averages of squared velocity fluctuations, multiplied by the fluid density.

**Note u_* is taken as $\sqrt{gRS}$ in which g = acceleration of gravity; S = water surface slope, and R = hydraulic radius ≈ Y for open-water conditions or Y/2 for ice-covered conditions.

Lau (1985) and can be used to estimate E_z (Fig. 4). Noteworthy is that, for straight channels, K_z has the well-known value of ~ o.2 but increases to ~ 1.0 in a stream of sinuosity = 1.3. The large scatter of the data points in Fig. 4 suggests that additional factors may have an influence on E_z.

Recently, Pavlovic and Rodi (1985) and Demuren and Rodi (1986) have further demonstrated the mixing ability of secondary currents through numerical modelling in two and three dimensions.

LONGITUDINAL DISPERSION

As discussed earlier, the term dispersion is commonly applied to the spreading process caused by differential advection. Longitudinal dispersion by far exceeds longitudinal turbulent diffusion in rivers and is essentially caused by transverse variations of the longitudinal velocity (Fischer et al., 1979). The lack of prismaticity, i.e. variations in cross-sectional properties along the river, further enhances the dispersive capacity of natural streams (Beltaos, 1980; Li, 1989). Very little experimental information exists with regard to the effects of an ice cover on longitudianl dispersion. Based on current understanding of the relevant factors, and invoking the two-layer flow concept, we would expect that the longitudinal dispersion capability is reduced by the presence of an ice cover. However, test data are needed to check this extrapolation.

SEDIMENT TRANSPORT

Many aspects of the transport of sediment by rivers have been elucidated in the past few decades (e.g. see Yalin, 1972) and the subject is still under active research. Nearly all of this work relates to open-water conditions. Once the bed shear stress exceeds a threshold value, the bed sediment begins to move as "bed load" and as "suspended load". The bed load is the amount of bed material being transported per unit time in close proximity to the bed. It is strongly dependent on the bed shear stress as well as on sediment and fluid properties. The suspended load is material that is transported mostly in suspension, with only infrequent contact with the bed. Vertical diffusivity and flow velocity are important factors in determining the suspended load, in addition to bed shear and sediment/fluid properties.

For the same discharge, the presence of an ice cover generally reduces the sediment "driving" parameters (shear stress, velocity, diffusivity) so the sediment transporting capacity should be significantly reduced. This expectation has been confirmed by Lau and Krishnappan (1985). Their experiments and analysis supported use of the two-layer concept of ice-covered flow, provided the vertical diffusivity is evaluated realistically, e.g. see Fig. 2.b. More experimental data are needed, however, both in the laboratory and in the field so as to fully define the effect of an ice cover (see also Sayre and Song, 1979; Wuebben, 1986).

The preceding considerations apply to relatively coarse sediments that are not subject to formation of cohesive bonds and consequent flocculation. Relatively little is known about the behaviour of fine cohesive sediments (size ≤ 62 μ) in open-water flow (Partheniades, 1986). When it comes to flow under ice, the writer is not aware of any investigations or data. A major environmental effect of fine sediments is their strong adsorptive tendency so that the fate of many aquatic contaminants is governed by the transport, erosion and deposition of fine particles. Clearly, a sustained research effort is needed to understand these processes and how they are influenced by flocculation.

SCOUR

River bed scour occurs wherever the incoming amount of sediment is exceeded by the outgoing, and is generally divided into two categories, "general" and "local" scour.

General scour occurs over a large portion of the river width and length and is caused by gradual variations in flow characteristics. For example, general scour occurs at a constriction because of the longitudinally increasing flow velocities and shear stresses. The opposite is true downstream of the constriction so that we would expect deposition to take place. Local scour results from localized and highly variable flow types such as jets and vortices created by obstacles or artificial boundary configurations. For example, local scour occurs near bridge piers due to vortices forming as a result of the three-dimensional configuration of the flow around the pier.

Ice jams are the main scour-causing ice cover type. Non uniformities in the longitudinal configuration of a jam cause longitudinal gradients of the sediment transport capacity, thus leading to general scour and deposition regions as shown in Fig. 5 (e.g. see Mercer and Cooper, 1977, Wuebben, 1988;). Of course, the occurrence of scour presupposes that flow velocities and thence bed shear stresses are strong enough to exceed the "threshold" condition which may or may not be the case under an ice jam, depending on bed material size and flow discharge.

