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CRITERIA FOR THE ESTABLISHMENT OF AN EXPERIMENTAL PROGRAM FOR THE MEASUREMENT OF FLOWS IN RIVERS WITH SOLID ICE COVER

By

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SUMMARY

The Water Survey of Canada, under the guidance of its Committee for the Measurement of Flow Under Ice, is preparing to conduct a field measurement program during the winter of 1989/90. The data will be used to examine present flow measuring practices of the Water Survey of Canada and examine new results obtained with a mathematical model developed by Lau (1982) and verified in the laboratory by Krishnappan (1984). In this report criteria for the establishment of experimental measuring sites and measurement procedures are presented based on hydraulic principles. Implementation of the guidelines will help to ensure that a sound data base for future operational and scientific investigations will be obtained.

RÉSUMÉ

La Division des relevés hydrologiques du Canada sous la direction de son Comité de mesure des débits sous la glace est en train de préparer un programme de mesure sur le terrain pendant l'hiver de 1989-1990. Les données recueillies serviront à examiner les méthodes actuelles de mesure de débits de la Division des relevés hydrologiques du Canada et les nouveaux résultats obtenus grâce à un modèle mathématique mis au point par Lau (1982) et vérifié en laboratoire par Krishnappan (1984). Dans ce rapport, les critères d'établissement des emplacements et des méthodes de mesure expérimentale qui sont présentés se fondent sur les principes de l'hydraulique. On espère que l'application des lignes directrices permettra d'établir une base de données fiable pour les futures recherches opérationnelles et scientifiques.

MANAGEMENT PERSPECTIVE

Uncertainties in the measurement of stream flow during periods of ice cover have long been the concern of water resources data managers. In the past the larger errors associated with winter records have been considered to be acceptable because flows during this period are usually small relative to the flows during the remainder of the year. This attitude, in view of present water quality concerns, is no longer viable. The transport of toxic chemicals by the lower winter flows, although small in terms of total annual loading, may be particularly harmful because of high concentrations.

At the present time the Water Survey of Canada, with the assistance of the National Water Research Institute is in the process of implementing an experimental winter flow measuring program on approximately 36 different streams across Canada. The purpose of this program is to set up a data base with which measurement methods and standards for the measurement of flows under ice covers can be examined and new techniques developed. The resulting data base will provide important information for engineers and researchers for many years to come.

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PERSPECTIVE DE GESTION

Les incertitudes relatives à la mesure du débit des cours d'eau pendant les périodes où ils sont couverts de glace ont pendant longtemps créé des problèmes aux responsables des données sur les ressources en eau. Dans le passé, les erreurs plus grandes associées aux données recueillies pendant l'hiver étaient jugées acceptables, les débits pendant cette période étant généralement faibles par rapport à ceux du reste de l'année. Étant donné les problèmes actuels relatifs à la qualité de l'eau, une telle attitude n'est plus de mise. Le transport de substances chimiques toxiques au moment des débits plus faibles de l'hiver, bien que peu important en regard de la charge annuelle totale, peut être particulièrement dommageable à cause des concentrations élevées.

À l'heure actuelle, la Division des relevés hydrologiques du Canada avec le concours de l'Institut national de recherche sur les eaux est en train de mettre en oeuvre, à titre expérimental, un programme de mesure des débits d'hiver d'environ 36 cours d'eau différents dans tout le Canada. Ce programme a pour but d'établir une base de données qui permettra d'examiner les méthodes et les normes de mesure des débits sous la couverture de glace et de mettre au point de nouvelles techniques. La base de données ainsi obtenue constituera une importante source d'information tant pour les ingénieurs que pour les chercheurs pendant les années à venir.

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TABLE OF CONTENTS

1.0 INTRODUCTION

The Water Survey of Canada conducts an extensive streamflow measurement program across the country to provide the necessary data for management of national water resources, engineering works and various research studies. Ice conditions in rivers during the winter months present major difficulties to obtaining accurate discharge records. Individual discharge measurements made under ice conditions are generally known to be less accurate than those made in open water (Dickenson, 1967). This is largely due to the variable roughness of the under - surface of the ice (Lau, 1982) and the shape of the crossection (Gerard, 1980). In addition the presence of frazil ice may affect the operation of the meter and the presence of slush ice increases the uncertainty in the measurement of the total flow (Strilaeff and Wedel, 1970). As a result, the accuracy of the winter records are highly dependent upon the number and distribution of the discharge measurements made during the winter period.

In the past the larger errors obtained for winter records have been considered to be acceptable because flows during this period are usually small relative to the remainder of the flows during the year, so that the annual discharge value is affected only slightly (Dickenson, 1967). This contention, in view of present water quality concerns, is no longer acceptable. The transport of toxic chemicals by the lower winter flows, although small in terms of total annual loading, may be particularly harmful because of high concentrations. Clearly, more accurate winter flow records are required for effective monitoring of environmental pollution.

In view of this requirement, the Water Survey of Canada, with the assistance of the National Water Research Institute, is reviewing measurement standards and methods presently in use through its " Measurement of Flow Under Ice Committee." A major thrust of this effort will be a carefully designed flow measuring program at selected, representative, existing hydrometric sites. In this report the basic criteria for selecting these measurement sites are presented. This report was prepared at the request of the Water Survey of Canada.

2.0 PRELIMINARY CONSIDERATIONS

2.1 Location of Measuring Section in the Channel Reach

The overall accuarcy of the streamflow measurement is governed to a large extent by the physical and hydraulic characteristics of the river channel in which the chosen cross section is located. The channel should be of straight and uniform cross - section and slope to ensure parallel and tranquil flow and to reduce the chance of abnormal transverse velocity distribution. Ideally, the length of straight reach should be no less than three times the width of the channel with the measuring section located at least in the downstream half of the reach (Lambie, 1978). Such ideal channel reaches may not always be available. As a result, in some cases, flow measurement sections may be located just downstream of a bend, resulting in uneven flow distributions and possibly oblique flows through part of the cross - section. Flow measurements at such sites must be done very carefully taking fully into account the spacial distribution and alignment of the flow.

2.2 Flow Measurement Method

The standard procedure for measuring the discharge of a of a river is the velocity - area method. The total area of the cross - section is divided into small sections and the area and mean velocity of each are determined separately. The small sections are each bounded by the stream bed, the ice cover and two imaginary vertical lines called verticals as shown in Figure 1. Each vertical, therefore, being a common dimension for two adjoining sections, fixes the point at which observations of depth and velocity are made through a hole cut into the ice cover. Sufficient velocity observations are made to establish the mean velocity in each of the two verticals forming the side boundaries of a section and the velocities in the two verticals are then averaged to determine the mean velocity in the section. The area of the section is the distance between the verticals and the mean of the distance between the bed and the ice cover. The product of the mean velocity and the area of the section is the discharge passing through the section. The total discharge of the river is the sum of the discharges of all the sections.

The accuracy of the discharge measurement depends on the accuracy in determining the average velocity and the area of each of the partial sections. The number of such sections required, in turn depends on the cross - sectional shape of the measuring reach. The shape of the vertical velocity curve under a continuous ice cover depends on the relative roughness of the wetted ice surface and the stream bed. If the wetted ice surface is hydraulically rougher than the stream bed, then the vertical velocity profile will be distorted as shown in Figure 2. If the stream bed is rougher than the ice surface then the reverse trend will apply. In the event that both ice and stream bed have the same roughness the vertical velocity curve will be symetrical about the mid depth (Lau, 1982). Buchanan (1966) has recommended that the 0.2 and 0.8 depth method be used for effective depths of 0.75 m or greater and the 0.6 depth method was recomended for effective depth less than 0.75 m. The 0.2 and 0.8 depth method has been found to agree within 2% of the true mean velocity for most flows by Lau (1982) in carefully conducted flume measurements using floating covers of different roughness. Barrows and Horton (1907), using 352 vertical velocity curves under ice covers, also found that the 0.2 and 0.8 method agreed on average within 2% of the true mean velocity and that a correction of 0.92 had to be applied to the measurements at the 0.6 depth. When measurements were made at the 0.5 depth, Barrows and Horton found that the correction coefficient was 0.88. Lau (1982) found that this correction coefficient varied from 0.83 to 0.93 with the value of the coefficient increasing as the roughness of the ice cover decreased. The average value of 0.88 agrees with the value found by Barrows and Horton (1907). The Water Survey of Canada uses the 0.2 and 0.8 depth method and the 0.88 correction factor for the velocity at the 0.5 depth as the standard for its flow measurement programs.

