ANALYSIS OF UNCERTAINTIES IN RIVER DISCHARGE AND THE INVESTIGATION OF THEIR RELATIVE SIGNIFICANCE USING MULTIOBJECTIVE ANALYSIS TECHNIQUES

PATRICE M. PELLETIER, P.ENG.

SUBMITTED IN PARTIAL FULFILMENT OF
MASTER OF SCIENCE IN CIVIL ENGINEERING
THE UNIVERSITY OF MANITOBA

MAY 1990

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ISBN 0-315-63335-2

ANALYSIS OF UNCERTAINTIES IN RIVER DISCHARGE AND THE INVESTIGATION OF THEIR RELATIVE SIGNIFICANCE USING MULTIOBJECTIVE ANALYSIS TECHNIQUES

BY

PATRICE M. PELLETIER

A thesis submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
of the degree of

MASTER OF SCIENCE

ABSTRACT

This thesis presents the results of a literature review of more than 275 publications on the uncertainties in the determination of river discharge. The uncertainties in a single determination of discharge, which includes uncertainties in sampling the cross-sectional area and the mean velocity in time and in space, and in the current meter, are emphasized. The objectives of the literature review were to determine all the possible sources of uncertainties in a current meter measurement, to quantify these uncertainties based on past investigations, and to determine if additional research was required to improve the overall accuracy of hydrometric data in Canada. It was determined that uncertainty values found in the reviewed literature do not adequately cover the stream or river types (i.e. hydraulic and morphologic character of a stream) encountered in Canada. Moreover, the uncertainty values given in the literature are often referring to measurements performed under ideal conditions. These ideal conditions are seldom encountered. In fact, due to the conditions imposed naturally (e.g. droughts, very low runoff, or winter ice) or imposed by management needs or budgetary restrictions (e.g. locating stations at available bridges or below a dam), the gauging agency can be forced to operate outside of the ideal conditions and the preferred ranges of widths, depths, and velocities. To determine the relative significance of the different sources of uncertainties in sampling the mean velocity, multiple objective analysis techniques were used. Two different multiple-objectives techniques were used, these are: ELECTRE I and COMPROMISE PROGRAMMING techniques. In general, both techniques gave similar results in terms of preferred alternatives. The first preferred alternative is the technique used in North America by the Water Survey of Canada, and the United States Geological Survey. This technique is based on a large number of verticals (minimum of 20), a small number of points per vertical (one or two), and a relatively short observation time (45 seconds). The second alternative, which is preferred in Europe (e.g. Scandinavia), is based on a small number of verticals (5), velocity profiles for each vertical, and long time of observation. Both techniques are more or less equivalent in terms of total uncertainty, if ideal conditions are prevailing at the site. However, ideal conditions are rarely encountered in nature, therefore the technique used in North America is a more conservative solution to all types of conditions. Based on the exhaustive literature review presented in this thesis, additional research is required: on the calibration of current meters, including analysis of standard versus individual ratings, single versus composite current meter rating curves, and effect of suspension type (rod versus weights of various types on cable); on the effect of turbulence on the response of the Price current meter, including the effect of pulsation using field and laboratory testings; on the the uncertainty in a single determination of discharge for Canadian streams, with emphasis on streams with shallow depths and low velocities (e.g. Prairie streams); on the accuracy of streamflow measurements and computation procedures under winter (ice) conditions; and on the uncertainty in the stage-discharge relation and in the computation of the discharge hydrograph.

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ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance and guidance received during the development of this thesis from Dr. Slobodan P. Simonovic, Associate Professor, at the University of Manitoba.

Also, the author gratefully acknowledges the support and assistance received from Mr. Dale R. Kimmett, Director of the Water Resources Branch of Environment Canada, and from Mr. Ian S. McLaurin, Head of Data Services Section of Water Survey of Canada, a division of the Water Resources Branch of Environment Canada.

Finally, the financial support received from SNC Inc., and in particular the support of Mr. André Gagnon, Vice-President of the Power and Heavy Civil Works Division, is very much appreciated.

1. INTRODUCTION

In Canada, the Water Resources Branch is the national agency responsible for the collection, interpretation, and dissemination of standardized surface water quantity data and information. Most of the data collected relate to streamflows and water level variations in rivers, streams, and lakes. Sediment data are also collected.

Under formal agreements signed with all provinces and with the Department of Indian and Northern Affairs (on behalf of the Yukon and Northwest Territories), the Branch operates a Canada-wide network of 2500 gauging stations that provide information vital to federal and provincial water-related programs as well as to a wide range of public users. For example, three types of data (i.e. historical, current-year, and real-time) are used in the planning, design, and operation of **billions of dollars** worth of water-related facilities each year. The same data are also used for policy, planning and program implementation by federal, provincial and municipal governments, and the private sector.

The Water Survey of Canada, a division of the Water Resources Branch, was established in 1908, and is responsible for measuring streamflows, water levels, and sediment concentrations in the field; making the necessary computations and interpretations; archiving the data in its national data bank HYDAT; and distributing it to a wide range of clients and users.

Annually, the Water Resources Branch distributes 15 000 data products to users (publications, computer tapes and disks, maps, etc.), and responds to some 5 000 written or telephone data requests at headquarters and regional offices. As well, thousands of requests for real-time data are met by automatic telephone answering devices installed on-site or through computer links with regional offices.

User surveys carried out periodically across the country continue to show that these data products are essential, frequently used, and highly valued. Each station operated serves, on average, three different uses simultaneously.

Knowing the uncertainty[1] of a discharge measurement is important not only to determine the relative accuracy of the collected sample, but also to assess the method and equipment by which the sample was collected. Once the uncertainty of a single discharge measurement has been determined, the uncertainty in the stage-discharge relation used to derive the daily streamflow record may be established. Then, the confidence level in forecasts, models, and decisions in water resources may be evaluated.

An impressive number of articles discussing the accuracy of streamflow data were found in the literature. However, the majority of these references are qualitative studies, i.e. the author makes qualitative statements on the accuracy of discharge measurement or refers to the work of others. Also, a large number of quantitative studies used a very small sample (1 or 2 streams) to reach their conclusions.

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[1] Uncertainty is defined as the range within which the true value of a measured quantity can be expected to lie expressed at a particular confidence level (e.g. at 95% level, i.e. at two standard deviations).

This thesis presents a compilation of reference material on subjects related to the error, accuracy, or uncertainty in the determination of river discharge by the velocity-area method using a current meter for velocity observation. The uncertainty in this method has been reviewed because it is the most widely used technique for the determination of discharge. Other streamflow measurement methods such as dilution methods, flow measuring structures (e.g. weirs, flumes), and electromagnetic and ultrasonic methods were also reviewed, but not to the same detail.

The principle of the velocity-area methods consists of measuring flow velocity and cross-sectional area. A measuring site is chosen conforming to the specified requirements. The width, depending on its magnitude, is measured either by means of steel tape or by some other surveying method, and the depth is measured at a number of verticals along the width, sufficient to determine the shape and area of cross-section. Velocity observations are made at each vertical preferably at the same time of depth measurement, especially in the case of unstable beds. They are made by any one of the standard methods using current-meters. The principle involved is based on the proportionality between the local flow velocity and the speed of the rotor. Under certain circumstances, velocity observations are also made using surface-floats and velocity rods. The mean velocity is generally computed from the individual observations; however, in certain methods such as the integration method, the mean velocity is obtained directly. The discharge is computed either arithmetically or graphically by summing the products of the velocity and corresponding area for a series of observations in a cross-section.

From the literature review, it was observed that there has been only one complete systematic investigation into the accuracy of discharge measurement. This study was carried out by Herschy (1975a) on British streams, and the results were used in large part to derive the uncertainty values presented in international standards (ISO 748, 1979).

Earlier important investigations carried out by Murphy (1901, 1902[a,b], 1904) on the accuracy of streamflow measurements have also been very influential.

Anderson (1961) and Carter and Anderson (1963) also carried out an extensive investigation, but did not consider all the uncertainties (e.g. area, stage), did not determine the uncertainty in the stage-discharge relation, and did not consider systematic uncertainties.

Carter and Anderson's approach in combining random uncertainties differs from Herschy (1975a). However, their sample analyzed was larger than Herschy's (1975a) in terms of number of streams. One of the difficulties in interpreting Carter and Anderson's results is that only final averages are shown in their published work, and the origin of the data used to derive the uncertainty values is unclear. For example, Kolupaila (1964) reported that uncertainty values due to the limited number of points taken in the vertical, which were estimated by Carter and Anderson, were derived from data collected over the period of 1882 to 1951.

A distinction between the results of Carter and Anderson (1963) and Herschy (1975a) should be made: for the former, the uncertainties are given at the 68% level (one standard deviation); for the latter, the uncertainties are given at the 95% level (two standard deviations). Uncertainty values in this thesis are given at the 95% confidence level.

An extensive review of the accuracy of discharge measurement has been carried out by Dickinson (1967). The present study is an extension of Dickinson's work. It includes the results found in the literature over the last 20 years and also summarizes (Pelletier, 1988b) the important results in a systematic way.

One common observation that can be drawn from the review of all these studies is that the procedures (including equipment) used by the different investigators were different. For example, the computation of the particular uncertainty was done differently; the error equations (combination of uncertainty) used were different; different types of current meters were used (generally horizontal axis in Europe and the U.S.S.R. and vertical axis in the U.S.A. and Canada); different types of streams (area, velocity) were used (generally medium to large); and sometimes the sample size was not stated in the paper. Therefore, the comparison of these results for a precise determination of the uncertainty is somewhat difficult .

The thesis is organized as follows:

- Section 2 gives the general methodology followed to conduct the literature review. More than 275 references and abstracts are included in this thesis which covers a wide range of subject matter related to uncertainties in hydrometric data.
- in Section 3, a general description of the statistics as applied to stream gauging is given.
- in Section 4, all uncertainties (random and systematic) which relate to the single determination of river discharge are reviewed, summarized, and discussed. The combination of uncertainties, using error equations, are also investigated. Uncertainties present in other phases of development of streamflow records, are then discussed, including uncertainties which relate to the measurement of streamflow under ice conditions. Finally, methods other than the velocity-area method are briefly described, and their associated uncertainties given.
- in Section 5, a brief description of two multi-objective analysis techniques are given, and their application for the determination of the relative significance of different types of uncertainties discussed.
- finally, in Section 6, the conclusions, and recommendations are given.

2. LITERATURE EVALUATION METHODOLOGY

2.1 PURPOSE OF THE LITERATURE REVIEW

The purpose of the literature review was to trace the basis for the establishment of hydrometric practices and standards in Canada. Through the review of approximately 100 years of research in hydrometry, answers were found to very basic questions concerning hydrometric standards and principles. The results of this study were used to determine if additional research was required to achieve a better understanding of the uncertainties involved in the development of a streamflow record, and therefore to enhance the quality of hydrometric data.

Considering that the large majority of the investigations into the accuracy of streamflow measurement has been carried out by agencies outside of Canada it is essential to determine if the results of these numerous studies are applicable in Canada. Moreover, the relative importance of these studies had to be established.

Through the literature review, the following questions were always kept into perspective:

- Which error components (e.g. area, velocity) were analyzed?
- How large was the sample analyzed?
- What type of streams (e.g. mountain, plain) were analyzed?
- What type of current-meters (vertical, horizontal axis) were used?
- What type of errors (e.g. random, systematic) were analyzed?

Finally, an even more important objective was to determine if additional research is required to achieve a better understanding of the uncertainties involved in the development of a streamflow record, and therefore to enhance the quality of hydrometric data.

2.2 SEARCH METHODOLOGY

Computerized literature searches were performed using the CAN/OLE system (Canadian Online Enquiry System).

Several keywords were used for the literature search, these were grouped into three categories, and are given in Table 2.1.

Different combinations of these keywords were prepared and various information databases (National Research Council [1986]) were used for the computerized literature searches (see Table 2.2).

Manual searches were also performed using the references and bibliography of the different articles. In particular, the references and bibliographies of the following authors were extremely helpful: Yarnell and Nagler (1931), Dickinson (1967), and Herschy (1975). Proceedings from International Symposium on Hydrometry were also consulted, such as the Proceedings of the Koblenz Symposium (1970) and of the Exeter Symposium (1982).

Table 2.1 Keywords for computerized literature search

I	II	III
accuracy	river	measurement
error	hydrometric	data
inaccuracy	flow	determination
uncertainty	stream	
reliability	streamflow	
precision	discharge	

Table 2.2 Information Databases

AQUAREF - Canadian Water Resources References
CODOC - Cooperative Documents Project
COMPENDEX or EI - Computerized Engineering Index
EIM - EI Engineering Meetings
ELIAS - Environment Canada Departmental Library
MICROLOG - Government and institutional sources (Canada)
NRCPUBS - NRC Publications
NTIS - National Technical Information Service

2.3 LIMITATION OF THE LITERATURE REVIEW

Only articles in English and French were reviewed. In some cases, articles which were translated from another language (e.g. Russian, Japanese, German) to English or French were also used.

The outstanding bibliography of hydrometry published by Kolupaila (1961) is highlighted. This bibliography includes 7370 titles of papers in 38 languages, by 4500 authors. After reviewing Kolupaila's monumental work, it was found that the majority of the articles related to the accuracy of discharge measurements were written in other languages than in English. In fact, most of these papers (approximately 100) are available only, if at all, in German or in Russian. However, the majority of these papers investigates of the accuracy of horizontal axis current meters (e.g. Woltman, Ott), which are not commonly used in Canada, nor in the United States.

Also, not included in this literature review, are approximately 50 very short papers published in the Water Resources Bulletin, for technical personnel of the Water Resources Division of the U. S. Geological Survey. These articles contain valuable contributions and discussions of the U.S.G.S. field and office personnel. These publications are not available in any library. However, Kolupaila's bibliography includes these contributions.

While the author believes that most of the major references have been included in this investigation it is realized that this compilation may still remain incomplete.

3. STATISTICS AS APPLIED TO RIVER GAUGING

The terms, definitions, and error analysis theory given in this section are taken from ISO 5168 (1978).

3.1 TERMINOLOGY

Error: In a result, the difference between the measured and true values of the quantity measured.

True Value: The value which characterizes a quantity perfectly defined in the conditions which exist at the moment when that quantity is observed (or the subject of a determination). It is an ideal value which is assumed to exist and which could be known only if all causes of error were eliminated.

Uncertainty: The interval within which the true value of a measured quantity can be expected to lie with a stated probability; it is given as $\pm$ t S_y, with the value of t equal to that corresponding to the chosen probability, and S_y is the estimate of the standard deviation of the variable y.

Confidence Level: The confidence level associated with the uncertainty indicates the probability that the interval quoted (uncertainty) will include the true value of the quantity being measured.

It is worth noting a fundamental difference between error and the uncertainty, which is that the former is by definition unknown whereas the latter may be estimated.

Before proceeding further, let us examine accuracy and precision, two concepts that are important to the ensuring treatment of errors.

Precision: Precision is the agreement between a set of observations or deviations. It is the scatter, spread or dispersion of them and if the scatter is small then the observations are precise. More narrowly, precision is the term given to one of a number of indices which are measures of the agreement.

Accuracy: Accuracy as a broad term refers to the correctness of the observations. In its narrower meaning, it is the departure of the observation from the true value. A measurement is accurate (or has no error) if the best value of a set of observations shows no deviation from the true value sought. Results may be precise without being accurate, i.e. observations may show small scatter or dispersion although the best value of the observations departs from the true value sought. Results may be accurate without being precise, i.e. the best value of the observations may exhibit no departure from the true value, although the scatter of observations may be wide, but this is rarely found in industrial work.

Deviation: A deviation is the difference, departure or error of an observed or calculated quantity from the true value or a specified quantity.

Standard Deviation: the standard deviation is a measure of the dispersion (or scatter) of the observations about the arithmetic mean of the sample. It is defined as the positive square root of the arithmetic mean of the squares of the deviations from the arithmetic mean and is given by the equation

$$S_y = \left\{ \frac{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}{n - 1} \right\}^{1/2}$$

where S_y is the standard deviation of the observations

$\bar{Y}$ is the arithmetic mean of the observations, Y_i

Y_i is the independent random observations of the variable Y

n is the number of observations

If a sample fits a normal distribution (bell-shaped symmetrical distribution), then by statistical inference the dispersion about the mean is measured in standard deviations. Then, on average, 68% of the observations will lie within one standard deviation of the mean, 95% will lie within 2 standard deviations of the mean, and 99% will lie within 3 standard deviations (see Table 3.1). International Organization for Standardization have recommended that all probability levels should be taken at the 95% level (2 standard deviations). Therefore all the uncertainties in this report are estimated at 2 standard deviation.

Percentage Standard Deviation: The standard deviation is expressed as a percentage by the following equation

$$PS_y = \left\{ \frac{\left(\sum_{i=1}^{n} \frac{(Y_i - \bar{Y})^2}{n - 1} \right)^{1/2}}{\bar{Y}} \right\} \times 100$$

Expressed in this form, the standard deviation is also known as the coefficient of variation (CV).

The terms defined above are shown schematically in Figure 3.1.

Table 3.1 Confidence level

Uncertainty	Confidence level
± 0.674 S_y	0.50
± 0.954 S_y	0.66
± 1.960 S_y	0.95
± 2.576 S_y	0.99

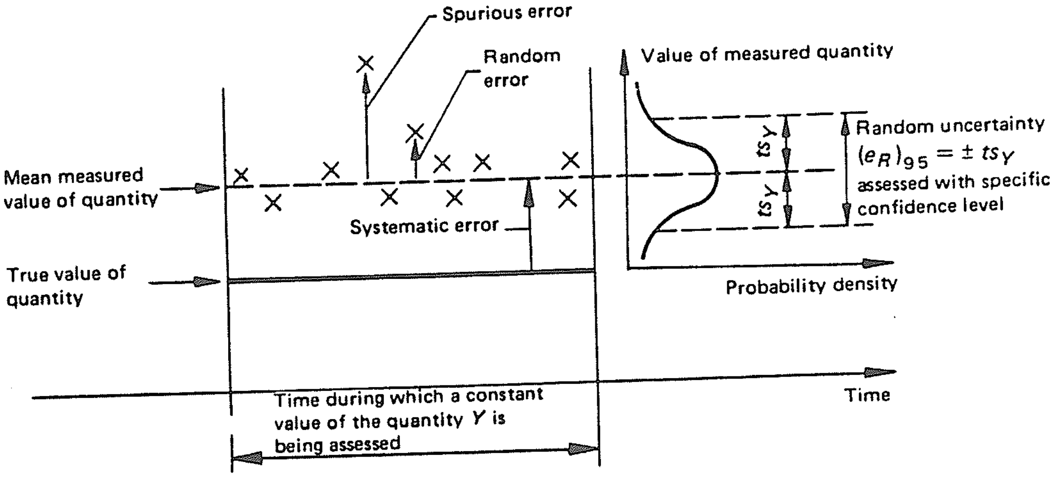

Figure 3.1 Basic statistical terms

3.2 NATURE OF ERRORS

There are four types of error which must be considered:

a) spurious errors;
b) random errors;
c) constant systematic errors; and
d) variable systematic errors.

3.2.1 Spurious Errors

These are errors such as human errors, or instrument malfunction, which invalidate a measurement. Such errors should not be incorporated into any statistical analysis and the measurement must be discarded.

Whenever it is suspected that one or more results have been affected by errors of this nature, a statistical "outlier" test should be applied.

3.2.2 Random Errors

Random errors are sometimes referred to as precision or experimental errors. They are caused by numerous, small, independent influences which prevent a measurement system from delivering the same reading when supplied with the same input value of the quantity being measured. The data points deviate from the mean in accordance with the laws of chance, such that the distribution usually approaches a normal distribution as the number of data points is increased.

It is possible to calculate statistically the uncertainty in a measurement of a variable when the associated error is purely random in nature. To do this it is necessary to compute the standard deviation of the error and to decide on the confidence level which is to be attached to the uncertainty (e.g., by the International Standard, the 95% confidence level is used).

The random error in the result can be reduced by making as many measurements as possible of the variable and using the arithmetic mean value, since the standard deviation of the mean of n independent measurements is $(n)^{1/2}$ times smaller than the standard deviation of the measurements themselves.

3.2.3 Systematic Errors

Systematic errors are those which cannot be reduced by increasing the number of measurements if the equipment and conditions of measurements remain unchanged. they may be divided into two groups, namely: constant and variable systematic errors.

Constant Systematic Errors

These are common to all measurements made under the same conditions and are constant with time but, depending on the nature of the error, may vary with the value obtained for the measurement.

Variable Systematic Errors

These may arise from inadequate control during the test or experiment, being caused by, for example, changes in temperature which are not allowed for during the use of a pressure gauge which had been calibrated at a fixed temperature, or by progressive wear in the bearings of an instrument.

A second type of variable systematic error may occur where digital measurements are taken on a continuously varying quantity. Here, the measurement of a series of discrete objects or events with some imprecision in the definition of the beginning and ending of the set. The uncertainty in the measurement due to its digital nature then depends on the order of the final digit.

The uncertainty associated with systematic errors cannot be assessed experimentally without changing the equipment or conditions of measurement. Whenever possible this should be done since the alternative is to make a subjective judgement on the basis of experience and consideration of the equipment involved.

The procedure to be followed for arriving at the systematic uncertainty depends on the information available on the error itself, but is the same whether a constant or a variable systematic error is being considered:

a) if the error has a unique, known value then this should be added to (or subtracted from) the result of the measurement, and the uncertainty in the measurement due to this source is then taken as zero;

b) when the sign of the error is known but its magnitude has to be estimated subjectively, the mean estimated error should be added to the result of the measurement and the uncertainty taken as one-half of the interval within which the error is estimated to lie.

The result of a measurement, R, to be used is then given by the following equation

$$R = M + \frac{\delta t_1 + \delta t_2}{2}$$

with an uncertainty of

$$\pm \frac{\delta t_1 - \delta t_2}{2}$$

where δt is the systematic error, and M, the measured value.

c) when the magnitude of the systematic uncertainty can be assessed experimentally, the uncertainty should be calculated as for random errors. Such situation would arise where, for example, a current meter which has not been calibrated individually is used, but where batches of identical current meters have been previously tested to provide a mean and standard deviation of the error associated with such current meters.

d) when the sign of the error is unknown and its magnitude is assessed subjectively, the mean estimated error is equal to zero and the uncertainty should again be taken as one-half of the estimated range of the error.

3.3 PROPAGATION OF ERROR

Although it may be possible to attach values to the uncertainties in the various individual measurements used to obtain a measure of flow-rate, it is the uncertainty in the value of the flow-rate ultimately obtained which is of fundamental interest. It is, therefore, essential to have an agreed method of combining the various uncertainties associated with each of the variables, which must be measured in order to calculate flow-rate. In open channels these would be variables such as water level and cross-section depths.

Spurious errors introduce no problem since any measurement shown by a statistical test (Dixon test) to be an outlier must be discarded (provided that there is independent reason for doubting the measurement). The techniques for combining random uncertainties are well developed, but if the simplest statistical formulae are to be used the different variables must be independent. Thus, every variable must be examined in order to ensure that this is so. If not, any interdependent variables must be broken down into more fundamental variables until true independence is reached.

Since the quantities in the various expressions from which the flow-rate may be calculated are not normally independent, each variable should ideally be examined individually to determine the independent variables on which it depends. It may often be impractical or indeed impossible to carry out this procedure and in such instances the formula for the calculation of the overall uncertainty should incorporate terms which allow for the dependence between the variables.

If the uncertainty in a variable Y_i is denoted e_i the concept of interdependent uncertainties, $e_{i,j}$, may be introduced in order to produce these additional terms. The quantity $e_{i,j}$ then allows for the interdependence between variables Y_i and Y_j.

In calculating the uncertainty, e_a, in a result all uncertainties should thus be combined using the relation

$$e^2_a = \sum_{i=1}^{k} (\Theta_i\, e_i)^2 + 2 \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \Theta_i\, \Theta_j\, e_{i,j} \qquad \ldots(3\text{-}1)$$

where

$$e_{i,j} = \frac{4}{n-1} \sum_{r=1}^{n} [(Y_i)_r - \bar{Y}_i]\; [(Y_j)_r - \bar{Y}_j] \qquad \ldots(3\text{-}2)$$

where, Θ_i is a dimensional sensitivity coefficient of the quantity Y_i.

Note that the above equation (3-2) holds only when the distribution of all of the sources of uncertainty, e_i, can be assumed to approach a normal distribution, and when the e_i are at the 95% confidence level. In addition the approximation is made that the confidence limits lie at plus and minus twice the standard deviation, but this should introduce negligible error in the calculation of the overall uncertainty.

Three special cases are worth mentioning:

a) it is recommended that whenever possible only independent variables should be used, and in this case equation (3-1)

$$e^2_a = \sum_{i=1}^{k} (\Theta_i\ e_i)^2 \qquad \ldots(3\text{-}3)$$

b) when the result, R, is given by a simple sum, i.e.

$R=Y_1+Y_2+...+Y_k$

then all the Θ_i are unity and equation 3-1 becomes

$$e^2_a = \sum_{i=1}^{k} (e_i)^2 + 2 \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} e_{i,j} \qquad \ldots(3\text{-}4)$$

c) when the result, R, is a function only of factors, then the dimensionless sensitivity coefficient for each factor is the exponent of the factor.

For the relation:

$R=K\ Y^a_1 Y^b_2 / Y^c_3$

where Y_1, $Y_{,2}$, and Y_3 are independent of each other, then

$\Theta^*_1=a;\ \Theta^*_2=b;\ \Theta^*_3=-c$

and

$E_A = [(aE_1)^2+(bE_2)^2+(cE_3)^2]^{1/2}$

where Θ^*_i is a dimensionless sensitivity coefficient of the quantity Y_i, and a,b,c are constants.

4. UNCERTAINTY IN A SINGLE DETERMINATION OF DISCHARGE

4.1 GENERAL

In the velocity-area method, the discharge is derived from the sum of the products of stream velocity, depth and distance between verticals (see Figure 4.1), the stream velocity usually being obtained by a current meter (Herschy, 1985). For a continuous record of discharge in a stable prismatic open channel with no variable backwater effects, a unique relation exists between water level (stage) and discharge. Once established, this stage-discharge relation is used to derive discharge values from recordings of stage.

Errors may be incurred during three phases of the development of a record of streamflow at a river station.

Initially, there are errors introduced by measurement instrumentation and technique in a single-stream gauging observation. The establishment of a stage-discharge relationship involves those errors which cause the relationship to be non-unique in nature. The last phase, involving the use of the rating curve, incorporates stilling-well and stage-recorder errors, and those introduced by the methodology of calculating daily discharge values.

Whenever measurements are made, errors are made-the single exception being when the measurement is a discrete count. Because no measurement is free from error, steps must be taken to evaluate the accuracy and the precision of the measurement. To preclude a false sense of accuracy, one must investigate the nature of error, as well as the sources, types, and magnitude of errors made at various stages of the measurement operation, and the interrelation among errors. Only then is it possible to predict the order of magnitude of the error in the final result.

4.2 OVERALL UNCERTAINTY

Theoretically, the river discharge is expressed by the integral of a velocity field over a cross-section:

$$Q = \iint_A v(x,y)\ dx\ dy \qquad \text{...(4-1)}$$

where

Q is the unknown true discharge;
A is the cross-sectional area; and
v(x,y) is the velocity field over width, x, and depth, y.

In practice, however, the integral (4-1) is approximated by finite summations:

$$Q_c = \sum_{i=1}^{m} b_i\ d_i\ v_i \qquad \text{...(4-2)}$$

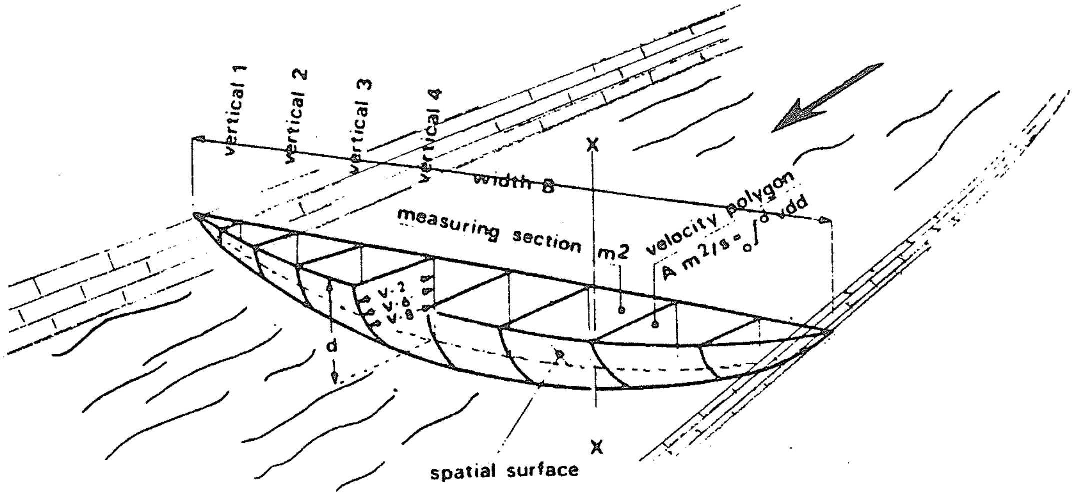

Figure 4.1a The measuring section.

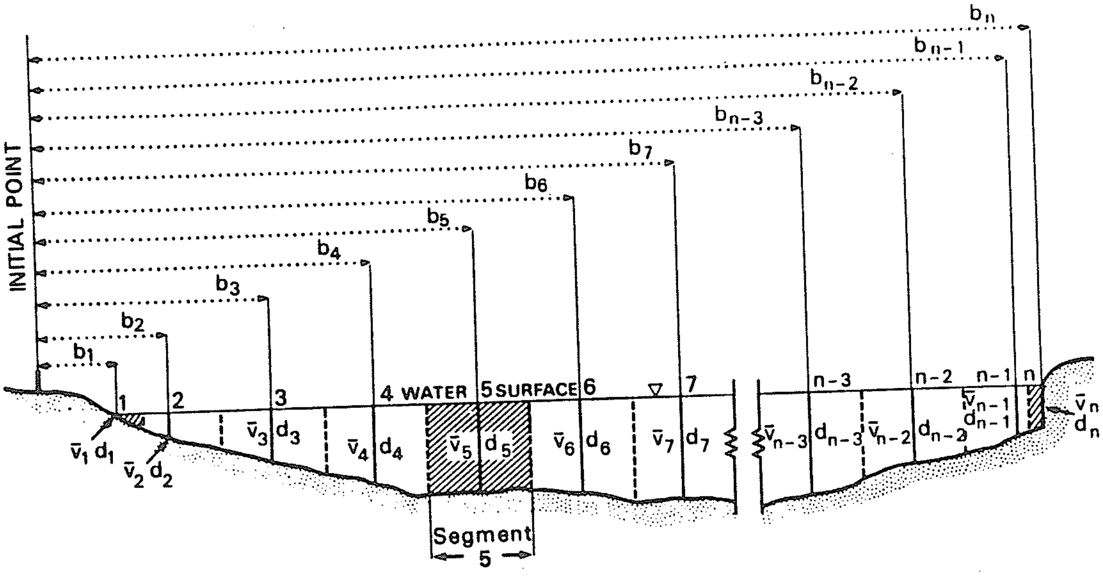

Figure 4.1b The mid-section method.

where

Q_c is the total calculated discharge in the cross section;
b_i is the width of the segment i;
d_i is the depth of the vertical i;
v_i is the mean velocity in the vertical i; and
m is the number of verticals.

A vertical is defined as the vertical line in which depth measurements or velocity measurements are made (ISO 772, 1978).

In Canada, a standard discharge measurement is usually performed using an individually rated Price AA current meter and taking at least 20 verticals across the cross-section, in which one or two velocity observations are taken in each vertical at 0.6 of the depth or at 0.2 and 0.8 of the depth (see Figure 4.1a). The velocity at each point is observed for at least 40 seconds. The measurement is then computed using the mid-section method (see Figure 4.1b).

The overall uncertainty (random and systematic) in the determination of discharge is then due to uncertainties

- in the determination of the cross-sectional area, i.e., in determination of widths (b_i) and depths (d_i);
- in the determination of the individual measurements of the flow velocity necessary for the determination of v_i;
- by approximation of the integral (equation [4-1]) by finite summations (equation [4-2]).