The surges which accompany the release of ice jams (Fig. 6) are known to propagate at very high celerities, C, and create unusually high water velocities, V_s (Henderson and Gerard, 1981; Beltaos and Krishnappan, 1982). Values of 5 m/s for V_s are not uncommon. For a friction factor of 0.05, this value of V_s translates to a bed shear stress of 150 Pa which, in turn, implies that the flow can move bed material particles as large as 20 cm in diameter.

Such flow conditions, though transient and perhaps not causing a large amount of general scour, will have two effects: (a) will generally set the river bed in motion which may be detrimental to aquatic life attached to the bed; and (b) will cause considerable local scour which may be detrimental to the safety of structures in the river or at the river banks. For example, Ashton (1987) mentioned an instance where an entire island disappeared from a river during the ice breakup, an event thought to have been caused by surging water and ice. Doyle (1988) reported on cases where rip-rap was damaged by the same process.

Virtually no quantitative information exists on the scouring caused by river ice. Field data would require considerable expense to obtain but no major difficulties are foreseen, especially if impulse-radar systems are utilized.

SUMMARY

The presence of an ice cover in a river alters the flow field by introducing a new boundary. The resulting changes are fairly well understood and can be quantified with judicious use of the two-layer, composite flow concept.

Mixing processses are largely governed by turbulence and advection and a fair understanding exists of the effects of ice covers. Gaps in knowledge on the ice effect are related to corresponding gaps on open-water flow. For example, the transverse mixing coefficient of ice-covered rivers is not fully predictable largely because the dispersive influence of helical motions at bends is not fully known.

Present understanding of coarse sediment transport in open channels suggests that the ice cover should cause a reduction of the river's transporting capacity but this needs more detailed verification than is presently available both in the laboratory and in the field. When it comes to transport of fine, cohesive sediments, known to carry various contaminants in a sorbed state, relatively little is known under open-water conditions and nothing about the effect of the ice.

Ice jams appear to have the most serious effects on flow and transport processes, not only with regard to frequent flooding but also with respect to general and local scour and potential damage to river structures. Very little information exists, however, for predicting the scour that can be caused by ice jams. Both laboratory and field investigations are needed.