2.3 Ice Cover Conditions

Channel ice covers can have many configurations, as shown in Figure 3 (Gerard, 1980). The most familiar ice cover is solid and continuous, with an under surface that is generally smoother than the channel boundary. At the other extreme, an ice cover can be a continuous accumulatiion of ice "fragments", such as those that form during freeze - up. Such ice covers are usually rougher than the channel boundary and their thickness is governed by the drag of the flow on them.

The problem of flow measurement under ice covers is often complicated by the formation of frazil - slush when conditions are right for its formation. The frazil is swept by the current under the ice cover and transported along the underside. The frazil crystals and clusters that are suspended in the turbulent flow will also add to the ice transported along the underside of the ice cover as they agglomerate and float up to the ice cover. Deposition of the frazil ice begins at the leading edge of the ice cover because it is near the source of the transported ice supply. The deposition to the underside of the leading edge continues until the local flow velocity is increased to the critical value at which further deposition ceases to occur at the leading edge. The accumulated ice at the leading edge creates a flow separation and additional frazil ice is deposited in the resultant wake because velocities in this region are below the critical value. This process causes the gradual displacement of the wake and thus the growth of the frazil accumulation in the down stream direction (Tsang, 1982).

The presence of the frazil slush under the ice cover complicates the measurement of stream flow. The boundary of the slush with the free flow is quite irregular and therefore the true depth of the free flow cannot be measured very accurately. In addition it is not known what percent of the total flow passes through the slush layer. In many rivers in Canada, the percentage of the cross - sectional area occupied by frazil slush can be substantial, as shown in Figure 4. However, flow measurements account only for the free - flowing component of the total flow and therefore the true discharge is not known. At the present time the only recourse to the problems of slush accumulation is careful selection of flow measuring sites.

2.4 Sources of Error in the Discharge Measurements

Uncertainties in the flow measurements may be introduced by measurement instrumentation, the method of measurement used and the properties of the river cross - section selected for the measurement. Each source contributing to the error in the total discharge must be considered in order to arrive at an effective program for the measurement of stream flows under solid ice covers. Dickenson (1967) and Pelletier (1988) have conducted extensive literature reviews on the errors in a single discharge measurement for flows with a free surface. The results of these reviews together with additional considerations for flows under solid ice covers are summarized in Table 1.

3.0 HYDRAULIC CONSIDERATIONS

3.1 Discharge Through the Cross - Section

The overall accuracy of stream flow measurements is governed to a large extent by the physical and hydraulic characteristics of the river reach in which the measuring cross - section is located. In selecting a suitable river reach, it is important to consider the basic variables which influence the total flow. In a natural channel, particularly under ice conditions, the cross - sectional shape and the boundary roughness are irregular and the flow through the measuring reach is three dimensional. Therefore, for the purpose of selecting measuring sites, the variables governing the three dimensional flow, excluding the presence of frazil ice, can be expressed in the following functional form:

$$f \left[Q,\ B,\ d,\ k_{sb},\ k_{st},\ S,\ \rho,\ \nu,\ \gamma_s \right] = 0 \qquad (1)$$

where Q = the mean daily historical winter discharge passing through the measuring reach, B = the top width of the flow at the measuring section, d = the effective depth defined as the area A of the flow cross - section divided by the top width B, k_{sb} = equivalent grain size roughness of the channel bed, k_{st} = equivalent grain size roughness of the underside of the ice cover, S = the bed slope of the measuring reach, ρ = the density of the water, ν = the kinematic viscosity of the water, γ_s = the specific submerged weight of the bed material and f denotes a function. The bed slope is used in equation (1) because, when considering a short river reach, the flow may be considered to be approximately uniform and therefore, the water surface slope may be taken to be approximately equal to the bed slope.

The nine variables in equation (1) completely define the flow passing through the measuring reach. Such a large number of variables makes it very difficult to set up useful criteria for the selection of measuring sites. Dimensional analysis, using the Buckingham Pi Theorem can be used to organize the nine parameters in equation (1) into six dimensionless groupings from which the most significant can be selected. Following this procedure, equation (1) can be reduced to the following, more efficient dimensionless form:

$$f_1 \left[\frac{\rho Q^2}{\gamma_s d^5}, S, \frac{k_{sb}}{d}, \frac{B}{d}, \frac{k_{st}}{k_{sb}}, \frac{Q}{\nu d} \right] = 0 \qquad (2)$$

where f_1 denotes another function. For the conditions being considered, the flows are always fully rough turbulent and therefore the parameter $Q/\nu d$ can be omitted from further considerations. Solving equation (2) for $\rho Q_2/\gamma_s d^5$, one now obtains the following relationship:

$$\frac{\rho Q^2}{\gamma_s d^5} = f_2 \left[\frac{k_{sb}}{d}, \frac{B}{d}, S, \frac{k_{st}}{k_{sb}} \right] \qquad (3)$$

where f_2 denotes another function.

The dimensionless independent variables in equation (3) uniquely specify the discharge for a uniform flow passing through the measurement cross-section shown schematically in Figure 5. Therefore, these variables should be considered as a basic guide for the development of an experimental flow measurement program. The parameter k_{st}/k_{sb} represents the relative roughness of the wet ice surface with respect to the river bed and affects the vertical velocity profiles, k_{sb}/d represents the relative roughness of the bed with respect to the effective depth and B/d represents the width to depth ratio of the measuring reach.

3.2 Vertical Velocity Distributions

The accuracy of the discharge measurement depends on how well the vertical velocity distribution is defined. It is customary to determine the average velocity in the vertical by making measurement at specified points such as the 0.2 and 0.8 depth when flow depth are greater than 0.75 m and the 0.5 depth when depths are less than 0.75m. The 0.2 and 0.8 depth measurement method is customary for flows with a free surface. However, investigations by Barrows and Horton (1907), confirmed by Lau (1982), have shown that the 0.2 and 0.8 depth method is also applicable to flow under floating ice covers. In order to develope effective criteria for selecting experimental flow measurement field sites it is important to determine if the 0.2 and 0.8 depth and the 0.5 depth methods give satisfactory results for different conditions. Data from Lau (1982), generated with a mathematical turbulence model, which has since been shown to give excellent agreement with carefully conducted experimental measurements (Krishnappan, 1984), are used here to examine the measurement criteria used by Water Survey of Canada.

3.2.1 The mean velocity

The mean velocity at a vertical in the cross - section can be expressed in terms of the pertinent independent variables by writing

$$U = \Phi \left[h,\ U_*,\ k_{sb},\ k_{st},\ \rho,\ \nu \right] \tag{4}$$

where U = the mean velocity in the vertical, U_* = the shear velocity, h = the flow depth at a given vertical and Φ denotes a function. Dimensional analysis and considerations similar to those applied to equation (1) results in

$$\frac{U}{U_*} = \Phi_1 \left[\frac{h}{k_{sb}},\ \frac{k_{st}}{k_{sb}} \right] \tag{5}$$

where Φ_1 denotes a function.

3.2.2 The 0.2 and 0.8 depth method

When the flow depth is greater than 0.75 m, the 0.2 and 0.8 depth method is used to obtain the average velocity in the vertical. The average velocity is computed as

$$U_c = \frac{U_{0.2} + U_{0.8}}{2} \tag{6}$$

where U_c is the computed average velocity. The average velocity U_c can be expressed in dimensionless form as a function of the same independent variables given in equation (5). This is given as

$$\frac{U_c}{U} = \Phi_2 \left[\frac{h}{k_{sb}} , \frac{kst}{k_{sb}} \right] \qquad (7)$$

where Φ_2 denotes a function.