In addition, the uncertainty in the mean velocity depends on the uncertainty due to the limited time of exposure; the uncertainty due to the limited number of points taken in the vertical; the uncertainty due to the limited number of verticals; and the uncertainty in the current meter rating (Carter and Anderson, 1963; Herschy, 1975a; ISO 748, 1979).

The values of uncertainties given in this thesis are percentage standard deviations at the 95% confidence level (two standard deviations), except where stated otherwise.

The results that are presented in the following pages are organized as follows: first, the type of uncertainty is stated and the causes described; second, the major investigators are presented; and finally, uncertainty values commonly found in the literature are presented.

4.3 UNCERTAINTY IN THE MEASUREMENT OF CROSS-SECTIONAL AREA

There has been very little research into the uncertainties of flow depth and width measurements.

Using a sample of 22 streams, Wahl (1977) has shown that trained individuals measure width more consistently than depth.

Uncertainties in depth and width may be either random or systematic, or both. They are generally considered to be small or even negligible (Dickinson, 1967). Carter and Anderson (1963) did not include any component for uncertainties in depth or width in their error equation.

Uncertainty values for width and depth measurements in the literature are given by Prochazka (1960), Herschy (1969-85), Wahl (1977), and ISO 748 (1979).

4.3.1 Uncertainty in width

Inaccuracies in width measurement are most likely to occur if the channel is large or under ice conditions. In these cases, the necessary corrections for sag, pull, slope, and temperature of the measuring tape or wire should be made (ISO 748, 1979).

For width measurement, the random uncertainty is between ±0.1 and ±0.5% (at the 95% level) depending on the actual width, and the systematic uncertainty (at the 95% level) is ±0.5% (see Table 4.1).

4.3.2 Uncertainty in depth

Errors in depth soundings are likely to occur in cross-sections having great depths and velocities (Corbett et al., 1957; ISO 748, 1979; Rantz et al., 1982). To eliminate these uncertainties, adequate sounding weights should be selected and corrections applied, i.e. air-line and wet-line corrections (ISO 748, 1979; Coon and Futrell, 1986). Inaccuracies will also be introduced if the bed is soft, causing the penetration of the bed by the sounding weight or rod. Uncertainties can also be caused by the presence of boulders or bedrock irregularities in the streambed. If the stream is covered by ice, several additional uncertainties will arise, e.g. in the determination of effective depth because of the presence of ice cover and frazil ice.

For depth, the random uncertainty is between ±1% and ±3%, depending on the depth; the systematic uncertainty is less than ±0.5%; as given in Table 4.2 (Herschy, 1970, 1975a; ISO 748, 1979).

4.4 UNCERTAINTY IN THE MEASUREMENT OF VELOCITY

It is not possible to predict accurately the uncertainties which may arise, but there are four main causes,

1) uncertainty due to the limited time of exposure of the current meter;

2) uncertainty due to the use of a limited number of points in the vertical;

3) uncertainty due to the current-meter rating;

4) uncertainty due to the use of a limited number of verticals.

Table 4.1 Uncertainties in river width measurements

Random Uncertainty in % (at the 95% level)	± 0.1 to 0.5 depending of the actual width
Systematic Uncertainty in % (at the 95% level)	± 0.5

Table 4.2 Uncertainties in river depth measurements

Random Uncertainty in % (at the 95% level)
± 1.0 to 3.0 depending of the actual depth
Systematic Uncertainty in % (at the 95% level)
± 0.5

4.4.1 Uncertainty due to the limited time of exposure

The velocity at any point in a stream is continuously and randomly fluctuating with time. These fluctuations in velocity are known as pulsations or oscillations. They are present in all open channels in some form or another, and are caused by hydraulic conditions in the stream (e.g. obstructions, bends or rapids and the general regime of the river).

Because of turbulence the velocity fluctuates continuously over the wet cross-section. The mean velocity at any point, determined from a measurement during a certain time (in practice between 40 and 60 seconds), is an approximation of the true mean velocity at any particular point. Therefore, an error which is related to the time period of observation of velocity at a point is introduced.

While Hoyt and Grover (1907) recommended a 100-second observation time, Hoyt (1910) recommended 40 seconds with a check observation, and Corbett et al. (1957) and Rantz et al. (1982) recommended 40 to 70 seconds. In Canada, it is recommended that the point velocity be observed for 40 to 80 seconds (Terzi, 1981). In practice, however, the velocity is observed for 40 to 50 seconds. The actual rationale of the 40-second standard is unclear.

The fluctuation in velocity was the subject of several investigations in the late 1800's. Murphy (1904) reported that Henry (1871) observed pulsations on small and large streams, Unwin (1882-83) on the Thames River, and Mackenzie (1884) on the Mississippi River.

Major investigations have been carried out in the U.S.S.R., the U.S.A., and the U.K. Dement'ev (1962) reviewed early Russian work (1870's to 1950's) and analyzed data collected on 32 mountain streams in the U.S.S.R. in 1959-60; Carter and Anderson (1963) analyzed data from 23 streams in the U.S.A.; Herschy (1970, 1975[a,b]), and Herschy et al. (1978) analyzed data from 2 streams in the U.K.; Savini and Bodhaine (1971) analyzed data from the Columbia River (U.S.A.); Hall and Johnston (1971) analyzed data from one stream in England; and ISO 7178 (1983) investigations (ISO DATA 2, 1978) included the analysis of four streams in the U.K., four in India, one in the Netherlands, and two in the U.S.A.

Results from some of these investigators will be further analyzed and discussed.

Note that the results of the ISO investigation were first officially reported by Herschy (1975b), and then published by ISO (ISO 7178, 1983).

Dement'ev (1962)

Dement'ev reviewed early Russian work (covering the period 1870's to 1950's) into the investigation of velocity pulsations on typical mountain streams (Tables 4.3 and 4.4). Dement'ev's paper also contains results of work carried out by the Central Asian Expedition on 32 mountain rivers in Russia, at 37 locations, between 1959 and 1961 (Table 4.5).

Table 4.3 Meter time exposure required to obtain a 4% accuracy (at the 95 per cent level) for a point velocity – Dement'ev (1962).

			Exposure time, in minutes				
Author	Year	River	S	0.2D	0.6D	0.8D	B
N.N. Sokolov A.B. Shafalovich	1907-09	Zee	-	2	-	8	-
Remarks: large Ott meter; 20 min. duration							
M.M. Musselius	1910	Tura Tobol	-	2	-	8	-
E.V. Bliznyck A.A. Ziring	1911	Yenisey	-	1	-	2	-
Remarks: 12 min. duration							
S.I. Moiseyenko	1911-12	Chusova	-	2.3	-	5.6	-
		Sylva	-	2.5	-	9	-
S.I. Kollupaylo	1914-16	Western	1.5	1.5	2	4	7
		Dvina	3	1.5	1.5	2	5
Remarks: open water conditions on Western River, and ice conditions on Dvina River							
V.M. Sokol'nikov O.K. Blumberg	1931-32	Neva	1.5	2	4	-	6

Note: S is for surface, and B for bed

Table 4.4 Percentage Standard Deviation at the 95% level, of the velocity pulsations for various exposure times - Dement'ev (1962).

Author,River, Year *Remarks	Time	Percentage Standard Deviation (95% level)				
		S	0.2D	0.6D	0.8D	B
E.V. Bliznyck	Mean	4.8	2.2	3.0	-	6.6
A.A. Ziring	Max	7.6	4.2	7.2	-	14.2
*midstream						
*(2 min)						
on the Yenisey River in 1911						
I.I. Moskvitinov	20 s	-	4.4	7.4	10.2	-
N.A. Girillovich	60 s	-	2.4	4.8	5.8	-
*midstream	120 s	-	1.8	3.4	4.2	-
*1-hour duration	300 s	-	1.2	2.2	2.8	-
on the Syr-Dar'ya River	600 s	-	0.8	1.4	2.0	-
in 1915						
		S	0.1D	0.4D	0.7D	B
A.N. Kalmykov	20 s	7.6	5.4	4.4	8.0	-
*Ott-Price	60 s	5.6	3.8	3.0	5.2	-
*20 min. duration	120 s	3.8	2.6	2.0	3.6	-
*ice cover	300 s	2.2	1.4	1.2	2.0	-
on the Syr-Dar'ya River	600 s	1.2	0.8	0.6	1.2	-
in 1925						
N.M. Mexheraup						
*Midstream	300 s	from 10.0 to 16.0%				
*Banks		from 12.0 to 24.0%				
on the Luga River in 1932-33						
A.A. Kalinskiy		from 14 to 48%				
on the Mississippi River in 1943						
I. Prokhazka	120 s	from 9.2 to 19.2%				
*bottom layer (0.8-0.95D)						
on the Danube, Vaga, and						
Vltava Rivers in 1955						
S.I. Koplan-Diks	100-120 s			± 6% (max 16%)		
*5 min duration						
on the Polomet River						
in 1955-1957						

Table 4.5 Summary of results of observations on pulsations of currents in mountain rivers of Central Asia 1959 to 1960 - Dement'ev (1962)

Characteristic	Depth of points (m)			Percentage standard deviation (95% level) for exposure of meter, in minutes				
				0.5	1.0	2	5	10
Bank verticals		D (m)	V (m/s)					
Average for 25 mountain streams with pebble-stony beds	S	0.23	2.96	11.6	8.4	4.4	3.2	2.2
	0.2D	to	to	11.0	8.0	4.4	3.2	2.2
	0.6D	4.49	0.12	11.6	10.0	5.6	4.2	3.2
	0.8D			16.4	12.4	8.6	6.2	4.4
	B			25.4	20.4	13.2	8.4	5.6
Midstream verticals								
Average for 28 mountain streams with pebble-stony beds	S	0.78	4.86	6.4	4.6	3.2	2.0	1.4
	0.2D	to	to	6.0	4.2	3.6	2.6	1.8
	0.6D	7.00	0.40	8.1	6.0	4.8	3.2	2.4
	0.8D			12.4	9.6	6.8	4.2	3.0
	B			15.2	10.8	8.0	5.6	4.2
Bank verticals								
Average for 3 points of observation on rivers with sandy beds	0.2D	1.20	1.78	7.6	6.0	3.6	2.6	1.6
	0.6D	to	to	7.2	7.8	5.2	3.6	2.8
	0.8D	4.08	0.54	11.0	8.2	6.4	4.2	3.4
Midstream verticals								
Average for 3 points of observation on rivers with sandy beds	S			7.2	6.4	4.0	2.4	1.4
	0.2D	2.84	2.56	5.4	4.8	3.4	2.0	1.6
	0.6D	to	to	5.6	5.0	2.6	1.6	1.2
	0.8D	6.10	0.50	8.4	7.0	4.8	3.0	2.4
	B			8.8	7.8	4.8	3.4	2.6

Note: D and V are depth and velocity range, respectively.

The statistical terms for dispersion used by Dement'ev are: mean quadratic error (one standard deviation), arithmetic error (0.8 standard deviation), and probable error (0.674 standard deviation). In the presentation of these results the 95 per cent confidence level has been used and taken to equal 2 1/2 times the arithmetic error and 3 times the probable error.

The early Russian work was apparently concerned in obtaining the exposure time required to achieve a ±4 percent accuracy at the 95% level.

The first general conclusions as to the nature of velocity pulsation in the rivers of the plains can be drawn from the investigations of A.R. Garlyakher on the Elbe River in the 1870's and by E. Lauda on the Danube at Vienna in 1897. As a result of this work, it was established that:

1) pulsation of velocity in the same vertical increased with depth and is greatest near the bottom;

2) velocity pulsation in the transverse profile of the river increased from the midstream towards the banks;

3) with an increase in velocity the pulsation in the vertical increases;

4) pulsation increases with an increase in roughness (especially with an ice cover).

In 1903, N.N. Zhukovskiy studied the velocity pulsation of the current on the Volga River and confirmed the general conclusions as to the distribution of pulsation in the cross-section of the river and as to its dependence on the roughness of the bed, which were drawn from Garlyakher's investigations.

The results of several investigations carried out during the period of 1907-1932 are summarized in Tables 4.3 and 4.4. A summary of the results based on field measurements made by the Central Asian Expedition are presented in Tables 4.5, and the analysis of the effects of pulsations on the accuracy of measurements of velocity during various phases of the regime are shown in Table 4.6. The meter time exposures required to achieve a ±4% accuracy, at the 95 per cent level, for a point velocity (i.e. surface, 0.2D, 0.6D, 0.8D, and bottom), and for different locations in the metering section and various phases of the flow regime are presented in Tables 4.7 and 4.8.

The conclusions reached by Dement'ev, based on the analysis of large amounts of data of field measurements (mainly on mountain rivers), are summarized below:

1. A distinguishing characteristic of natural rivers is the presence of waves of large scale pulsations of stage, velocity of flow, and of discharge. The periods of the waves of large scale pulsations amount to from 1-3 to 40-50 minutes or more.

2. The pulsation of velocity in medium and small mountain rivers with pebble-stony beds and swift currents is considerably more clearly expressed and in magnitude exceeds the pulsation observed in plains rivers.

Table 4.6 Effect of pulsation of velocities in mountain rivers on the errors of measurement of the velocity in midstream verticals during various phases of the regime - Dement'ev (1962)

		Percentage standard deviation for exposure, in minutes				
	Regime/ Depth	0.5	1	2	5	10
Average of 5 mountain rivers including: Chirchik Pskem Chatkal Ugam Vakhsh	High water					
	Surface	6.4	4.8	3.4	2.4	1.6
	0.2 D	6.0	4.4	4.0	3.0	2.2
	0.6 D	8.4	6.4	5.6	4.2	2.8
	0.8 D	10.8	9.0	7.4	5.6	4.0
	Bottom	21.6	16.8	13.2	8.0	4.9
	Low water					
	Surface	4.6	2.8	3.0	1.6	0.8
	0.2 D	4.2	2.8	2.4	1.6	1.0
	0.6 D	6.4	4.8	4.2	2.8	2.0
	0.8 D	10.6	7.4	6.2	4.0	3.0
	Bottom	14.2	10.0	8.2	5.6	4.2

Table 4.7 Duration of current meter exposure (in minutes) at standard points in mountain rivers required to obtain an accuracy of velocity measurements of ± 4% (95 % level) - Dement'ev (1962)

Relative depth of the point	bankside verticals	Midstream verticals
Surface	2	1.5
0.2 D	3	1.5
0.6 D	5	3
0.8 D	10	5
Bottom	>10	10

Table 4.8 Duration of current-meter exposure (in minutes) at standard points for plain reaches required to obtain accuracy of velocity measurements of ± 4% (at the 95% confidence level) -Dement'ev (1962)

Relative depth of the point	Phase of the regime	
	High Water	Low Water
Surface	1.5	1
0.2 D	1.5	1
0.6 D	2	1
0.8 D	3	2
Bottom	4	3

3. The magnitude of pulsation on mountain rivers increases with the velocity of flow in the vertical or in the water cross-section.

   The errors of measurements of the mean point velocity and of velocity in the vertical are usually greater during high water than during low water.

4. The magnitude of pulsation increases with the roughness of the bed; it is considerably less in rivers with sandy beds and greater in those with pebble-stony beds, especially when boulders are present.

   Pulsations in the transverse profile increase from midstream to the banks.

5. Pulsation in the vertical of an open channel as a rule increases from the surface to the bottom, where it reaches a maximum.

6. On mountain rivers the 100-120 second exposures of current-meter recommended, do not ensure the required accuracy of measurement of individual points velocities or of the average velocity in the vertical.

   The percentage standard deviation due to pulsation in measuring point velocities for 2 minute exposure can reach 10-20% and in individual cases 40% (at the 95 per cent level).

7. With the usual hydrometric method the error of measurement of water discharge as a whole, resulting from pulsations, is not great, because of the velocity fluctuations in individual parts of the water cross-section are, to a large extent, compensated when they are summed up. The error due to pulsation is less than the errors resulting from other causes particularly the obliqueness of currents.

   The error in discharge resulting from pulsations, when computed by the theory of errors, was of the order of 3% for a 2 minute exposure. With unfavourable conditions (gauging sites with increased turbulence) the error might reach 6-8%.

8. Field measurements of large scale pulsations of velocity and of discharge in natural rivers are of great interest, both scientifically and practically, and must be continued and extended to investigations of rivers of various sizes with various hydraulic conditions.

Anderson (1961), Carter and Anderson (1963)

Anderson (1961), Carter and Anderson (1963) studied the nature of the fluctuations in velocity at gauging sites on 23 different streams in the United States. The measuring sections ranged in depth from 0.73 to 8.14 m and the velocities from 0.13 to 2.41 m/s.

Average velocities for consecutive time periods of 15, 30, 45, 60, 90, 120, 180, and 240 seconds were observed at points corresponding to 0.2, 0.4, 0.6, 0.8 depth for a 1-hour period. It should be noted that Anderson (1961) stated that the error was evaluated by comparing the mean velocity at a point for short time periods with the mean for a 2-hour period.

The percentage standard deviation of velocity pulsations about the mean velocity at the 95 per cent level of all the results is shown in Table 4.9. It should be noted that Carter and Anderson (1963) used the 68 per cent confidence level (i.e. one standard deviation). All their results have therefore been doubled.
After statistical analysis of the data, Carter and Anderson (1963) concluded that:

1) little correlation existed between consecutive values of point velocities. The average correlation coefficient was 0.17;

2) little correlation existed between the ratio of the velocity at each point to the mean in the vertical observed simultaneously, i.e. with current meters placed at several points in the vertical;

3) no correlation existed between the standard deviations (listed in Table 4.9) and the depths or the velocity of the streams;

4) the velocity fluctuations can be assumed to be randomly distributed in time and space in a given cross-section.

Finally, Carter and Anderson stated that the standard deviation of the pulsations in the section depends on the number of observations taken during a measurement. For example, if the 0.6D method is used and a single observation is taken for 45 seconds on each of the 20 verticals then the percentage standard deviation of the velocity pulsations is the percentage standard deviation of their mean, i.e., $11.2/(20)^{1/2} = 2.5$ % (at the 95 per cent level).

International Organization for Standardization (ISO 1971)

In 1968, in Paris, member countries of ISO were asked to investigate the error in the mean velocity at a point in the vertical due to pulsations using the following procedure (ISO 1088, Clause 3):

i) three verticals in the cross-section should be selected; at the deepest point and at depths of 0.6 and 0.3 of the deepest point;

ii) in each of these three verticals velocity measurements should be made at 0.2 D, 0.6 D, 0.8 D, and 0.9 D from the surface;

iii) each measurement should consist of an uninterrupted observation of 50 minutes, by a current meter, taking a reading every 30 seconds.

Data from 17 international rivers (ISO 7178, 1983) were processed with velocities ranging from 0.13 to 2.41 m/sec. The rivers included: Columbia and Mississippi Rivers in the United States; Lambourn, Derwent, Usk, Ouse, Tyne, Eden, Clyde Rivers, Gala Water, Yarrow Water, and Ettrick Water Rivers in the United Kingdom; IJssel River in The Netherlands; Yamuna, Ganga, Jalangi Rivers, and Visvesvaraya Canal in India. Exposure times of 30 seconds only were processed, and as in the Russian and American tests the total duration of the tests was restricted to 50 minutes.

A summary of the ISO results is presented in Table 4.10.

Table 4.9 Uncertainty due to limited time of exposure (at 95% level) - Carter and Anderson's results

Point d/D	Standard deviation (%) for indicated time, sec 15	30	45	60	90	120	180	240
0.20	11.4	9.4	8.4	7.6	6.6	5.8	5.0	4.0
0.40	11.8	10.0	9.0	7.8	7.0	6.0	5.2	4.6
0.60	15.0	12.8	11.2	10.4	10.4	9.2	7.2	6.8
0.80	20.6	16.0	14.4	12.8	11.2	10.0	8.8	7.2
$\frac{0.2+0.8}{2}$	11.8	9.2	8.4	7.4	6.6	5.8	5.0	4.2

Table 4.10a Characteristics of rivers from which data were collected for the ISO investigation

Country	River	Location	Year of measurement
USA	Mississippi	Vickburg	1963 1964
USA	Columbia	Bridgeport, Washington	1963
India	Ganga	Varanasi	1966
India	Jalangi	Swarup Ganj	1966
India	Visvesvaraya Canal	40 km from Krishnaragasagar	1967
India	Yamuna	Partappur	1967
The Netherlands	IJssel	Doesburg km 902, 630	1968 1969
United Kingdom	Usk	Llandetty	1969
United Kingdom	Lambourn	Hunt's Green	1969
United Kingdom	Tyne	Bywell	1969
United Kingdom	Eden	Sheepmount Carlisle	1969

Note: Data at several other rivers were collected but not processed, i.e., Rivers Ouse, Derwent, Gala Water, Yarrow Water, Clyde, Ettrick Water, Spey, Tay, and Tweed in the United Kingdom.

Table 4.10b ISO summary of pulsation results showing standard deviations at the 95% for 30 second exposure times and a time of duration of 50 minutes.

Percentage Standard Deviation (95 % level) due to pulsations											
Vertical at maximum depth				Vertical at 0.6 of maximum depth				Vertical at 0.3 of maximum depth			
0.2D	0.6D	0.8D	0.9D	0.2D	0.6D	0.8D	0.9D	0.2D	0.6D	0.8D	0.9D
11.8	17.4	19.2	23.1	12.1	16.1	17.6	18.6	11.9	15.3	19.7	20.3

Savini and Bodhaine (1971)

The following experiments were performed by these authors on the Columbia River, from 1961 to 1964:

- velocities were observed continuously for 4 minutes at each of 10 points in four or five selected verticals across the measuring section at three gauging sites on the Columbia River. These data were divided into intervals of 1, 2, and 4 minutes.

- synchronous velocity observations at 10 points in a vertical were recorded continuously for 66 minutes. Ten current meters were suspended on a long hanger bar at 0.10 depth intervals beginning at 0.05 depth from the water surface. The recorder was connected to each of the current meters, and at every fifth revolution, a signal was recorded on the strip chart. From the strip chart, velocities were determined for each 1-minute interval.

The principal characteristics of the rivers investigated by Savini and Bodhaine are given in Table 4.11a.

From the examination of the sixty-six 1-minute vertical velocity curves developed from the data in the 66-minute run, Savini and Bodhaine showed that no two curves are exactly alike in shape or in the vertical distribution of velocity. Although the shape and velocity distribution of the 66 curves differ, the mean velocity of one or more of these curves is often the same. There are 43 curves (19 sets) out of the sixty-six 1-minute curves that have mean velocities that are almost the same. Velocities at specific depths fluctuated considerably with no apparent relationship to changes in velocity above and below those depths. The largest variations in velocity occurred at the 55 percent depth; and the smallest were near the stream surface. The uncertainties (at the 95% level) ranged from 8.2% at the 5 percent depth to 22.0% at the 95 percent depth. These results are summarized in Table 4.11b.

Also, data obtained from the 66-minute run indicate that the ranges in velocities decrease rapidly between 1 and 4 minutes, then decrease at a gradual rate thereafter. Savini and Bodhaine then concluded that there is little need to extend a set of observations beyond about 4 minutes.

Preamble to Herschy's Investigation

The objectives of the three above investigations (Carter and Anderson, Dement'ev, and ISO) was to examine the uncertainty in the measured velocity at a point in the vertical due to the effect of pulsations in the flow and to make recommendations as to the amount of dispersion about the measured velocity.

These studies and tests indicated that:

1. the uncertainty due to pulsations varied with depth and with the position of the vertical in the cross-section;

2. the uncertainty due to pulsations varied with the velocity;

3. the uncertainty due to pulsations decreased with an increased in exposure time;

Table 4.11a Principal river characteristics of the Columbia River - Savini and Bodhaine (1971)

Station	Discharge (cfs)	Area (sq. ft)	Width (ft)	Mean depth (ft)	Maximum depth (ft)	Mean vel. (ft/s)
At Grand Coulee	505000	44600	785	56.8	91.7	11.32
	75600	22100	560	39.5	56.8	3.42
At Bridgeport	488000	43000	1100	39.1	52.1	11.36
	64800	13600	850	16.0	23.7	4.76
At Rocky Reach Dam	506500	53000	1270	41.7	61.6	9.56
	59800	25800	910	28.4	36.4	2.35
At Trinidad	531800	48300	1470	32.9	60.1	11.01
	60400	16800	750	22.4	30.2	3.60
Below Priest Rapids Dam	505900	54200	1305	41.5	53.5	9.33
	72000	24800	1130	21.9	29.1	3.10
Paterson Ferry	604100	85200	2490	34.2	46.5	7.00
	84500	44000	2210	19.9	27.0	1.92
Hood River Bridge	648500	192000	4150	65.7	46.1	3.39
	194800	137000	3910	52.0	35.1	1.42

Table 4.11b One-minute simultaneous velocity measurements for 66 minutes - Columbia River - Savini and Bodhaine (1971).

Percent of Depth	Percentage Deviation (95% level)	Mean Velocity (ft/s)
5	8.2	3.89
15	8.8	3.81
25	9.2	3.72
35	10.6	3.62
45	11.0	3.52
55	12.2	3.37
65	13.8	3.20
75	15.8	3.02
85	17.6	2.70
95	22.0	2.14
mean	10.2	3.30

4. pulsations waves of up to 20 minutes were present at one particular site;

5. pulsations of water level were observed to be related to pulsations in flow;

6. pulsations and their effect varied from river to river.

A summary table, showing comparing the results of Russian, American, and ISO investigations, is presented in Table 4.12.

Herschy (1975)

Herschy conducted a detailed investigation into the effect of velocity pulsations on the accuracy of a current-meter measurement.

Prior to this investigation, the British Standard simply suggested an exposure time of at least 40 seconds and recommended a standard error for this exposure time of 12% (at the 95 per cent level) to allow for random fluctuations in velocity due to pulsations.

Based on the experience gained by the Russian, American, and ISO investigations, Herschy decided to use 40 current meters in the measuring section, the distribution being 8 verticals with 5 meters on each vertical, i.e. at 0.2 D, 0.4 D, 0.6 D, 0.8 D, and 0.9 D from the surface (according to ISO 768). The current meters chosen were the Braystoke propeller meters. Three sites were selected, River Derwent at Low Hutton, and at Samford Bridge; and River Rye at Nunnington (see Table 4.13).

Before the tests, the sections were cleared of weeds, debris, and trash, etc. The duration of the tests ranged from 4 to 6 hours, with readings every 30 seconds.

More than forty thousand 30-sec exposures of velocities were processed and analyzed in order to investigate the effect of an increase in exposure time on the standard deviation. Herschy, then concluded that :

1. The standard deviation (95 % level) decreased with an increase in exposure time;

2. The distortion normally found in vertical velocity curves is due to pulsations in velocity. The times of exposure normally used in river gauging (1 to 3 minutes) are not adequate to reduce the scatter to obtain curves approaching the logarithmic distribution.

3. In general, the largest value of the standard deviation in any single vertical is found at 0.8 D (or 0.9 D where a reading had been taken);

4. For the points 0.2 D, 0.4 D, 0.6 D there was a definite tendency for the standard deviation to increase from 0.2 D to 0.6 D if the velocities decreased. Where velocities did not decrease this rule generally no longer applied;

5. The standard deviations of the velocities due to pulsations were dependent on both the measured value of the velocity at any point and the depth of that point in the vertical;

Table 4.12 Comparison of Russian, United States and ISO results, in percentage standard deviation at the 95% level.

Author(s)	Depth of Points	Velocity Range (m/s)	Exposure time, in min.				
			0.5	1	2	4	5
Anderson (1961) Carter and Anderson (1963)	0.2D	0.13	9.4	7.6	5.8	4.0	-
	0.6D	to	12.8	10.4	9.2	6.8	-
	0.8D	2.41	16.0	12.8	10.0	7.2	-
Dement'ev (1962)							
<u>Pebble-Stony Beds</u>							
Bank Verticals	0.2D	0.12	11.0	8.0	4.4	-	3.2
	0.6D	to	11.6	10.0	5.6	-	4.2
	0.8D	2.96	16.4	12.4	8.6	-	6.2
Midstream Verticals	0.2D	0.40	6.0	4.2	3.6	-	2.6
	0.6D	to	8.1	6.0	4.8	-	3.2
	0.8D	4.86	12.4	9.6	6.8	-	4.2
<u>Sandy Beds</u>							
Bank Verticals	0.2D	0.54	7.6	6.0	3.6	-	2.6
	0.6D	to	7.2	7.8	5.2	-	3.6
	0.8D	1.78	11.0	8.2	6.4	-	4.2
Midstream Verticals	0.2D	0.50	5.4	4.8	3.4	-	2.0
	0.6D	to	5.6	5.0	2.6	-	1.6
	0.8D	2.56	8.4	7.0	4.8	-	3.0
ISO (1971) Verticals at Maximum depth	0.2D	0.02	11.8				
	0.6D	to	17.4				
	0.8D	1.97	19.2				
Vertical at 0.6 maximum depth	0.2D	0.14	12.1				
	0.6D	to	16.1				
	0.8D	2.17	17.6				
Vertical at 0.3 maximum depth	0.2D	0.16	11.9				
	0.6D	to	15.3				
	0.8D	1.11	19.7				

Table 4.13 Sites selected - Herschy's Investigation

River	Max Vel. (m/s)	Depth (m)	Width (m)
River Derwent at Low Hutton	0.3	1-2	22.5
River Derwent at Stamford Bridge	0.37	1-1.8	22.5
River Rye at Nunnington	0.4	0.7-1.3	11.0

6. The differences in the standard deviations between 0.2 D, 0.4 D, and 0.6 D were due more to the differences in velocities than to the position in the vertical;

7. In general, the standard deviations appeared to follow the values of the velocities and increased from the surface to the bed as the velocities decreased;

8. The values of percentage standard deviation recommended for British rivers are presented in Table 4.14. This table shows the standard deviations for corresponding point velocities in metres per second and exposure time of 30 seconds, and 1, 2, and 3 minutes. It should be noted that instead of averaging the standard deviations for the respective depths in the vertical irrespective to velocities (as was done by Russian and American investigations), the standard deviation of velocity pulsations was related to both velocity and depths in the vertical.

9. It is inadvisable to employ a single 30 second exposure time other than for unavoidable occasions such as measurements of floods where the time factor is of utmost importance because of the rapidly changing stage.

10. In using Table 4.14, for the 2 point method, the overall value should computed by averaging the 2 corresponding values.

11. Although the investigations were for 3 rivers sections only, the conclusions and results can be applied to most British lowland and highland rivers where sufficient depth is available to dissipate the effect of the bed and well defined control affords a reliable stage-discharge relation.

Summary

Generally, these studies and tests have shown that the uncertainty due to pulsations:

- varied with depth and with the position of the vertical in the cross-section;
- varied with the velocity. In general the uncertainty increased from the surface to the bed as the velocities decreased;
- decreased with an increase in the time of exposure; and
- pulsations and their effects varied from river to river.

Also, Herschy (1975a) showed that the differences in uncertainty between the 0.2, 0.4, and 0.6 of the depth were due more to the differences in velocities than to the position in the vertical.

Pulsation effects were also analyzed and quantified by Kalinske (1945) in the U.S.A., Karasev and Chizhov (1970) in the U.S.S.R., Botma (1970) in the Netherlands, Muszkalay (1970, 1979) in Hungary, Asano (1983) in Japan and the U.S.A., and Reid and Pentland (1964) and Pelletier (1988c, 1989) in Canada.