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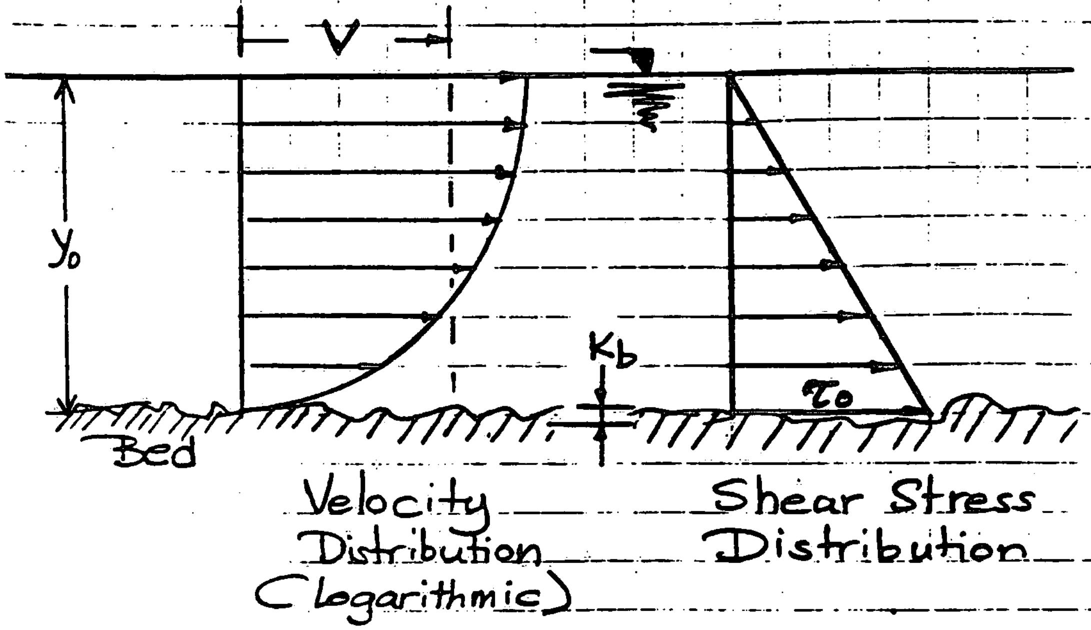
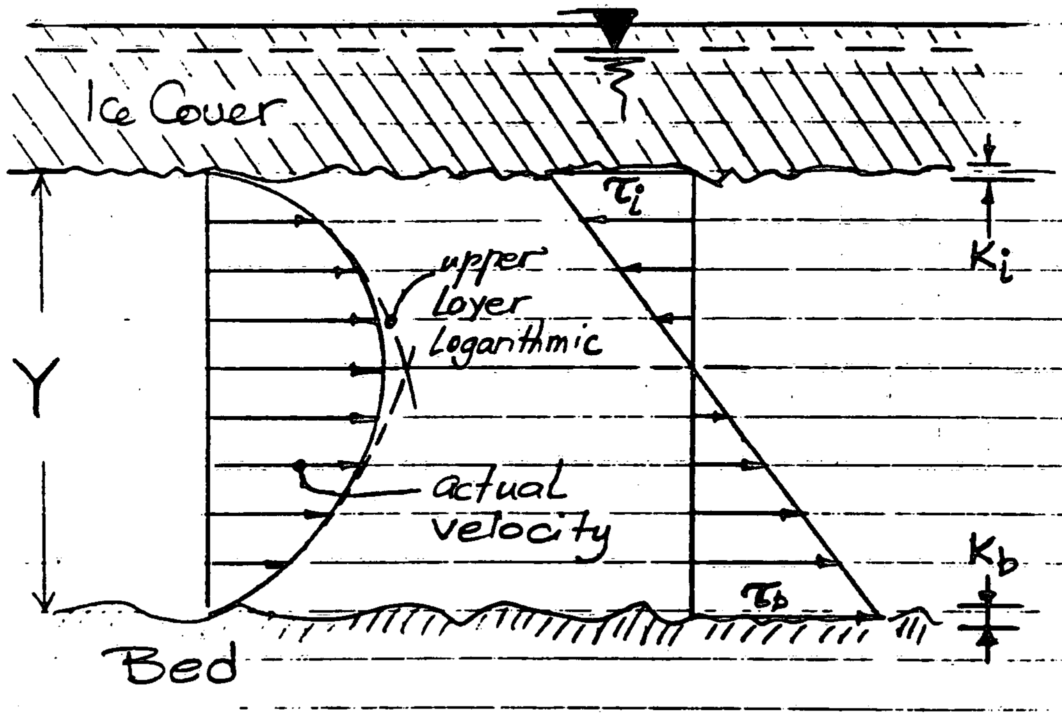
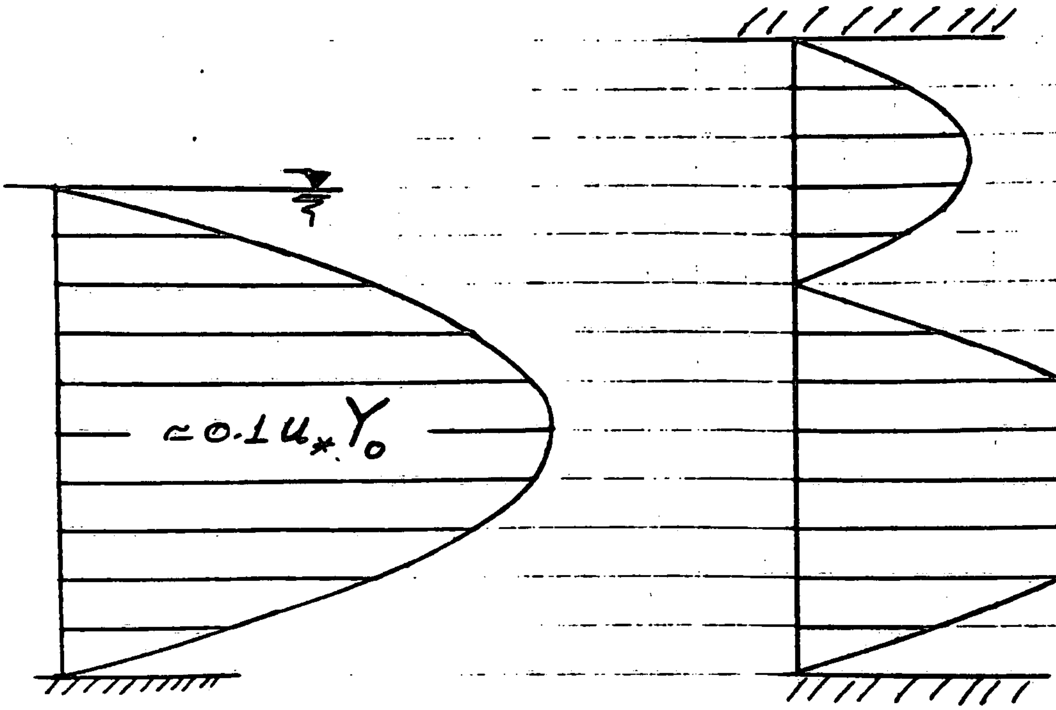