Values of U_c /U are plotted as a function of h/k_{sb} with k_{st}/k_{sb} as a parameter in Figure 6. The plot shows that U_c/U is independent of h/k_{sb} for values of $h/k_{sb} > 10$ when $k_{st}/k_{sb} > 0.5$. being about 1% greater than the true average velocity. As the ice cover becomes smoother, that is as k_{st}/k_{sb} decreases, values of U_c/U increase from 1.01 to 1.02 for values of h/k_{sb} in the range $10 < h/k_{sb} < 100$. This increase in U_c/U may be due to a small Reynolds number effect as a result of the increased smoothness of the ice cover. This Reynolds number effect will increase as the smoothness of the ice increases. However, it is encouraging to observe that values of U_c/U do not vary by more than about 2% over a hundred - fold change in relative ice cover roughness k_{st}/k_{sb}.

3.2.3 The mid depth velocity method

When the flow depth is less than 0.75 m, the velocity is measured at the 0.5 depth in the vertical. A coefficient of 0.88 is then used to adjust the measured value to obtain the average velocity in the vertical. In general 0.5 depth velocity must also be a function of h/k_{sb} and k_{st}/k_{sb}. This can be written as

$$\frac{U_{0.5}}{U} = \Phi_3 \left[\frac{h}{k_{sb}}, \frac{k_{st}}{k_{sb}} \right] \qquad (8)$$

where Φ_3 denotes a function. The dimensionlee midpoint velocity $U_{0.5}/U$ can be expressed as a velocity adjustment coefficient by writing

$$\frac{U}{U_{0.5}} = \Phi_4 \left[\frac{h}{k_{sb}}, \frac{k_{st}}{k_{sb}} \right] \qquad (9)$$

where Φ_4 denotes a function. Values of $U/U_{0.5}$ were plotted as a function of h/k_{sb} with k_{st}/k_{sb} as a parameter in Figure 7. The plot shows that $U/U_{0.5}$ has the lowest values and is most sensitive to changes in h/k_{sb} for the largest value of k_{st}/k_{sb}. This can be interpreted to mean that the effect of h/k_{sb} decreases as the ice cover becomes smoother for a given bed roughness k_{sb}. When $k_{st}/k_{sb} < 0.05$, $U/U_{0.5}$ is independent of h/k_{sb} for $h/k_{sb} > 100$. However, considering that the mid depth method of velocity measurement is restricted to flow depths less than 0.75 m, then the region of primary practical interest is that for values of $h/k_{sb} < 100$. In this region values of $U/U_{0.5}$ are strongly dependent on h/k_{sb} for values of k_{st}/k_{sb} as low as 0.05. For very smooth ice cover (ie: $k_{st}/k_{sb} = 0$), the change in $U/U_{0.5}$ with h/k_{sb} is small having an average value of 0.92 and varying by only about 0.8%. Over the full range of roughnesses tested, values of $U/U_{0.5}$ varied from about 0.83 to 0.93. The coefficient value of 0.88 used by the Water Survey of Canada is the middle of this range. Therefore, the use of this coefficient, depending on the condition of the ice cover, provides the average velocity in the vertical within an error margin of about 5%. This error could be reduced if some knowledge regarding the condition of the ice cover is available.

3.2.4 The point of maximum velocity

The point of maximum velocity, shown in Figure 8, is important information for many of the equations for ice cover roughness and can be written in dimensionless form as

$$\frac{Y_m}{h} = \Phi_5 \left[\frac{h}{k_{sb}}, \frac{k_{st}}{k_{sb}} \right] \qquad (10)$$

where Y_m = the point of maximum velocity with respect to the bed and Φ_5 denotes a function. Values of Y_m/h are plotted as a function of h/k_{sb} with k_{st}/k_{sb} as a parameter in Figure 9. The plot shows that Y_m/h is independent of the relative depth for values of h/k_{sb} >100. For values of h/k_{sb} < 100 the dependence of Y_m/h on h/k_{sb} increases slightly as the roughness of the ice surface relative to the bed roughness given by k_{sb}/k_{sb} decreases. It can also be seen from Figure 9 that values of Y_m/h increase as the values of k_{st}/k_{sb} decrease (ie: the ice becomes smoother). This means that when the ice is smoother than the bed, the maximum velocity is closer to the ice. When the ice surface and the bed have the same roughness, the maximum velocity is exactly at mid depth. The position of the maximum velocity can be easily obtained during a conventional flow measurement at selected verticals. The information can then be used to determine the characteristics of the ice cover. This in turn will be helpful in selecting a suitable correction coefficient when flow measurements are made using the 0.5 depth method.

4.0 EXPERIMENTAL FIELD PROGRAM

In order to be successful, the field flow measuring program must be designed so that all the data required to examine the present measurement standards used by the Water Survey of Canada as well as improve present methods are obtained. The information contained in Table 1 and the hydraulic considerations examined in the previous section are used toward this end.

4.1 Site Selection

The independent dimensionless variables governing the hydraulics of the total average flow are k_{sb}/d, B/d, S and k_{st}/k_{sb}. Of these variables the least defineable is k_{st}/k_{sb} because ice conditions vary from year to year and are not known apriori. However, it has been shown, that for a floating continuous ice cover, the effect of k_{st}/k_{sb} on the average velocity obtained with the 0.2 - 0.8 depth method was small. In addition, the correction coefficient for the mean velocity obtained with the 0.5 depth method, varied about the normally used method of 0.88 by no more than 5% depending on the value of h/k_{sb}. Therefore, k_{st}/k_{sb} need not be a primary variable for choosing measurement sites. The slope of the stream essentially drives the flow, however, for the purpose of flow measurement it will not have a significant impact. Therefore, the slope need also not be a primary factor in the selection of flow measuring sites. As a result, flow measuring sites should be selected based on the two variables k_{sb}/d and B/d.

4.1.1 The k_{sb}/d parameter

Investigations by Kemphuis (1974), Engel (1983) and Van Rijn (1985) have shown that for a rigid bed, $k_{sb} = nD_m$, where D_m is the particle diameter so that m % of the particles in the total grain size distribution are smaller than D_m and n is a coefficient which depends on the choice of m. For the purpose of flow resistance the value of m should be 65 (Krishnappan, 1983). When the bed is mobile, it is deformed into sand waves, the properties of which depend on the bed material and the flow conditions. In this case k_{sb} becomes primarily a function of the geometry of the sand waves (Yalin, 1977).

It is clear that k_{sb}/d is easier to determine for a rigid bed than for a mobile bed. However, even for a rigid bed it would take considerable effort to determine an average value of D_m for a flow measuring reach. For a mobile bed, because the bed form geometry varies with the flow conditions, any attempt at determining k_{sb}/d is impractical for the purpose of flow measuring reach selection.

In view of these practical difficulties, it is suggested to define the effect of k_{sb}/d in a more qualitative way. The bed roughness can be accounted for by designating streams in three general categories: a) sand bed streams, b) gravel bed streams, and c) cobble and boulder streams. In each of these three categories, effective flow depths d based on the historical mean daily winter discharge in suitable depth ranges can be considered. Combinations of the roughness designations and the effective depths will ensure that representative measuring sites are selected. The required information can be obtained from available records.

4.1.2 The B/d parameter

Values of B/d vary over a wide range. Examination of river data collected by Barnes (1967) shows that B/d varies from values of about 5 to values greater than 100 for flood flows. Similar values can be expected for the winter flows. These data show that for rivers having nearly the same value of B/d, values of the effective depth are substantially different. Therefore care should be taken that a sufficiently wide range of B/d is selected. The required information can be obtained from existing records.

4.2 Velocity Measurements

In order to determine the quality of velocity measurements for different conditions it is necessary to obtain complete vertical velocity distributions at all the verticals in a cross - section, including the point of maximum velocity. Analysis of the velocity profiles will make it possible to verify the 0.2 - 0.8 depth and the 0.5 depth methods as well as relate the shapes of the velocity profiles to the variables h/k_{sb} and k_{st}/k_{sb}. The values of k_{st}/k_{sb} for a given set of velocity profiles at a given river cross - section can be determined with the turbulence model used by Lau (1982). This will make it possible to relate the values of the correction coefficient for the 0.5 depth method to the actual ice conditions. It is expected that in this way more accurate adjustments can be made to the measured velocity to obtain a value closer to the true value.