Table 4.14 Percentage standard deviation (95 per cent level) of velocity pulsations - general application to British Rivers (based on Yorkshire Rivers Investigation)

Velocity m/s	Point in Vertical: 0.2 D 0.4 D or 0.6 D				0.8 D or 0.9 D			
	Exposure Time, in Minutes							
	0.5	1	2	3	0.5	1	2	3
0.050	50	40	30	22	80	60	50	40
0.075	33	26	19	16	50	40	28	23
0.100	27	22	16	13	33	27	20	17
0.125	22	19	14	11	27	22	16	14
0.150	19	16	12	9	22	20	14	12
0.175	17	14	10	8	19	16	12	10
0.200	15	12	9	7	17	14	10	8
0.225	13	10	8	6	15	12	9	7
0.250	12	9	7	6	13	10	7	6
0.275	11	8	7	5	11	8	7	6
0.300	10	7	6	5	10	7	6	5
0.400	8	6	6	5	8	6	6	5
0.500	8	6	6	4	8	6	6	4
0.5-1.0	7	6	6	4	7	6	6	4
Over 1.0	7	6	5	4	7	6	5	4

The results of the Russian (Dement'ev, 1962), and American (Carter and Anderson, 1963) research are shown in Figure 4.2a. In contrast, Herschy (1975a) carried that analysis a step further by establishing a relation between the uncertainty due to pulsations and the velocity (see Figure 4.2b). Also, in Herschy's investigation, up to 40 current meters on 8 verticals were operated simultaneously. Because the data are to be analyzed statistically, and pulsation waves of 20 to 40 minutes have been observed (Dement'ev, 1962), the sample taken should be as long as possible. It was found, however, that the total time of exposure to determine the "true" mean velocity differed greatly from one investigation to another (e.g. 60 minutes for Carter and Anderson [1963] to 4 to 6 hours for Herschy [1975a]).

There are large differences between uncertainty values given by the investigators, as shown in Figure 4.2. Based on their particular experiments, the different investigators recommended values to their respective water agencies. Dement'ev (1962) recommended that the duration of current meter exposure in mountain streams be between 1 and 3 minutes at 0.2 depth (between 1 and 2 minutes for plain reaches), and from 5 to 10 minutes at 0.8 depth (between 2 and 3 minutes for plain reaches), instead of the 100 seconds recommended in the U.S.S.R. manual (Main Administration of the Hydrometeorological Service, 1975). These exposure times would be required in order to obtain a ±4% measurement accuracy. Herschy (1975a) and ISO 748 (1979) reported that in order to achieve a ±4% measurement accuracy, an exposure time of 3 minutes would be necessary. In comparison, Carter and Anderson (1963) reported that an exposure time of 45 seconds would provide a measurement accuracy of ±4%.

In summary, the time of exposure for a velocity observation should be selected based on the desired level of accuracy.

Therefore, there is a definite need for research into the influence of velocity pulsation on the accuracy of discharge measurement, as pointed out by several authors, including Dickinson (1967), and Starosolszky (1983). Such study should be conducted using pre-established guidelines (ISO 1088, 1985).

The knowledge gained from this type of investigation would necessarily result in improvements to the instrumentation and data.

4.4.2 Uncertainty due to the limited number of points in the vertical

The computation of the mean velocity in a given vertical as an average or a weighted average of a number of point velocities results in an approximation of the true mean velocity in the vertical considered.

The uncertainty due to the limited number of points used in the vertical does not take into account uncertainties due to pulsation and is related to the shape of the vertical velocity curve.

The two-point method (0.2 and 0.8 depth) is based on investigations in the early 1900's and also on the theory that the vertical velocity curve corresponds to part of a parabola with the axis horizontal at the point of maximum velocity, for which the average velocities at 0.2114 and 0.7886 of the depth is equivalent to the mean velocity (Barrows and Horton, 1907;

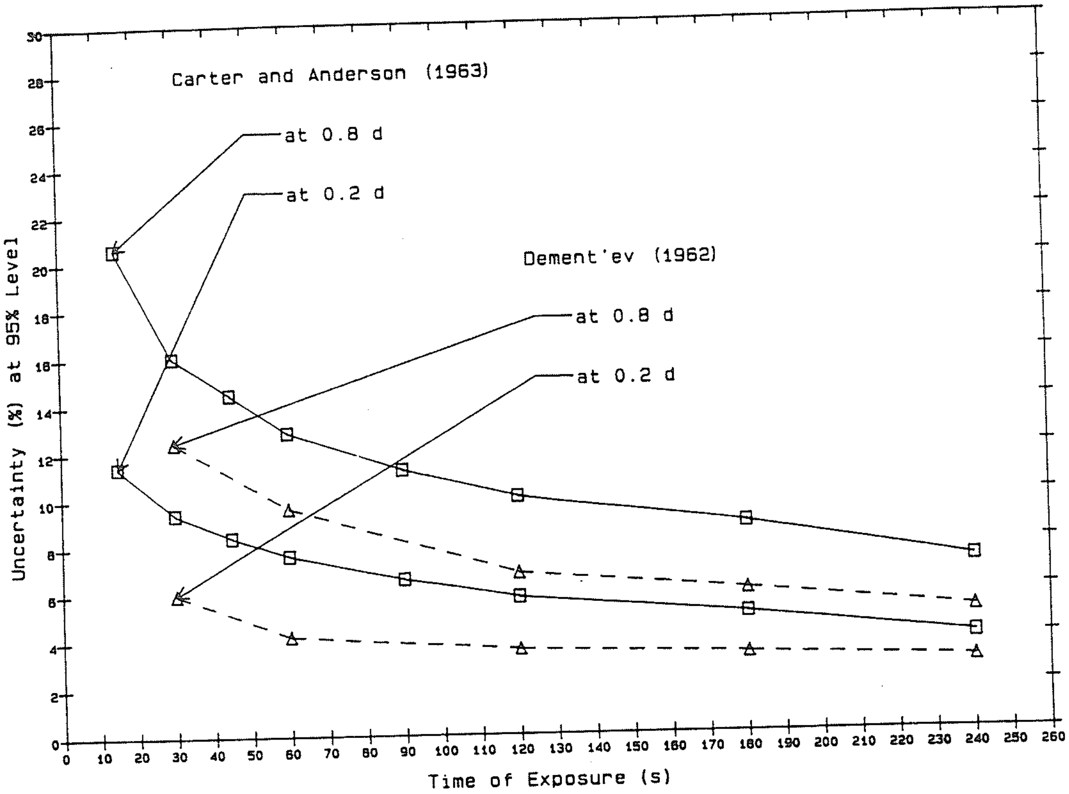

Figure 4.2a Uncertainty due to limited time of exposure (95% level) U.S.A. and U.S.S.R. results.

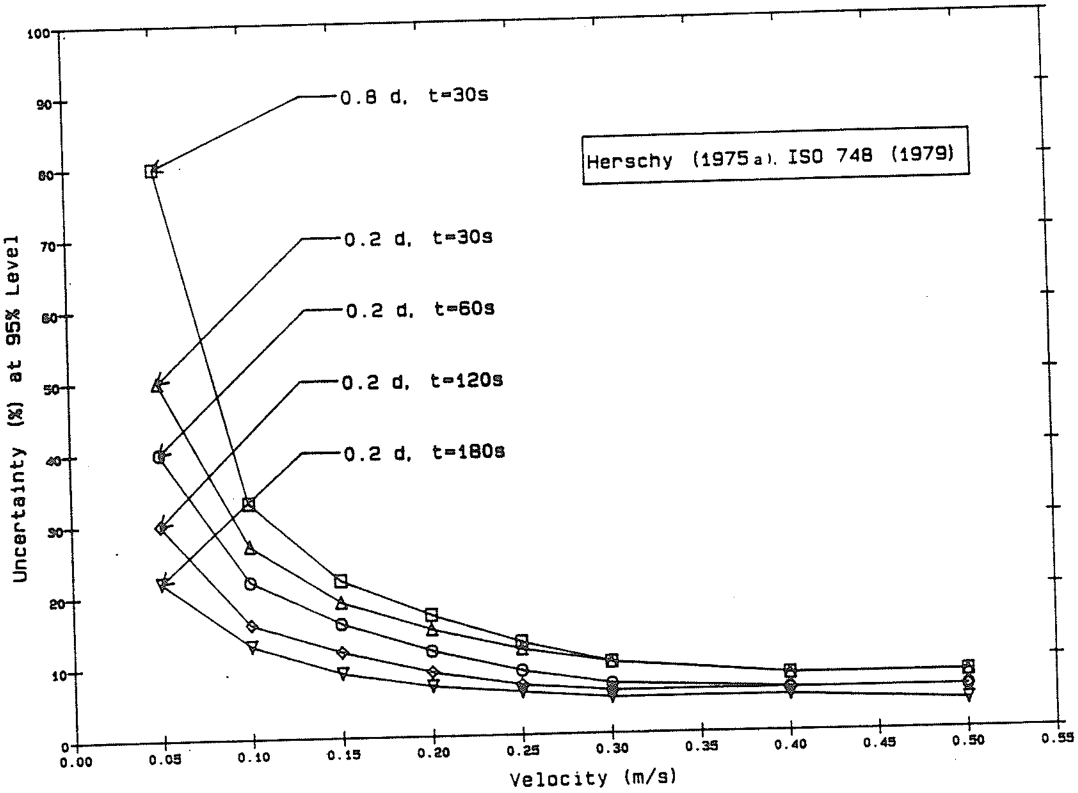

Figure 4.2b Uncertainty due to limited time of exposure (95% level) U.K. and ISO results.

Hoyt, 1910; Barrows in discussion in Hoyt, 1910; Pardoe, 1916; Liddell, 1927; Corbett et al., 1957).

The one-point method (0.6 depth) is also based on the theory that the vertical velocity curve is a parabola with the maximum abscissa between zero and one-third the depth, in which case the mean ordinate lies between 0.58 and 0.67 of the depth below the surface (Hoyt, 1910; Pardoe, 1916; Liddell, 1927; Corbett et al., 1957).

In Canada, the 0.6 depth method is used for measurement where depths are less than 0.75 m, and the 0.2 and 0.8 depth method where depths are greater than 0.75 m (Terzi, 1981).

A major investigation into the vertical velocity curves for streams under ice cover was carried out by Barrows and Horton (1907). Their investigation resulted in the adoption of the two-point method. They recommended, however, that several velocity curves be sampled and correction coefficients be established. This procedure was also recommended by several authors, including Hoyt (1913), Corbett et al. (1957), Rouse (1959), Rantz et al. (1982), and Herschy (1985). It is not, however, considered a standard field procedure. Barrows and Horton (1907) found that the average coefficient for obtaining the mean of velocity from mean velocity at 0.2 and 0.8 depth was 1.002, the range being 0.98 to 1.04. The average coefficient for obtaining mean velocity from that at mid-depth (0.5 depth) was 0.878, the range being 0.82 to 0.92.

Uncertainties based on experiments and discussions of experimental vertical velocity profiles may also be found in Kasugaya (1958a), Prochazka (1960), Hulsing et al. (1966), Bennett (1968), Botma (1970), Bridge and Jarvis (1977), Bonacci (1979), Morton (1983), and Pelletier (1987a). However, the samples used were generally small.

Theoretical and empirical analysis of vertical velocity curves have been carried out by Vanoni (1941), Kolupaila (1964), Matalas and Conover (1965), Dickinson (1967), and Lau (1982). The theoretical velocity profiles analyzed by these and other authors include logarithmic, parabolic, hyperbolic, and elliptic profiles.

In practice, both the parabolic and logarithmic velocity distributions are used to approximate the actual velocity distribution (Gray, 1973).

Since the turn of the century, many streams have been investigated for the number of points taken in the vertical. Murphy (1902a, 1904) analyzed data from southern rivers in the U.S.A. with 301 vertical velocity curves and conducted flume experiments; Hoyt and Grover (1907) analyzed more than 1605 vertical velocity curves; Harding (1915) analyzed 96 measurements from canals and flumes; Carter and Anderson (1963) analyzed data from 100 streams in the U.S.A.; Herschy (1970, 1975a) analyzed data from 2 streams in the U.K. (565 velocity curves from the Derwent River and 115 curves from the Thames River); Savini and Bodhaine (1971) analyzed data from the Columbia River (600 vertical velocity curves); and ISO 7178 (1983) investigations (ISO DATA 2, 1978) included the analysis of data from 13 international rivers.

The results from some of the investigations will be further analyzed and discussed below.

Hoyt and Grover (1930)

Based on stream gaugings obtained from 1905-1916 by the U.S. Geological Survey, Hoyt and Grover (1930) prepared 1605 vertical velocity curves. The results of these experiments are summarized in Table 4.15.

They established that water moved in the vertical in the form of a logarithmic distribution and that in particular, the reduced points methods (2 or 1 point) gave the mean in the vertical within close limits, these points giving the mean in a logarithmically distributed curve (Vanoni 1941).

Todd and Whitaker (1961)

Verticals from 3 international rivers were examined, including: 28 verticals from River Adige (Italy); 24 verticals from River Bovenrijn (Holland); and 4 verticals from River Volga (U.S.S.R.).

A summary of their results is presented in Table 4.16.

Anderson (1961), Carter and Anderson (1963)

Over 100 stream sites were analyzed by Anderson (1961). Observations were made at 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 95 % depth at from 25 to 30 verticals at each site. The ratio of the velocity at each point to the mean in the vertical was computed for approximately 1800 sets of data. The results are shown in Table 4.17.

The mean ratio for the average of the 0.2 and 0.8 observations is exactly one, and the percentage standard deviation, at the 95 per cent level, 8.6%.

Additional analysis of the data showed that the average correlation coefficient, r, between ratios for a given section was 0.04.

Carter and Anderson proposed to compute the standard deviation of the section ratio, by using the following equation

$$S_s = \frac{S_{rs}\ [1 + (N-1)\ r]^{1/2}}{(N)^{1/2}} \qquad \ldots (4\text{-}3)$$

where N is the number of verticals, and S_{rs} is the standard deviation of velocity ratio.

International Organization for Standardization (1971)

ISO examined 23 stream sites from 13 international rivers. The velocities were measured at 10 different points in the vertical, i.e. near the surface; 0.2 D; 0.3 D; 0.4 D; 0.5 D; 0.6 D; 0.7 D; 0.8 D; 0.9 D ; and near the bed. The exposure time was 1 minute, and the measurement was repeated 5 times. The mean velocity was determined by planimeter and this velocity was taken as the basis for comparison of the reduced point methods.

A summary of the results is given in Table 4.18.

Table 4.15 Percentage standard deviation due to limited number of points taken in the vertical (95 % level) - Hoyt and Grover (1930)

Method	Percentage standard deviation <u>estimated</u> (95 % level)
2 point	3
1 point	4

Table 4.16 Percentage Standard Deviation due to the limited number of points taken in the vertical - Todd and Whitaker (1961)

Method	Percentage Standard Deviation (95 % level)
6 points	1.8
5 points	2.9
3 points	4.3
2 points	5.4
1 point	8.5

Table 4.17 Mean Ratio and Percentage Standard Deviation of the mean velocity at various relative depths in the vertical (at the 95 per cent level) - Carter and Anderson (1963)

Point $1-y/y_o$	Mean ratio p	Percentage Standard Deviation (95% level) S_p
0.1	1.111	-
0.2	1.118	30.2
0.3	1.109	-
0.4	1.106	-
0.5	1.053	-
0.6	1.007	22.4
0.7	0.930	-
0.8	0.837	45.2
0.2-0.8	1.000	8.6

Table 4.18 Percentage Standard Deviation due to the limited number of points taken in the vertical - ISO/TR 7178 (1983)

Method	$\bar{V}$	Percentage Standard Deviation (95% level)
6-pts	$0.1(V_{surface}+2V_{0.2}+2V_{0.4}+2V_{0.6}+2V_{0.8}+Vbed)$	4.2
5-pts	$0.1(V_{surface}+3V_{0.2}+3V_{0.6}+2V_{0.8}+V_{bed})$	4.4
3-pts	$0.25(V_{0.2}+2V_{0.6}+V_{0.8})$	8.8
2-pts	$0.50(V_{0.2}+V_{0.8})$	6.8
1-pt $V_{0.6}$		15.0
other methods tested		
$\bar{V} = 0.96\ V_{0.5}$		9.6
$\bar{V} = 0.4\ V_{0.2} + 0.3\ V_{0.6} + 0.25\ V_{0.8}$		6.6
$\bar{V} = 1/2\ (V_{0.2} + V_{0.6} + V_{0.8})$		7.4
$\bar{V} = 1/4\ (V_{0.2} + V_{0.4} + V_{0.7} + V_{0.9})$		4.4
$\bar{V} = 1/6\ (V_{surface} + V_{0.2} + V_{0.4} + V_{0.6} + V_{0.8} + V_{bed})$		5.0

Savini and Bodhaine (1971)

Seventeen discharge measurements were made at seven gauging sites on the Columbia River, in Washington and in Oregon, U.S.A. A minimum of two measurements were made at each site. From 22 to 40 verticals were included in each discharge measurement. Velocities were observed at 10 points in each vertical and these velocity observation points were spaced at intervals of 0.10 depth beginning at 0.05 depth (5 percent of total depth measured from water surface at indicated vertical) and ending at 0.95 depth, except where the distance from the 0.95 depth to the streambed was less than the 1.5 foot distance between the current meter and the base of the sounding weight. In addition to the 10 velocity observations, velocities were also observed at 0.20 and at 0.80 depths. Note that a predetermined sequence of measuring the velocities was not used for all measurements.

Ten-point velocity observations were made at selected verticals during regular discharge measurements at four gauging sites.

From these experiments, Savini and Bodhaine concluded that:

- the shape of the vertical velocity curve differs significantly from the shape assumed in practice (i.e. a parabola, the axis of which is parallel to the water surface; Corbett et al., 1957). The velocities generally increase continuously from the streambed to the water surface, the maximum occurring near the water surface.

- of the two methods for extending the vertical velocity curve below 0.95 depth, the logarithmic method showed no agreement at all between the log curve fitted to points plotted above and below that depth. The power function, when applied to that part of the velocity curve below 0.95 depth, agrees with the plotted data although agreement with field data above the 0.95 depth is not good.

- The averages of the continuous velocity observations for 66 minutes at 10 points constituted the basis for allowing construction of a smooth vertical velocity curve that increased continually from the streambed to the water surface. The 10-point mean was virtually identical to the integrated-curve mean.

- Both the integrated-curve and 10-point mean velocities were used as a basis for comparing the accuracy of mean velocities determined by other methods. The one- and two-point methods obtained velocities that were slightly greater than the mean velocity and yielded a mean velocity of acceptable accuracy (Table 4.19a).

Savini and Bodhaine did not calculate the uncertainties due to the limited number of points taken in the vertical. In order to assess this type of uncertainty in their data set, the data for Columbia River at Grand Coulee Dam were analyzed, and the final results are presented in Table 4.19b. It shows that the uncertainty (at the 95% level) in the two-point method, using 4 different measurements and 98 verticals, was 13%. Note that the mean velocity was based on the 10-point method.

Table 4.19a Comparison of mean velocities of discharge measurements of the Columbia River - Savini and Bodhaine (1971).

Date	Base river velocity	10-point mean		2-point mean		1-point mean	
		vel.	diff.	vel.	diff.	vel.	diff.
At Grand Coulee Dam, Wash.							
1961-04-24	4.81	4.81	0	4.84	+0.6	4.72	-1.9
1962-06-20	7.29	7.22	-1.0	7.40	+1.5	7.18	-1.5
1962-07-07	7.31	7.26	-0.7	7.43	+1.6	7.18	-1.8
1963-06-19	8.23	8.27	+0.5	8.32	+1.1	8.15	-1.0
At Bridgeport, Wash.							
1961-04-25	5.82	5.81	-0.2	5.80	-0.3	5.83	+0.2
1961-06-20	10.54	10.57	+0.3	10.47	-0.7	10.58	+0.4
At Rocky Reach Dam, Wash.							
1961-04-26	4.10	4.08	-0.5	4.10	0	4.09	-0.2
1961-06-21	8.93	8.87	-0.7	9.06	+1.4	8.93	0
1962-11-20	2.35	2.32	-1.3	2.35	0	2.31	-1.7
At Trinidad, Wash.							
1961-06-21	10.54	10.52	-0.2	10.50	-0.4	11.01	+4.4
1961-09-22	3.60	3.66	+1.7	3.60	0	3.75	+4.2
Below Priest Rapids Dam, Wash.							
1961-04-28	3.78	3.77	-0.3	3.77	-0.3	3.77	-0.3
1961-06-20	9.29	9.28	-0.1	9.29	0	9.25	-0.2

Cont. Table 4.19a Comparison of mean velocities of discharge measurements of the Columbia River - Savini and Bodhaine (1971).

Date	Base river velocity	10-point mean vel.	diff.	2-point mean vel.	diff.	1-point mean vel.	diff.
At Paterson Ferri, Oreg.							
1961-06-16	7.00	7.02	+0.3	7.00	0	7.02	+0.3
1961-10-11	1.90	1.89	-0.5	1.92	+1.0	1.92	+1.0
At Hood River Bridge. Oreg.							
1961-05-05	1.44	1.43	-0.7	1.42	-1.4	1.45	+0.7
1961-06-05	3.37	3.36	-0.3	3.39	+0.6	3.36	-0.3
Average			-0.2		+0.3		+0.1
Range			3.0		3.0		6.3

Notes: - Velocity in feet per second;

-Difference in percent;

-Base river velocity obtained by integrating the velocity curves.

Table 4.19b Uncertainties in point velocities for the the Columbia River at Grand Coulee Dam, U.S.A. - Savini and Bodhaine (1971).

Percent of depth	Uncertainties in correction factor required to convert a specific point velocity to the mean velocity			
	Dates of discharge measurements			
	1961-04-24	1962-06-20	1962-07-09	1963-06-19
0.05	26.62	15.86	23.89	17.99
0.15	18.25	14.44	16.11	29.15
0.20	20.56	16.26	15.74	18.08
0.25	13.59	18.42	15.32	14.56
0.35	19.72	13.02	11.60	13.02
0.45	19.48	18.78	26.90	19.65
0.55	16.65	21.25	16.01	16.28
0.60	12.27	14.81	19.30	14.16
0.65	20.44	24.77	26.69	23.59
0.75	27.22	32.63	23.59	26.50
0.80	62.17	38.30	18.42	24.90
0.85	23.88	42.58	21.81	29.00
0.95	40.47	38.20	128.84	119.85
$\frac{V_{0.2}+V_{0.8}}{2}$	14.45	13.99	10.94	12.22
number of verticals	18	26	28	26
ACF1[1]	1.046	1.033	1.018	1.011
ACF2[2]	0.995	0.982	0.984	0.996

[1]: average correction factor required to convert the velocity using the one-point method to the mean velocity

[2]: average correction factor required to convert the velocity using the two-point method and the mean velocity

Herschy (1975)

Previous investigations were reviewed and Herschy concluded that:

1. The results from previous studies did not show close agreement (see Table 4.20);

2. The exposure time was not long enough to eliminate or attenuate the uncertainty due to pulsation;

3. The investigation carried out by Hoyt and Grover, 60 years ago, was extensive. However, proper comparison with ISO, Carter and Anderson was not possible.

4. Carter and Anderson and ISO results for the 2 point method show good agreement (8.5 Vs 6.8 %). However, for the 1 point method (0.6 D) the agreement between Carter and Anderson, and ISO is not good, i.e., 22.4 vs 15.0 %, at the 95 per cent level.

Based on these considerations, Herschy investigated the uncertainty due to the limited number of points taken in the vertical. The investigation included the analysis of 565 vertical velocity curves for the River Derwent. The 5 point method was used. Exposure time ranged from 0.5 to 60 minutes.

The results are summarized in Table 4.21.

Based on Carter and Anderson (1963), ISO (1971), and his own investigation, Herschy recommended values (Table 4.22) for the evaluation of the uncertainty arising from the use of a limited number of points in the vertical.

Some of the results from Carter and Anderson (1963), Herschy (1975a), and ISO investigations are shown in Figure 4.3.

4.4.3 Uncertainty Due to the Limited Number of Verticals

In the computation of a discharge measurement, the depth and the velocity are assumed to vary linearly with the distance between the verticals in the cross-section.

The value of the uncertainty depends not only on the number of verticals, but also on the size and shape of the channel, the variation in the bed profile and the horizontal distribution of the velocity profile. In Canada, it is recommended that a minimum of 20 to 25 observation verticals be taken in the cross-section. For narrow streams, however, this is often reduced to fewer than 10 verticals.

The major studies of this type of error have been carried out on U.S. streams, with the exception of the ISO investigations. Harding (1915) analyzed 89 measurements from canals and flumes with an average of only 16 verticals; Carter and Anderson (1963) analyzed data from 127 stream sites, which included depth and velocity observations at more than 100 verticals per section; Herschy (1978a) analyzed 196 discharge measurements from streams of 46 U.S. states, using between 51 and 310 verticals; and ISO 7178 (1983) investigations (ISO DATA 2, 1978) included the analysis

Table 4.20 Comparison of Percentage Standard Deviation at the 95 per cent level - Herschy (1975b)

	2 point	1 point
Hoyt and Grover	3	4
Todd and Whitaker	5.4	8.5
Carter and Anderson	8.6	22.4
ISO	6.8	15.0

Table 4.21 Percentage standard deviation due to the limited number of points taken (based on River Derwent, Herschy 1974)

Method	Percentage standard deviation at the 95 per cent level
2 point	7
1 point	15

Table 4.22 Percentage standard deviation due to the limited number of points taken (based on Carter and Anderson, ISO, Herschy)

Method	Percentage standard deviation at the 95 per cent level
Velocity distribution	1
5 point	5
2 point	7
1 point	15

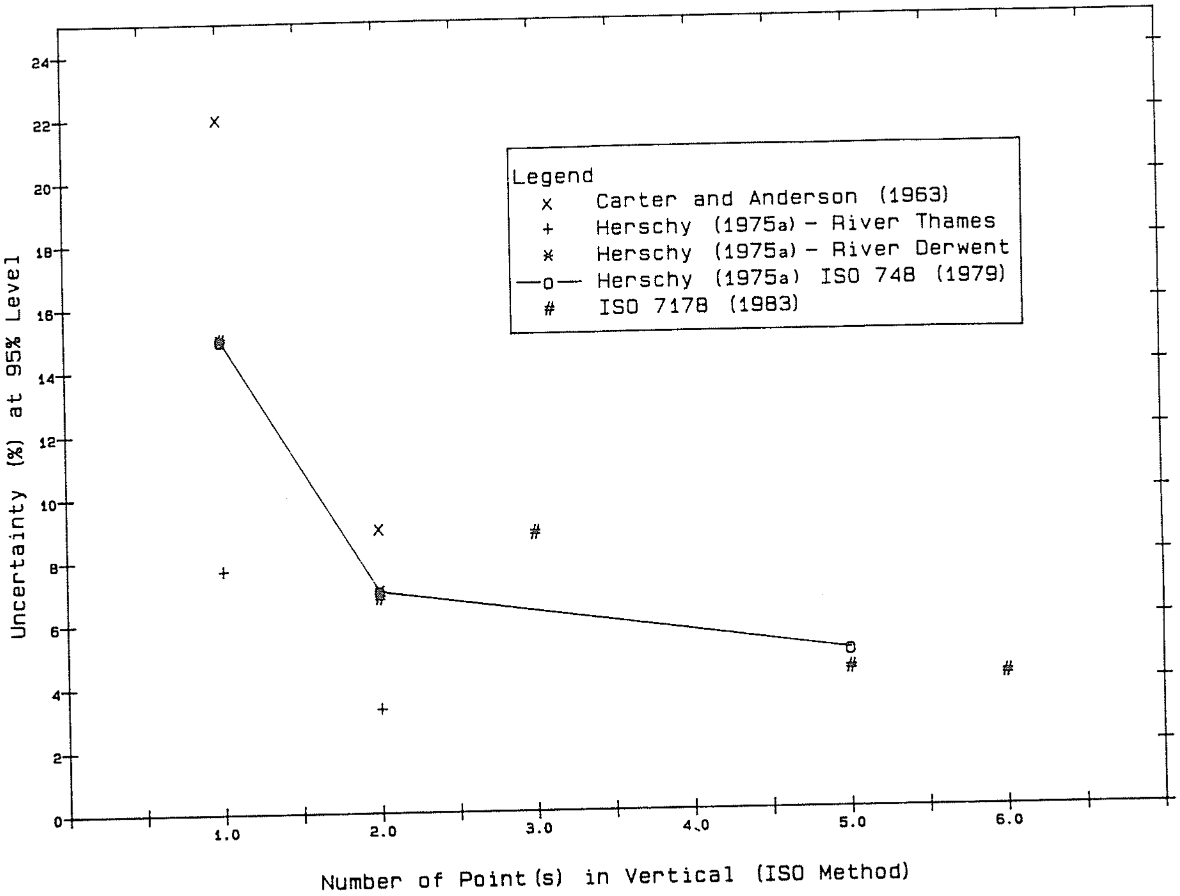

Figure 4.3 Uncertainty due to limited number of points taken in the vertical (95% level)

of 10 international rivers with an average of 50 verticals (varying between 35 and 66).

Other investigations have been carried out by Kasugaya (1958b, 1958c), Prochazka (1960), Botma (1970), Bonacci (1979), ISO TC 113 (1981), Boahman and Carswell (1986), and Pelletier (1988c, 1989).

The results from some of the most important investigations will be further analyzed and discussed below.

Anderson (1961), Carter and Anderson (1963)

The error was evaluated by analysis of special discharge measurements made at 127 different stream sites. The discharge measurement at each site included velocity and depth observations at more than 100 verticals in the section. The discharge at each site was computed using the data for 1/2, 1/4, 1/5, 1/7. and 1/10 of the total number of verticals. Their results are summarized in Table 4.23.

International Organization for Standardization (1971)

The ISO investigation was carried out according to ISO 1088. Verticals were taken at intervals of 1/50 of the total width subject to a minimum spacing of 0.50 m. Velocity observations were taken at 0.6 D for exposure time of 2 minutes.

The average number of verticals used was about 50 (varying from 35 to 66). The number of verticals used for comparison was based of 90, 80, 60, 50, 40, 20, and 10 per cent of the total number of verticals.

The results of the ISO investigation are summarized in Table 4.24.

The following conclusions were drawn:

1. calculating a discharge from a restricted number of verticals gives results which are systematically too low;

2. the selection of the verticals based on the profile in the cross-section leads to good results;

   The selection of the verticals according to the equidistant criterion leads to results which seem to be slightly better than those obtained using the criterion of equal flow. However, the difference is insignificant.

3. For large rivers ($Q > 120$ m^3/s), the interpolation of the horizontal velocity profile affects the extent of the error more than the interpolation of the bed profile. However, the difference is small.

   For small rivers ($Q < 120$ m^3/s), the interpolation of the bed profile influences the error much more than the interpolation of the horizontal velocity profile.

Table 4.23 Percentage Standard Deviation (95% level) of the uncertainty due to the limited number of vertical used - Carter and Anderson (1963)

Number of Verticals	Percentage standard deviation (95 per cent level)
8-11	8.4
12-15	8.2
16-20	4.2
21-25	4.0
26-30	3.2
31-35	3.2
104	0

Table 4.24 Percentage Standard Deviation of the uncertainty due to the limited number of vertical used - ISO/TR 7178 (1983)

Number of Verticals	Percentage standard deviation (95 percent level)		
	Bed Profile in the cross-section	Verticals equidistant	Sections of equal flow
5	15.4		
6	14.0		9.0
10	8.8	5.2	6.7
15	6.0	4.0	5.2
20	4.4	3.3	4.1
25	3.4	2.9	3.5
30	2.6	2.6	3.2
35	2.0		3.1
40	1.6		
45	1.4		

Legend of criteria:

Bed profile: surveyors will usually choose verticals according to irregularities of the profile read from an echogram, bearing in mind that the distances between verticals should not vary too much.

Verticals equidistant: In this method, the number of verticals is decided beforehand and they are spaced equally across the width. In cross-section where variations in profile and horizontal velocity distribution are gradual, equal discharge in the various sections is approximated.

Sections of equal flow: In this method, the verticals are located in such a way that the discharge from each of the sections is equal, but this requires that the discharge-distribution in the cross-section be known beforehand.

4. Errors in discharge caused by the interpolation of the velocity profile and depth respectively are related. This relation is based on the interdependence between flow velocity and depth in the vertical.

5. The error in discharge can be decreased considerably by using knowledge of the continuous profile when determining the discharge, instead of using only the depth in the verticals where the flow velocity is observed.

Herschy(1975)

Based on a review of previous studies (Carter and Anderson (1963), ISO (1971)), Herschy recommended values for the estimation of the uncertainty arising from the limited number of verticals used. These values are presented in Table 4.25. These values are now the standard values recommended by ISO 748 (1979). A graphic representation of some of these results is shown in Figure 4.4.

4.4.4 Uncertainty in the current meter

A current meter is calibrated by towing the meter through still water at various constant speeds and recording the number of revolutions of the rotor in a measured interval of time.