OPEN-WATER CONDITION

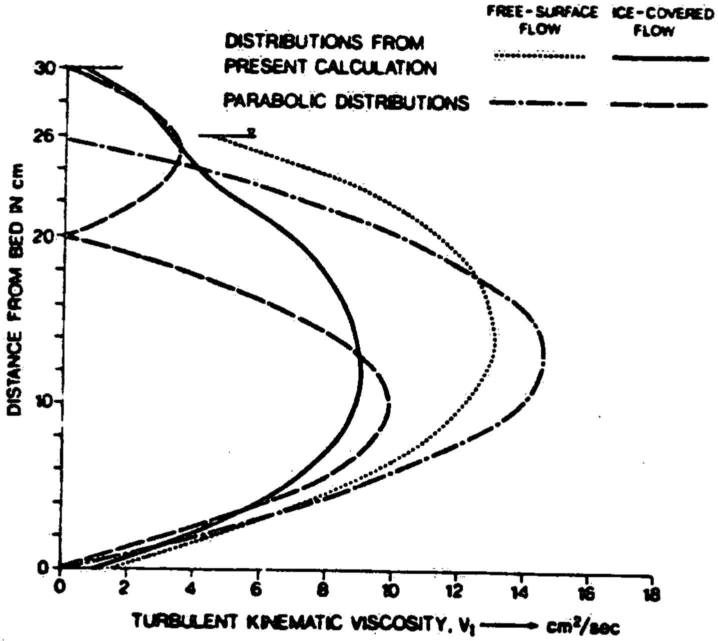


ICE-COVERED CONDITION

FIG. 1. Velocity and Shear Stress Distributions in Uniform, Unidirectional Flows.



(a) Parabolic distributions for open-water and ice-covered conditions; the latter is implausible.



(b) Calculated using kappa-epsilon model (Lau and Krishnappan, 1981)

