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EFFECTS OF BED LEVEL FLUCTUATIONS ON DISCHARGE MEASUREMENT IN ALLUVIAL STREAMS

by

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MANAGEMENT PERSPECTIVE

The Milk River is an international river and its water is shared by Canada and the United States as dictated by the Boundary Waters Treaty. Satisfactory streamflow records at this site are presently difficult to obtain because of unstable stage-discharge relationships caused by shifting channel bed and migrating sand waves.

This report examines two alternative methods of obtaining discharge data. The first method consists of using a three dimensional submerged weir and the second method is an application of electro-magnetic principles. Results from model tests indicate that the weir may be affected by sediment deposition during flow recessions whereas the electro-magnetic method is unaffected by changes in the flow measurement cross-section. Further investigation is required before either method can be used with confidence in sand bed streams of widths greater than 25 metres.

The solution of the discharge measurement problems for the Milk River will be applicable to other sand bed rivers.

Dr. J. Lawrence
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PERSPECTIVE DE GESTION

La rivière Milk est une rivière internationale dont les eaux sont régies par le Canada et les États-Unis en vertu du traité sur les eaux frontalières. Il est difficile à l'heure actuelle d'obtenir des relevés satisfaisants du débit à cet endroit à cause de l'instabilité des courbes de débits jaugés attribuable au déplacement du lit du canal et des dunes de sable.

Nous examinons dans ce rapport deux nouvelles méthodes pour obtenir des données sur le débit. La première consiste à utiliser un déversoir noyé tridimensionnel; la seconde est une application des principes d'électromagnétique. Les résultats des essais avec modèle révèlent que le déversoir peut être perturbé par le dépôt des sédiments pendant les périodes de décrues tandis que la méthode électromagnétique n'est aucunement perturbée par les changements dans la section de mesure du débit. D'autres études devront être faites avant que l'on puisse utiliser l'une ou l'autre des méthodes avec confiance dans les cours d'eau à lit sableux de largeur supérieure à 25 m.

La solution des problèmes de mesure de débit dans la rivière Milk pourra s'appliquer aux autres cours d'eau à lit sableux.

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RÉSUMÉ

Des analyses théoriques et dimensionnelles ont été effectuées parallèlement à des essais sur des panaches recréés en laboratoire pour évaluer l'application de méthodes de mesure du débit total faisant appel à un déversoir tridimensionnel ou à des principes électromagnétiques dans les cours d'eau à lit sableux. Les résultats obtenus avec le déversoir révèlent que, pour des débits dominants inférieurs à 20 m^3/s, le dépôt des sédiments à l'entrée du canal peut créer des situations pour lesquelles le coefficient de débit n'a pas été vérifié expérimentalement. Pour ces débits, il se pourrait que la hauteur effective du déversoir au-dessus de l'approche du canal ne soit pas assez élevée et entraîne une variation suffisante du coefficient de débit pour rendre la courbe des débits jaugés instable. D'autres essais sont prévus afin d'étudier le coefficient de débits dans ces conditions. Les résultats obtenus avec la méthode électromagnétique révèlent que le rapport entre le débit et le produit du voltage et de la profondeur de l'eau n'est pas perturbé par les changements dans la section de mesure. Cette méthode semble donc prometteuse pour une application dans les cours d'eau dont la géométrie de section change continuellement par suite du décapage et du dépôt des sédiments.

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ABSTRACT

Theoretical and dimensional analysis together with tests conducted in laboratory flumes were used to examine a submerged three dimensional weir and the electromagnetic total flow measuring method for application to sand bed streams. The results for the weir show that, for the dominant discharges of less than 20 m^3/s, sediment depositon in the approach channel may create situations for which the discharge coefficient has not been experimentally verified. For such flows the effective weir height above the bed of the approach channel may be small enough to cause the discharge coefficient to vary sufficiently and render the head-discharge relationship unstable. Further tests are planned to examine the discharge coefficient under such conditions. Results with the electromagnetic method show that the relationship between discharge and the product of voltage and water depth is not affected by changes in the measuring cross-section. Therefore this method shows promise for application in streams where the geometry of the cross-section is always changing as a result of scour and deposition of sediment.