It is assumed that this rating or calibration is valid when the current meter is used to measure velocity of turbulent flow in open channels. Errors may be introduced by this assumption and by errors in the rating tank (Carter, 1970).

The uncertainty of the current meter is by far that one which has been subject to the largest number of investigations; approximately 50% of all the articles address this concern. Approximately one half of these papers are devoted to the current meters with a vertical axis (e.g. Price, Watt) and one half to meters with a horizontal axis (e.g. Ott, Braystoke).

The major investigations into the uncertainty in calibration of current meters were carried out by Lambie (1966, not published, cited from Herschy [1975a, 1982]), Smoot and Carter (1968), and Grindley (1970, 1971[a,b,c,d], 1972).

In Canada, investigations of the response of the Price current meter to different effects were performed by Engel (1976, 1987), Engel and DeZeeuw (1977, 1978, 1979, 1980, 1981, 1983, 1984[a,b]), Engel et al. (1985, 1986), and Pelletier (1988c, 1989) at the National Water Research Institute of Environment Canada.

The results of these numerous investigations are difficult to compare because the current meters used were different. Through the years, the design of current meters has continued to evolve. For example, the Price current meters used in the earliest investigations, from which hydrometric standards and procedures were established, were sometimes Large Price (35 or 24 inches long) or Small Price (617, 618 models). A description of the long history of the Price current meter from 1882 may be found in Frazier (1967).

Table 4.25 Percentage Standard Deviation of the uncertainty due to the limited number of vertical used - Herschy (1975b).

Number of verticals	Percentage standard deviation (95 percent level)
5	15
10	9
15	6
20	5
25	4
30	3
35	2
40	2
45	2

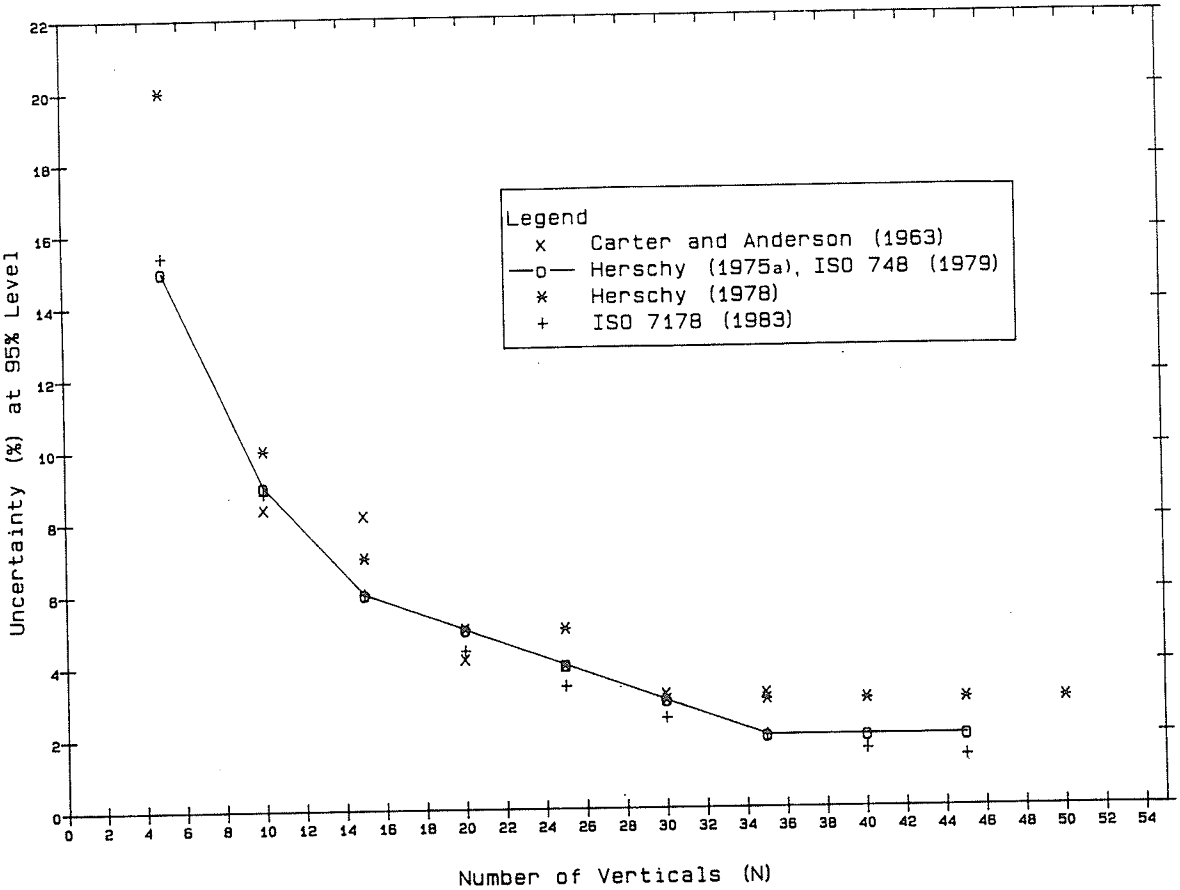

Figure 4.4 Uncertainty due to the limited number of verticals taken in the cross-section (95% level)

Because of the number and diversity of investigations, it is necessary to consider the various factors in separate sub-sections.

Repeatability

A random uncertainty will arise from the scatter of the calibration points about the line of regression and a systematic uncertainty, due to the rating tank, revealed by the shift of that line.

Lambie (1966) (cited by Herschy [1975a, 1982]) rated the same meter eight times in a short period, and found that the uncertainty from the standard rating was ±1.5% above 0.3 m/s; below 0.3 m/s, however, the uncertainty reached ±16%.

By rating two Price current meters in a towing tank at different speeds, Smoot and Carter (1968) found that the uncertainty decreases as the velocity increases and is less than 2% (at 95% level) for velocities greater than 0.3 m/s. The uncertainty increases, however, as the velocity decreases from 0.3 m/s (e.g., 4.5% at 0.076 m/s).

The International Current Meter Group (ICMG) carried out a rating tank comparison during the period of 1968-69. The meter used was an Ott Mark V with four different propellers, and was rated in eight European rating tanks. With the exception of the low velocity range, the uncertainty was ±1% (Herschy, 1975a).

Anderson (1961) reported that a group of Price meters were rated at the David Taylor Model Basin and at Colorado State University in addition to the original calibrations at the National Bureau of Standards. The deviations of ratings for any one meter was less than 1%.

More recently, Pelletier (1988c, 1989) investigated differences between the U.S. Geological Survey and Environment Canada calibration practices, and found that uncertainty increases at low velocities.

Individual Rating Versus Group (or Standard) Rating

Major investigations have been carried out by Lambie (1966), using 15 used Watts cup-type meters; by Smoot and Carter (1968), using 140 Price meters; and by Grindley (1970, 1971c), using 201 new and used screw-type meters and 20 new cup-type meters. The results of these investigations are presented in Tables 4.26 and 4.27.

They concluded that a group rating is as accurate as an individual rating, and the errors are mainly due to errors in the rating procedures. Therefore, a significant reduction in cost can be achieved by using a standard or group rating. Strict control of manufacturer's tolerances would be an essential requirement, however, for the implementation of a standard or group rating (Herschy, 1982).

Based on Smoot and Carter (1968), the U.S. Geological Survey discontinued its practice of rating each meter individually and implemented quality control standards in the manufacturing process to ensure consistency in the product.

Table 4.26 Summary of investigations into **individual** ratings of current meters by Smoot and Carter (1968), and Grindley (1970-72)

Velocity	Percentage Uncertainty (95% level)	
	Smoot & Carter[1]	Grindley[2]
0.031		20.30
0.077	4.5	2.53
0.152	3.5	0.85
0.229	2.0	0.69
0.307	1.7	0.55
0.460	1.3	0.29
0.613		0.34
0.748		0.45
0.899		0.35
0.996		0.24
2.463		0.20
2.514		0.34

1: Used 136 observations, and one type of meter

2: Used 494 observations, and three types of meters

Table 4.27 Summary of investigations into **standard** ratings of cup type current meters by Lambie (1966), Smoot and Carter (1968), and Grindley (1970-72)

Velocity	Percentage Uncertainty (95% level)		
	Lambie[1]	Smoot & Carter[2]	Grindley[3]
0.076	20	6	9
0.152	13	3	5
0.228	10	2	3
0.305	8	2	3
0.458	7	1	3
0.610	6	1	3
1.524	5	1	3
2.438	5	1	3

1: Used Watts meters were utilized by Lambie

2: New Price meters were utilized by Smoot and Carter

3: New Watts meters were utilized by Grindley

In fact, Hoyt (1910) demonstrated from rating several small Price meters that the percentage of deviation from the mean curve of different curves was generally less than ±1%, except for velocities lower than 0.15 m/s. Hoyt (1907, 1910) also noted that serious errors may be introduced if the small Price meter is used at velocities lower than 0.15 m/s.

It is generally accepted that in calibrating a Price current meter, a composite rating should be developed, i.e. one rating curve for low and one for high velocities (intersection at approximately 1 rev/s or 0.6 m/s) (Price, 1895; Hoyt, 1910; Corbett et al., 1957; Smoot and Carter, 1968; Herschy, 1975a, 1978b, 1985). However, this is not a standard practice in Canada. It is believed that a change to a composite rating curve for the Price meter would result in a better estimate of discharge at low velocities.

Uncertainty values for group and individual ratings commonly found in the literature are graphically represented in Figure 4.5.

Overall Uncertainty in the Current Meter

Herschy (1970, 1975a, 1982) reviewed the results of the investigations of Lambie (1966), Smoot and Carter (1968), and Grindley (1970, 1971c), and recommended random uncertainty values for individual and group ratings. The random uncertainty values are generally small (±1%) for velocities greater than 0.3 m/s, and the systematic uncertainty assumed to be ±1%. These values are summarized in Table 4.28. Carter and Anderson (1963) suggested a total uncertainty of ±2% (at the 95% level). The values suggested in ISO (ISO 748, 1979) are given in Table 4.29.

To evaluate possible changes in current meter ratings after extensive field use, Smoot and Carter (1968) re-rated 40 Price current meters brought in from the field and found that changes were in the order of ±1% to ±2%, depending on the condition of the meter and the calibration velocity. They also found that physical changes in the pivot and upper bearing have little influence on the rating. However, damage to the rotor (slightly dented cups) can cause appreciable change in the rating.

Also, Alming (1969) reported that uncertainties in a given calibration of a current meter due to wear is of the same order of magnitude as the uncertainty in the calibration between different calibration institutions. His results were based on seven Ott current meters.

Fluid Properties (Changes in Temperature and in Density)

Calibrations of current meters are generally performed at water temperatures close to ambient conditions of the rating centre's indoor facilities (Engel, 1976). In the field, however, these meters are used at temperatures which vary greatly from the rating tank (as much as 16 C). From a theoretical analysis, Engel (1976) concluded that temperature effects may be considered to be negligible. Robson (1954), using a temperature change of 14°C (from 17°C to 3°C) at the Calgary outdoor rating facility, concluded that within the limits of accuracy of the current meter rating tables (2 decimal places), there was no indication of change in calibration with variation in water temperature.

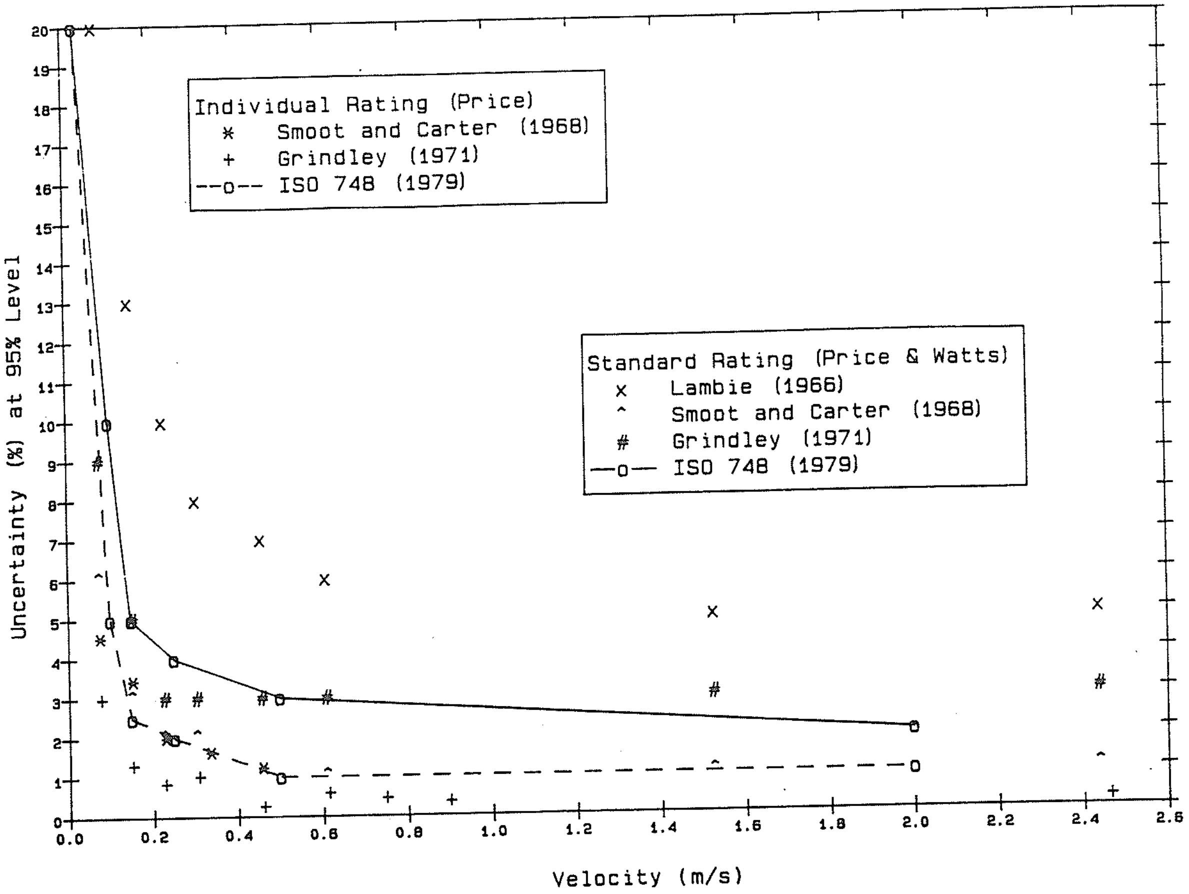

Figure 4.5 Uncertainty in current meter rating (95% level).

Table 4.28 Herschy's (1975b) recommended uncertainty values for individual and standard ratings

Velocity (m/s)	Uncertainty (at the 95% level)	
	Individual Rating	Standard Rating
0.031	20	
0.038		20
0.076		10
0.100	5	
0.152	2.5	6
0.229	1.0	4
0.305	1.0	3
0.456 and over	1.0	2

Table 4.29 ISO 748 (1979) recommended uncertainty values for individual and standard ratings

Velocity (m/s)	Uncertainty (at the 95% level)	
	Individual Rating	Standard Rating
0.03	20	20
0.10	5	10
0.15	2.5	5
0.25	2	4
0.50	1	3
over 0.50	1	2

Schubauer and Mason (1937) also concluded that changes of density occurring in the field do not cause appreciable error. Their conclusions were derived by rating Price meters in water and in air (density factor of approximately 800). Also, Engel (1976) found that the velocity error owing to fluid density greater than fresh water was less than 1%, and that the effects on measurement accuracy were not significant. Morel (1966) also concluded that changes in water density were negligible.

Effect of Suspension

If a current meter is rated on one suspension (e.g. rod), but is used in the field on a different suspension (e.g. cable), errors are introduced. Depending on the sounding weights used and the velocity range, the uncertainty will vary greatly and can cause some serious under- or over-estimation of discharge.

In Canada, the Price AA current meter is calibrated on rod suspension, and on cable suspension using a 30-lb (13.6-kg) Columbus-type sounding weight. The current meter is not calibrated with the other standard weights used in the field, such as the standard 15-lb (6.8-kg), 50-lb (22.7-kg), 75-lb (34.0-kg), and 100-lb (45.4-kg) Columbus-type sounding weights.

The effect of Columbus weights on the performance of the Price current meter was investigated by Engel and DeZeeuw (1984b). They concluded that the Price current meter response curve obtained with a 30-lb standard suspension (Columbus weight) was very similar to that obtained when the meter was attached to a standard rod. However, they also concluded that the response curves obtained with the 15-lb, 50-lb, and 100-lb standard suspension differ significantly from that obtained with a standard rod suspension.

The effect of cable suspension has also been reported by Murphy (1904), Chow (1964), Chapman (1968), ISO 2537 (1974), ISO 3455 (1976), Herschy (1978b, 1985), and Teuber (1987).

In Canada, the WSC winter meter (Price AA with modified yoke) is generally used to measure streamflow under ice conditions. This current meter is calibrated on rod suspension only. However, it is frequently used on cable suspension using Pancake, Slush-n-all, and NACA sounding weights. The effect of cable suspension for these winter weight assemblies has been identified as an important factor by Scheinder and Futrell II (1984) and Pelletier (1988c, 1989). For example, Scheinder and Futrell II showed that for the Slush-n-all weight, the meter rotates 3% to 9% slower for a cable suspension than for a rod suspension.

The review indicates that the method of suspension and the sounding weight used will affect the calibration, and that a current meter should be calibrated with the suspension equipment it is to be used with in the field.

Boundary Effects

Investigations by Rumpf (1914) conducted in a rating tank, showed that the screw-type meter (Fteley and Stearns) over-registered when placed near the side walls, while the cup-type (Price) showed increased velocities on one side and decreased on the other side.

Pierce (1941) conducted an extensive laboratory investigation to determine the performance of current meters (small Price and pigmy current meters) in water of shallow depth (depth ranging from 0.06 to 0.46 m, and velocities ranging from 0.03 m/s to 0.46 m/s). Pierce developed coefficients, to be applied as correction factors to velocities obtained by current meters when used in very shallow depth, for the 0.6 depth method and 0.2 and 0.8 depth method. For example, a coefficient of 1.02 would be used with the 0.6 depth method if the velocity at one observation point was 0.15 m/s and the depth of water was 0.15 m, and a coefficient of 1.07 if the depth was 0.12 m. In comparison, a coefficient of 1.04 would be used with the 0.2 and 0.8 depth method if the velocity was between 0.15 and 0.30 m/s and the depth of water was 1 m.

Pierce's investigation into the distribution of velocities in a 3.65-m wide flume also included analysis of vertical velocity curves and pulsation effect.

In summary, these investigations have shown that flow boundaries can exhibit effects on current meter response. If the meter is placed near very rough boundaries and in shallow depths, the current meter may respond erroneously (Dickinson, 1967; Engel and DeZeeuw, 1983).

Effect of Oblique Flow

All current meters may be equally accurate in parallel filaments of steady flow. Their performance will diverge, however, under currents which are not normal or perpendicular to the cross-section (Kolupaila, 1958).

For horizontal or vertical oblique flow to the cross-section, the component in the direction on the channel axis ($V = V_o \cos ß$, where ß is the measured angle to the perpendicular) is of interest, not the local velocity V_o.

The cup-type meter (e.g. Price) tends to register the magnitude of the maximum velocity vector, regardless of its orientation in the flow, resulting in an over-registration of the velocity. In contrast, the screw-type meter (e.g. Ott) is designed to measure the projection of velocity on its axis ($V = V_o \cos ß$).

Generally tests to determine the effect of oblique flow on the response of current meters have been done by towing the meters in still water with the meter axis inclined at various horizontal and vertical angles, by holding the meters stationary in a steady current with the meter axis turned at various angles to the direction of the flow, and by oscillating the meter laterally or vertically while towing it in still water (Nagler, 1935).

Investigations on effect of oblique flow have been carried out by Stearns (1883), Rumpf (1914), Brown and Nagler (1914-15), and Kolupaila (1958).

More recently, Grindley (1971a) concluded that if a cup meter (Price and Watt) is heading at right angles to the cross-section of a channel and the flow is oblique, the meter will usually over-register. In contrast, the screw-type will measure, within limits, the component of velocity normal to the cross-section. Grindley (1971a) also concluded that tilting has a greater effect on the behaviour of a cup-type meter than it has on a screw-type.

Engel and DeZeeuw (1979) showed that the Price meter is more sensitive to deviations in alignment above the horizontal compared to similar deviations below the horizontal. Also, the Price meter will always under-register for misalignments above and below the true horizontal position. For example, the errors in measuring velocity (at 0.3 m/s) for angles above horizontal of 5° and 15° would be, respectively, -3% and -12%, compared to -2% and -2% for angles below the horizontal of 5° and 15°, respectively.

Engel and DeZeeuw (1983) showed that the Price meter is subject to measurement error when placed in a flow with a transverse velocity gradient across the rotor. If the gradient is positive, the Price meter will over-register; if the gradient is negative, the meter will under-register. If the velocity gradient ($\Omega=(V_1-V_2)/D$, where V_1 and V_2 are the flow velocity at the open and closed side of the rotor cups respectively, and D is the effective diameter of the rotor) is equal to 0.1 s^{-1} (meaning that for any flow the velocity difference across the Price rotor is about 0.008 m/s) and the velocity is 0.3 m/s, the error would be 3.5% and if the velocity gradient is equal to 0.3 s^{-1}, the error would be 10%. Finally, they concluded that the effect of velocity gradients is greatest at low velocities and becomes less as the velocities increase.

Effect of Vertical Motion

Kallio (1966) investigated the effect of vertical motion (e.g., caused by wave action or rocking of a boat) on the performance of three types of current meters (Ott, Price, and U.S.G.S. vane) at various stream velocities. Kallio showed that for velocities below 0.75 m/s, the accuracy of all three meters is significantly affected. For example, if a vertical motion of 0.12 m/s is assumed, the error in measuring stream velocity using a Price meter on cable suspension would be +10% at a stream velocity of 0.15 m/s and -6.7% at 0.46 m/s. The errors were, however, smaller for the Ott meter than for the Price meter. Both the rate of vertical motion and the frequency of vertical oscillation affect the registration of the meter.

Using an inflatable boat in a towing tank, Moody (1982) also showed that the Price meter is affected by vertical motion. Recently, the effect of vertical motion was investigated by Thibodeaux and Futrell (1987). They showed that the Price type AA current meter is affected adversely by the rate of vertical motion and the distance of vertical travel. Generally, the type AA over-registers in observed meter velocity. The coefficients ranges from 0.33 to 1.07. They also concluded that when making a current meter measurement from a boat or a cableway, errors in observed velocity will occur when the bobbing of a boat or cableway places the current meter in vertical motion. These errors will be significant when the flowing water is less than 2 ft/s and the rate of vertical motion is greater than 0.3 ft/s.

Effect of Turbulence

It has been stated in the literature by many investigators (Murphy, 1904; Groat, 1913, 1927; Brown and Nagler, 1914-15; Fortier and Hoff, 1920; Yarnell and Nagler, 1931; Nagler, 1935; Wood, 1945; Kolupaila, 1949, 1958, 1964; O'Brien and Folsom, 1948; Yang, 1967; Burtsev and Baryshnikova, 1970; Muszkalay and Starosolszky, 1981; etc.) that stream turbulence will cause over-registration by the cup-type meter and under-registration by the screw-type meter. Moreover, that over-registration of the cup-type is significantly higher than the under-registration of the screw-type meter.

However, Carter and Anderson (1963) stated that the Price current meter is not affected by stream turbulence. They based their statement on discharge measurement analyses performed by Townsend and Blust (1960). Townsend and Blust reported that current velocities simultaneously measured by cup- (Price) and screw- (Ott) type current meters on the lower Niagara River gave identical results. Moffatt (1978-79) reported similar results. Also, Jepson (1967) (cited by Hall and Johnston [1971]) has shown that registration errors for miniature propeller-type meters in laboratory flumes may be either positive or negative depending upon the dominance of axial or transverse velocity fluctuations within the flow.

In summary, there is some confusion in the literature on the definite effect of stream turbulence on the registration of cup-type current meters, such as the Price meter, which is used as the standard current meter by the United States and Canada. Research is needed to quantitatively determine the effect of turbulence on current meter response, in particular on the Price current meter. This area of research has also been suggested by Dickinson (1967), and by Starosolszky (1983).

4.5 UNCERTAINTY IN THE DISCHARGE MEASUREMENT COMPUTATION FORMULA

The most common method of measuring discharge in North America is to divide the measuring cross-section into several smaller sections or segments (in general, 20 to 30) to measure the depth and velocity in each vertical, and then to combine them to obtain the flow estimate.

Through the years, two methods have been used to compute the flow between consecutive verticals. They are the mean-section and mid-section methods.

In computing the discharge by the mean-section method, a linear change in velocity and depth from vertical to vertical in the measuring cross-section is assumed. In the mid-section method, the mean velocity and depth observations for a given velocity profile are assumed to be valid throughout an area that extends halfway to the preceding and suceeding verticals (Savini and Bodhaine, 1971).

Stevens (1908) compared the difference between what he called a standard formula and rectilinear (including mean-section and mid-section methods) and curvilinear formulas. He concluded that the mean- and mid-section methods consistently gave the smallest errors when compared to the other methods. Moreover, Stevens (1908) found that the mid-section method produced errors twice as large as the mean-section method, and in the opposite direction. For example, the largest error detected (based on a sample of only six) was +1.8% for the mid-section and -0.9% for the mean-section. Stevens (1908) recommended the mid-section method, however, because of its mathematical and computational simplicity.

Young (1950) performed a comparative study of the mid-section and mean-section methods, using more than 200 discharge measurements. He concluded that the mid-section method was more accurate than the mean-section method. The "true" discharge estimate in the section was assumed to be one with four times the usual number of verticals. Young's results contradict Stevens (1908).

Based on Young's investigation, the mid-section method was adopted by the U.S. Geological Survey (Rantz et al., 1982) and by the Water Survey of Canada (Terzi, 1981). The principal advantage of the mid-section method is its simplicity (Stevens, 1908, Terzi, 1981, and Rantz et al., 1982).

Savini and Bodhaine (1971) compared the two methods using 17 discharge measurements on the Columbia River (see Table 4.30). The percentage difference in discharge obtained by the two methods ranged from -0.2% to -1.6%. The average was 0.6% less by the mean-section method.

Grunsky (in discussion in Hoyt, 1910), Colby (1964), Dickinson (1967), and Fulford and Sauer (1986) also discussed these and other methods.

4.6 ERROR EQUATION FOR SINGLE DETERMINATION OF DISCHARGE

The total uncertainty "S" in a discharge measurement, using the error model proposed by Carter and Anderson (1963), is expressed as:

$$S^2 = Sm^2 + \left\{\frac{Se}{(Np)^{1/2}}\right\}^2 + \left\{\frac{Sp * [1+(N-1)*0.04]^{1/2}}{(N)^{1/2}}\right\}^2 + Sc^2 \qquad \ldots(4\text{-}4)$$

where

S is the standard deviation of the total discharge;

Sm is the standard deviation due to the limited number of verticals;

Se is the standard deviation due to velocity fluctuation (pulsation) at a point;

Sp is the standard deviation due to the limited number of points used in a vertical (i.e. shape of the vertical velocity curve);

Sc is the standard deviation due to instrument error (current meter);

Np is the number of observation points; and

N is the number of verticals.

In comparison, the error model proposed by Herschy (1970, 1975a) and ISO 748 (1979) to compute the overall uncertainty (Xq) is expressed as the summation of the overall random (X'q) and systematic (X"q) uncertainty:

$$Xq = \pm\ [(X'q)^2 + (X''q)^2]^{1/2} \qquad \ldots(4\text{-}5)$$

Table 4.30 Comparison of Columbia River discharge computed by mid-section and mean-section methods from mean velocities obtained from integrated vertical curves - Savini and Bodhaine (1971).

Date	Mid-section Discharge (cfs)	Mean-section Discharge (cfs)	Difference (percent)
At Grand Coulee Dam, Wash.			
1961-04-24	115700	115100	-0.5
1962-06-20	219200	215600	-1.6
1962-07-07	219500	218500	-0.5
1963-06-19	267300	265400	-1.4
At Bridgeport, Wash.			
1961-04-25	110800	110400	-0.4
1961-06-20	427000	424800	-0.5
At Rocky Reach Dam, Wash.			
1961-04-26	116300	115700	-0.3
1961-06-21	448100	446200	-0.4
1962-11-20	60800	60300	-0.8
At Trinidad, Wash.			
1961-06-21	473100	470700	-0.5
1961-09-22	60400	60100	-0.5
Below Priest Rapids Dam, Wash.			
1961-04-28	104700	104400	-0.3
1961-06-20	494000	490600	-0.7

Cont. Table 4.30 Comparison of Columbia River discharge computed by mid-section and mean-section methods from mean velocities obtained from integrated vertical curves - Savini and Bodhaine (1971).

Date	Mid-section Discharge (cfs)	Mean-section Discharge (cfs)	Difference (percent)
At Paterson Ferri, Oreg.			
1961-06-16	596900	593900	-0.5
1961-10-11	83400	83000	-0.5
At Hood River Bridge. Oreg.			
1961-05-05	197100	196200	-0.5
1961-06-05	648300	647100	-0.2
Average			**-0.6**
Range			**1.4**

where

$$X'q = \pm \left\{ (X'm)^2 + \frac{\sum_{i=1}^{m} [(b_i d_i v_i)^2 \; ((X'b_i)^2 + (X'd_i)^2 + (X'v_i)^2)]}{\left\{ \sum_{i=1}^{m} [(b_i d_i v_i)] \right\}^2} \right\}^{1/2} \qquad \ldots(4\text{-}6)$$

If the segment discharges ($b_i d_i v_i$) are nearly equal and the random uncertainties $X'b_i$ are nearly equal and of value $X'b$, and similarly for $X'd_i$, $X'v_i$, equation (4-6) may be reduced to

$$X'q = \pm \left[(X'm)^2 + \frac{1}{m} \left((X'b)^2 + (X'd)^2 + (X'v)^2 \right) \right]^{1/2} \qquad \ldots(4\text{-}7)$$

with

$$X'v = \pm \left[(X'e)^2 + (X'p)^2 + (X'c)^2 \right]^{1/2}$$

where

$X'm$ is the random uncertainty due to the limited number of verticals;

$X'b$ is the random uncertainty in measuring width of segments;

$X'd$ is the random uncertainty in measuring depth of segments;

$X'v$ is the random uncertainty in measuring the mean velocity;

$X'e$ is the random uncertainty due to the limited time of exposure;

$X'p$ is the random uncertainty due to the limited number of points taken;

$X'c$ is the random uncertainty due to the current meter rating; and

m is the number of verticals.

Although the segment discharge or the contributing uncertainties in a stream gauging are seldom, if ever, equal, it has been found in practice that equation (4-7) gives results which are not significantly different from those given by the "exact" equation (4-6) (Herschy, 1975a, 1978[a,b]; ISO 748, 1979).

The systematic uncertainties are combined also by the root-mean-square method. In the velocity-area method, the error equation for the systematic uncertainty ($X''q$) is given as:

$$X''q = \pm \left[(X''b)^2 + (X''d)^2 + (X''c)^2 \right]^{1/2} \qquad \ldots(4\text{-}8)$$

where

X"b is the systematic uncertainty in the instrument measuring width;

X"d is the systematic uncertainty in the instrument measuring depth;

X"c is the systematic uncertainty in the current meter rating tank.

Using uncertainty values proposed by Carter and Anderson (1963) in their proposed error model (equation 4-4), uncertainties were calculated for a 45-second exposure, using the one- and two-point methods. It should be noted that Carter and Anderson's uncertainty values were multiplied by 2 in this thesis, to express the uncertainty at the 95% confidence level (two standard deviations). Their results were originally expressed at the 68% confidence level (at one standard deviation).

Curves were also developed using the uncertainty values recommended by Herschy (1975a) and his suggested error model (equation 4-5), assuming that the mean velocity in the vertical was 0.25 m/s, and that the meter used was individually rated.