4.3 Flow Pulsations

Large scale velocity pulsations are determined by the dimensions and geometry of the stream bed upstream of the flow measuring section (Dickenson, 1967). The existence of these pulsations presents a problem of sampling velocity in time. The order of magnitude of the period of these large scale pulsations must be taken into account in determining the optimum duration of the sampling time in order to obtain a representative mean point velocity. Extensive review of the literature by Dickenson (1967), has shown that the velocity pulsations tend to be greatest near the flow boundary. In rivers with a free surface the pulsations were greatest near the bed. When rivers have an ice cover, pulsations can be expected to be greatest near the ice surface and the bed. It is quite probable that the relative intensity of the pulsatins at the ice surface and the bed depends on the ratio k_{st}/k_{sb}. If that is true, then one would expect that if the ice cover is less rough than the stream bed, the velocity pulsations near the ice surface are less than near the bed. Alternately, if the ice cover is rougher than the bed, the pulsations near the ice surface would be greater.

Knowledge of the relative roughness of the ice cover is usually not available in advance of a flow measurement. As a result, it is difficult to assign exposure times for point velocity measurements for a particular stream cross - section. However, information summarized by Dickenson (1967) given in Table 2 provides some indication of the exposure times required. It is clear from this information that the flow measurements, which are to be used to examine present metering methods, will be quite time consuming.

In order to determine exposure times which are suitable to a particular measuring cross - section, current meters should be placed at the 0.2 and 0.8 depth and the depth of maximum velocity Y_m/h to obtain continuous velocity records to determine the extent and periodicity of velocity pulsations in the flow. The velocity sampling times in each case should be taken as being the average period of the pulsations recorded continuously for no less than 0.5 hours. Considering that the pulsations decrease with distance from the boundary, then the determined sampling times at the 0.2 and 0.8 depth and Y_m/h can be used to obtain estimates of the sampling times at the other measurement positions of the vertical profile by linear interpolation as shown in Figure 10.

The effect of velocity pulsation must be one of the first items to be investigated to ensure that velocity measurements and consequently the discharge determinations are sufficiently accurate for development of a data base for the determination of measuring standards. Tests should be conducted to determine if the method embodied by Figure 10 is a realistic criterion for the establishment of sufficiently long sampling times to obtain data for vertical velocity profiles.

4.4 Lateral Measurement Density

Considerable work has been conducted for free surface flow conditions to determine the number of verticals required for a discharge measurement of a given accuracy (Carter and Anderson, 1963; Dickenson, 1967; Pelletier, 1988). These studies have shown that for standard discharge measurements, twenty to twenty - five verticals, depending on the geometry of the cross - section, provided sufficient accuracy. However, little is known on the effect of measurement density across the channel width for streams with continuous ice cover. It is expected that the additional variability introduced by the roughness of the ice cover may have to be taken into account by using a larger number of measuring verticals than is used for free surface flows. In order to provide the proper data base to investigate the measurement density requirement, the measurement program must include provisions to make discharge measurements at some representative field sites using as many as 40 verticals. This will make it possible to examine the rate of change in measurement accuracy as a function of the number of verticals used, by using the measurement with the maximum verticals as the reference.

4.5 Current Meter Assemblies

All velocity measurements should be made with the equipment approved by the Committee for Measurement of Flow Under Ice (CMFUI). Care should be taken that each current meter has been properly calibrated with the same weight suspension with which it is used. It is important that all cold weather procedures such as warming the meter and maintenance procedures be conducted in accordance with standards approved by the CMFUI. Once approved, all procedures must be carefully repeated each time a new discharge measurement is made.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This study has examined the basic requirements for the establishment of an experimental program to develop a data base which can be used to examine present measurement methods used by the Water Survey of Canada. Careful considerations should be given to the following conclusions and recommendations.

5.1 Conclusions

5.1.1 Analysis of available information from the literature indicates that the relative roughness of the ice cover to the bed roughness, represented by the variable k_{st}/k_{sb}, may be only of secondary importance. However, these results are based on flume experiments amd mathematical models. The results need to be verified with carefully obtained field data.

5.1.2 Results from flume measurements and mathematical models have shown that average velocities obtained with the 0.2 and 0.8 depth method yield results within 2% of the mean velocity.

These results also show that the correction coefficient of 0.88 used with the 0.5 depth method should give the true mean velocity with an accuracy better than 5%. This needs to be confirmed with the data from the measurement program.

5.2 Recommendations

5.2.1 Measuring cross - sections should be located in relatively straight river reaches and should have continuous ice cover with no frazil slush depositions under the ice cover. A variety of different types of cross - sections based on the variables k_{sb}/d and B/d with respect to historical mean daily winter flows should be selected. This will ensure that data from rivers of different sizes and bed roughness will be included in the data base.

5.2.2 During a discharge measurement the roughness of the ice cover is not known. It is suggested that ice cover conditions be documented when flow measurements are made at the experimental sites. Values of the relative ice cover roughness can be obtained by applying the turbulence model used by Lau (1982) to measured velocity profiles to determine values of k_{st}/k_{sb}. These values can then be related with the documentation of the ice cover at the measuring site. This type of information will help in choosing a velocity correction coefficient for the 0.5 depth method based on information available at the time of the discharge measurement.

5.2.3 Pulsations in the flow velocity can significantly contribute to the error in the discharge measurement. At each experimental measuring site the average period of the pusation obtained at the 0.2 and 0.8 depth at one vertical, should be used to determine the sampling times for measuring the velocity profiles.

5.2.4 Considerations should be given to using 40 verticals at the experimental measuring stations to provide sufficiently reliable reference discharge measurements for development of a measurement strategy.

5.2.5 All experimental flow measurements should be conducted in accordance with standards and equipment approved by the Committee for the Measurement of Flow Under Ice.

ACKNOWLEDGEMENT

The author is grateful to K. Wiebe, M. Spitzer, M. Murray and I. McLaurin for their valuable comments and discussions.

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TABLE 1. SOURCES OF ERRORS FOR DISCHARGE MEASUREMENTS IN RIVER REACHES WITH SOLID ICE COVER

Source of Error	Error Type	Contributing Factors
Current meter	R	Precision of calibration equipment, presence of frazil ice and air temperature
Properties of	S	Sediment concentration, Frazil Fluid concentration
Boundary Effects	S	Meter characteristics, depth, relative roughness of ice cover and stream bed, velocity distribution
Oblique Currents	S	Meter characteristics, angle of alignment
Micro - Turbulence	S	Meter characteristics, turbulence intensity
Vertical Velocity Distribution	S	Difference between true and assumed distribution
Vertical Sampling	R	Placement of meter at correct depth
Horizontal Velocity Distribution	R	The number of verticals used
Pulsations in the Flow Regieme	R	Distribution of point velocities in time, position and bed and ice cover roughness.
Measurement of Depth	R	Instruments and technique bed and ice cover roughness
Measurement of Width	R	Measuring technique
Depth Distribution in the horizontal	R	Difference between true and assumed bed configuration

R - denotes random errors
S - denotes systematic errors

TABLE 2. METET EXPOSURE TIME REQUIRED TO OBTAIN A PRESCRIBED ACCURACY FOR A POINT VELOCITY MEASUREMENT (from Dickenson, 1967)

Author	Exposure Time in Minutes for 2% Accuracy Surface	0.2h	0.6h	0.8h	Bottom
Sokolov (1909) Shafalovich (1909) on Zee River in open water *	--	2.0	--	8.0	--
Bliznyak and Ziring (1911) on Yenisey River in open water *	--	1.0	--	2.0	--
Moyseyenko (1911) on Chusova River in open water	--	2.5	--	5.6	--
on Sylva River in open water *	--	2.5	--	9.0	--
Kolupaila (1914 - 1916) on Western Dirna River in open water	1.5	1.5	2.0	4.0	7.0
Ice Conditions *	3.0	1.5	1.5	2.0	5.0
Sokolnikov (1932) on Neva River in open water *	1.5	2.0	4.0	--	6.0
Dement'ev (1962) Mountain Streams					
mid - stream	1.5	1.5	3.0	5.0	10.0
bank - side	2.0	3.0	6.0	10.0	> 10
Large Plains Rivers					
at low water	1.0	1.0	1.0	2.0	3.0
at high water	1.5	1.5	2.0	3.0	4.0