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INTRODUCTION

Sand bed streams often present a problem in determining their discharge at a gauging station because they are subject to changes in bed roughness and bed elevation due to scour and deposition. As a result, stage-discharge relationships are often poorly defined and corrections based on frequent water discharge measurement must be applied. The Milk River at Eastern Crossing, Montana (Figure 1) is an example of such a stream. The waters of the Milk River are shared by Canada and the United States in accordance with the Boundary Waters Treaty of 1919 and a 1921 Order of the International Joint Commission. Satisfactory apportioning of the water requires that reliable discharge records are obtained at the Eastern Crossing gauge. During the irrigation season, April to October, flows in the Milk River are supplemented by diversions from the St. Mary River system in the order of 15 to 22 m^3/s. The typical hydrograph at Eastern Crossing is depicted in Figure 2. This diversion gives the hydrograph a plateau-like appearance for a five to six-month period with possibly some added peaks due to rain storm and snow melt events. Once the diversion is shut off, the flows at Eastern Crossing quickly recede to base flow levels of 1 to 3 m^3/s. The river width during the normal summer flow is approximately 50 metres with a mean depth in the order of 0.5 to 0.7 metres.

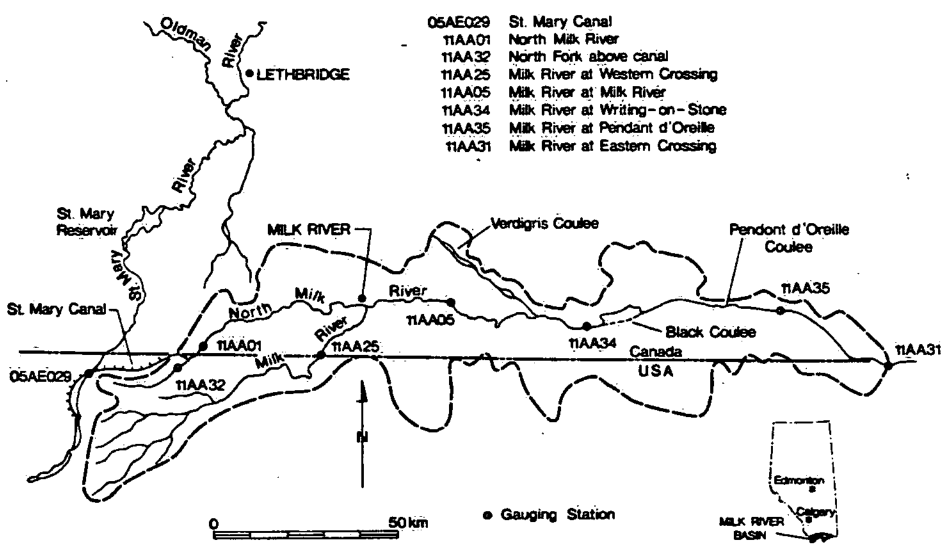

FIGURE 1. Milk River basin

Various methods to improve the measurement of discharge on the Milk River have been examined by Engel, Lau and Dick (1986) and Engel (1988). Requirements of good sensitivity at low flows, stability over the full