The comparison between the two error models is shown in Figure 4.6. Both models give fairly consistent results for the two-point method (0.2 and 0.8 depth). However, for the one-point method (0.6 depth), the uncertainty values given by Carter and Anderson are higher. For example, if 20 verticals are taken with the one-point method with an exposure time of 45 seconds, and the measurement is performed under ideal conditions, the uncertainty at the 95% level would be ±8.5% using Carter and Anderson's equation and ±6.7% using Herschy's equation (at 0.25 m/s), a difference of ±1.8%. In comparison, the uncertainty of a discharge measurement performed under ideal conditions with the two-point method would be ±5.6% using Carter and Anderson's error equation and ±6.1% using Herschy's error equation.

The major differences between these two error models is that Herschy includes the mean velocity as a variable in the equation. This is shown in Figure 4.7, where the uncertainty given by both models at 95% level, is plotted against the mean velocity.

Other error models found in the literature were developed by Prochazka (1960), Dickinson (1967, 1969), Herschy (1970), Karasev (1978, 1980), Rumyantsev (1981), and ISO 7178 (1983).

The theoretical error model for a discharge measurement proposed by Dickinson (1967, 1969) is distinct from the two previous models and will now be described.

The discharge passing through a metering section of a river may be expressed as the integral over the cross-sectional area and over the measurement time of the velocity vector perpendicular to the section, i.e.

$$Q = \frac{1}{T} \iint_{(x,z)} \int_{t=0}^{T} v(x,z,t)\ dx\ dz\ dt \qquad \ldots(4\text{-}9)$$

where

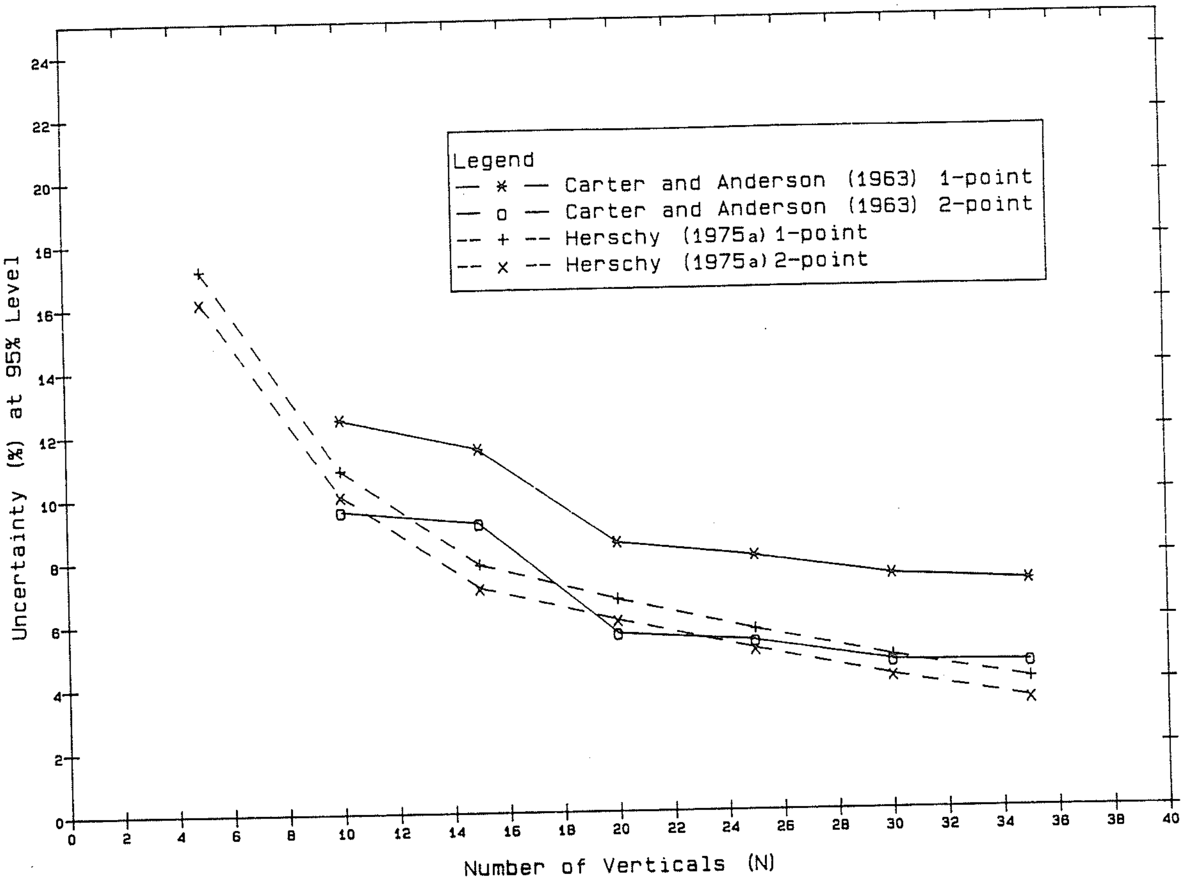

Figure 4.6 Uncertainty in a single determination of river discharge at the 95% confidence level for a 45-s exposure time and a velocity of 0.25 m/s.

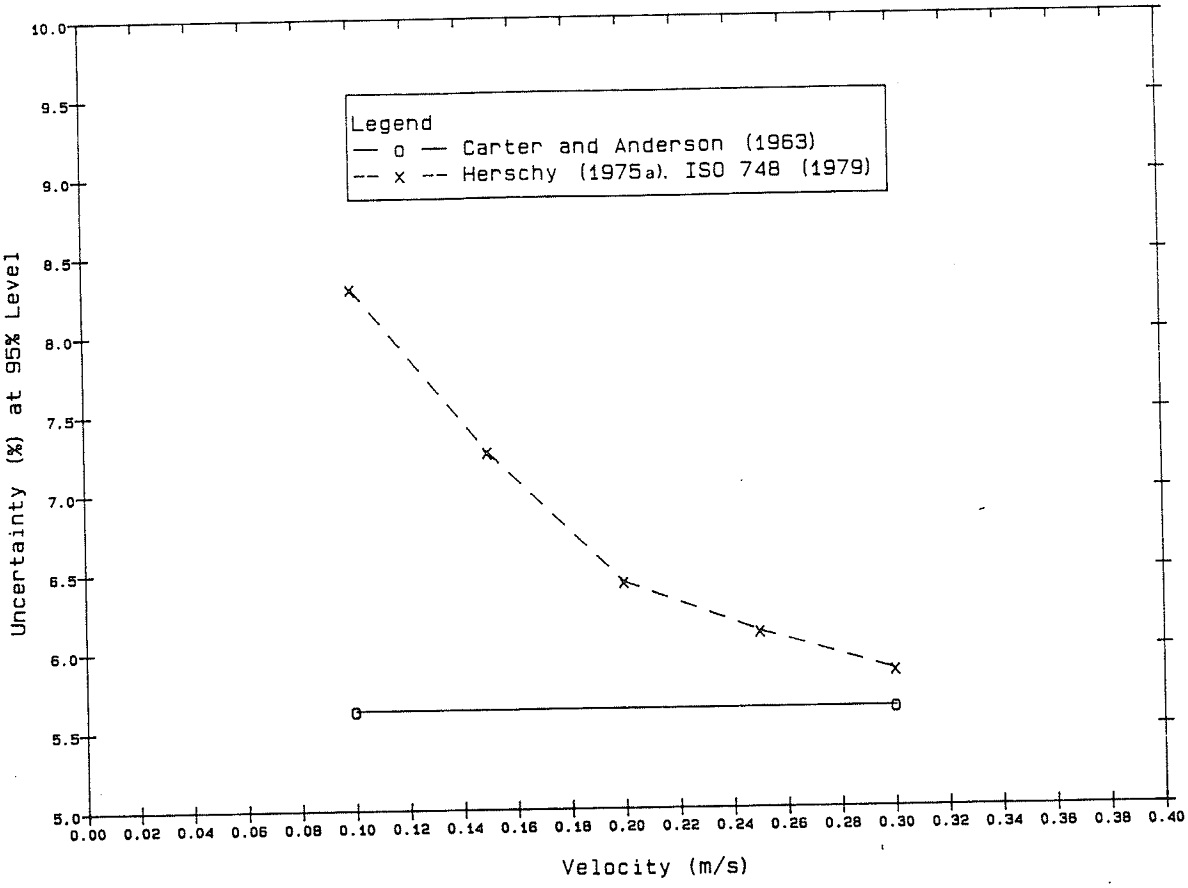

Figure 4.7 Error models comparison, 20 verticals, two-point method, and 45-s exposure time.

Q represents the mean discharge over the time interval T,

(x,z) are the coordinates defining the measuring section,

$V(x,z,t)$ represents the velocity vector perpendicular to the section.

Assuming that the cross-section is divided into n vertical sections, the above relationship

$$Q = \sum_{i=1}^{n} A_i \bar{V}_i \qquad \ldots(4\text{-}10)$$

where

A_i is the time-average area of the i^{th} vertical,

$\bar{V}_i$ is the time- and area-average velocity of the i^{th} vertical.

However, in practice, the discharge is estimated by,

$$\tilde{Q} = \sum_{i=1}^{n} \tilde{A}_i \tilde{V}_i \qquad \ldots(4\text{-}11)$$

where ~ indicates the parameters estimated by a measurement.

Therefore, the error in a single discharge measurement may be expressed as

$$q = \tilde{Q} - Q = \sum_{i=1}^{n} \{ \tilde{A}_i \tilde{\bar{V}}_i - A_i \bar{V}_i \} \qquad \ldots(4\text{-}12)$$

Then $\tilde{A}_i$ and $\tilde{\bar{V}}_i$ may be defined as follows:

$$\tilde{A}_i = A_i + a_i$$

$$\tilde{\bar{V}}_i = \bar{V}_i + v_i$$

then

$$q = \sum_{i=1}^{n} \{ A_i v_i + \bar{V}_i a_i + v_i a_i \} \qquad \ldots(4\text{-}13)$$

where a_i, v_i, q are the errors in the determination of A_i, $\bar{V}_i$, and Q, respectively.

Note that the last term in Equation (4-13) was neglected by Dickinson's.

Thus,

$$q \approx \sum_{i=1}^{n} \{ A_i v_i + \bar{V}_i a_i \} \qquad \ldots(4\text{-}14)$$

The error in a vertical sectional area, a_i, will first be considered. The area of the i^{th} vertical is given by

$$A_i = \int_{W=0}^{W_i} D\,dW = W_i\,\bar{D}_i$$

and the estimate of A_i is

$$\tilde{A}_i = \tilde{W}_i\,\tilde{\bar{D}}_i$$

where

$\tilde{W}_i$ is an estimate of the width associated with the i^{th} vertical, W_i,

$\tilde{\bar{D}}_i$ is an estimate of the mean depth of the i^{th} vertical, $\bar{D}_i$

Then,

$$a_i = \tilde{W}_i\,\tilde{\bar{D}}_i - W_i\,\bar{D}_i$$

As outlined previously, the estimated values may be written in the following form:

$$\tilde{W}_i = W_i + w_i$$

$$\tilde{\bar{D}}_i = \bar{D}_i + d_i$$

and the error in the i^{th} vertical area may be expressed as:

$$a_i \approx W_i\,d_i + w_i\,\overline{Di}$$

In addition the error in the mean velocity estimate for the i^{th} vertical can be expressed as:

$$v_i = \tilde{\bar{V}}_i - V_i$$

and using the approach given above:

$$\bar{V}_i = \sum_{j=1}^{m_i} (R_{ij}\,\bar{V}_{ij})$$

and,

$$\tilde{\bar{V}}_i = \sum_{j=1}^{m_i} (R_{ij}\,\tilde{\bar{V}}_{ij} + v_p)$$

thus,

$$v_i = \sum_{j=1}^{m_i} (R_{ij}\,\tilde{\bar{V}}_{ij} + v_p - R_{ij}\,\bar{V}_{ij})$$

which may be reduced to,

$$v_i = \sum_{j=1}^{m_i} (R_{ij}\ v_{ij} + v_p)$$

where

R_{ij} is the appropriate weighting factor attributable to each time average velocity, $\bar{V}_{ij}$; there being m_i points selected in the i^{th} vertical for sampling the vertical velocity profile,

v_p is the error in sampling the vertical velocity profile,

v_{ij} is the error in measuring the time-average velocity at a point.

The error in measuring $\bar{V}_{ij}$, may be expressed as:

$$v_{ij} = \tilde{\bar{V}}_{ij} - V_{ij} = v_c + v_o + v_s + v_t$$

where

v_c is the error introduced by the current-meter calibration equation;

v_o is the error caused by oblique currents;

v_s is the error in sampling the velocity in the horizontal direction;

v_t is the error in sampling the velocity in time.

Substituting the derived error relationships into the basic error equation for single discharge measurement, gives:

$$q \approx \sum_{i=1}^{n} \{Ai \sum_{j=1}^{m_i} [R_{ij}(v_c+v_o+v_s+v_t)+v_p] + \bar{V}_i \{ W_i\ d_i + w_i\ \bar{D}i \} \} \qquad \ldots(4\text{-}15)$$

The above equation is the general error model which includes the error components only in general form.

4.7 OTHER SOURCES OF UNCERTAINTY

4.7.1 Uncertainties in other phases of development of streamflow records

Once the uncertainty in single discharge measurements has been determined, the following uncertainties in the development of a streamflow record may be considered: uncertainty in the stage or water level; uncertainty in the stage-discharge relation; uncertainty in the computation procedure; and finally, uncertainty in the daily, monthly, and annual mean discharges. For a more detailed discussion of these uncertainties, the reader is referred to Pelletier (1987b).

One must realize that even if a discharge measurement is considered to be accurate, it does not necessarily imply the accuracy of the daily discharge records. Conditions in which a measurement will deviate from a stage-discharge relation are, for example; shifting controls caused by scour, fill, ice, or vegetal and aquatic growths at the gauging station; or the gauging station being affected by variable slope caused by variable backwater, changing discharge, or by both. Therefore the accuracy of a streamflow record will generally depend on the accuracy of the individual measurements, the number of measurements, their distribution in time and stage, the computational procedure, and intervening hydrologic events which may changed the cross-sectional characteristics (Grover and Hoyt, 1916).

The uncertainty in stage or water level data has been investigated by Stevens (1919), Rothacher and Miner (1965), Herschy (1969, 1970, 1975a, 1978b, 1985), Leupold and Stevens, Inc. (1978), Muszkalay and Starosolszky (1981), Van Der Made (1982), and Freestone (1983). Herschy (1975a) reported, based on Robertson's experiments in 1960 for the Surface Water Survey in cooperation with the Wear and Tees River Board, that uncertainty (at the 95% level) may range from ±3 mm for the measurement by float tape in a stilling well to ±6 mm for the measurement by staff gauge, to ±14 mm for the method of measurement from 10:1 reduction of a recorder chart.

The uncertainty in the stage-discharge relation and the accuracy of streamflow records have been the subject of relatively few investigations when one considers that the relation is generally used to derive daily streamflow records. Models have been proposed by Dickinson (1967, 1969), Herschy (1969, 1970, 1975a, 1978b, 1985), Burkham and Dawdy (1970), Venetis (1970), Manley (1977), ISO 1100 (1982), and Dymond and Christian (1982). Dickinson (1967, 1969) did not include the uncertainty in stage in his error model (Dymond and Christian, 1982). Moreover, Herschy (1975a) ignored the effect of temporal correlation of errors in the discharge record (Moss and Gilroy, 1980). In recent years, the Kalman filtering technique has been used by the U.S. Geological Survey to determine the accuracy of streamflow records (Moss and Gilroy, 1980; Fontaine et al., 1983; and Kitanidis et al., 1984).

Most of the investigation results presented in this thesis were for streams under open water conditions. There have been surprisingly few studies of the accuracy of discharge measurements and the accuracy of streamflow records under winter ice conditions. The most important investigation on ice conditions was carried out by Barrows and Horton (1907). Other studies were carried out by Hoyt (1913), Collier (1962), Rosenberg (1966), Bennett (1968), Burkham and Dawdy (1970), Rosenberg and Pentland (1983), and Morton (1983).

Rosenberg and Pentland (1983) analyzed data from seven Canadian streams and concluded that the computational techniques typically available produced high uncertainties for small streams in moderate temperature zones and low uncertainties for large rivers in frigid zones.
Moreover, there has been very little research into the accuracy of streamflow measurements in small channels or under conditions of low velocities, or both, such as commonly experienced in the interior plains of North America over almost half of the hydrologic year.

Investigations into the accuracy of streamflow measurements under low flow conditions are required because of the large uncertainty that may be present in the procedures and equipment used. These studies should focus on measurement in shallow water (e.g., less than 1 m) with low velocities (e.g., less than 0.3 m/s), with a restricted number of verticals (because of narrow channel, e.g., less than 2 m), and with a very soft bed. In addition, the accuracy of other available streamflow measurement methods (e.g., dilution, weir, flume, electromagnetic, ultrasonic, etc.) should be assessed and compared to the velocity-area method. Also, future research should focus on the measurement and computation of streamflow under ice conditions, including frazil ice conditions.

The uncertainties associated with the measurement of streamflow under ice conditions will be further discussed below.

4.7.2 Uncertainties in current meter measurements under ice conditions

As for open-water discharge measurement, the overall uncertainty, random and systematic, in a single determination of river discharge using the velocity-area method in combination with a current meter, is due to the following uncertainties:

- in the determination of the cross-section area, i.e., in the determination of widths and depths;
- in the determination of the individual measurements of the flow velocity necessary for the determination of the mean velocity;
- by approximation of the integral of the product of a velocity field over a cross-section by finite summations of the product of width, depth, and mean velocity.

Cross-Sectional Area

The uncertainty in the width determination for a stream under ice cover, or partial ice cover arises because of the difficulties of locating the edges of flow under ice cover. Damage to the equipment (i.e., cutting blade of the ice auger) are likely to happen when the technician tries to locate edges of flow under ice. Also, for large streams, corrections for sag, pull, slope, and temperature of the measuring tape or wire should be made.

Errors in depth soundings are likely to occur in cross-sections having great depths and velocities, and those with frazil ice accumulation.

The ice thickness, and frazil depths are assumed to vary linearly between verticals or sampling points. However this is not necessarily the case, therefore introducing additional error in the cross-sectional area determination.

Sampling of Mean Velocity in Time

The mean velocity at any point, determined from a measurement during a certain time (e.g. 40 to 50 seconds), is only an approximation of the true mean velocity at any particular point. Therefore, an error is introduced, which is related to the time period of observation of velocity at a point. Although the majority of the investigations carried out to determine the uncertainty due to limited time of exposure were performed in open channels, they indicated that an observation time of 40 to 50 seconds is insufficient to obtain a measurement of sufficient accuracy.

Sampling of Mean Velocity in Space

In the computation of a discharge measurement, the depth and the velocity are assumed to vary linearly with the distance between the verticals in the cross-section. The value of the uncertainty depends not only on the number of verticals, but also on the size and shape of the channel, the variation in the bed profile and the horizontal distribution of the velocity profile. Based on several investigations, the minimum number of verticals taken in the cross-section (i.e., 20 to 25) is adequate in most situations.

The computation of the mean velocity in a given vertical as an average or a weighted average of a number of point velocities results in an approximation of the true mean velocity in the vertical considered. Due to the roughness of the underside of the ice cover the location of the filament of maximum velocity is some distance below the underside of the ice. The velocity distribution under ice cover is similar to that in a pipe with a lower velocity near the underside of the ice.

It is generally assumed that a vertical velocity distribution curve for a stream under ice cover follow a logarithmic distribution. However, considerable uncertainties still remain in the shapes of the velocity distribution for ice-covered rivers. For example, Lawson et al. (1986) showed that velocity profiles ranged from logarithmic distribution to a very flat vertical distribution through most of the water column. In Canada, Alford and Carmack (1987a, 1987b), and Pelletier (1988c) reported similar observations.

The standard procedure used by Water Survey of Canada for vertical velocity measurements under ice cover was developed by Barrows and Horton (1907). They analyzed 400 profiles from 25 gauging stations in five U.S. states. They found that the average coefficient for obtaining the mean velocity from the mean of the velocities at 0.2 and 0.8 depth was 1.002, and showed that the range was 0.98 to 1.04. Also, the average coefficient for obtaining the mean velocity from that at mid depth was 0.878, the range being 0.82 to 0.92. They suggested that vertical velocity profiles be taken and appropriate coefficients be derived from these at each metering site.

Barrows and Horton also showed that the coefficient changes for different types of ice cover (e.g., very rough ice). Lau (1982) suggested a guide for a better correction coefficient based on the ice and bed roughness, and showed that the velocities at 0.2 and 0.8 of the depth may deviate significantly from the overall average velocity.

The sampling of vertical velocity curves is a not a standard procedure for Water Survey of Canada. Based on results of an investigation on the Red River in Manitoba, Pelletier (1988c) recommended that further investigations be undertaken to determine the variability in the coefficients required for Canadian streams for obtaining the mean velocity from the two- and the one-point methods. It was also recommended that vertical velocity curves be sampled to establish the appropriate coefficient for each particular stream.

Current Meter Calibration

The current meter is calibrated by towing the meter through still water at various constant speeds and recording the number of revolutions of the rotor in a measured interval of time. It is assumed that this rating or calibration is valid when the current meter is used to measure velocity of turbulent flow in open channels and in ice-covered rivers. Errors may be introduced by this assumption and by errors in the rating tank.

The various factors affecting the overall uncertainty in the current meter calibration are: calibration procedure (i.e. number of tests, curve fitting technique, individual versus group rating); repeatability of calibration data; change in fluid densities (i.e. temperature and density); effect of suspension; boundary effects; effect of oblique flow; effect of vertical motion; and effect of turbulence. Some of these factors are further described below.

It was stated previously that WSC winter current meters are calibrated on rod suspension only. However, they often are used on cable suspension using a wide range of winter weight assemblies. Recent studies (Schneider and Futrell, 1984; Pelletier, 1988c) have shown that if a meter is rated on rod suspension but used in the field on cable suspension, with winter weights used by Water Survey of Canada, significant differences would occur. For example, Pelletier (1988c) determined that the WSC winter meter rotates approximately 4% to 17% slower, depending on the velocity, when mounted with a winter weight assembly (i.e., Winnipeg type) than when mounted on a rod.

Note also, that similar observations on the effect of suspension using open water weight assemblies were made by Engel and DeZeeuw (1984b).

Because of the importance and complexities of the effect of suspension on the calibration of the current meters, further investigations were recommended (Pelletier, 1988c) and are planned to be carried out jointly between the Water Resources Branch and the National Water Research Institute.

A random uncertainty will arise from the scatter of the calibration points about the line of regression and a systematic uncertainty, due to the rating tank, revealed by the shift of that line.

It has been noted in the literature (Smoot and Carter, 1968; Herschy, 1982; Pelletier, 1988c) that the uncertainty in a cup-type current meter increases as the velocity decreases. This is of particular importance at velocities lower than 0.3 m/s, which are often encountered under ice cover conditions. The results of an extensive literature review (Pelletier, 1988b) showed the large differences and inconsistencies between the results of the different investigators and suggested that further investigations be carried out. Such investigations are expected to be carried out by the Water Resources Branch jointly with the National Water Research Institute (Pelletier, 1988c).

Summary

Generally, an ice cover will significantly modify the characteristics and morphological processes of rivers. The hydraulic processes are more complex than open channel conditions and are not well understood.

Changes in river flow from ice-free flow to ice flow regimes have been identified mainly by theoretical and laboratory analyses. These studies have shown that an ice cover generally increases the normal flow depth and decreases flow velocity. An ice cover modifies the velocity and shear stress distributions. The precise form of these distributions under different winter flow regimes encountered in Canada remains in question. The variables of heat transfer, ice physics, and ice and flow history make the solution complex.

In general, winter discharge measurements are less accurate than measurements made under open water conditions for the following reasons:

- the presence of ice in the river, either covering the surface, attached to the bottom or banks in the form of anchor ice, or floating throughout the cross-section as frazil ice;
- the inability of the cup-type current meter to accurately measure low velocities (less than 0.3 m/s) as is often encountered during the ice period;
- the freezing of the meter while the technician is passing it from one measuring point to another, or making necessary repairs;
- the accumulation of frazil ice in the cups of the current meter, resulting in under-estimation of the mean velocity;
- the inability of the hydrometric technician to detect under surface ice eddies or other conditions that disturb the distribution of the flow, and the tendency to measure velocities at too few points;
- the impossibility of measuring the effective cross-section as accurately under ice cover as in open water, especially when frazil ice is present;
- hurry in the work, due to physical discomfort of the technician making the discharge measurement;
- the possibility of the stream having a different velocity profile that the standard assumed for winter measurements; and
- presence of thin or moving ice or overflow, making the physical access to the flow cross-section unsafe or simply impractical.

Once the streamflow measurements have been obtained, the computation of daily discharges for the ice affected period can not be computed by the standard stage-discharge relation because of the presence of other variables. Variables or factors that may come into play are:

- growth of ice due to temperature;
- formation of closed conduit flow;
- reduction and/or blockage of the cross-section due to ice growth and/or frazil ice;
- changes in roughness of ice from thermal processes;
- formation of frazil and/or anchor ice in response to weather and flow conditions;
- a wide range of freeze-up processes from the slow thermal growth to the episodic formation of frazil ice dams; and
- ice break-up, jams, and releases as determined by ice flow and channel characteristics.

Some factors of winter hydrology are not fully understood nor quantified, making data interpretation, estimation and computation process subjective and difficult. Examples include: flow change due to the initial ice cover formation; effect of temperature change on groundwater releases; abstraction of flow to form fixed ice.

The problems described in this section may be divided into three main areas for further investigations. They are: streamflow measurement; daily flow computation and estimation; and winter hydrology. Accurate discharge measurements are essential for accurate daily discharge computations, and to the understanding of winter hydrology. Therefore, emphasis and research effort should first be placed on resolving the problems and uncertainties in streamflow measurement techniques under winter ice conditions.

The cost of obtaining discharge measurements under winter ice conditions is considerably higher than at other periods of the year, due to factors such as: the time required to access the metering site and to perform the measurement; and the need for two-person field crews because of dangerous field conditions. Not only are discharge measurements obtained under ice conditions more costly, and more difficult to obtain, but also very often they are considered to be less accurate than open water discharge measurements.

Over the last two years increasing effort (Lawson et al., 1986; Alford and Carmack, 1987a, 1988b; Pelletier, 1988a, 1988c, 1989) has been made to better understand the factors modifying the flow regime of streams affected by ice conditions. These investigators generally noted that systematic, quantitative field studies of ice-covered rivers were lacking, and therefore recommended that further investigations be carried out.

Since the problems described in this section are commonly encountered in northern countries, and the solutions to these problems may be applicable to other countries, joint international investigations, will be beneficial and cost effective in resolving uncertainties in streamflow measurement and computation under winter ice conditions. Such joint studies may lead to the development of an international standard on the techniques for measurement and computation of streamflow under winter ice conditions.

The Water Resources Branch of Environment Canada has recognized the problems and uncertainties encountered in the collection of hydrometric data at sites affected by winter ice conditions, and decided to formulate, in cooperation with other national and international data collection agencies, a plan for further investigations in order to improve the overall quality of these hydrometric data. The plan includes: a survey of the conditions encountered across the country and a comparison with other northern countries; assessment of the present techniques (methods and instruments) used to measure and compute streamflow at sites affected by winter ice conditions, including determination of uncertainties in measured discharge, and daily computed discharge; and development of new instrumentation, including plastic current meter rotors with an optic head, and an ultrasonic velocity meter.

4.8 SUMMARY OF AVAILABLE METHODS FOR STREAMFLOW MEASUREMENT

In this section various methods that are available for streamflow measurement in open channel, other than those discussed above, will be briefly described. This section constitute a preamble to section 4.9, in which the selection of method is discussed, including selection criteria (e.g. uncertainty), and limiting conditions.

Methods which are available and suitable for flow measurement in open channels are as follows (ISO, 1986):

(a) Velocity-area method

  (i) by wading
  (ii) from a bridge
  (iii) using a cableway
  (iv) using a static boat
  (v) using a moving boat
  (vi) using floats

(b) Slope-area method

(c) Ultrasonic method

(d) Electromagnetic method

(e) Dilution method

  (i) with a chemical tracer (continuous injection)
  (ii) with a chemical tracer (sudden injection)
  (iii) with a radioactive tracer (sudden injection)
  (iv) with a radioactive tracer (continuous injection)

(f) Cubature method

(g) Thin-plate weirs

  - (i) sharp crest, V-notch
  - (ii) sharp crest, rectangular, with suppressed side conditions
  - (iii) sharp crest, rectangular, with side contractions

(h) Weirs

  - (i) broad crested with sharp upstream edge
  - (ii) broad crested with rounded upstream edge
  - (iii) triangular profile
  - (iv) triangular profile, flat-V
  - (v) V-shaped, broad crested

(i) Flumes

  - (i) rectangular throated
  - (ii) trapezoidal throated
  - (iii) U-shaped throat

(j) Free overfalls, end-depth method (rectangular and non-rectangular channels).

4.8.1 Velocity-area methods

Methods using current meters

The velocity and cross-sectional area of flow in an open channels are measured. The discharge is determined from the product of this velocity and area.

The velocity may be measured by a current meter (cup or propeller-type). The current meter may be mounted on a wading rod (wading method), or on a cable and reel suspension (bridge, cableway, and static boat methods).

When measurements using current meters are not feasible, the velocity is measured by floats.

Moving boat method

The moving boat method employs a modification of the conventional current meter measurements in the velocity-area method of determining discharge. The method requires no fixed installation and lends itself to the use at alternative sites.

The principal difference between a conventional measurement and the moving boat measurement is in the method of data collection.

In the case of the conventional technique, the mean velocity in the segments of a cross-section of the stream is determined by point velocities or an integrated mean velocity in the vertical.

A propeller-type current meter is suspended from a boat about 1 m below the surface and the boat traverses the channel along a pre-selected path normal to the streamflow. During the traverse an echo sounder records the geometry of the cross-section and the continuously operating current meter records the resultant of the stream velocity and the boat velocity.

4.8.2 Ultrasonic method

The velocity of sound in water is measured by simultaneously transmitting pulses in both directions through the water from transducers located in the bank on each side of the river. Alternatively, the two transducers can be on the same bank with a reflector or transponder on the other.

The transducers are located so that the pulses in one direction travel against the flow and in the other direction with the flow. The difference between the velocities of the ultrasonic waves is related to the speed of flowing water at the elevation of the transducers. This velocity can be related to the average velocity of flow over the whole cross-section, and by relating the cross-sectional area and water level, the discharge may be deduced from measurements of water velocity and stage.

4.8.3 Electromagnetic method using a full channel width coil

Small electrical potentials are set up between opposite banks of the river by means of electromagnetic induction as the water flows through a vertical magnetic field. The field is set up by a coil buried below the bed or bridged across the river. The potential generated is proportional to the width of the river, the magnetic field and the average velocity in the cross-section. The discharge is then obtained by multiplying this average velocity by the cross-sectional area of flow.

4.8.4 Measuring Structures

Weirs

The relation between head over the crest of the weir and the discharge is established, usually in a laboratory and applied to field installation. The head over the weir is measured and this value inserted in the appropriate formula to obtain a value of discharge. If the flow is non-modular (water level downstream is sufficiently high to influence the water level upstream of the weir and the discharge), the head over the weir and the head at the crest or downstream are measured to determine discharge.

Flumes

The relation between the head upstream of the throat of the flume and the discharge is established. Thereafter, as with weirs, the discharge is determined from the measurement of the upstream water level. If the flow is non-modular, measurements of head both upstream and downstream are necessary.

Free overfalls (end-depth method)

In a device creating abrupt drop in the flow, the channel depth at the brink of the drop and the flow area of the channel at the brink section are measured. The discharge is then determined using the appropriate equation.

4.8.5 Dilution methods

A tracer liquid is injected into a stream, and at a point further downstream, where turbulence has mixed the tracer uniformly throughout the cross-section, the water is sampled. The ratio of the concentrations between the solution injected and the water at the sampling station is a measure of the discharge.

4.8.6 Other methods

Slope-area method

The cross-section of a channel is measured at several sections along a reach which is as straight and as uniform as practicable. The roughness of the channel is estimated after examination of the channel or measurement of the bed features. The discharge is determined by measuring the water level at two or three sections a known distance apart and inserting the slope, breadth, depth and roughness in an open channel flow equation (e.g., that of Chezy or Manning).