* References taken from Dement'ev (1962)

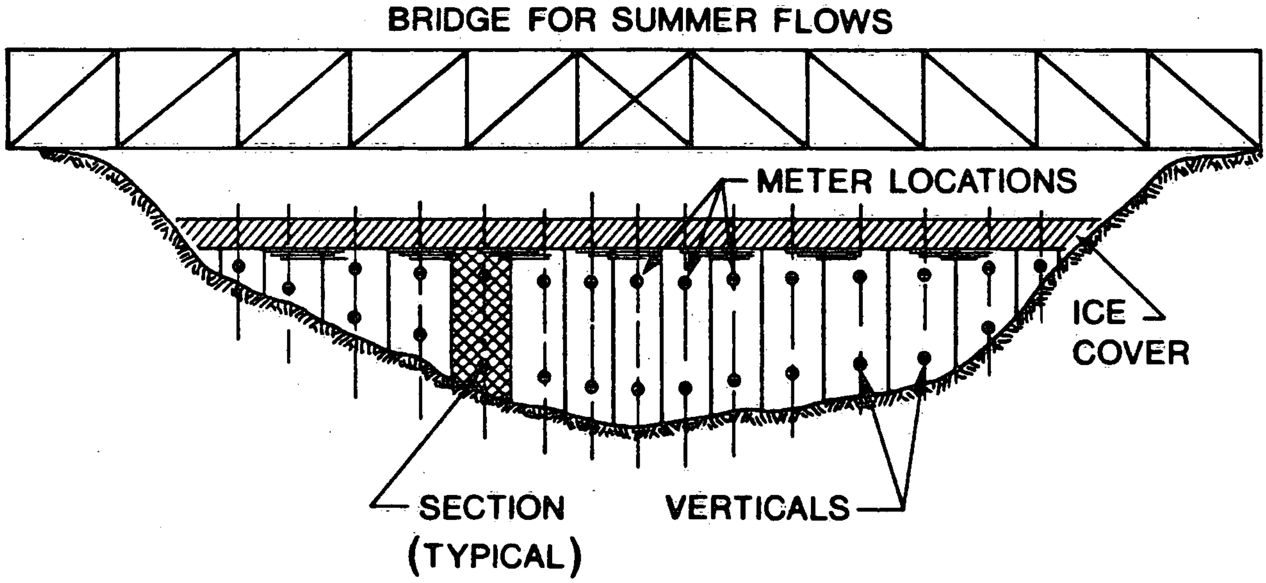
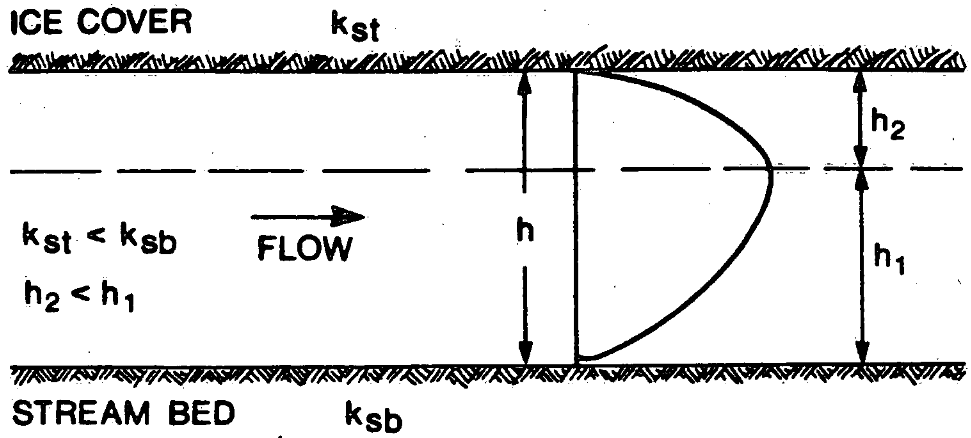
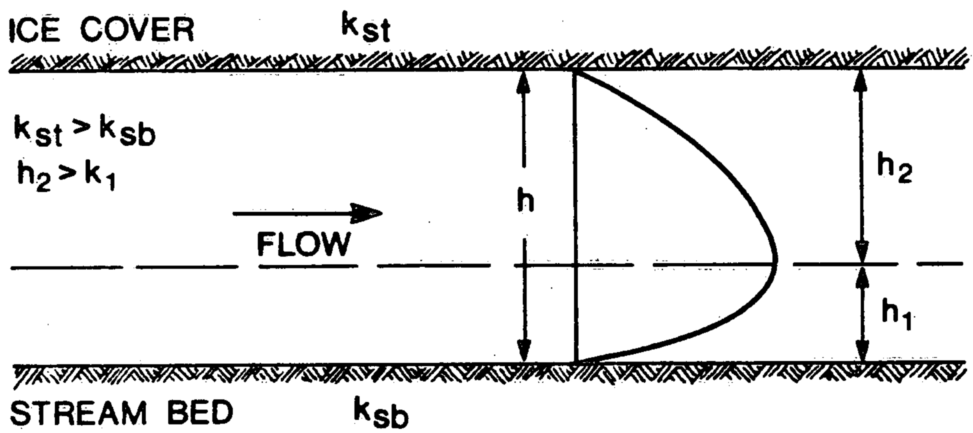


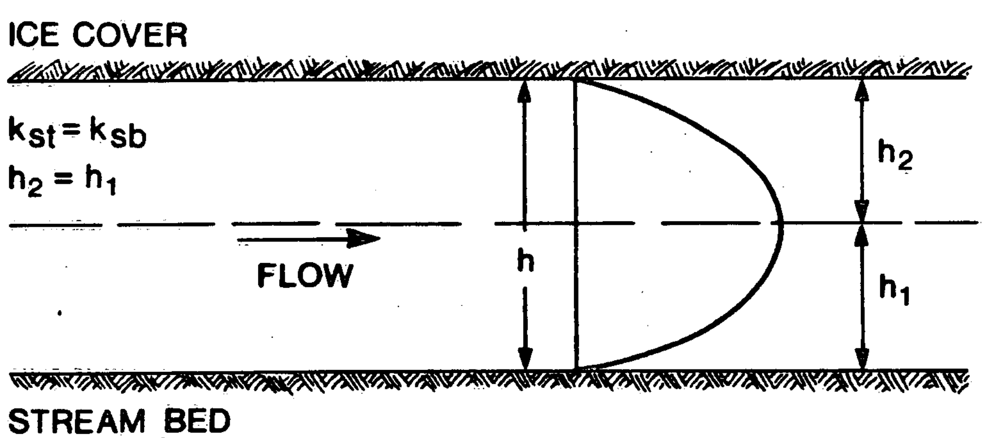
FIGURE 1. LOCATION OF VERTICALS IN MEASUREMENT CROSS-SECTION (LAMBIE, 1978)