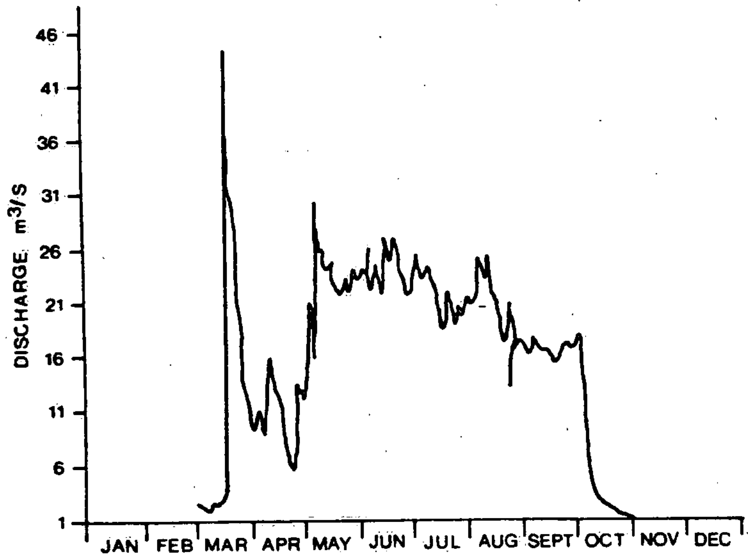

Figure 2. TYPICAL HYDROGRAPH FOR MILK RIVER AT EASTERN CROSSING

flow range as well as good sediment and debris passing capability, indicate that a Flat-Vee (FV) weir as given by White (1970) and Bos (1976) would be suitable. However, there is some uncertainty regarding changes in bed level in the approach channel on the performance of the weir. The weir crest must be located above the channel bed by some minimum height at all flows and be free of sediment in order for the coefficient of discharge to be stable. The FV weir has been found to operate satisfactorily in the range $0.4 < P/H_b < 7$ (P and H_b are defined in Figure 3, (White, 1971).

A second method that appears to be promising for application to sand bed streams is the electro-magnetic (EM) method. This method is a direct application of Faraday's Law of Induction. The mean discharge is determined from measurements of the voltage between electrodes placed at the edges of the flow and elevation of the water surface in the plane of the electrodes. Hershey (1978) and Newman (1982) among others have claimed that this method is unaffected by silt or gravel deposition in the measuring section. If this claim can be confirmed experimentally, then the EM method could be an attractive option for use in small sand bed rivers.

The variability in stream bed elevation and its affect on the performance of the FV weir and the EM method is the subject of this paper. This investigation is part of a study to determine a suitable method to obtain reliable discharge records for the Milk River at Eastern Crossing.

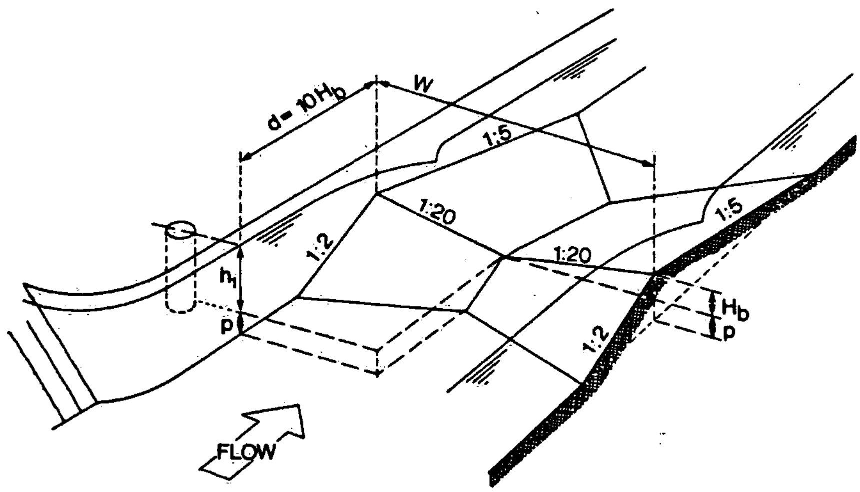

FIGURE 3 Triangular profile flat-V weir.

EFFECT ON FV WEIR

The primary concern regarding the weir is the deposition of sediment in the approach channel. It is necessary to determine if the conditions under which the FV weir is known to operate successfully can be realized in an alluvial channel bed composed of fine sand and to quantify the variability of P/H_b in terms of the discharge passing the weir and the grain size of the sediment. Using dimensional analysis it can be shown that P/H_b can be expresed as

$$[1] \quad P/H_b = \phi_1(h_1/H_b,\ d/H_b, W/H_b,\ D_{50}/H_b,\ \gamma_s D_{50}^3/\rho\nu^2)$$