Cubature method

This method is restricted to situations where flow causes a change in water level and the volume of stored water. The water level and surface area of the stored water are measured on two occasions at a known time interval. The mean discharge is obtained by dividing the volume of water stored, or released from storage, by the time interval.

4.9 SELECTION OF METHOD FOR FLOW MEASUREMENT

In this section the process for the selection of a method for streamflow measurement is outlined, including the criteria that must be considered, and the limiting conditions of the methods.

4.9.1 Selection Criteria

The selection of the most suitable flow measurement method to employ at any streamflow gauging station depends on a number of factors, which can be summarized as follows (Herschy, 1985; Pelletier, 1988b):

(a) capital available

(b) size of the river

(c) access

(d) hydraulic conditions of flow including:

    (i) river regime
    (ii) relation between stage and discharge
    (iii) backwater conditions
    (iv) stability of the channel reach
    (v) conditions of flow in reach

    (vi) geometry of channel reach
    (vii) velocity distribution
    (viii) head loss available
    (ix) range of velocities
    (x) bed conditions

(e) range of flows

(f) ice conditions

(g) weed conditions

(h) sediment transport conditions

(i) installation facilities available

(j) maintenance facilities available

(k) operational facilities available

(l) staffing available

(m) equipment available

(n) data processing available

(o) availability of electrical power.

To make a systematic decision from among the numerous flow measurement methods, the user has to determine requirements of the measurement. These requirements and restrictions may be based:

- on the physical characteristics of the site under investigation:
  - width, depth, and mean velocity in the cross-section;
  - are there cross-currents in the flow?;
  - is the channel free from vegetation?;
  - is the channel free from ice, frazil ice, anchor ice?;
  - is the channel fairly straight and uniform?;
- on the time available to perform the measurement, i.e., some stream gauging methods may take one hour, others may take up to 6 hours, and this may become a serious restriction (during rising stage, flood conditions)
- on the availability of trained experts for the stream gauging methods available
- on the type of velocity distribution of flow (e.g., subcritical) in the cross-section under investigation

- on the quantity of suspended sediment in the water, on the presence of entrained air, etc. which might affect the performance of a certain method (eg. ultrasonic)
- on the availability of equipment:
  - types of current meters (vertical or horizonal axis);
  - type of suspension (cable or rod);
  - suspension weight assemblies (open water or ice cover);
- on the availability of (gauging) structures necessary for certain stream gauging methods:
  - a bridge for the velocity area method from bridge;
  - a cableway for the velocity area method from cableway;
  - a boat for the velocity area method from static boat method;
  - the moving boat package for the velocity area method using the moving boat;
  - flumes;
  - weirs;
  - etc.

Another important factor in the decision process, is that the user must determine what is the desired accuracy. For example, in the single determination of river discharge, using the velocity area method with a current meter, Pelletier (1988b) has shown that the uncertainty in streamflow measurement is related to uncertainties in the cross-sectional area data; uncertainties in the mean velocity; and uncertainties in the discharge computation formula.

Moreover the uncertainty in the mean velocity, is related to uncertainties in sampling the mean velocities in time (which is related to the time of exposure) and to uncertainties in sampling the mean velocity in space (which is related to the number of points in the vertical and the number of verticals in the cross-section).

As one can see, expertise in the selection of the **most** suitable stream gauging method for a particular site under consideration is fairly complex, and much of the decision process is generally based on a combination of field and theoretical experience. However, hydrometric specialists from national agencies which have the mandate to monitor streams and to determine which stream gauging methods are to be used, usually tend to use only methods that they know fairly well (i.e., methods that they have expertise in), therefore restricting the types of methods they could be using, and their possible benefits (e.g., in terms of accuracy, cost).

For example, in North America the velocity area is generally used with vertical axis meter, versus, in Europe, where the horizontal axis meter is preferred. Also, in Europe, fewer number of verticals are taken in a stream than in North America, however, more observation points are taken per vertical in Europe than in North America. In the U.K. gauging structures (eg. weirs) are widely used when compared to Canada, and in France dilution methods are used extensively in comparison with Canada.

4.9.2 Limiting Conditions and Selection of Method

The selection of the most suitable method for measuring discharge should be based on the limiting conditions indicated in Table 4.31 (ISO 1986, Starosolszky 1987). The symbols used in Table 4.31 are explained in Table 4.32.

Additional or more detailed on limiting conditions may be found in the International Standards relevant to each method (see Table 4.33 for list of available standards) or in ISO (1983).

As one can see the selection of a stream-gauging method based on a particular application and criterion is a fairly complex process. Therefore, to help the user (who is not an expert in all the available stream gauging methods) determine which method is should be used, an **expert system** prototype for the selection of the most suitable method for flow measurement in open channels could be developed.

An expert system is defined as a program that behaves like an expert, or a combination of several experts, for a problem domain (i.e., selection of a flow measurement method). Its characteristics are that it should be capable of explaining its decisions and the underlying reasoning, and it should be able to deal with uncertain and incomplete information.

On the other hand, an expert is defined as a person who, because of training and experience, is able to do things more competently than most technical users. Experts are not only proficient but also smooth and efficient in the actions they take. Experts have considerable knowledge for applying what they know to problems and tasks; they are also good at eliminating irrelevant information in order to get at basic issues, and they are good at recognizing and solving problems they face as instances of types with which they are familiar.

A prototype expert system called ESSEM (Pelletier, 1987; Simonovic, 1990) for the selection of a suitable method for flow measurement in open channels was developed in conjunction with the work described in this thesis. ESSEM was designed to assist in selecting the "optimal" streamflow measurement method for a particular gauging station or river, considering various factors such as site and flow conditions, and required uncertainty.

In summary, the uncertainties associated with each of the methods described in the previous sections, depends on a number of factors, but the most important ones are (Herschy, 1985)

a) hydraulic conditions of flow;

b) measurement of head or stage;

c) number of verticals taken in a current meter measurement;

d) coefficient of discharge in the weirs and flume methods;

e) the stage-discharge relation in the velocity-area method;

f) operation and maintenance of the station.

For good measurement practice carried out to ISO standards the attainable uncertainties in a single measurement of discharge are given in Table 4.34. The values of uncertainties in Table 4.34 may be considered attainable for average flow conditions but have to be adjusted for conditions of extreme low flows or floods.

Authors that gives information and/or uncertainties values for stream-gauging methods (other than for the velocity-area method using a current meter) includes: Arnberg (1971); Bos (1976); Day (1976); Derecki and Quinn (1987); Drenthen and Vermeulen (1981); Dyer (1970); Gordon (1989); Halliday et al. (1975); Harp (1974); Herschy (1978b, 1985); Holmes et al. (1970); Jarrett (1987); ISO; Kenney (1977); Kinosita (1970, 1982); Kirby (1987); Klein and Yufit (1983); Laenen (1985); Laenen and Smith (1982); Lawson et al. (1986); Lowell and Hirschfeld (1979); Newman (1976, 1982); Rantz (1982a, b); Rodda (1976); Trout (1988); and WMO (1980a, b).

Table 4.31 Limiting conditions

No.	Description	Relevant ISO	Width	Depth	Velocity	Sediment load	Approach condition	Time	Minimum Uncertainty	
1	Velocity-area, by wading	748	L,M,S	S	S,M		b,c,d	J,K	3	A,B
2	Velocity-area, from bridge	748	M,L	M,L	M,L		b,c,d	K	3	A,B,C,D
3	Velocity-area, cableway	748	M,L	M,L	M,L		b,c,d	K	4	A,B,C
4	Velocity-area, static boat	748	M,L	M,L	M,L		b,c,d	K	4	A,B,C,E
5	Velocity-area, moving boat	4369	L	M,L	M,L		b,c,d	K	6	A,B,E
6	Velocity-area, floats	748	M,L	M,L	M,L,S		b,c,d	K	10	F
7	Slope-area	1070	M,L	M,L	M,L		b,c,d	K,N	10	Q
8	Ultrasonic	6416	M,L	M,L	M,L,S	R	b,c,d	G,J,H	5	
9	Electromagnetic	TR 9213	M,S	S,M	S,M		b,d	G,H,J	5	T
10	Dilution, chemical, continuous injection	555/1	S,M	S,M	S,M		c,g,k	K,N	3	
11	Dilution, chemical, sudden injection	555/2	S,M	S,M	S,M		c,g,k	K	3	
12	Dilution, radioactive tracer, sudden injection	555/3	S,M	S,M	S,M		c,g,k	K	3	
13	Dilution, radioactive tracer, continuous injection	555/3	S,M	S,M	S,M		c,g,k	K,N	3	
14	Cubature	2425						K	10	H
15	Thin-plate weirs, sharp crest, V-notch	1438/1	S	S	M,S	I	a,b,e,j	J,G	3	
16	Thin-plate weirs, sharp crest, rectangular, suppressed	1438/1	S	S	M,S	I	a,b,e,f,j	J,G	1	
17	Thin-plate weirs, sharp crest, rectangular	1438/1	S	S	M,S	I	a,b,e,f,j	J,G	1	
18	Weirs, broad-crested with sharp upstream edge	3846	M,S	S	M,S	I	a,b,e,h,j	J,G	5	
19	Weirs, broad-crested with rounded upstream edge	4374	M,S	S	M,S	I	a,b,e,h,j	J,G	5	
20	Weirs, triangular profile	4360	M,S	S	M,S	I	a,b,e,j	J,G	5	
21	Weirs, triangular profile, flat-V	4377	M,S	S	M,S	I	a,b,e,j	J,G	5	
22	Weirs, V-shaped, broad-crested	8333	M,S	S	M,S	I	a,b,i	J,G	5	
23	Flumes, rectangular	4359	M,S	S	M,S	I	a,b	J,G	5	
24	Flumes, trapezoidal	4359	M,S	S	M,S	I	a,b	J,G	5	
25	Flumes, U-shaped	4359	M,S	S	M,S	I	a,b,i	J,G	5	
26	Free overfalls, rectangular channels (end-depth method)	3847	M,S	M,S	M,S		a,b	J,G	10	
27	Free overfalls, non-rectangular channels (end-depth)	4371	M,S	M,S	M,S		a,b	J,G	10	

Table 4.32 Explanation of symbols used in Table 4.31

a	Flow should be subcritical
b	Flow should have no cross-currents
c	Channel should be relatively free from vegetation
d	Channel should be fairly straight and uniform in cross-section
e	Channel should be fairly straight and symmetrical in cross-section for about 10 channel widths upstream
f	Channel should have vertical walls and a level floor for a distance of not less than 10 times the width of the nappe at maximum head
g	Flow in the channel should be turbulent (even including a hydraulic jump) to ensure mixing
h	Channel should be rectangular for a distance upstream of at least twice the maximum head
i	Channel should be nearly U-shaped
j	Velocity distribution should be fairly uniform
k	Channel should be free from recess in the banks and depressions in the bed
A	For velocity-area method, with velocity observed at 0.6 times the depth, or with two-point method, the minimum uncertainty may be up to 5%
B	For velocity-area method, with velocity observed at surface, the minimum uncertainty may be up to 10%
C	Corrections may be required because of distance of air- and wet-line effects
D	Major error can be caused by pier effects
E	Major error can be due to drift, obstruction of boat and heaving action
F	This method is recommended for use only when the effect of the wind is small and where no other will serve. Such conditions are likely to be so variable that no representative accuracies can be quoted, but usually the accuracy of this method is lower than conventional methods using current-meters and higher than the slope-area methods
G	Method suitable for more frequent discharge measurements
H	Method suitable for tidal waterways

Cont. Table 4.32 Explanation of symbols used in Table 4.31

I	Heavy sediment concentration not permissible
J	Quick method (less than 1 hour)
K	Slow method (1 to 6 hours)
L	Large width (more than 50 m) or high velocity (more than 3 m/s) or large depth (more than 5 m)
M	Medium width (between 5 and 50 m) or medium velocity (between 1 and 3 m/s) or medium depth (between 1 and 5 m)
N	Very slow method (more than 6 hours)]
Q	Approximate method used when velocity-area method not feasible and slope can be determined with sufficient accuracy
R	Suspended material concentration should continue to be low in order to avoid too large a loss of acoustic signal; for the same reason, the flow should be free from bubbles
S	narrow width (less than 5 m) or shallow depth (less than 1 m) or low velocity (less than 1 m/s)
T	May be used in rivers with weed growth and moving bed material

Table 4.33 ISO/TC 113 Standards Printed

ISO 555/I-73	Dilution methods for measurement of steady flow - Part I: Constant rate injection method.
ISO 555/II-87	Dilution methods for measurement of steady flow - Part II: Integration method.
ISO 555/III-82	Dilution methods for measurement of steady flow - Part III: Constant rate injection methods and integration method using radioactive tracers.
ISO 748-79	Velocity-area methods.
ISO 772-78	Vocabulary and symbols.
ISO 1070-73	Slope-area method
ISO 1088-85	Velocity-area methods - Collection of data for determination of errors in measurement.
ISO 1100/I-81	Establishment and operation of a gauging station.
ISO 1100/II-82	Determination of the stage-discharge relation.
ISO 1438/I-80	Thin plate weirs.
ISO 2425-75	Measurement of flow in tidal channels (with Amdt I)
ISO 2537-85	Cup type and propeller type current meters.
ISO 3454-83	Direct depth sounding and suspension equipment (first revision)
ISO 3455-76	Calibration of rotating-element current meters in straight open tanks.
ISO 3716-77	Functional requirements and characteristics of suspended sediment load samplers.
ISO 3846-77	Free overfall weirs of finite crest width (rectangular broad crested weirs).
ISO 3847-77	End depth method for estimation of flow in rectangular channels with free overfall.
ISO 4359-83	Rectangular, trapezoidal and U-shaped flumes.
ISO 4360-84	Triangular profile weirs (first revision).
ISO 4363-77	Methods for measurement of suspended sediment.

Cont. Table 4.33 ISO/TC 113 Standards Printed

ISO 4364-77	Bed material sampling.
ISO 4365-85	Equipment in streams and canals - Determination of concentration, particle size distribution and relative density.
ISO 4366-79	Echo sounders for water depth measurements.
ISO 4369-79	Moving boat method.
ISO 4371-84	End depth method for estimation of flow in non-rectangular channels with a free overfall (approximate method).
ISO 4374-79	Water level measuring devices.
ISO 4375-79	Cableway system for stream gauging.
ISO 4377-82	Flat-V weirs.
ISO 6416-85	Measurement of discharge by the ultrasonic (acoustic) method.
ISO 6418-85	Ultrasonic (acoustic) velocity meters.
ISO 6419/I-84	Hydrometric data transmission system - Part I: General
ISO 6420-84	Position fixing equipment for hydrometric boats.
ISO 8333-85	V-shaped broad-crested weirs.
ISO 8363-86	General guidelines for the selection of method.
ISO 8368-85	Guidelines for the selection of flow gauging structures.
ISO/TR 7178-83	Velocity-area methods - Investigation of total error.
ISO/TR 9123-86	Stage-fall-discharge relations

Table 4.34 Uncertainties in a single measurement of discharge

Method	Percentage Uncertainty (95% level)
Current meter measurement	5
Floats	10-20
Slope-area	10-20
Fall-discharge	10-20
Dilution techniques	5
Thin plate weir	1-4
Thin plate V-notch	1-2
Triangular profile (Crump) weir	2-5
Flat V weir	2-5
Rectangular profile weir	5
Round nosed weir	5
Flumes	5
Moving boat	5
Ultrasonic	5
Electromagnetic	5

5. MULTIPLE-OBJECTIVE ANALYSIS TECHNIQUES

5.1 DESCRIPTION OF MULTIPLE-OBJECTIVE TECHNIQUES

In this section two techniques will be used, namely: the ELECTRE I and the compromise programming technique for investigating the relative importance of various uncertainty components within the velocity-area method. A short description of these techniques (taken from Goicoechea et al., 1982) will first be given, followed by the application of these two techniques for the determination of the relative importance of uncertainties of different sources in the river discharge determination.

5.1.1 ELECTRE I

The ELECTRE method attempts to structure a partial ordering of alternatives which is stronger than the incomplete ordering implied by noninferiority and which still allows some incomparability to remain (Cohon and Marks, 1975).

The multicriterion algorithm ELECTRE I (elimination and choice translating algorithm) is a procedure which reduces the size of the set of nondominated solutions (Goicoechea et al., 1982). It is especially suitable for problems with a discrete number of alternatives. The method was first suggested by Benayoun, Roy and Sussman (1966) and was subsequently improved by Roy (1971).

Essentially, a search is made for a subset of nondominated alternatives in which a certain degree of discussion or discord is accepted in the dominance relationship. That is, an alternative "i" qualifies for membership in the subset if it can be said that alternative "i" is preferred to alternative "j" (i.e., $i > j$), from almost every viewpoint. Thus the method structures a partial ordering of alternatives which is stronger that the incomplete ordering implied by nondominance, but allows some incomparability to remain.

The construction of the subset is accomplished by the definition of a binary relation "R" which captures the preferences of the decision maker (DM) that can be well accounted for by means of the available data. This relation "R" is called an **outranking relationship** and is built from value judgments supplied by the decision maker. The method does not require that the relationship be translative, i.e. a^1Ra^2 and a^2Ra^3 does not necessarily imply a^1Ra^3 (where a^1, a^2, and a^3 are three different alternatives or actions). The method recognizes that the reasons which allows one to decide a^1Ra^2 and those which allow a^2Ra^2 may be too distinct to allow a^1Ra^3.

The outranking relationship (defined below) is used to form a graph in which each node represents a nondominated alternative. Next, the kernel of the graph is found.

The nodes contained in the kernel represent those alternatives which are preferred on the basis of the outranking relationship. The nodes not in the kernel can be eliminated from further consideration.

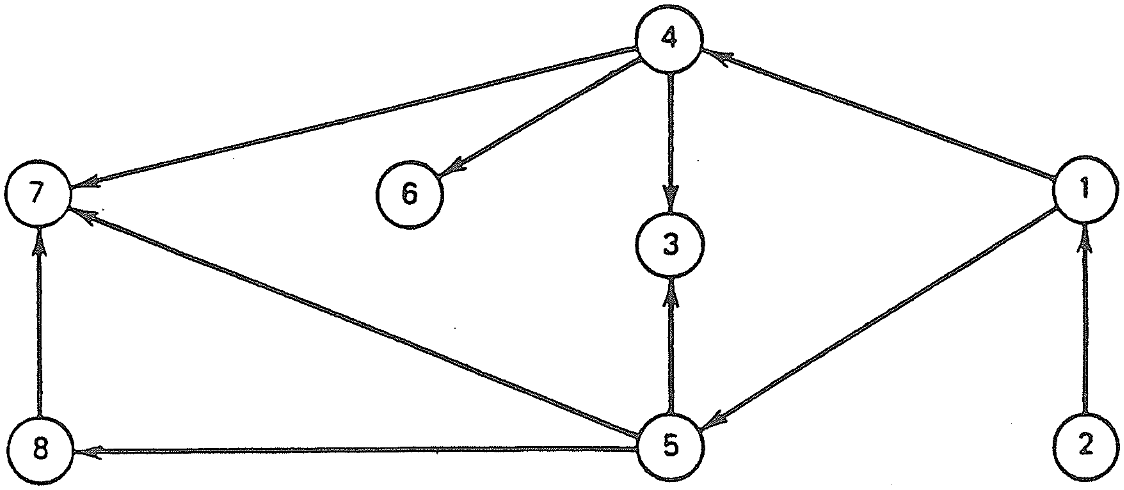

Figure 5.1 ELECTRE1 graph

An example of the type of graph with which the ELECTRE I method is concerned is illustrated in Figure 5.1. In this graph each node is represented by a circled number. Each node corresponds to a nondominated alternative; thus, there are eight members of the nondominated set. The arrows emanating from the nodes are called directed paths and correspond to the outranking relation; they are analogous to a preference relationship. That is, it can be said that alternative 1 is preferred to alternative 5, alternative 4 is preferred to alternative 6, etc. The kernel of this graph consists of nodes 2,4, and 5 and is the subset of nondominated alternatives which the ELECTRE I method defines.

The graph and its kernel will now be defined. First, note that a **cycle** is defined as a directed path beginning in a node and coming back to this node. Relative to a preference relationship, such a directed path is regarded as expressing indifference. Also in the definition below a' and a" denote any two possible alternatives. The graph, Gc, and its kernel, Kc, are defined as follows (Roy, 1971). Let:

> C be the **equivalence relation** defined by a'Ca" if and only if there exists in R a cycle passing by a' and a";
>
> B denote the **set of classes** in the equivalence C;
>
> R_c denote the relation defined on B and verified by the couple of classes (b',b") if and only if there exist a'εb' and a"εb" such that a'Ra"; when R is acyclic: B=A and R_c=R;
>
> G_c by the **acyclic graph** associated with the relation R_c (i.e., a directed path from node a' to node a" exists if and only if a'R_ca"). A subset K_c c B is called a **kernel** of G_c if:
>
> i) ¥ b',b" in B: there is no b' such that b' R_c b"
> ii) ¥ b ε B-K_c there exists k ε K_c such that k R_c b.

The only item which is yet to be explained concerning the ELECTRE method is the specification of the outranking relationship. It is this relation that allows a partial ordering of the nondominated alternatives. The relationship between the ith and jth alternatives for a given criterion can be represented as follows:

$$\text{i preferred to j: } \overrightarrow{i > i} \text{ ; i and j equivalent : } \overleftrightarrow{i=j}$$

Thus, preference relationships between the ith and jth alternatives can be established for each criterion. ELECTRE I synthesizes these m preference relationships for each alternative to produce the desired outranking relationship between the n alternatives. The synthesis is achieved through a concord index, c(i,j) and a discord index, d(i,j). The concord index measures the weighted relative frequency of viewpoints (criteria) where alternative i is preferred to alternative j. It can be viewed as a measure of the satisfaction the decision maker (DM) receives in choosing alternative i over alternative j. The discord index measures the strength of the viewpoints in greatest disagreement assuming i is chosen over j. It can be viewed as a measure of the dissatisfaction of choosing i over j.

Preliminary to defining the concord index, let $I=\{1,2,...,m\}$ represent the set of m criteria. Furthermore, let $\{w_k:k=1,2,...m\}$ represent the set of weights associated with the m criteria. The criterion weights are determined by the value judgements of the DM.

The criterion considered the most important receives the highest weight, the next most important receives the next highest weight, etc.

Next, partition the set I with three subsets:

$I^+ = I^+(i,j) = \{k \varepsilon I:i>j\}$,

$I^= = I^=(i,j) = \{k \varepsilon I:i=j\}$, and

$I^- = I^-(i,j) = \{k \varepsilon I:i<j\}$

Then define

$$W^+ = \sum_{k\varepsilon I^+} w_k$$

$$W^= = \sum_{k\varepsilon I^=} w_k$$

$$W^- = \sum_{k\varepsilon I^-} w_k$$

And finally the concord index is defined as

$$c(i,j)=(W^+ + 1/2\ W^=) \ / \ (W^+ + W^= + W^-)$$

It is often convenient to present the concord indices in a matrix C where c(i,j) is the ith, jth element of the matrix.

In order to define the discord index, an interval scale common to all m criteria is defined. The desire is to be able to compare the discomfort caused by going from level k_1 to level k_2 of criterion r with discomfort of going from level k_3 to level k_4 of criterion s. This objective is achieved by defining a scale such that a certain number of points out of a maximum of 100 (arbitrary value) is assigned to every criterion. Choice of the number of points to assign to each criterion depends on the level of importance the DM wishes to attach to the range between the best and the worst levels of each criterion. That is, the higher the point assignment the greater the possible discomfort as one moves from one level to the next of each criterion. With this understanding, the discord index can then be defined as

$$d(i,j) = \frac{\text{maximum interval where } i<j}{\text{total range of scale}}$$

$$= \frac{\text{maximum interval where } i<j}{100}$$

Thus the normalized discord interval is calculated for each criterion where alternative j is preferred to alternative i, and the largest normalized discord interval of these criteria is defined as the discord coefficient for alternatives i and j. Again a discord matrix D can be constructed in which d(i,j) is the ith,jth element.

The concordance condition and discordance condition are used to define the outranking relation, R. The outranking relation R is then used to form a composite graph G_c. Composite graphs are defined by controlling the concord index and the discord index of the arcs allowed to belong to a graph. Specifically, alternative i is preferred to alternative j (i.e., an arc (i,j) will appear in the composite graph) if and only if

$$c(i,j) \geq p$$

and

$$d(i,j) \leq q$$

where p, and q are respectively threshold values of the concord index and discord index.

With the outranking relation defined and the graph constructed, the only remaining step is to determine the kernel of the graph. The kernel contains the nodes which represent those alternatives which are preferred on the basis of R. The remaining nodes (i.e., those not in the kernel) are eliminated from further consideration. generally, the make-up of the kernel is fairly insensitive to the **pair of threshold values (p,q)**.

5.1.2 Compromise programming

The method of compromise programming identifies solutions which are the closest to the ideal solution as determined by some measure of distance. Compromise programming in some ways resembles goal programming. The solutions identified as being closest to the ideal solution are called **compromise solutions** and constitute the **compromise set**.

The ideal solution is defined as the vector $z^*=(z^*_1,z^*_2,\ldots,\ z^*_p)$ where the z^*_i are the solutions of the following problems;

$$\max\ z_i(x)$$

subject to

$$x \in X$$

$i=1,2,\ldots,p$

If there were a feasible solution vector, x^*, common to all problems, then this solution would be the optimal one since the nondominated set (in objective space) would consist of only one point, namely $z^*(x^*)=(z^{*1}(x^*), z^*_2(x^*),\ldots,z^*_p(x^*))$.

Obviously, this is most unlikely, and the ideal solution is generally not feasible. However, it can serve as a standard for evaluation of the attainable nondominated solutions. Since all would prefer the ideal point if it were attainable (as long as the individual underlying utility functions are increasing), then it can be argued that finding solutions that are close as possible to the ideal solution is a reasonable surrogate for utility-function maximization.

The procedure for evaluation of the set of nondominated points is to measure how close these points come to the ideal solution. One measure of closeness frequently used is a family of L_s **metrics**, defined in either of two operationally equivalent ways,

$$L_s = [\sum_{i=1}^{p} a^s_i(z^*_i - z_i(x))^s]^{1/s} \qquad \ldots(5\text{-}1)$$

or

$$L_s = \sum_{i=1}^{p} a^s_i(z^*_i - z_i(x))^s \qquad \ldots(5\text{-}2)$$

where $1 \le s \le \infty$.

Finally, a compromise solution with respect to s is defined as x^*_s such that

$$\min L_s(x) = L_s(x^*_s) \qquad \ldots(5\text{-}3)$$

subject to

$$x \in X$$

The compromise set is simply the set of all compromise solutions determined by solving equation (5-3) for a given set of weights, $\{a_1, a_2, \ldots, a_p\}$ and for all $1 \le s \le \infty$.

Operationally, three points of the compromise set are usually calculated, i.e. those corresponding to $s=1,2$, and ∞. To understand the role of the a_i and s parameters, consider the following special cases:

Let $a_1=a_2\ldots=a_p=1$ and let $w_i=z^*_i-z_i(x)$. With these conditions equation (5-2) becomes

$$L_s = \sum_{i=1}^{p} w^{s-1}_i(z^*_i - z_i(x)) \qquad \ldots(5\text{-}4)$$

For $s=1$, $w^{s-1}_i=1$, and we have

$$L_s = L_1 = \sum_{i=1}^{p} (z^*_i - z_i(x))$$

Thus all deviations are weighted equally. For $s=2$, equation (5-4) assumes the form

$$L_s = L_2 = \sum_{i=1}^{p} w_i(z^*_i - z_i(x))$$

Now each deviation is weighted in proportion to its magnitude. The larger the deviation, the larger the weight. As s becomes larger and larger, the largest deviation receives more and more weight, until finally at s=∞ we observe that

$$L_\infty = \max_{\text{all } i} \; (z^*_i - z_i(x))$$

Clearly, the choice of s reflects the DM's concern with respect to the maximal deviation. The larger the value of s, the greater that concern.

Introduction of a_i allows the expression of the DM's feelings concerning the relative importance of the various objectives. Thus a double-weighting scheme exists. The parameter s reflects the importance of the maximal deviation and the parameter ai reflects the relative importance of the ith objective.

Consider the following version of equation (5-2)

$$L_s = \sum_{i=1}^{p} a^s_i w^{s-1}_i (z^*_i - z_i(x))$$

The deviation $z^*_i - z_i(x)$ is weighted proportionately by the choice of s and then weighted by the sth power of the objective weights. Again, as s increases, the maximal a_i and the maximal deviation receive more and more emphasis until

$$L_\infty = \max_{\text{all } i} \; a_i \; (z^*_i - z_i(x))$$

If the objective functions are not expressed in commensurable terms, then a scaling function $S_i(D_i)$, with $D_i = z^*_i - z_i(x)$, is defined to ensure the same range for each objective function. Usually, this range corresponds to the interval (0,1).

This scaling is accomplished by defining the scaling function as

$$S_i(D_i) = \frac{z^*_i - z_i(x)}{z^*_i - z^{**}_i} \qquad \ldots(5\text{-}5)$$

where z^{**}_i is defined as

$$z^{**}_i = \min_{x \varepsilon X} z_i, \quad i=1,2,\ldots,p$$

With the indicated transformation, equation (5-3) is modified by substituting equation (5-5) for $D_i = z^*_i - z_i(x)$, i.e.

$$\min \{L_s(x) = \sum_{i=1}^{p} a^s_i \; [(z^*_i - z_i(x))/(z^*_i - z^{**}_i)]^s\} = L_s(x^*_s) \qquad \ldots(5\text{-}6)$$

subject to

$$x \varepsilon X$$

Expression (5-6) is the operational definition of a compromise solution for a given p.

Interestingly, solution of equation (5-6) always produces a nondominated point for $1 \leq s < \infty$. For $s=\infty$, there is a least one nondominated solution, x^*_s (Yu, 1971). Compromise programming results in a reduction of the nondominated set. If the compromise set is small enough to allow the DM to choose a satisfactory solution, then the algorithms stops. If not, then the DM is asked to redefine the ideal point and the process is repeated. Accordingly, the interaction requirement of compromise programming is slight.

Compromise programming does not have to be restricted to continuous settings; it can be adapted to discrete settings as well. In a discrete setting the ideal solution is defined as the best value in a finite set of values of $z_i(x)$. Essentially, the ideal solution in a discrete setting would be defined as the vector of best values selected from the payoff table. The vector of worst values defines the minimum objective function values, that is, the z^{**}_i. With these values defined and the a_i and p given, the compromise solution can be determined by calculating the distance of each alternative from the ideal solution and selecting the alternative with the minimum distance as the compromise solution.

5.2 APPLICATIONS

For the application of the multiple-objective systems analysis techniques the ISO 748 (1979) data set will be used. Also, in the following discussion the DM (Decision Maker) refers to the author.

As described in the previous sections, the random uncertainties in the single determination of river discharge using the velocity-area method may be attributed to uncertainties in the determination of width, depth, mean velocity. Furthermore, the uncertainties in the determination of the mean velocity may be subdivided into uncertainties in sampling the velocity in time and in space.

The main objective of the application of the multiple objective analysis techniques is to determine relative significance of the different sources of uncertainties in sampling the mean velocity.

The uncertainties (at the 95% confidence level) in determination of the mean velocity, as given by ISO, are given in Tables 5.1a to 5.1d.

5.2.1 ELECTRE I

Four criteria will be used, namely: the number of verticals taken in the cross-section (NV), the number of points taken in the vertical (NPV), the time of exposure at each point in the vertical (TE), and the type of current meter rating (CMR).