(a) ICE COVER SMOOTHER THAN STREAM BED



(b) ICE COVER ROUGHER THAN STREAM BED



(c) ICE COVER AND STREAM BED HAVE SAME ROUGHNESS

FIGURE 2. EFFECT OF ICE COVER ON VELOCITY PROFILE

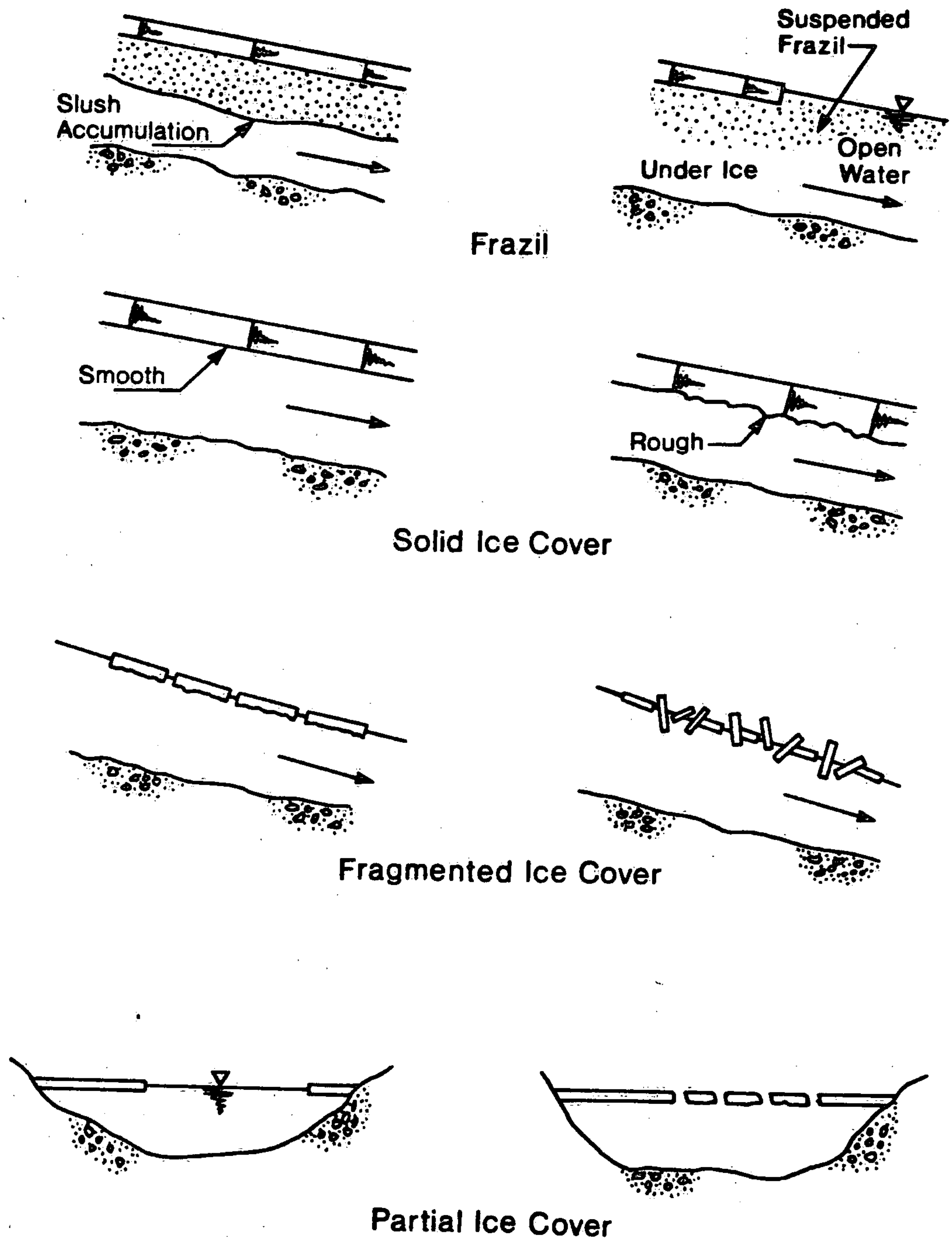
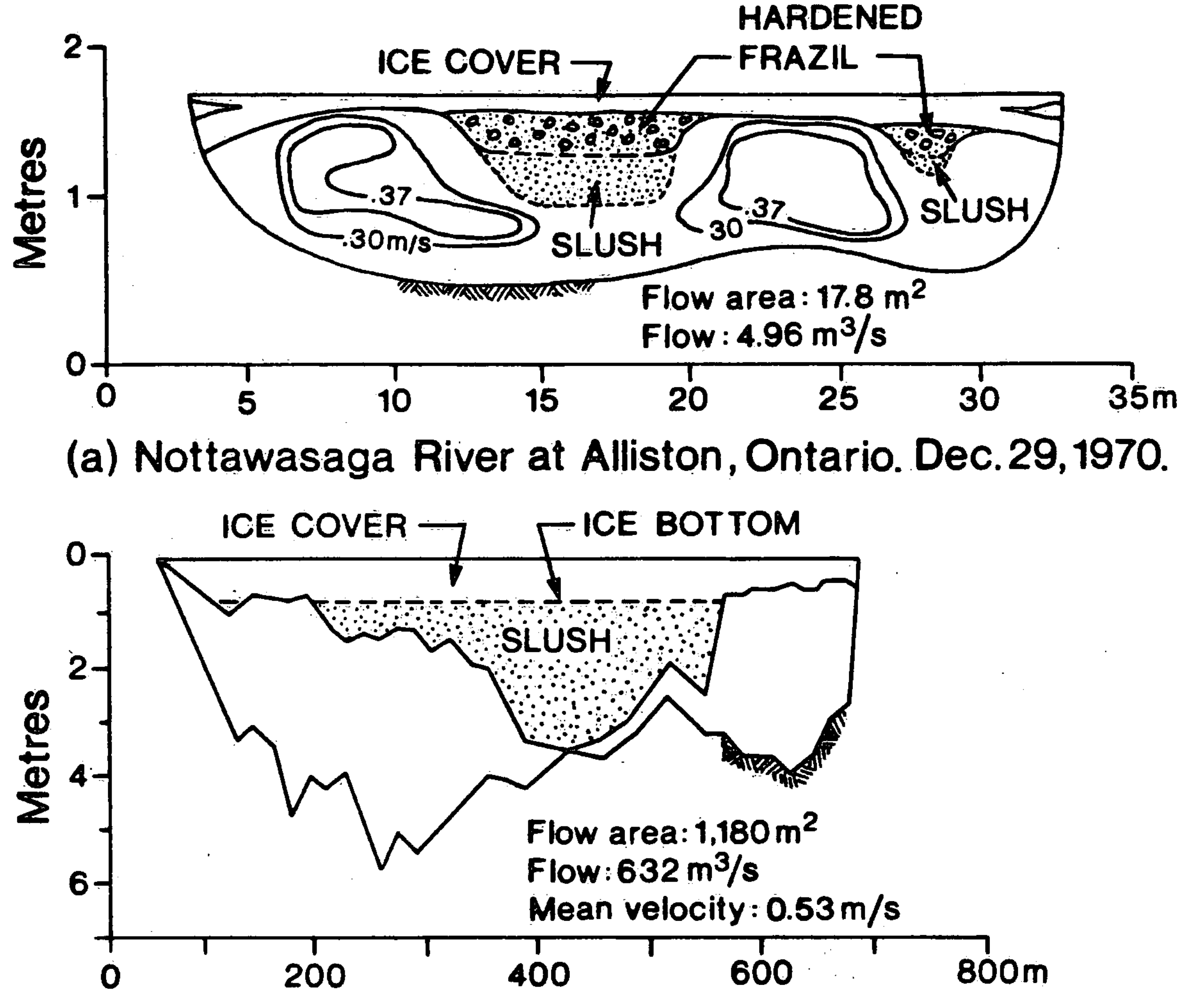


FIGURE 3. RIVER ICE CONDITIONS (Gerard, 1980)



(a) Nottawasaga River at Alliston, Ontario. Dec. 29, 1970.

(b) Peace River at Peace Point, Alberta, Dec. 12, 1966

FIGURE 4. FRAZIL SLUSH CONDITIONS IN RIVER CROSS-SECTIONS (TSANG, 1982)