where ϕ denotes a function, h_1 = the measured head on the weir, W = the width of the approach channel, d = the length of reach of the approach channel measured from the weir for which the average bed level is determined, ρ = the density of water, ν = the kinematic viscosity of water, D_{50} = the median diameter of the sand and γ_s = the submerged specific weight of the sand. The variables are shown schematically in Figure 3. For a given weir installation W/H_b is constant and if d/H_b is also kept constant, then both W/H_b and d/H_b may be dropped from equation (1). If one now writes $D_* = \gamma_s D_{50}^3/\rho\nu^2$, then equation (1) becomes

$$[2] \quad P/H_b = \phi_2(h_1/H_b, D_{50}/H_b,\ D_*)$$

If the fluid properties and specific gravity of the sediment are kept constant, then each grain size represents a constant value of D_*. By keeping D_* constant, the effect of h_1/H_b and D_{50}/H_b can be revealed. The difficulty with solving equation (2) with a physical model is that one cannot get a 1:1 correspondence between the model and the prototype values of D_{50}/H_b, because prototype values of D_{50} are of the order of 0.1 mm to 0.2 mm and therefore values of D_{50} in the model will be too small (Engel, Lau and Dick, 1986). Unfortunately this problem cannot be resolved with a distorted model and therefore, values of P/H_b obtained from laboratory measurements must be scaled up with the aid of theoretical methods.

The average height of the weir P for a given discharge is the distance between the weir crest and the level of the bed for which the sediment particles are just at the point of being transported (the critical condition). Therefore, to estimate P/H_b it is necessary to solve simultaneously the equations governing the discharge over the weir and the critical condition of the sand bed. The equation for discharge under critical condition for fine sand beds is given by equation (3) from Engel and Lau (1988) while the discharge over the weir is given by equation (4) from White (1971).

$$[3] \quad Q = 2.5 \left(\frac{\gamma_s D_{50}}{\rho} Y_c\right)^{1/2} \ln\left\{3.32[D_* Y_c]^{1/2} \left[\frac{h_1+P}{D_{50}}\right]\right\} W(h_1+P)$$

$$[4] \quad Q = 0.4\, g^{1/2} \frac{W}{H_b} C[H^{5/2} - (H - H_b)^{5/2}]$$

where

$$[5] \quad H = h_1 + \frac{Q^2}{2gW^2(h_1+P)^2}$$

H = the total energy head on the weir, C = a discharge coefficient which was obtained empirically, $Y_c = U^2_{*c}/\gamma_s D_{50}$ is the mobility number for the critical condition in which U_* is the shear velocity and the term $(H - H_b)^{5/2}$ is omitted when $H < H_b$. All other variables have been previously defined. The correct value of P can be obtained by assuming different values until the discharge calculated from equation (3) for critical shear stress is equal to the discharge calculated from the weir-discharge equation (4). From these results the dimensionless variables P/H_b, h_1/H_b and D_{50}/H_b can be computed.

Values of P/H_b were generated for the model condition and these were compared with values of P/H_b obtained from measurements in a sediment flume conducted by Engel and Lau (1988) and data from White

(1971). Differences, designated as $\Delta P/H_b$ between the predicted and measured values were then determined for values of h_1/H_b up to 2.0. The results indicated that $\Delta P/H_b$ may be independent of D_{50}/H_b for a given value of D_*. If one accepts that $\Delta P/H_b$ is not affected by changes in D_{50}/H_b and is therefore the same for model and prototype, then the actual prototype values of P/H_b can be determined by adding $\Delta P/H_b$ to the values of P/H_b generated for the prototype condition. The prototype curve of P/H_b versus h_1/H_b is given in Figure 4. The curve clearly shows that P/H_b is very sensitive to changes in h_1/H_b and that the crest of the weir is above the upstream bed level (i.e. $P/H_b > 0$) for values of $h_1/H_b > 0.5$. Based on data from White (1970) it was shown by Engel and Lau (1988) that the discharge coefficient of the FV weir could be taken as being constant with minimum error for values of $P/H_b > 0.4$. Bos (1976) recommends that the FV weir is functional for values of $P/H_b > 0.05$. However, the variability of the discharge coefficient in the range $0.05 < P/H_b < 0.4$ is not known. Therefore, the stage-discharge curve for the FV weir can only be considered to be stable for values of $h_1/H_b > 0.65$. For the Milk River at Eastern Crossing, this is equivalent to a discharge of about 20 m^3/s which represents the average flow during the irrigation season.