FIG. 2. Vertical Diffusivity Distributions in Uniform, Unidirectional Flows

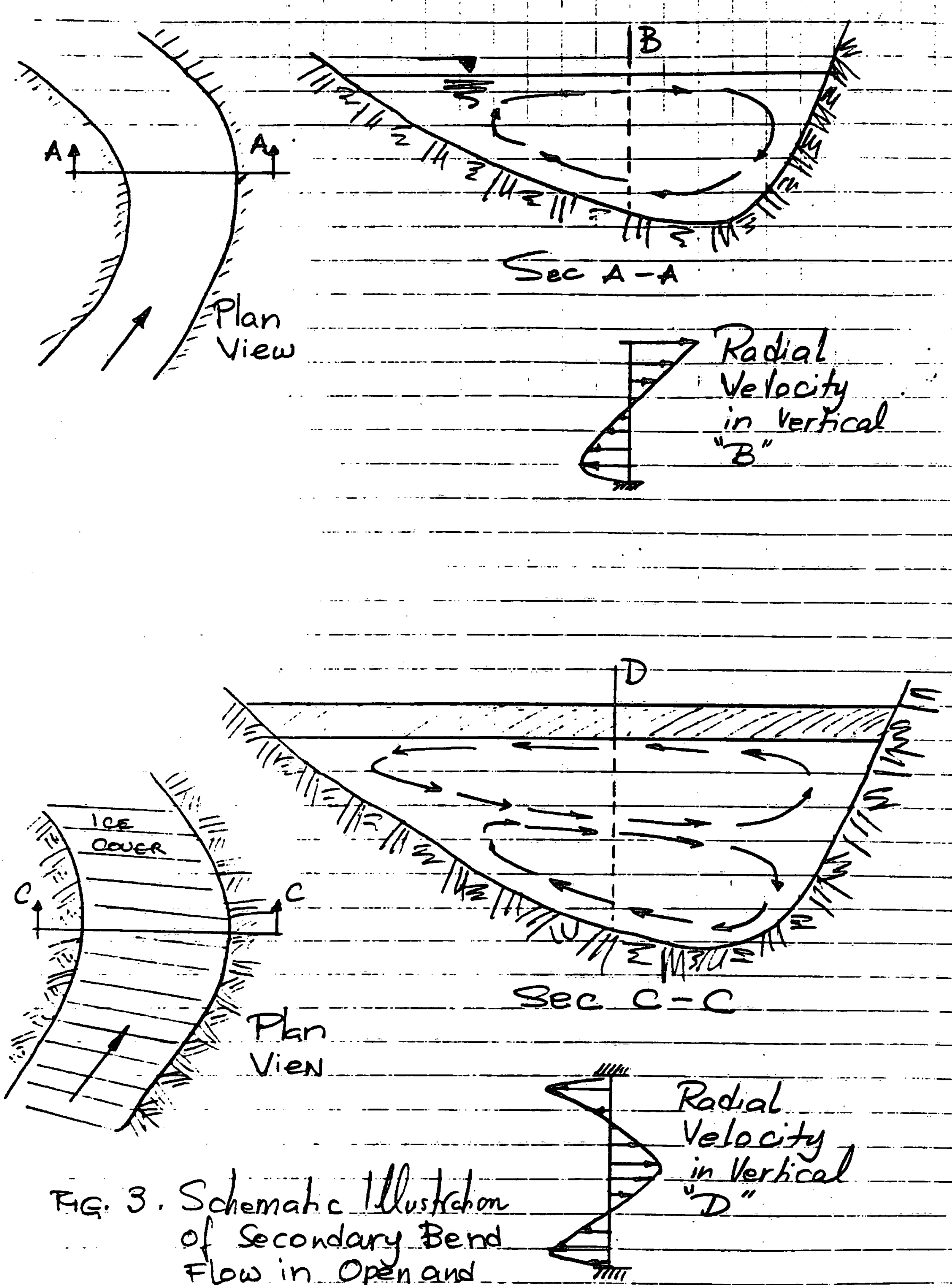


FIG. 3. Schematic Illustration of Secondary Bend Flow in Open and Ice-Covered Channels