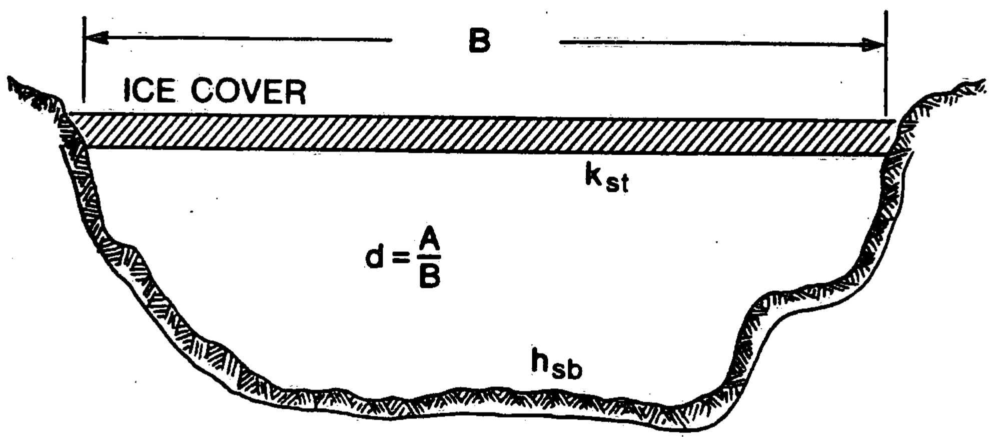


FIGURE 5. SCHEMATIC REPRESENTATION OF A THREE-DIMENSIONAL FLOW THROUGH A CROSS-SECTION

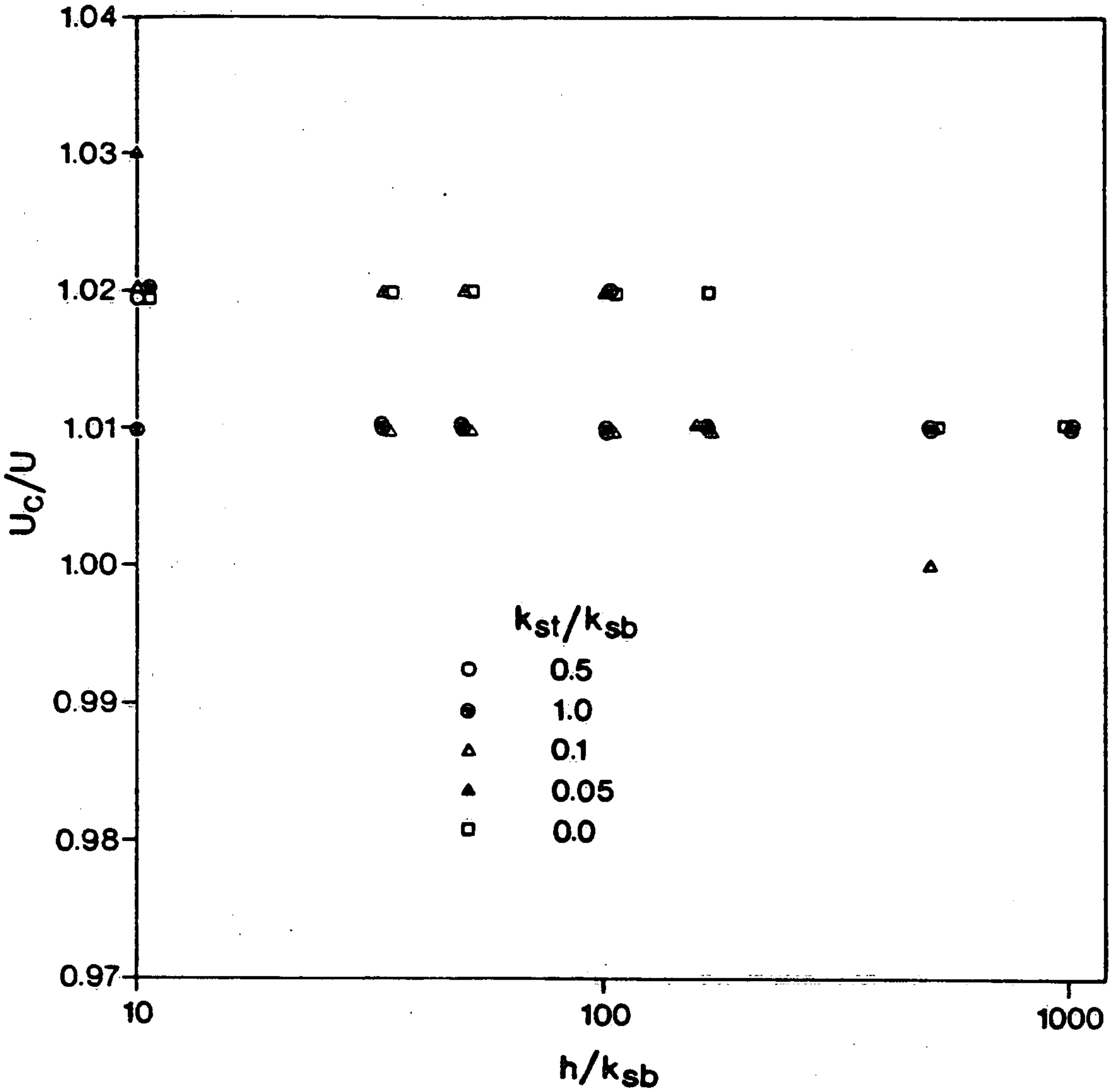


FIGURE 6. EFFECT OF h/k_{sb} AND k_{st}/k_{sb} ON U_c/U (DATA FROM LAU, 1982)

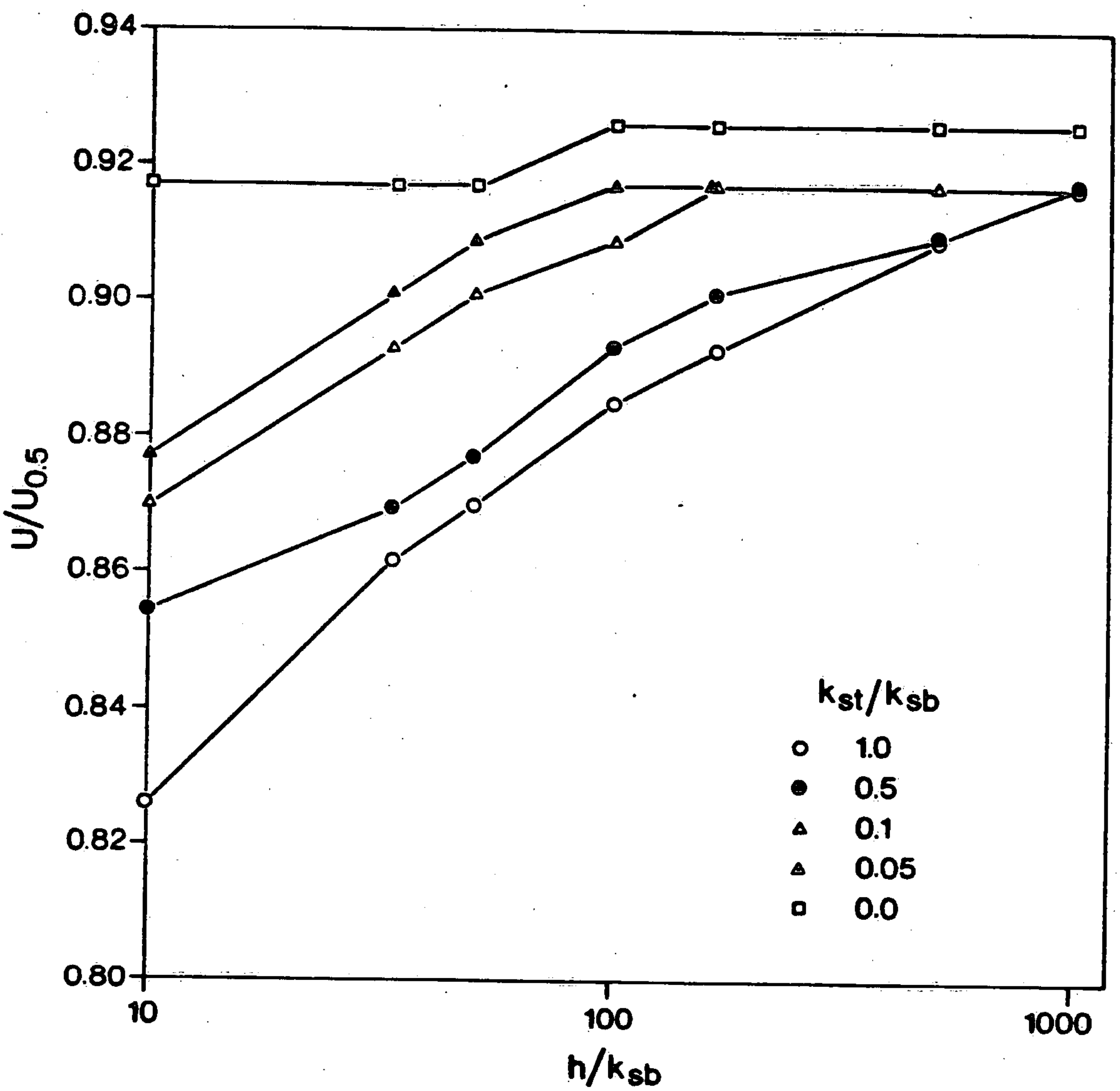


FIGURE 7. VELOCITY ADJUSTMENT COEFFICIENT $U/U_{0.5}$
(DATA FROM LAU, 1982)