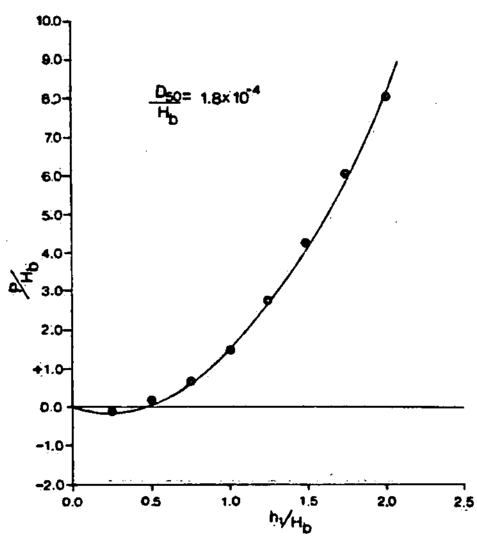

Figure 4. PREDICTED VARIATION IN P/H_b FOR MILK RIVER AT EASTERN CROSSING.

EFFECT ON THE EM METHOD

The operation of the EM flow meter is based on the principle that, if a conductor of length b moves at an average speed U through a magnetic field of intensity B, then an electric field of intensity E is induced in the conductor. This in turn sets up a potential V between the ends of the conductor given by

[6] $V = Eb$

If the conductor is linear and its length is perpendicular to the direction of motion and the magnetic field, then the electric field intensity can be given by

[7] $E = UB$

Combining equations (6) and (7) results in

[8] $U = V/Bb$

In applying this principle to the measurement of stream flow, the water is taken as the moving conductor having a flow width b. A magnetic field is generated by means of a coil bridged over the river or buried under the river bed. The potential V is measured by placing an electrode on each side of the stream at the distance b apart so that the plane passing through the electrodes is perpendicular to the direction of the flow. A schematic illustration of the EM method is shown in Figure 5. For the cross-section between the electrodes the discharge can be expressed as

[9] $Q = Ubh$

where h = the distance between the water surface and the base of the electrodes and the remaining variables have been previously defined. Combining equations (8) and (9) and introducing a site specific coefficient K, the discharge can now be expressed as

[10] $Q = Vh/K$

where K accounts for the electrical properties of the site such as end shortening of the magnetic field (Hershey, 1978) and conductivity of the stream bed (Newman, 1982).

In order to determine the effect of changes in bed elevation on the performance of the EM flow meter, tests were conducted in a small flume especially constructed for this purpose (Engel and Roy, 1986). The tests were conducted in two phases. The first phase consisted of measuring the discharge in the flume with the measuring section having a simple rectangular cross-section with a level horizontal bed. In the second phase, a hollow trapezoidal vertical contraction was placed in the flume at the measuring section. This contraction forced all the flow to pass over the new elevated bed but allowed water to fill the hollow cavity of the contraction thereby fully submerging the electrodes. The contraction is shown schematically in Figure 6. In both phases tests were conducted over the same range of flows. Values of Q, h and V were measured.

The data for the plane bed and elevated bed conditions were plotted in Figure 7 as Q vs Vh. The plot clearly shows that the data for both

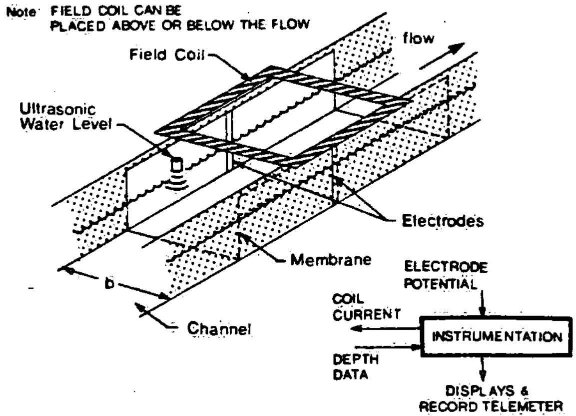

Figure 5. SCHEMATIC LAYOUT OF OPEN CHANNEL ELECTROMAGNETIC FLOW METER. AFTER NEWMAN (1982).