Table 5.1a Criteria and associated uncertainties- ELECTRE I

TE: Times of exposure (X'e)

Velocity	Exposure time (min)							
	0.2 or 0.4 or 0.6 d				0.8 or 0.9 d			
(m/s)	.5	1	2	3	.5	1	2	3
0.050	50	40	30	20	80	60	50	40
0.100	27	22	16	13	33	27	20	17
0.200	15	12	9	7	17	14	10	8
0.300	10	7	6	5	10	7	6	5
0.400	8	6	6	5	8	6	6	5
0.500	8	6	6	4	8	6	6	4
1.000	7	6	6	4	7	6	6	4
> 1.000	7	6	5	4	7	6	5	4

Table 5.1b Criteria and associated uncertainties- ELECTRE I

NPV: Number of points in the vertical (X'p)

Method of measurement	Uncertainties
velocity distribution	1
5 points	5
2 points	7
1 point	15

Table 5.1c Criteria and associated uncertainties- ELECTRE I

NV: Number of verticals (X'm)

Number of verticals	Uncertainties
5	15
10	9
15	6
20	5
25	4
30	3
35	2

Table 5.1d Criteria and associated uncertainties- ELECTRE I

CMR: Current meter rating (X'c)

Velocity (m/s)	Uncertainties	
	Individual rating	Group or Standard rating
0.03	20	20
0.10	5	10
0.15	2.5	5
0.25	2	4
0.50	1	3
> 0.50	1	2

The criteria with the scales or levels that were established are presented in Table 5.2.

In this first phase, the most important criterion for the DM is the number of verticals (NV) followed by number of points to be taken in each vertical (NPV) and by the time of exposure (TE), and then slightly less important criteria of type of current meter rating (CMR).

Based on the ISO data set and the number of parameters used to determine the uncertainty in the mean velocity, the total number of possible models is 224. These models are summarized in Table 5.3. For practical purposes, not all of these models have to be analyzed (e.g. in Canada, the number of verticals rarely exceeds 25), in fact 25% of the total number of possible models will be considered in this application, i.e. 56 models. These models are presented, in coded values, in Table 5.4.

Concord Index

The criteria have been assigned the following weights (by the DM):

Number of verticals (NV) : 4
Number of points in vertical (NPV) : 3
Time of exposure (TE) : 2
Current meter rating (CMR) : 1

Σ weights = 10

Note that the criterion considered the **most important** receives the **highest weight**, the next most important receives the next highest weight, etc.

Discord Index

The criteria have been assigned the following maximum scale intervals (by the DM):

Number of verticals : 90
Number of points in vertical: 90
Time of exposure: 60
Current meter rating: 24

Note that the choice of the number of points to assign to each criterion depends on the level of importance the DM wishes to attach to the range between the best and worse levels of each criterion, i.e. the **higher the point** assignment the **greater the possible discomfort** as one moves from one level to the next of each criterion.

The complete program listing for the ELECTRE I method is presented in Appendix B.

The results (a summary is presented in Table 5.5) generally showed that for values of p equal or less than 0.70, and corresponding values of q equal or less than 1.0, the following models were preferred:

49 52 53 54 55 56

with models 52, 54, and 56 being selected the most frequently.

Table 5.2 Criteria and associated scales - ELECTRE I

Criteria	Levels	Code and Uncertainties[1]	
i=1: NV	5	90	15
	10	54	9
	15	36	6
	20	30	5
	25	24	4
	30	18	3
	35	12	2
i=2: NPV	1	90	15
	2	42	7
	5	30	5
	VP	6	1
i=3: TE	30	60	10
	60	42	7
	120	36	6
	180	30	5
i=4: CMR	standard (S)	24	4
	individual (I)	12	2

[1] Notes: Uncertainty values in % at the 95% confidence level for a mean velocity value of 0.30 m/s.

Table 5.3a Possible models - ELECTRE I

Type	Models 1 to 56						
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	30	30	30	30	30	30	30
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	30	30	30	30	30	30	30
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	60	60	60	60	60	60	60
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	60	60	60	60	60	60	60
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	120	120	120	120	120	120	120
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	120	120	120	120	120	120	120
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	180	180	180	180	180	180	180
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	1	1	1	1	1	1	1
TE	180	180	180	180	180	180	180
CMR	I	I	I	I	I	I	I

Refer to Table 5.2 for code and uncertainty relative to each level.

Table 5.3b Possible models - ELECTRE I

Type	Model 57 to 112						
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	30	30	30	30	30	30	30
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	30	30	30	30	30	30	30
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	60	60	60	60	60	60	60
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	60	60	60	60	60	60	60
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	120	120	120	120	120	120	120
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	120	120	120	120	120	120	120
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	180	180	180	180	180	180	180
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	2	2	2	2	2	2	2
TE	180	180	180	180	180	180	180
CMR	I	I	I	I	I	I	I

Refer to Table 5.2 for code and uncertainty relative to each level.

Table 5.3c Possible models - ELECTRE I

Type	Models 113 to 168						
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	30	30	30	30	30	30	30
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	30	30	30	30	30	30	30
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	60	60	60	60	60	60	60
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	60	60	60	60	60	60	60
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	120	120	120	120	120	120	120
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	120	120	120	120	120	120	120
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	180	180	180	180	180	180	180
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	5	5	5	5	5	5	5
TE	180	180	180	180	180	180	180
CMR	I	I	I	I	I	I	I

Refer to Table 5.2 for code and uncertainty relative to each level.

Table 5.3d   Possible models - ELECTRE I

Type	Models 169 to 224						
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	30	30	30	30	30	30	30
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	30	30	30	30	30	30	30
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	60	60	60	60	60	60	60
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	60	60	60	60	60	60	60
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	120	120	120	120	120	120	120
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	120	120	120	120	120	120	120
CMR	I	I	I	I	I	I	I
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	180	180	180	180	180	180	180
CMR	S	S	S	S	S	S	S
NV	5	10	15	20	25	30	35
NPV	VP	VP	VP	VP	VP	VP	VP
TE	180	180	180	180	180	180	180
CMR	I	I	I	I	I	I	I

Refer to Table 5.2 for code and uncertainty relative to each level.

Table 5.4a Selected Models - Coded Values - ELECTRE I

New Model Number	Criteria			
	NV	NPV	TE	CMR
1	30	90	60	24
2	24	90	60	24
3	30	90	60	12
4	24	90	60	12
5	36	90	42	24
6	30	90	42	24
7	24	90	42	24
8	36	90	42	12
9	30	90	42	12
10	24	90	42	12
11	54	90	36	24
12	54	90	36	12
13	90	90	30	24
14	90	90	30	12
15	30	42	60	24
16	24	42	60	24
17	30	42	60	12
18	24	42	60	12
19	36	42	42	24
20	30	42	42	24
21	24	42	42	24
22	36	42	42	12
23	30	42	42	12
24	24	42	42	12
25	54	42	36	24
26	54	42	36	12
27	90	42	30	24
28	90	42	30	12

Legend:

Criteria	Levels	Code	Uncertainties
i=1: NV	5	90	15
	10	54	9
	15	36	6
	20	30	5
	25	24	4
	30	18	3
	35	12	2
i=2: NPV	1	90	15
	2	42	7
	5	30	5
	VP	6	1
i=3: TE	30	60	10
	60	42	7
	120	36	6
	180	30	5
i=4: CMR	S	24	4
	I	12	2

Table 5.4b Selected Models - Coded Values - ELECTRE I

New Model Number	Criteria			
	NV	NPV	TE	CMR
29	30	30	60	24
30	24	30	60	24
31	30	30	60	12
32	24	30	60	12
33	36	30	42	24
34	30	30	42	24
35	24	30	42	24
36	36	30	42	12
37	30	30	42	12
38	24	30	42	12
39	54	30	36	24
40	54	30	36	12
41	90	30	30	24
42	90	30	30	12
43	30	6	60	24
44	24	6	60	24
45	30	6	60	12
46	24	6	60	12
47	36	6	42	24
48	30	6	42	24
49	24	6	42	24
50	36	6	42	12
51	30	6	42	12
52	24	6	42	12
53	54	6	36	24
54	54	6	36	12
55	90	6	30	24
56	90	6	30	12

Legend:

Criteria	Levels	Code	Uncertainties
i=1: NV	5	90	15
	10	54	9
	15	36	6
	20	30	5
	25	24	4
	30	18	3
	35	12	2
i=2: NPV	1	90	15
	2	42	7
	5	30	5
	VP	6	1
i=3: TE	30	60	10
	60	42	7
	120	36	6
	180	30	5
i=4: CMR	S	24	4
	I	12	2

Table 5.5 Results of the application of ELECTRE I technique on the ISO data set (N=56)

p	q	composition of the kernel
0.10	0.00	52 54 56
0.10	0.10	empty
...	...	
0.10	1.00	empty
0.20	0.00	52 54 56
0.20	0.10	empty
...	...	
0.20	1.00	empty
0.30	0.00	52 54 56
0.30	0.10	empty
...	...	
0.30	1.00	empty
0.40	0.00	52 54 56
0.40	0.10	52
0.40	0.20	empty
...	...	
0.40	1.00	empty
0.50	0.00	52 54 56
0.50	0.10	52
...	...	52
0.50	1.00	52
0.60	0.00	49 52 53 54 55 56
0.60	0.10	49 52
...	...	49 52
0.60	1.00	49 52
0.70	0.00	7 10 11 12 13 14 21 24 25 26 27 28 35 38 39 40 41 42 44 46 49 50 51 52 53 54 55 56
0.70	0.10	7 10 21 24 35 38 44 46 49 50 51 52 53 54 55 56
...	...	7 10 21 24 35 38 44 46 49 50 51 52 53 54 55 56
0.70	1.00	7 10 21 24 35 38 44 46 49 50 51 52 53 54 55 56

The results indicates that, based on the criteria and corresponding weights given above, the number of points taken in the vertical is the controlling factor, and that the number of verticals could be reduced as low as 5, if the velocity profile method was used in conjunction with a time of exposure of 180 seconds, and an individual current meter rating (model 56). Models 52 and 54 cannot be considered as practical solution as they imply an extremely long measurement time by taking vertical velocity profile at respectively 10 and 25 verticals with time of exposure of 120 and 60 seconds.

Note that the above conclusion on model 56 is only valid for streams with fairly regular streambed and uniform flow.

In order to confirm the above, the number of stream gauging alternatives was further reduced from 56 to 14, to include only present stream gauging procedures, and possibly more effective procedures. These alternatives are presented in Table 5.6, and associated results in Table 5.7a.

The results (a summary is presented in Table 5.7a) generally showed that for values of p equal or less than 0.55, and corresponding values of q equal or less than 1.0, the following models were preferred:

8 10 12 14

with model 14 selected the most frequently, followed by models 10 and 8.

Models 8, 10, 12 and 14 correspond respectively to models 24, 36, 40, and 56 of the previous simulation (for n=56).

As in the previous simulation, the results indicate that the number of points taken in the vertical combined with long exposure times are the controlling factors. The "best" solution is given by:

model 14, consisting of

5 verticals
vertical velocity profiles for each vertical
time of exposure of 180 sec at each point
individual calibrated current meter

However, the analysis also revealed three other good solutions, one of which corresponds to actual hydrometric practices in North America (model 8) these are:

model no. 10, consisting of

15 verticals
5 observation points for each vertical
time of exposure of 60 sec at each point
individual calibrated current meter

model no. 8, consisting of

25 verticals
2 observation points for each vertical
time of exposure of 60 sec at each point
individual calibrated current meter

model no. 12, consisting of

10 verticals
5 observation points for each vertical
time of exposure of 120 sec at each point
individual calibrated current meter

The above results are only valid for streams with a fairly regular streambed and uniform flow. In fact this is the major problem with the model 14 (or 56) which minimizes the number of verticals in favour of a high number of points in a vertical and a high time of exposure. However, if the section is irregular and wide, the uncertainty in river determination, due to the reduced number of verticals, would be increased in model 14 in comparison to model 8, for example.

A sensitivity analysis was conducted on the various weights given to the four criteria. The following changes were made:

Criteria	initial weights	new weights	new weights	new weights
NV	4	3	3	3
NPV	3	4	3	3
TE	2	2	2	3
CMR	1	1	1	1
results in Tables	5.7a	5.7b	5.7c	5.7d

Using the various weights, as given in the table above, no significant differences were noted in the solutions using the ELECTRE 1 method. The results of this analysis are summarized in Tables 5.7a to 5.7d.

In summary, the analysis using the ELECTRE I technique on the ISO data set revealed that present North American stream-gauging technique (i.e. model 8), as employed by Water Survey of Canada, is adequate for most applications. This solution represents a good compromise in comparison with other procedures which would favour a lesser number of verticals in the metering section, in combination with a larger number of points in each vertical, and a long exposure time.

Table 5.6 Reduced number of alternatives - ELECTRE I

New Model Number	Criteria			
	NV	NPV	TE	CMR
1	30	90	60	12
2	24	90	60	12
3	30	90	42	12
4	24	90	42	12
5	30	42	60	12
6	24	42	60	12
7	30	42	42	12
8	24	42	42	12
9	36	30	42	24
10	36	30	42	12
11	54	30	36	24
12	54	30	36	12
13	90	6	30	24
14	90	6	30	12

Legend:

Criteria	Levels	Code	Uncertainties
i=1: NV	5	90	15
	10	54	9
	15	36	6
	20	30	5
	25	24	4
	30	18	3
	35	12	2
i=2: NPV	1	90	15
	2	42	7
	5	30	5
	VP	6	1
i=3: TE	30	60	10
	60	42	7
	120	36	6
	180	30	5
i=4: CMR	S	24	4
	I	12	2

Table 5.7a Results of the application of ELECTRE I technique on the ISO data set (N=14)

p	q	weights of 4, 3, 2, 1 composition of the kernel
0.05	0.00	8 10 12 14
0.05	0.10	10 14
0.05	0.20	empty
0.15	0.00	8 10 12 14
0.15	0.10	10 14
0.15	0.20	empty
0.25	0.00	8 10 12 14
0.25	0.10	10 14
0.25	0.20	empty
0.35	0.00	8 10 12 14
0.35	0.10	8 10 14
0.35	0.20	empty
0.45	0.00	8 10 12 14
0.45	0.10	8 10 14
0.45	0.20	empty
0.55	0.00	8 10 12 14
0.55	0.10	8 10 14
0.55	0.20	8 14
0.55	0.30	8 14
0.55	0.40	14
.	.	
0.55	1.00	14
0.65	0.00	4 6 8 9 10 11 12 13 14
.	.	
0.65	1.00	4 6 8 9 10 11 12 13 14
0.75	0.00	2 4 6 7 8 9 10 11 12 13 14
.	.	
0.75	1.00	2 4 6 7 8 9 10 11 12 13 14
0.85	0.00	2 3 4 5 6 7 8 9 10 11 12 13 14
.	.	
0.85	1.00	2 3 4 5 6 7 8 9 10 11 12 13 14
0.95	0.00	1 2 3 4 5 6 7 8 9 10 11 12 13 14
.	.	
0.95	1.00	1 2 3 4 5 6 7 8 9 10 11 12 13 14

Table 5.7b Results of the application of ELECTRE I technique on the ISO data set (N=14)

		weights of 3, 4, 2, 1
p	q	composition of the kernel
0.05	0.00	8 10 12 14
0.05	0.10	10 14
0.05	0.20	empty
0.15	0.00	8 10 12 14
0.15	0.10	10 14
0.15	0.20	empty
0.25	0.00	8 10 12 14
0.25	0.10	10 14
0.25	0.20	empty
0.35	0.00	8 10 12 14
0.35	0.10	10 14
0.35	0.20	empty
0.45	0.00	8 10 12 14
0.45	0.10	8 10 14
0.45	0.20	empty
0.55	0.00	8 10 12 14
0.55	0.10	8 10 14
0.55	0.20	10 14
0.55	0.30	10 14
0.55	0.40	10 14
0.55	0.50	10 14
0.55	0.60	14
.	.	
0.55	1.00	14

Table 5.7c Results of the application of ELECTRE I technique on the ISO data set (N=14)

p	q	weights of 3, 3, 2, 1 composition of the kernel
0.06	0.00	8 10 12 14
0.06	0.10	10 14
0.06	0.20	empty
0.16	0.00	8 10 12 14
0.16	0.10	10 14
0.16	0.20	empty
0.26	0.00	8 10 12 14
0.26	0.10	10 14
0.26	0.20	empty
0.36	0.00	8 10 12 14
0.36	0.10	8 10 14
0.36	0.20	empty
0.46	0.00	8 10 12 14
0.46	0.10	8 10 14
0.46	0.20	14
.	.	
0.46	1.00	14
0.56	0.00	8 10 12 14
0.56	0.10	8 10 14
0.56	0.20	8 10 14
0.56	0.30	8 10 14
0.56	0.40	10 14
0.56	0.50	10 14
0.56	0.60	14
.	.	
0.56	1.00	14

Table 5.7d Results of the application of ELECTRE I technique on the ISO data set (N=14)

		weights of 3, 3, 3, 1
p	q	composition of the kernel
0.05	0.00	8 10 12 14
0.05	0.10	10 14
0.05	0.20	empty
0.15	0.00	8 10 12 14
0.15	0.10	10 14
0.15	0.20	empty
0.25	0.00	8 10 12 14
0.25	0.10	10 14
0.25	0.20	empty
0.35	0.00	8 10 12 14
0.35	0.10	10 14
0.35	0.20	empty
0.45	0.00	8 10 12 14
0.45	0.10	8 10 14
0.45	0.20	empty
0.55	0.00	8 10 12 14
.	.	
0.55	0.30	8 10 12 14
0.55	0.40	10 14
0.55	0.50	10 14
0.55	0.60	14
.	.	
0.55	1.00	14

Table 5.8 Results of the application of COMPROMISE PROGRAMMING technique on the ISO data set (N=56)

weights $a_1=a_2=a_3=a_4=1$

Rank	s=1	s=2	s=3	s=50
1	52	52	52	52
2	51	51	56	56
3	50	50	46	46
4	54	56	51	51
5	38	46	50	45
6	37	54	45	50
7	24	38	54	54
8	36	45	38	38
9	23	37	24	42,32
10	40	24	42,32	

weights $a_1=4$ $a_2=3$ $a_3=2$ $a_4=1$

Rank	s=1	s=2	s=3	s=50
1	52	52	52	52
2	51	49	49	49
3	50	46	46	46
4	38	44	44	44
5	49	51	51	38
6	46	48	48	35
7	37	45	38	32
8	24	38	45	30
9	48	43	35	24
10	54	50	43	21

5.2.2 COMPROMISE PROGRAMMING

As in the ELECTRE I, four criteria will be used, namely: the number of verticals taken in the cross-section (NV), the number of points taken in the vertical (NPV), the time of exposure at each point in the vertical (TE), and the type of current meter rating (CMR).

The criteria with the scales or levels, are the same that were established for the ELECTRE I method, and are presented in Table 5.2.

For the simulation which includes 56 models, and using weights (a_i) of 1.0 for all 4 criteria, and various values of s, the ten best solutions are presented in Table 5.8. As described previously, the parameter a_i reflects the relative importance of the ith objective, and the parameter s reflects the importance of the maximal deviation, i.e., the larger the value of s, the greater the concern.

The results of the application of the compromise programming technique on the ISO data set, using a total of 56 models and equal weights of 1, give the following best five solutions:

models	s=1	models	s=2	models	s=99
52	3.600	52	1.833	52	1.011
51	3.509	51	1.785	56	1.011
50	3.418	50	1.741	46	1.011
54	3.345	56	1.732	51	1.007
38	3.314	46	1.732	45	1.007

The results shows that model 52 is the best alternative. However, as discussed in the previous section, this alternative is not practical, as it involves a very long measurement time and implies a stream with fairly regular streambed and uniform flow.

Based on the above results it is fairly clear that the only feasible and practical solution, is the alternative model 56.

It is interesting to note that, an alternative is ranked first on the basis of a maximum value from the Ls Metrics. This result is valid if the values assigned to a particular criteria are given in descending order, i.e., for a same criteria a high number is worst than a low number. For example, for the "NV" criteria, 5 verticals corresponds to a coded value of 90 (uncertainty of 15%) compare to 25 verticals which corresponds to a coded value of 24 (uncertainty of 4%). In order to corroborate this statement, another data set was prepared in which coded values were assigned in ascending order. For example, for the "NV" criteria, 5 verticals corresponds to a coded value of 85 (uncertainty of 15%) compared to 25 verticals which corresponds to a coded value of 96 (uncertainty of 4%). Using this new matrix of coded values, the results were identical, but this time the alternative ranked first was the one with minimum value from the Ls Metrics.

As in the ELECTRE I analyses, the number of alternatives was further reduced from 56 to 14, to include only present stream gauging procedures, and possibly more effective procedures. These alternatives examined were the same as those for the ELECTRE I and are presented in Table 5.6, and associated results in Table 5.9.

The results of the application of the compromise programming technique on the ISO data set, using a total of 14 models and equal weights of 1, give the following five best solutions:

models	s=1	models	s=2	models	s=99
8	3.171	14	1.732	14	1.011
10	3.132	8	1.639	8	1.007
7	3.081	10	1.594	4	1.007
12	3.060	7	1.585	6	1.007
14	3.000	12	1.565	13	1.007

The results generally showed that models 14, 8, 10 and 4 are the preferred alternatives, with model 14 selected the most frequently, followed by models no. 8, 10 and 4.

Models 8, 10, 12 and 14 corresponds respectively to models 24, 36, 40, and 56 of the previous simulation (for n=56).

As in the previous simulation, the results indicates that the number of points taken in the vertical combined with long exposure times are the controlling factors. The best solution being given by **model 14.** The alternative to this model is given by model 8, which corresponds to actual hydrometric practices in North America.

In summary, the analysis using the COMPROMISE PROGRAMMING technique on the ISO data set revealed that present North American stream-gauging technique (i.e. model 8), as employed by Water Survey of Canada, is adequate for most applications. This solution represents a good compromise in comparison with other procedures which would favored a lesser number of verticals in the metering section, in combination with a larger number of points in each verticals, and a long exposure time (i.e. model 14).

Table 5.9 Results of the application of COMPROMISE PROGRAMMING technique on the ISO data set (N=14)

weights $a_1=a_2=a_3=a_4=1$

Rank	s=1	s=2	s=3	s=50
1	8	14	14	14
2	10	8	8	8
3	7	10	4	4
4	12	7	6	6
5	14	12	7	13,2

weights $a_1=4$ $a_2=3$ $a_3=2$ $a_4=1$

Rank	s=1	s=2	s=3	s=4
1	8	8	8	8
2	10	6	6	6
3	7	7	4	4
4	12	4	2	2
5	6	10	7	7,5,3,1

5.3 DISCUSSION AND TECHNIQUES COMPARISON

5.3.1 Comparison of results

The results of the application of the ELECTRE I technique on the ISO data set, using a total of 56 models, are as follows (i.e. the five best solutions):

49 52 53 54 55 56

In comparison, the following models were preferred, using the COMPROMISE PROGRAMMING,

52, 51, 50, 46, 56

The common factor or criteria to all of these solutions is the number of points in the vertical, i.e., a solution which includes vertical velocity profile for number of points in the vertical criteria will always be preferred over another solution which include a lesser number of points in the vertical.

The comparison shows that the results obtained by the two methods are similar, and that in both cases model 52 is the preferred solution. However, as it was discussed in the previous section this alternative is not practical as is involves a very long measurement time. Therefore, the preferred alternative is given by Model 56, which is based on the followings:

model 56

5 verticals
vertical velocity profile for each vertical
time of exposure of 180 sec at each point
individual calibrated current meter

Using the reduced set of alternatives, i.e., 14 instead of 56, the results of the application of the ELECTRE I technique on the ISO data set, are as follows (i.e. the three best solutions):

14 10 8

In comparison, using the COMPROMISE PROGRAMMING, the following models were preferred,

14 8 10

The results of the application of the two techniques on the ISO data set of 14 alternatives gave identical solutions, with model 14 preferred first, followed by model 8 and 10, and 10 or 8 for respectively the COMPROMISE PROGRAMMING and the ELECTRE I technique.

5.3.2 Selection of method

Both techniques gave, essentially, the same results in terms of preferred alternatives, i.e., model 14 was ranked as the best alternative followed by model 8. These two alternatives are based on the followings:

model 14, consisting of

5 verticals
vertical velocity profiles for each vertical
time of exposure of 180 sec at each point
individual calibrated current meter

model 8, consisting of

25 verticals
2 observation points for each vertical
time of exposure of 60 sec at each point
individual calibrated current meter

Model 8 is the preferred technique in North America by Water Survey of Canada, and United States Geological Survey, with the exception that USGS uses group calibrated current meters, instead of individually calibrated meters. In contrast, data collection agencies in Europe (e.g., Scandinavian countries) tend to use a stream gauging technique which resemble model 14.

Both techniques are more or less equivalent, with model 14 slightly superior under ideal conditions. However, ideal conditions are rarely encountered in nature, model 8 represent, therefore, a more conservative and practical solution to all types of conditions.

6. CONCLUSIONS AND RECOMMENDATIONS

The overall uncertainty in the determination of river discharge using the velocity-area method, is due to a combination of many sources of uncertainty. These include:

- uncertainties in the determination of the cross-sectional area, i.e., single depth and width determination;
- uncertainties in the determination of the mean velocity, i.e., single velocity determination, and sampling of the mean velocity in time and in space.
    - the uncertainty in single velocity determination may be caused by a combination of one or more of the followings: current meter still-water calibration; fluid properties; effect of suspension equipment; boundary effects; and effect of oblique flow, of vertical motion, and of turbulence.
    - the uncertainty in sampling the mean velocity in time depends on the uncertainty due to the limited time of exposure.
    - the uncertainty in sampling the mean velocity in space depends on the uncertainty due to the limited number of points in the vertical and due to the limited number of verticals in the metering cross-section.
- uncertainties by approximation of the integral of a velocity field over a cross-section by the finite summations.

There have been three major investigations conducted on the uncertainty or accuracy of streamflow measurements. These were carried out by Murphy (1904), Carter and Anderson (1963), and Herschy (1975a). Herschy's investigation results were used to a great extent to derive the uncertainty values presented in the International Standard (ISO 748). The uncertainty values in the velocity-area method proposed by Herschy were, in general, derived from streams in the United Kingdom (Yorshire, Derwent, and Thames rivers), using horizontal axis meters, and therefore may not be directly applicable to rivers in Canada.

Uncertainty values found in the reviewed literature do not adequately cover the stream or river types (i.e., hydraulic and morphologic character of a stream) encountered in Canada. The magnitude of various uncertainties may vary depending on the hydraulic and morphologic character of the stream. Those stream types could be classified, for example, as large, medium, and small streams; fast and slow moving streams; large and small gradient streams; and complete and partial ice covered streams.

In fact, the International Organization for Standardization (ISO 748) pointed out that the values given in ISO were the result of investigations that began in 1968, and stressed that the observations on which they were based did not include all kinds and sizes of rivers. Therefore, it should not be assumed that these are generally applicable.

ISO recommended that each user determine independently the values of the uncertainties that will apply to a particular case.

Moreover, the uncertainty values given in the literature (Carter and Anderson, 1963; Herschy, 1975a; ISO 748, 1979; and WMO, 1980) are often referring to measurements performed under the following ideal conditions: the stream at the metering section has a smooth bed; there is little turbulence; piers and other obstructions do not seriously affect the flow; the stage is fairly steady during the measurement; drift, aquatic vegetation, or ice do not interfere with the operation of the bucket wheel of the meter (if it is a Price meter); there is little or no angle of the current at the metering section; there is no strong wind affecting the velocity of the stream near the surface; the proper measuring equipment is available; and the proper stream gauging procedures are applied (Wood, 1945).

These ideal conditions are seldom encountered. In fact, due to the conditions imposed naturally, e.g., droughts, very low runoff, or winter ice or imposed by management needs or budgetary restrictions, e.g., locating stations at available bridges or below a dam, the gauging agency can be forced to operate outside of the ideal conditions and the preferred ranges of widths, depths, and velocities.

In order to determine the trade-offs between the different sources of uncertainties in sampling the mean velocity, multiple objective analysis techniques were used. Two different multiple-objectives techniques were used: ELECTRE I and COMPROMISE PROGRAMMING techniques.

Four criteria were used, namely: the number of verticals taken in the cross-section (NV), the number of points taken in the vertical (NPV), the time of exposure at each point in the vertical (TE), and the type of current meter rating (CMR). The criteria with the scales or levels were established based on ISO data set (ISO 748).

Both techniques gave essentially the similar results in terms of preferred alternatives, i.e., model 14 was ranked as the best alternative followed by model 8. These two alternatives are based on the followings:

---

model 14, consisting of

5 verticals
vertical velocity profiles for each vertical
time of exposure of 180 sec at each point
individual calibrated current meter

model 8, consisting of

25 verticals
2 observation points for each vertical
time of exposure of 60 sec at each point
individual calibrated current meter

Model no. 8 is the preferred technique in North America by Water Survey of Canada, and United States Geological Survey, with the exception that USGS uses group calibrated current meters, instead of individually calibrated meters. In contrast, data collection agencies in Europe (e.g., Scandinavian countries), tend to use a stream gauging technique which resemble model 14.

Both techniques are more or less equivalent, with model 14 slightly superior under ideal conditions. However, ideal conditions are rarely encountered in nature, model 8 therefore represent a more conservative and practical solution to all types of conditions.

The multiple-objective analysis techniques used in this thesis for determining the relative significance of the various uncertainties in single river discharge determination were found to be useful as they confirmed that present techniques used in North America and in Europe are "optimum" techniques under ideal conditions at the metering site.

However, it should be recognized that it is not possible to establish a unique streamflow measurement or computation technique for all types of sites and conditions. As shown in this thesis, the selection of the most adequate technique for stream gauging is a complex and subjective process. The technique selection depends on numerous factors, ranging for capital available to morphologic, hydrologic, and hydraulic conditions of the site being investigated.

Throughout the thesis, several possible areas of research were highlighted and reasons given for the purposes for these investigations. The main reason was that most of the investigations into the accuracy of streamflow measurement have been carried out on streams which are not representative of Canadian streams. Also, a large majority of the experiments were carried out in the early 1900's with equipment which has changed, evolved, or even disappeared through the years. Finally, when conducting investigations into the uncertainties in streamflow measurement, one should ensure that the collected sample is sufficiently large to be statistically analyzed.

Several investigations should be undertaken in order to achieve a better understanding of streamflow measurement. These are:

- calibration of current meters, including analysis of standard versus individual ratings, single versus composite current meter rating curves, and effect of suspension type (rod versus weights of various types on cable);

- effect of turbulence on the response of the Price current meter, including the effect of pulsation using field and laboratory testings;

- the uncertainty in a single determination of discharge for Canadian streams, with emphasis on streams with shallow depths and low velocities, e.g., Prairie streams;

- the accuracy of streamflow measurements and computation procedures under winter (ice) conditions; and

- the uncertainty in the stage-discharge relation and in the computation of the discharge hydrograph.

Technology such as the ultrasonic flow meter, the optical current meter, data acquisition equipment on site, and micro-computers is now available for scientists and engineers to resolve some of the uncertainties outlined in this thesis and to improve the stream gauging methods, the overall quality of the streamflow record, and therefore, the confidence one can place in the engineering and resource management decisions that are made.

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WMO 1980b. Manual on stream gauging. Volume II - Computation of Discharge. Secretariat of the World Meteorological Organization, Operational Hydrology Report No. 13, WMO - No. 519, 258 p.

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APPENDIX A

ABSTRACTS OF CITED REFERENCES

ADELOYE, A.J. 1987. Value of river flow data for water resources and water quality assessment. The University of Newcastle Upon Tyne, Department of Civil Engineering, Ph.D. Thesis, 352 p.

Abstract: The work presented in this thesis is concerned with the estimation of the economic value of river flow data for water resources and water quality assessment. A model, termed the opportunity loss (OL) model, was developed for doing this. The OL model estimates the value of a given level of hydrological data by establishing a link between the errors (or uncertainties) in decisions made with the data and the economic penalties (OLs) of each erroneous decisions. Using a simplified Bayesian analysis, the opportunity losses are then combined with the probability distribution of the errors to give an expected opportunity loss (EOL). The value of a given level of data is finally found as the difference between the EOL of the decision made with the data and the EOL of a decision made with an indirect approach which does not make use of the data directly.

The use of the OL model requires that the costs and benefits functions associated with the decision are available. The water resource assessement aspect was demonstrated by estimating the value of river flow data in the derivation of the capacity-reliability-yield function of surfave water reservoirs which are of the direct supply type. The reservoir design was achieved using simulation and the sampling errors associated with capacity estimates corresponding to different yield and reliability levels were evaluated using Monte Carlo simulation. The water supply benefits were approximated using the 'cost of the next best alternative" measure. The results showed that river flow data have value towards the design of medium to large reservoirs and that this value is sufficiently large to justify investment in its collection for the purpose. Extensive sensitivity studies later carried out revealed that the results were most sensitive to the interest rate, of all economic inputs into the analysis, and to the annual coefficient of variation of streamflow, of all hydrological parameters.