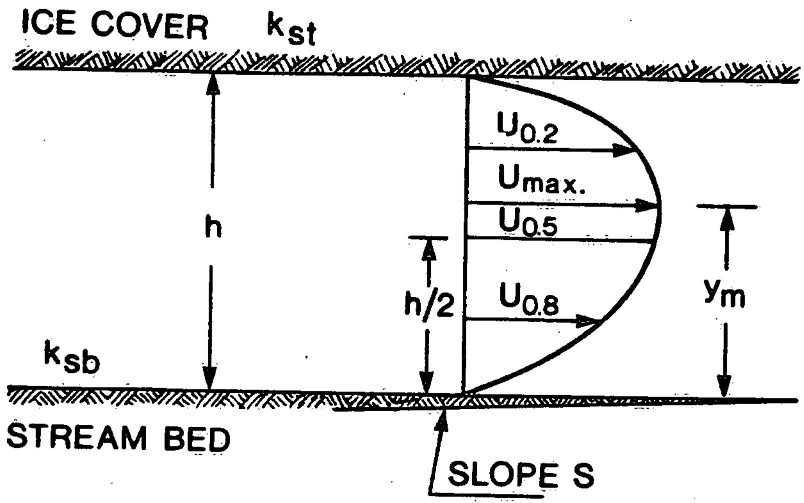


FIGURE 8. POINT OF MAXIMUM VELOCITY IN VERTICAL VELOCITY PROFILE

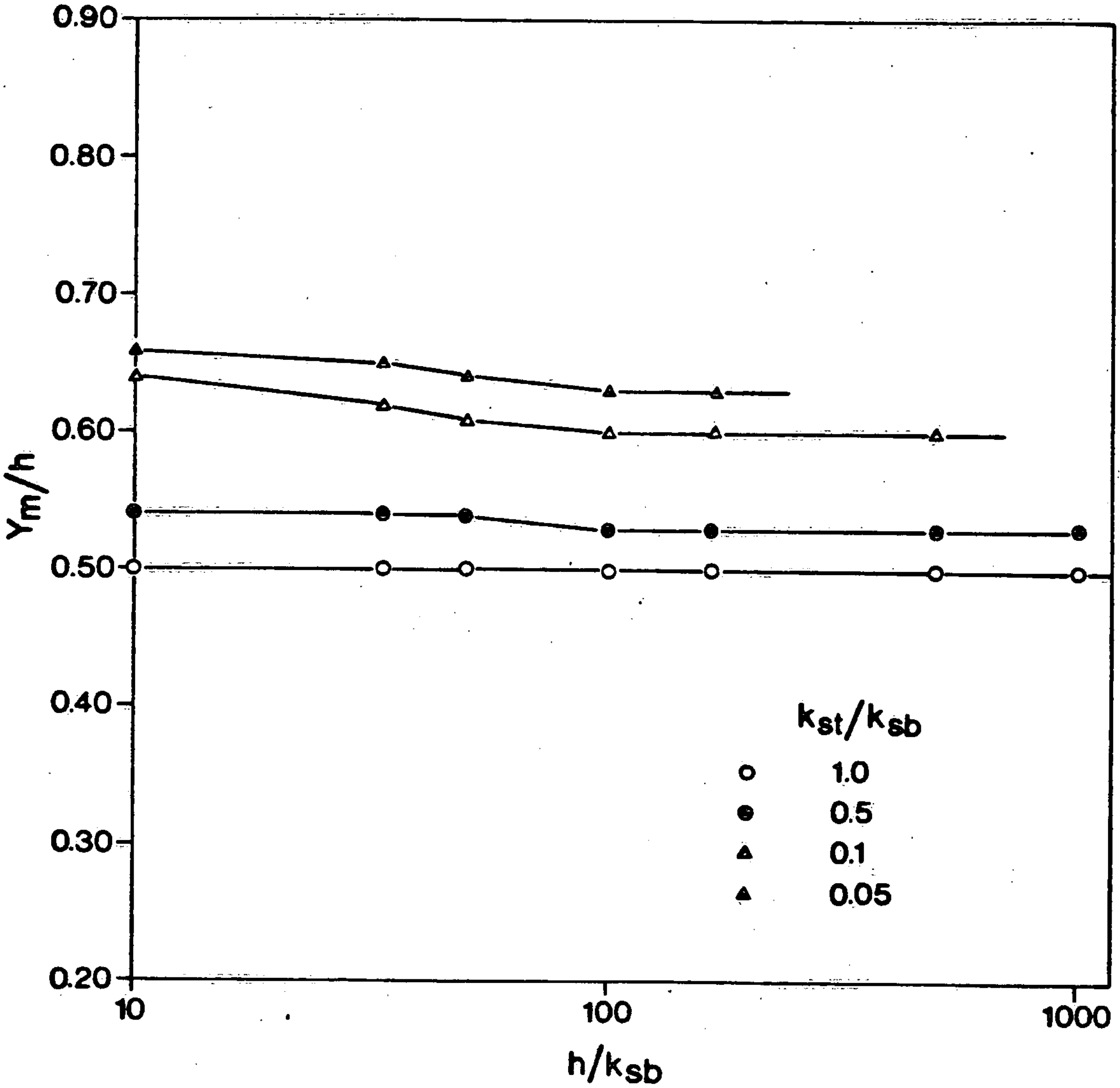


FIGURE 9. POSITION OF MAXIMUM VELOCITY (DATA FROM LAU, 1982)

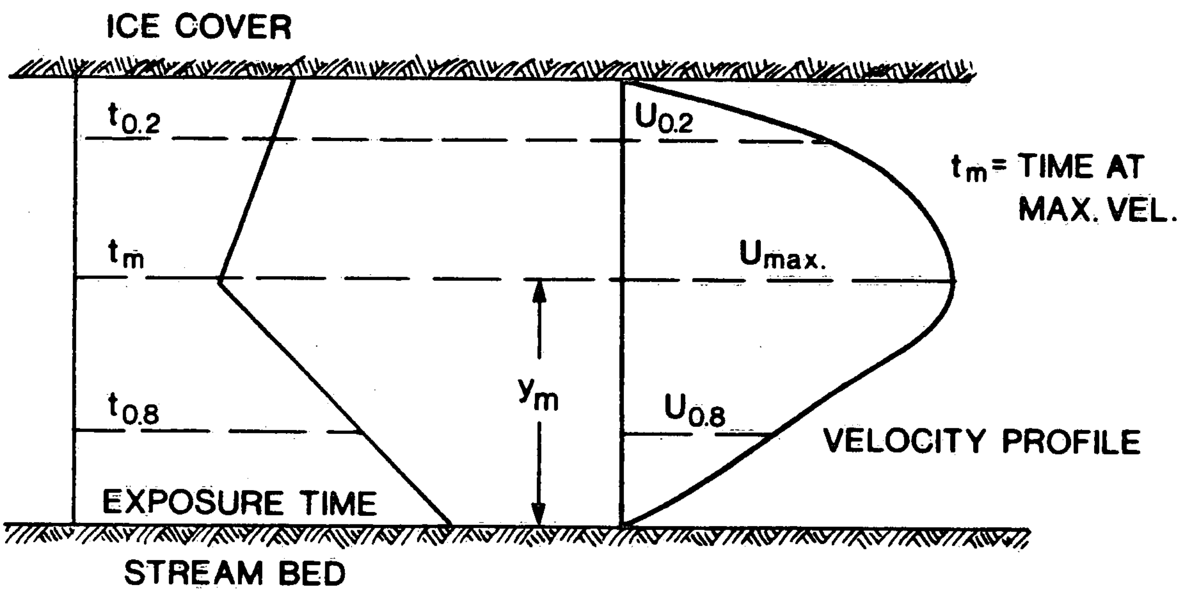


FIGURE 10. ANTICIPATED EXPOSURE TIME DISTRIBUTION FOR CURRENT METER DURING POINT VELOCITY MEASUREMENTS ON A VERTICAL VELOCITY PROFILE