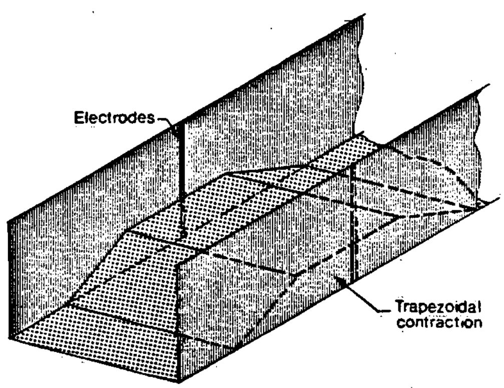

Figure 6. SCHEMATIC LAYOUT OF VERTICAL CONTRACTION IN METER SECTION OF FLUME.

phases can be represented by a single curve showing that the EM installation is not affected by the change in the flow measuring cross-section. This means that for a given discharge an increase in velocity caused by a change in cross-section results in an increase in the measured voltage which is compensated for by a decrease in the flow depth in such a way that the product Vh remains constant. Therefore, as long as the stream bed is never eroded to a level below the base of the electrodes it does not matter how much the measuring cross-section is altered by scour or deposition as long as all the flow passes between the electrodes. In addition, the curve in Figure 7 is linear and the slope indicates that the EM method would provide sufficient sensitivity for the development of daily discharge records. These properties could make the EM method suitable for use on sand bed streams such as the Milk River, although this method has never been used in streams of greater width than 25 m (the Milk River is 50 m wide).

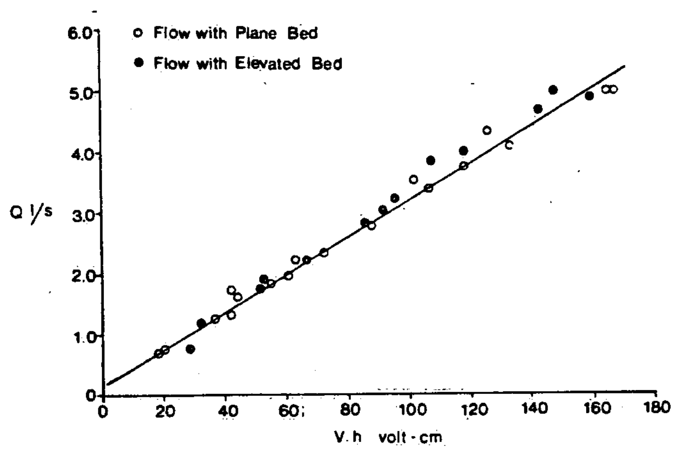

Figure 7. CALIBRATION EQUATION FOR ELECTROMAGNETIC FLOW METER

CONCLUSIONS

Theoretical analysis and experimental measurements indicate that the stage-discharge relationship of the FV weir may not be stable for values of $h_1/H_b < 0.65$. This is due to the fact that the flow intensity in the approach channel may not be large enough to maintain a value of $P/H_b > 0.4$. This could be especially serious during recessions after high flows when large amounts of sediments carried in suspension are deposited in the approach channel. Further tests are required to examine the behaviour of the coefficient of discharge for values of $P/H_b < 0.4$.

The calibration equation of the EM flow meter, taken as Q vs Vh, was found to be linear. As a result, the coefficient K is constant and may be considered to be a systems constant for a given installation. The calibration of the EM flow meter at a given measuring section is not affected by changes in bed elevation such as may be caused by deposition and scour in the approach channel.

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