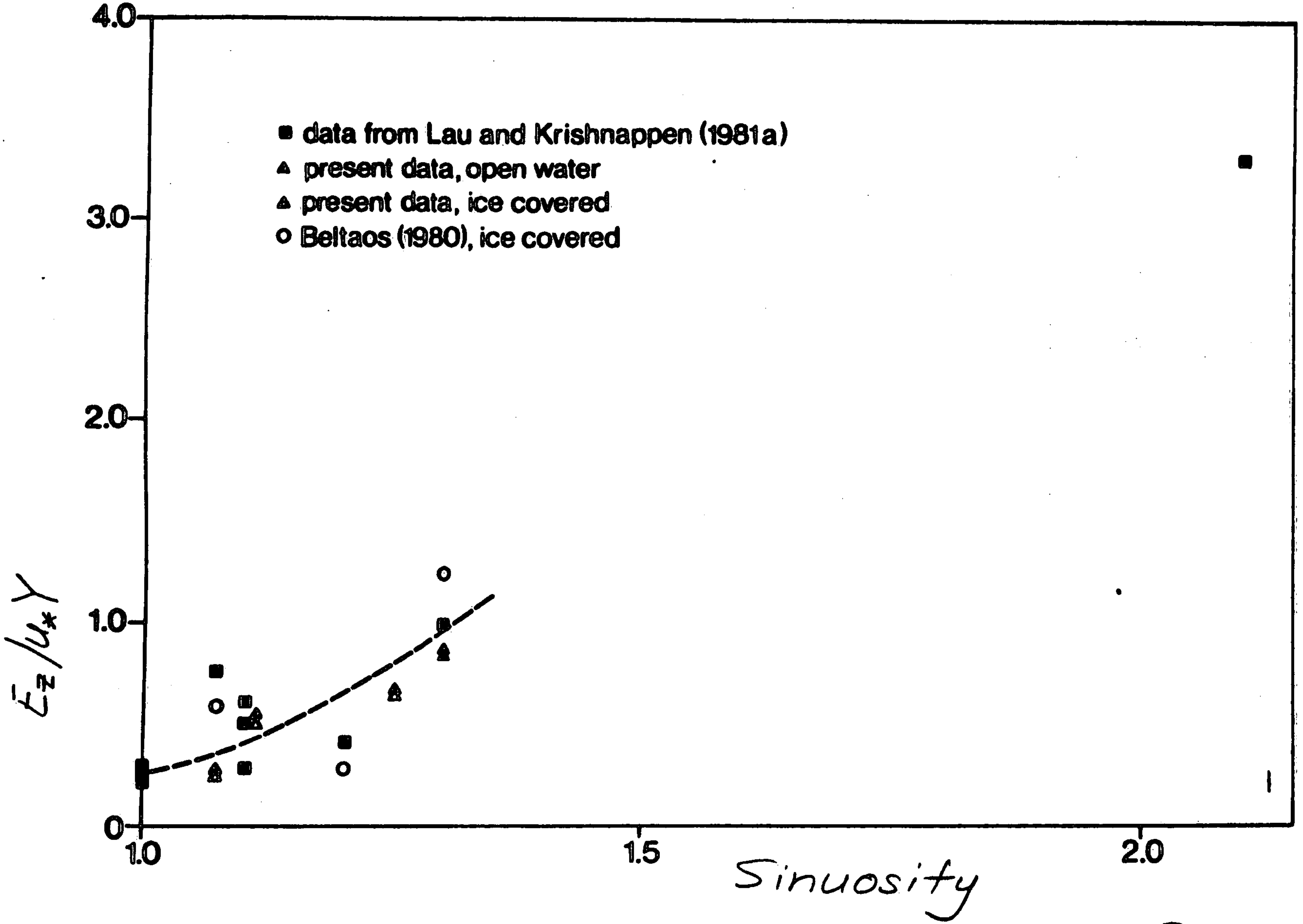


Fig. 4. Dimensionless Transverse Mixing Coefficients Versus River Sinuosity (from Lau, 1985, with changes).

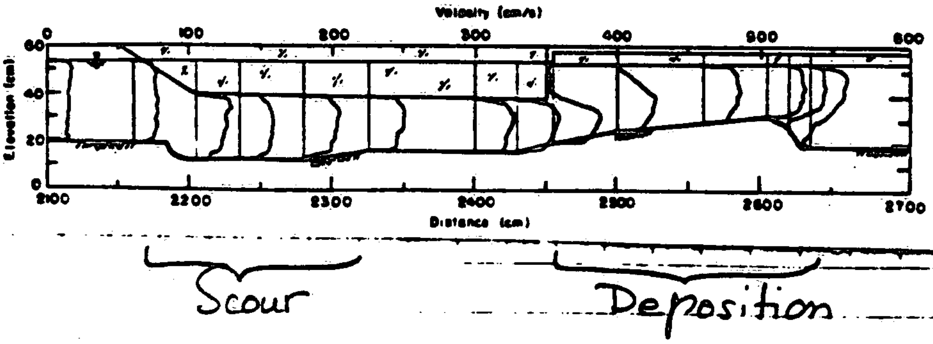
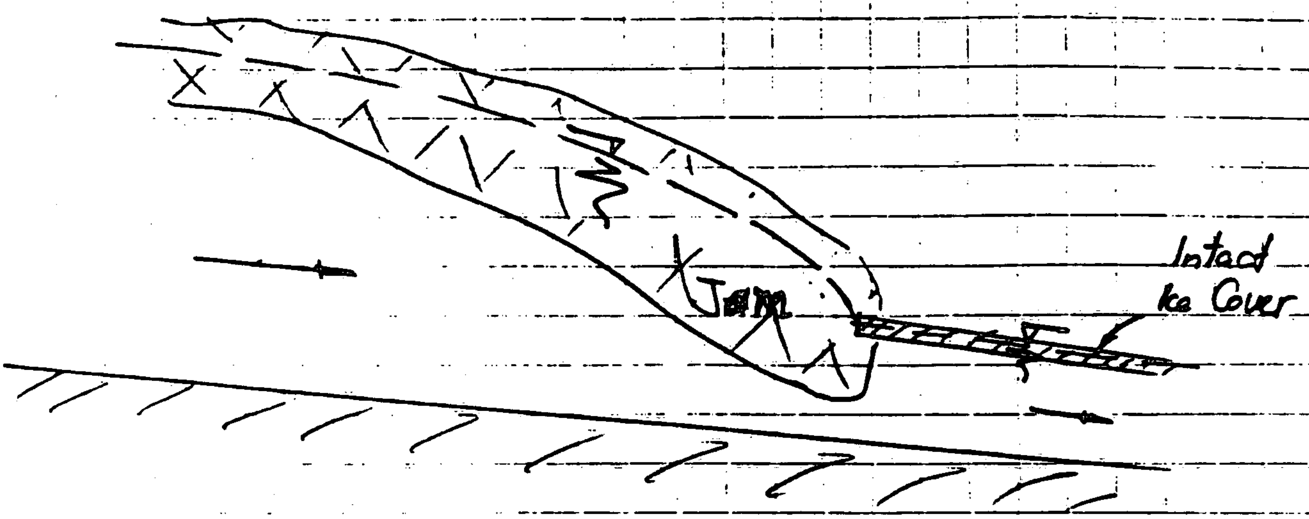
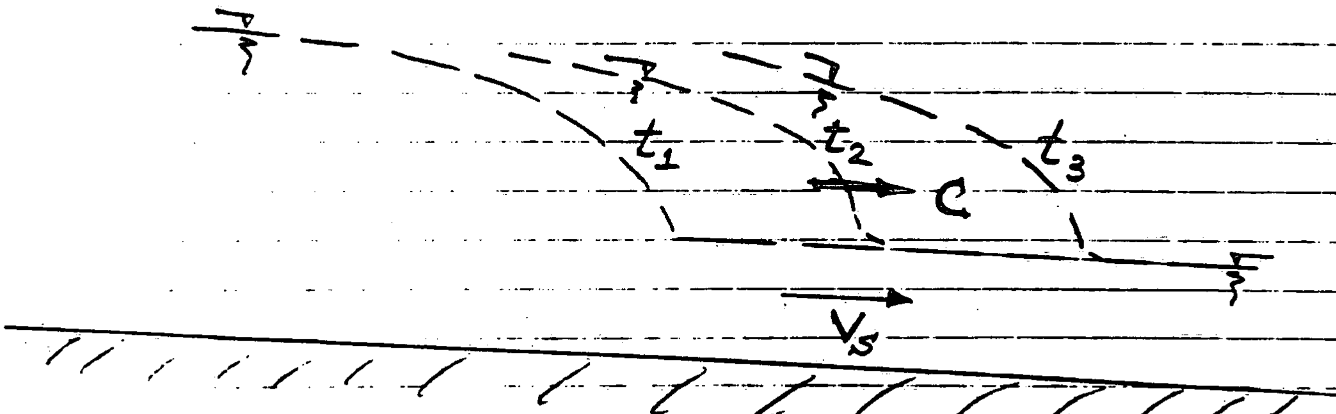


Fig. 5. Scour-Deposition Patterns Under a Simulated Ice Jam (From Laboratory tests by J. Wuebben, 1988).



Water Surface Profile along a Stationary Jam. Note wave-like form that is free to move upon release of the jam



Water Surface Profiles at different times $t_1 < t_2 < t_3$ following the release of a jam. Note C = celerity of wave propagation; V_s = velocity of water (average)

FIG. 6. Schematic Illustration of Surges due to Ice Jam Releases.