The water quality assessment aspect was demonstrated by investigating the errors in the derivation of the flow duration curve from which design streamflows for waste water treatment plants are estimated. The economic analysis associated with this application was, however, incomplete because of the lack of a suitable benefit function for water quality improvements.

Finally, the application of the value of river flow data for the economic design of gauging stations established to provide the data was demonstrated.

ALFORD, M.E. and CORMACK, E.C. 1987a. Observations on ice cover and streamflow in the Yukon River near Whitehorse during 1983/84. National Hydrology Research Institute, Paper No. 32.

Abstract: Covered in this report are: a review of historical data from the study area; a quantitative description of surface ice and frazil dam growth and decay; a description of the meteorological conditions and the associated heat budget for the reach; and an analysis of the effects of ice cover on the hydraulic resistance of the reach throughout the winter.

ALFORD, M.E. and CORMACK, E.C. 1987b. Observations on ice cover and streamflow in the Yukon River near Whitehorse during the 1984/85. National Hydrology Research Institute, Paper No. 34.

Abstract: A report is given of the second year of measurements obtained at the Whitehorse reach.

ALMING, K. 1969. Calibration of current meters - a comparison. Water Power Laboratory, Report No. 262, Presented at the 10th meeting I.C.M.G. in Stockholm, Norway, 3 p.

Abstract: From 1917 until today the data from 27 calibrations of 7 different current meters with 8 impellers have been collected and compared. The band of deviation for each impeller has been drawn showing the scatter to be roughly the double of that found from the comparative calibrations reported in ICMG report no. 38.

ANDERSON, I.E. 1961. Errors in streamflow measurement. Geological Survey Research 1961, Geological Survey Professional Paper 424-C, Paper 161, pp. C37-39.

Abstract: The accuracy of measurement of a constant discharge by current-meter method depends on the number of observations of depth and velocity which are obtained and the reliability of the revolution-velocity rating of the current meter. This relation has been defined by a study of the individual components of the total error.

ARNBERG, B.T. 1971. Practice and procedures of error calculations. Symposium on Flow, Its Measuremnt and Control in Science and Industry, Proceedings of the 1st Symposium, Pittsburgh, Vol. 1, Part 3, pp. 1267-1284.

Abstract: The purposes of this paper are to briefly summarize error analyses for measurement systems, and to apply the principles to critical (sonic) flowmeters in preparation for international standardization. Theliterature on error analysis is reviewed and inadequacies in current practices are discussed. Recommendations are made to reduce misunderstandings in terminology. Procedures are given for calculating and reporting the uncertainty in experimental results. The importance of performing separate analyses of random and bias errors is stressed. This paper covers the following topics: (1) types of measurements, digital and analog; (2) types of errors, illegitimate, constant and variable bias, random; (3) criteria for rejecting outliers, Thompson's Tau Test; (4) random error analysis, confidence levels, Students't, uncertainty estimation for individual and mean results, uncertainty in mean lines; (5) sensitivity determinations, dimensional and dimensionless; (6) error propagation, root-sum-square and linear addition of components errors; (7) method of equal effects for test planning and data analysis; (8) reporting of uncertainties. Most of the procedures are illustrated. A final example is given using a critical (sonic) flowmeter as a standard for calibration of a subsonic orifice flowmeter.

ASANO, Tomio. 1983. Evaluation of the accuracy in velocity measurement in alluvial rivers. American Society of Civil Engineers, Enigineering Mechanics Div Proceedings, pp. 1258-1261.

Abstract: In this paper, the author deals with the accuracy of the discharge observation quantitatively, and finds the relation between the accuracy and the averaging time in the observation, using the distribution profile of turbulent properties.

ASTM 1985. ASTM Standards on precision and bias for various applications. ASTM, Second Edition.

Abstract: Includes several standards, such as the standard practice for establishing consistent test method tolerances (D 4356-84).

BALLOFFET, A. 1958. Discussion: Common errors in measurement of irrigation water by C.W. Thomas. Journal of the Irrigation and Drainage Division, Proc. of the American Society of Civil Engineers, Vol. 84, No. IR2, Part 1, Apr., pp. 28-30.

BARROWS, H.K., and HORTON, H.K. 1907. Determination of stream flow during the frozen season. United States Geological Survey, Water-Supply and Irrigation Paper No. 187, 93 p.

Abstract: The paper is divided into the following sections: (1) methods of gaging streams during the winter season; (2) conditions during the winter season; (3) flow of streams under ice cover; (4) methods of obtaining winter records; (5) winter records, including station rating curve for ice cover and vertical velocity measurements under ice cover; (6) slope determination and values of n in Kutter's formula, under ice conditions; and (7) conclusions, including practicability of winter estimates of flow and recommendations as to methods.

BATHURST, J.C., et al. 1979. Secondary flow and shear stress at river bends. Journal of the Hydraulics Division, Vol.105, No. HY10, Oct., pp. 1277-1295.

Abstract: Many laboratory investigations of secondary currents have been made. However, there is still a lack of knowledge concerning the pattern of currents in rivers, particularly near banks, their variation with discharge, and their relationship with the distribution of boundary shear stress. This paper investigates these processes at bends of rivers with coarse alluvial beds. The current knowledge of the subject is introduced; field measurements of secondary currents and boundary shear stress are presented; and their interrelationships are reviewded.

BATHURST, J.C., et al. 1977. Direct measurements of secondary currents in river bends. Nature, Vol. 269, Oct., pp 504-506.

Abstract: The author reports here measurements of longstream and cross stream velocities carried out across sections of a river perpendicular to the outer banks of several bends using an electromagnetic meter.

BATHURST, J.C. 1982. Equations for estimating discharge in steep channels with coarse material. Advances in Hydrometry, Proceedings of the Exeter Symposium, July 1982, IAHS Publ. no. 134, pp. 63-71.

Abstract: The use of process-based conveyance equations for estimating discharge in steep channels with coarse bed material is discussed. As the hydraulic characteristics of such channels often preclude direct gauging techniques, it is necessary to use the indirect slope-area method in which peak discharges are calculated as functions of channel slope and conveyance, the latter itself being a function of channel cross-sectional shape and bed material size. Previous application has been hampered by

a lack of knowledge concerning flow processes in steep channels but, with the equations now available, variations of conveyance with deoth, bed material size and sediment movement can be estimated. Using data from the Yemen Arab Republic, it is shown that discharge by these equations have an accuracy of about 10% for low flows and are of the correct magnitude at a flood flow. the construction of a stage/discharge relationship is demonstrated and assumptions behind the method discussed.

BECKER, A., et al. 1982. Up-dating of discharge rating curves by means of mathemeatical models. Advances in Hydrometry, Proceedings of the Exeter Symposium, July, IAHS Publ. no. 134, pp. 37-48.

Abstract: An appropriate combination of precise flow measurements at selected well-established river gauging stations with flow computations along the river by means of mathematical models (streamflow routing techniques) can considerably help (a) to monitor and up-date discharge rating curves at all stations along the river, (b) to extrapolate the results of precise flow measurements performed at one or a few selected stations, e.g. under critical flood conditions, to neighbouring stations, (c) to avoid water balance descrepancies along the river.

A generalized technique has been developed in connection with the establishment and continuous operation of a real-time streamflow forecasting system for the River Elbe in the GDR.

BELLIN, K. 1970. The evaluation of discharge measurements in streams with changing flow conditions. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. no. 99, pp. 169-180.

Abstract: So far, discharge can only be measured discontinuously. The discharge hydrograph for the time interval between two measurements is obtained from the stage hydrograph by means of the stage/discharge curve.

Widely scattered values obtained for the stage/discharge relationship may be caused not only by weed conditions but also by moving sand, bank erosion or backwater. The values obtained at the Bienenbuttel decade gauge on the Illmenau river (F_N=1,457 sq. km) are taken as an example. With the aid of the improved Gil method, an obstruction factor n is derived from the fluctuations of the measured values which is representative of the water's discharge behaviour at the time of the measurement The n-hydrograph describes the changes in discharge as caused by weed, changes in the river bottom and backwater during a discharge period.

BENNETT, J.P. 1968. Turbulence measurement with a propeller flow meter. U.S. Geological Survey, Open-file Report, Sept., pp. 44-47.

Abstract: In this study, a propeller equation of motion is developed which describes the inertial averaging characteristics of propellers. A correlation function is developed which describes the spatial averaging effect on a particular propeller in a particular flow field, if the required statistical properties of the flow field are known.

Due to the complexity of the coefficients in the differential equation of motion of a propeller, experimental means were used in determining these coefficients. Similarly, the spatial averaging characteristics had to be determined experimentally for a particular type of turbulent flow, rough boundary open channel flow.

The experimentally determined system functions were used to correct field turbulence data for inertial averaging. It appears that propellers of the size used in this study can be used in open channel flows of three feet in depth with very little turbulence.

BENNETT, R.M. 1968. The stage-discharge relationship and winter discharge under ice cover for the Peace and Slave Rivers. Thesis for Master of Science in Water Resources Engineering, Utah State University, 63 p.

<u>Abstract</u>: A study of (1) the stage-discharge relationship and (2) the accuracy of winter discharge measurements under ice cover was carried out on the Peace and Slave Rivers during the winters of 1965-66 and 1966-67, for the purpose of developing an improved method of obtaining reliable discharge records.

Analyses indicate that the flow measurements taken at slush-free locations appear to be accurate to 5 percent, while measurements at heavy slush sections may be in error -20 percent, with water velocities through the slush varying from 0.10 to 0.65 feet per second. Both the two-point method and the 88 percent of 0.5-depth velocity method work well under ice cover.

A FORTRAN IV computer program, using two empirical equations of the form
$\text{Discharge} = A_0 + A_1\,(\text{stage}) + A_2(\text{stage})^2 + A_3(\text{date}) + A_4(\text{degree-day})$ was developed to compute discharge for (1) the recession portion of the winter hydrograph and (2) the period of rising stage prior to spring breakup. Monthly total flows computed for December through May deviated from the published discharges by less than 8 percent for the Slave River and 14 percent for the Peace River.

Recommendations are made to modify the program to include only three winter discharge measurements, test the method on other major northen rivers, and continue studies on slush and mobile bed behavior, as well as discharge behavior during freeze-up and breakup periods.

BOAHMAN, L.R., and CARSWELL Jr., W.J. 1986. A preliminary evaluation of a discharge computation technique that uses a small number of velocity observations. Selected papers in the hydrologic sciences, United States Geological Survey, Water-Supply Paper 2290, January, pp. 145-154.

<u>Abstract</u>: A study was made of a discharge measurement technique for unsteady flow being considered by the International Organization for Standardization. The new technique uses a small number of velocity observations and a measured channel cross-section to develop a lateral velocity distribution. The technique was tested using three, five, and seven vertical velocity observations from 25 discharge measurements at five streamflow gaging stations. An average bias of about +2.5 percent indicates that discharge may be overestimated by the new procedure when compared to the standard mid-section method. Percent differences ranged from +28.5 to -38.3 and decreased as either the number of velocity observations or discharge increased. A large part of the difference was probably the result of channel-bottom irregularities, pier influence, and extrapolation necessary between the last velocity observation and the bank.

It was determined that the location of velocity observations could probably be optimized to improve the accuracy of the method. The results of this study indicate further investigation of the technique and its potential as a discharge measurement tool for steady or unsteady flow at large rivers with uniform flow in the vicinity of the measurement section is warranted.

BONACCI, Ognjen 1979. Influence of turbulence on the accuracy of discharge measurements in natural streamflows. Journal of Hydrology, Elsevier Scientific Publishing Company, Vol. 42 - No. 3/4 - July, pp. 347-367.

Abstract: The objective of this study was to solve some basic and current problems in the field of practical hydrometry and hydrology. As a matter of fact, the basis of this study was that the problems have been theoretically dealt with but the results have found practical application. The problem of current meter measurement of discharge in natural streamflows has been analysed as well as the effect of the turbulent fluctuations (pulsations) on the possible accuracy of results obtained by this kind of measurement. Employing the mathematical model based on the results of the velocity distribution in a vertical (as defined by Nikitin) simulation of discharge in a schematized open river flow has been effected. By means of the analysis of variance the influence of the following four factors on the measurement accuracy has been estimated: (1) the number of velocity measurement point in a vertical; (2) the number of velocity measurement verticals; (3) the position of measurement points along the vertical; and (4) the position of verticals along the cross-section. The optimum number of measurements verticals, their position in the cross-section as well as the number and position of the points for measuring the velocity by the current meter have been defined. The effect of the possible accuracy of discharge estimations on the accuracy of defining the rating curve has also been studied. The original, approximate procedure for estimating the upper limit of the absolute error in discharge measurement is also presented.

BOS, M.G. 1976. Discharge measurement structures. International Institute for Land Reclamation and Improvement/ILRI, Publication No. 20, ILRI, Wageningen, pp. 401-417.

Abstract: This book presents instructions, standards, and procedures for the selection, design, and use of structures, which measure or regulate the flow rate in open channels. The book includes a section (Appendix II) on the overall accuracy of the measurement of flow.

BOTMA, H. 1970. Errors in measurement of flow by velocity area methods. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. no. 99, pp. 771-784.

Abstract: Routine measurements of flow in open channels, carried out using current meters and applying the velocity area method, do not give sufficient information to estimate the accuracy of the method. In order to determine the magnitude of the errors much more detailed measurements are needed. This paper deals with the analysis of these detailed measurements. Attention has been paid to errors due to: (1) using a finite time to measure the local point velocities; (2) using a finite number of points per vertical; (3) using a finite number of verticals.

Statistical methods have been used extensively in the nalysis. Results of the analysis of measurements in the River Yssel will be presented. This work is part of a project for the International Organization for Standardization.

BRIDGE, J.S., and JARVIS, J. 1977. Velocity profiles and bed shear stress over various bed configurations in a river bend. Earth Surface Processes, John Wiley & Sons, Vol. 2, No. 4, Oct.-Dec., pp. 281-294.

Abstract: Vertical velocity profiles measured over various bed configurations (plane beds, ripples, and dunes) in the meandering River South Esk, Glen Cova, Scotland are presented on semilogarithmic paper. Local bed shear stress and roughness height are calculated from the lowermost parts of the profiles using the Karman-Prandtl law of the wall; these parameters, and the geometrical properties of the profiles, are related to the various bed configurations. A graphical model is used to identify profiles developed on specific regions of dune geometry, in order to discriminate those profiles that define bed shear effective in transporting sedimensts over dunes. An assessment is made of the errors involved in estimating local mean velocity from extrapolating the law of the wall to the water surface. A Darcy-Weisbach friction coefficient is related to bed configuration and local stream power.

BROWN, E.H., and NAGLER, F. 1914-15. Preliminary reports of current meter investigations. Engineers' Society of Western Pennsylvania Proceedings, Vol. 30, pp. 415-24.

Abstract: The experimental work herein described was performed with view to determining possible causes of the over-registering of the cup type of current meter. It is preliminary to more extensive tests which were made in order to determine the relative extent to which various types of current meters and different forms of revolving elements for each type, will give true resultant components of velocity when the meter is subjected to angular flow.

BURKHAM, D.E., and DAWDY, D.R. 1970. Error analysis of stremflow data for an alluvial stream. Geological Survey Professional Paper 655-C, pp. C1-C13.

Abstract: Discharge measurements were used to determine the standard error in computed continuous records of discharge for two streamflow gaging stations on the Gila River. The major source of errors in computed discharge is from poor definition of the stage-discharge relation.

The standard errors of computation of discharge for the two stations were determined by randomly choosing a group of discharge measurements for use in rating analysis and using the remaining measurements as a control group. Discharge was computed corresponding to the stage and time of the measurement in the control group. The mean square difference (S^2_{m-c}) between measured and computed discharge was determined for different ranges of flow. (S^2_{m-c}) is the sum of the mean square difference of the measured discharge from the true discharge (S^2_m) plus the mean square difference of computed discharge from the true discharge (S^2_c). The variance (S^2_c) was obtained by subtracting the known variance (S^2_m) from (S^2_{m-c}).

BURTSEV, P.N., and BARYSHNIKOVA, M.M. 1970. The analysis of the possibilities of current meter operation in turbulent streams. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. no. 134, pp. 79-85.

Abstract: The present paper reviews the different current meters in operation in hydrometric networks. Special attention is paid to the analysis of the influence of turbulent flow upon the readings of current meters under different working conditions (rod or cable suspension).

Some recommendations are given concerning the application of current meters, depending on the hydrodynamic properties of the water courses and operational practice; probable errors for different types of current meters are determined.

CARTER, R.W., and ANDERSON, I.E. 1963. Accuracy of current meter measurements. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 8, No. HY4, Jul., Part 1, pp. 105-115.

Abstract: The probable accuracy of a stream-flow measurement made by the current meter method at a gaging site that was selected at random was evaluated. Standard deviation of discharge-measurement errors in percent of mean is determined from the variance of the partial errors. Variances of the partial errors resulting from the current meter, by velocity fluctuations, by shape of the vertical velocity curve, and by the number of observation stations in the section are defined by special measurements an many different streams. The information can be used to determine the observation procedure necessary to obtain a given accuracy of measurement.

CARTER, R.W. 1970. Accuracy of current meter measurements. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. no. 99, pp. 86-98.

Abstract: The probable accuracy of a streamflow measurement made by current meter has been assessed by evaluating the separate error components. Non-random error components are: (1) errors in the current meter rating; (2) the error of velocity observation at a point; (3) the error from measuring velocity only at selected points in a vertical; and (4) the error from assuming that the depth and velocity vary linearly between stations in the cross-section. Values for each of these error components are known, based on statistical analysis of special measurements made for this purpose on many different streams. Statistical combination of these errors indicates that the probable error of a streamflow measurement made by standard procedures is about 2 per cent. The information presented can be used to determine the optimum observation procedure to attain a desired accuracy.

CHAPMAN, E.F. UNDATED. A standard current meter rating for Price pattern current meters. Water Survey of Canada, pp. 2-10.

Abstract: The stream measurement program of the Water Survey of Canada makes widespread use of the current meter, and a high degree of accuracy is sought by having each meter reted for the full range of velocities in advance of issuing the meters to the field officers.

Current meters of the Water Survey of Canada generally require repair and re-rating after a year of continuous use. The Water Survey also provides rating services to other agencies that use current meters. As a result, there is a continuing need for this type of service.

Individual ratings have always been carried out because of inherent diffrences in meters. Although the ratings of current meters of the same type are generally similar, theses differences mitigate against the use of a single rating for all meters when a high degree of precision is sought.

The present practice of rating all current meters before issuing them to field personnel has periodically been brought into question by those who contend that a suitable standard rating could be established for all meters.

This report describes the operation of the rating station (Calgary, Alberta), discusses the present staff functions, and examines some of the effecets of a changeover to a standard rating system for the "Price Pattern" current meter. Although there are several diffrent types of meters which are briefly identified later in this report, it is the bucket-type Price Pattern meter and particularly the latest model known as the Pricve No. 622 Type AA Meter, which this report deals with.

CHAPMAN, E.F. 1968. Columbus type metering weights and their effect on the rating of the Price pattern type 622 AA current meter. Department of Energy, Mines, and Resources, Current Meter Rating Station at Calgary, Dec. 1968, 15 p.

Abstract: During the 1968 rating season, an experimental program was carried out. This program was initiated to establish the relationships of the ratings of the 622 pattern type AA Price pattern current meter using different Columbus weight sizes and different suspension systems.

CHOW, V.T. 1964. Handbook of Applied Hydrology. McGraw Hill, Chapter 15, pp. 9-27.

Abstract: Correction coefficients for suspension equipment are discussed.

COLBY, B.R. 1964. Discussion of "Accuracy of current meter measurements" by R.W. Carter and I,E. Anderson. Proccedings ASCE, Vol. 90, HY4, 1964, pp. 349-351.

Abstract: The author point out a technical inaccuracy that relates to the assumed horizontal distribution of velocity and depth (computation formula).

COLLIER, E.P. 1962. Investigation into the accuracy of winter streamflow records on some foothills streams in Alberta. Department of Northen Affairs and National Resources, Water Resources Branch, Hydraulics Division, Internal report No. 1, Nov., pp. 1-24.

Abstract: During the winter of 1957-58 an intensive gauging programme was undertaken by the Calgary District of the Branch on two streams in the foothills area of Alberta, Highwood and Sheep Rivers near Aldersyde, the object being to obtain a much more accurate knowledge of the winter discharges than would have been obtained by a normal gauging programme. The streams were measured on almost every day from November to February and several times on some particular days. The wealth of basic field data produced by this programme permitted the computation of daily discharges to a relatively high degree of accuracy.

In the investigation described in this report, various samples of thirty gauging programmes of the types that might be encountered in a routine hydrometric survey were drawn from the available data from the Highwood - Sheep survey. Daily discharges were computed for each programme by the various methods of computation in commom use. The results were compared with the more accurate figures derived by employing all the data from the intensive field investigation. The comparisons provided some insight into the relative magnitude of the errors in winter discharge data now being published for the type of stream under study; an indication of the relative merits of various types of field programmes or computation methods now employed by the Branch was also obtained. The results of the analysis are embodied in this report in a series of questions and the corresponding conclusions. Also included is a list of recommendations concerning possible modifications in field and office procedures fro streams of the type investigated and recommendations concerning the advisability of extending the scope of the investigation with a view to deriving further conclusions with broader application

COON, W.F. and FUTRELL II, J.C. 1986. Evaluation of wet-line depth-correction methods for cable-suspended current meters. U.S. Geological Survey, Water-Resources Investigations Report 85-4329, 31p.

Abstract: Wet-line depth corrections for cable-suspended current meter and weight not perpendicular to the water surface have been evaluated using cable-suspended weights towed by a boat in still water. A fathometer was used to track a Columbus sounding weight and to record its actual depth for several apparent depths, weight sizes, and towed velocities. Cable strumming, tension, and weight veer are noted. Observed depth corrections are compared to wet-line table values used for determining the 0.8-depth position of the souding weight under these conditions and indicate that questionable differences exist.

CORBETT, D.M., et al. 1957. Stream-gaging procedure - A manual describing methods and practices of the Geological Survey. U.S. Geological Survey, Water-Supply Paper 888, Reprinted, pp.

Abstract: The paper discusses U.S.G.S. stream gauging methods. Factors affecting the accuracy of measurements are discussed in pp. 65-76.

CROKER, G.N. 1951. Records of flows in the River Wye system, as determined by current meter meausrements, with a note on flood warning arrangements. Institution of Water Engineers (Great Britain), Journal, Vol. 5, pp. 39-97.

Abstract: The paper discusses the surface water resources of the River Wye Cetchament Area, explaining how they came to be measured and describing the difficulties encountered. The hydrological results obtained are compared with some other rivers and discussed. The measuring instrument used throughout by the Catchament Board was the current meter, and some comments are made on its powers of performance, whilst an opinion is offered as to its suitability for a task such as has been attempted on the Wye. Subjects for standardization in equipment and technique are suggested.

DAY, T.J. 1976. On the precision of salt dilution gauging. Journal of Hydrology, Vol. 31, pp. 293-306.

Abstract: The results of an extensive series of dilution experiments in four steep, gravel streams (409 individual slug injections representing 39 separate flow events) are presented. Precision, expressed as per cent probable error about the mean, of four pertinent parameters - tracer integral, mean velocity, discharge and flow area - is investigated. Individual errors range from 1 to 21%, with median values ranging from 4.7 to 7.3% and modal errors ranging from 3.6 to 6.8% depending upon the derived parameter.

DEMENT'EV, V.V. 1962. Investigations of pulsation of velocities of flow of mountain streams and of its effect on the accuracy of discharge measurements. Soviet Hydrology: Selected Papers, American Geophysical Union, No.6, pp. 588-623.

Abstract: This paper contains a brief review of previous investigations of velocity pulsation and a general description of pulsations in typical mountain streams. Factors which influence the magnitudes of velocity pulsations are defined. The existence in mountain streams of waves of large scale velocity pulsations with a period ranging from a few minutes to an entire hour was established from pulsation chronograms.

On the basis of several series of synchronous velocity measurements in mountain streams a clear relationship was established, for the first time, between velocity fluctuations in individual points of the vertical and in the water cross section as a whole. The constancy of a mean period of pulsation in the entire depth of the stream was established.

Magnitudes of errors in mean velocity in the vertical and in the total discharge, which are due to pulsation (the later was computed for the condition of consecutive measurements of velocities at various points of the cross section, which is common in hydrometric practice) were obtained from the data of synchronous measurements of velocities in mountain streams. With the recommended exposure of the current meter at a point for 100 seconds, the probable error of measurement of discharge does not, according to the available data, exceed 2%.

DERECKI, J.A. and QUINN, F.H. 1987. Use of current meters for continuous measurement of flows in large rivers. Water Resources Research, Vol. 23, No. 9, pp. 1751-1756.

Abstract: This study describes the experimental results of continuous flow measurements using electromagnetic current meters and an acoustic Doppler current profiler meter during the 1983-85 period, on the St. Clair River.

DICKINSON, W.T. 1967. Accuracy of discharge determinations. Hydrology Papers, Colorado State University, No. 20, June, pp. 1-54.

Abstract: The objective of this study was to analyze the errors that may be incurred in discharge determinations made on mountain streams. The possible sources of error were carafully considered, and a classification of these sources, including notations on the nature of the resulting errors, was prepared. A mathematical error model for a single discharge measurement has been hypothesized, and methodology presented for the evaluation of daily, monthly, and annual discharge estimates.

An exhaustive literature review was undertaken regarding the qualitative and quantitative aspects of the topic. This material was sorted in an attempt to divide the total error in a discharge determination into various component errors. Each component was analyzed separately, and with respect to the others, in order to yield information about the random or systematic nature of the error, and about possible functional relationships which might be involved. This information has been summarized in the form of a classification of errors.

Upon the completion of the first phase, a hypothetical error model was developed for a single discharge measurement. No attempt has been made to render this model a practical working tool. Rather, it was essentially a qualitative undertaking to reveal the manner of combination of the various component errors, and to clarify the nature of some of the errors. The expected value and variance of the model were studied in order that inferences could be made regarding the significant error terms.

Finally, consideration was given to the errors arising from the use of an estimated rating curve. A mathematical representation was given to the stage-discharge relationship and found to account for virtually all the variability in sample data for nine mountain stream-gaging stations in Colorado. The concept of a divisive discharge value was introduced to separate the rating curve into two portions: one along which the relative error was virtually constant; and the other along which the absolute error remained constant. Both confidence and tolerance limits were established for the estimated curves, and used for inferences regarding the error bounds on daily discharge estimates and future discharge measurements. After consideration was given to the correlation between errors in single discharge estimates, conclusions were drawn regarding the magnitude of the error bounds on monthly and annual discharge estimates.

DICKINSON, W.T. 1969. Discussion: Error analysis in hydrology. Discussion of paper entitled: Surface water by E.R. Peterson, Proc Hydrology Symposium No. 7, Victoria, B.C., Vol 2, p.54-63.

Abstract: It is hoped that the discussion and examples might focus some attention on the topic of error analysis in hydrology and the usefulness of an analytical approach to the problem. Because of the complex nature of hydrologic systems and sampling schemes, workers in the field have generally avoided the issue. Many topics and questions in hydrology can be studied further only after statements regarding the errors of measurement have been made.

DRENTHEN, J.G., and VERMEULEN, P.E.J. 1981. The accuracy of the total discharge determined by acoustical velocity measurement. Flow, Its Measurement and Control in Science and Industry, St. Louis, Vol 2, pp. 531-547.

Abstract: The present paper describes the reliability of the acoustic velocity measurement method together with the influence of the shape of the cross sectionnal bottom profile and the influence of the surges on the calculation of the total discharge.

Although the reliability analysis to be described is based upon the transmit-time difference method most of this analysis is also applicable to other methods like for instant the sing-around method.

DUBOE, A. 1970. La perche de jaugeage à intégration "AGAR" (The "AGAR" integrating flow gauge). International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. no. 99, pp. 181-187.

Abstract: This new apparatus is destined to replace the existing device for measuring the flows of deep or semi-deep waters. With it the average speed of the water at each abcissa can be ascertained by "direct integration", by moving an impulse spiral blade vertically from the bottom to top at a constant speed, which is checked by a speedometer. This device is electrical and semi-automatic, being powered by a small 9 W motor connected to the usual batteries. A meter, graduated in centimetres, shows by direct reading the water-depth at each abcissa. One switch allows the operator to set the chronometer, the revolution counter and the mechanism of the apparatus in motion, and the time required for a reading is about one-half and often one-third of that taken by usual methods.

No diagrams and planimetering are necessary to calculate the results. This can be done arithmetically, and the results can be obtained quickly on the spot.

DYER, A.J. 1970. River discharge measurement by the rising float technique. Journal of Hydrology, Vol. 11, pp. 201-212.

Abstract: A comparison is made of rising float and current meter measurements for three rivers having discharges of 250 cusecs, 3500 cusecs and 10000 cusecs.

The results suggest that an accuracy of a few per cent should be readily attained with a properly engineered rising float system. Although less accurate, the technique of using the difference in performance for floats having different terminal velocities could be usefully employed in some circumstances.

DYMOND, J.R., and CHRISTIAN, R. 1982. Accuracy of discharge determined from a rating curve. Hydrological Sciences Journal, IAHS, Vol. 27, No. 4, Dec., pp. 493-504.

Abstract: An error analysis shows that three types of errors influence the random error of a single discharge measurement determined from a rating curve. They are rating curve error, water level measurement error and an error caused by ignoring all physical parameters, other than water level, that affect discharge. Methods in the literature for evaluating the first two types of errors are reviewed and a method for evaluating the third type is given. The error of average discharge for an arbitrary period is also considered.

ENGEL, P. 1976. A universal calibration equation for Price meters and similar instruments. Environment Canada, Inlands Waters Directorate, Canada Centre for Inland Waters, Scientific Series No. 65, 12 p.

Abstract: A universal calibration curve has been developed using theoretical and empirical methods. The analysis shows that for a meter of given rotor diameter and fixed frictional resistance, the rate of rotation of the meter rotor is dependent only on the speed of the fluid and the fluid density. It is further shown that changes in temperature and small changes in temperature and small changes in density as experienced when changing from fresh water to salt water do not have a significant effect on measurement accuracy.

A practical form of the calibration equation is given by

$$V x (p) = x N x (p)$$

where V is the fluid velocity, p is the fluid density and N is the rate of rotation. Suggestions are made for applying the universal calibration equation to calibrations of current meters in wind tunnels. The principles developed can be applied to other current meters used in oceanographic and lake surveys as well as anemometers used to measure wind velocities.

ENGEL, P., and DEZEEUW, C. 1977. Determination of waiting times between successive runs when calibrating Price 622AA type current meters in a towing tank. Environment Canada, National Water Research Institute, Hydraulics Division, Canadian Centre for Inland Waters, Technical Note.

Abstract: Established the lengths of the waiting time between successive tests.

ENGEL, P., and DEZEEUW, C. 1978. The effect of horizontal aligment on the performance of Price 622AA current meter. Hydraulics Division, National Water Research Institute, Canada Centre for Inland Water, May, 15 p.

Abstract: Tests were conducted to study the performance of the Price 622AA current meter when placed at a horizontal angle to the direction of the flow. Results indicate that the behaviour of the meter is unsymmetrical for misalignment to the left and the right. In this respect, the Price meter should not be allowed to deviate from true alignment with the flow by more than 10° to the left and 15° to the right so as not to exceed errors due to alignment by one percent.

It was also found that the Price meter has a very poor cosine response and cosine components of the measured velocity should not be computed for angles greater than ± 10°.

The effect of the tail fin in increasing errors is insignificant for misaligned meters and can be neglected for practical purposes.

ENGEL, P., and DEZEEUW, C. 1979. The effect of vertical alignment on the performance of the Price 622AA current meter. Hydraulics Division, National Water Research Institute, Canada Centre for Inland Waters, July, 10 p.

Abstract: Tests were conducted to study the performance of the Price 622AA current meter when placed normal to the flow but aligned at different angles above and below the horizontal plane. Results indicate that the meter behaves differently for angles above and below the true horizontal position. In order to keep errors below one percent, the Price meter should not be allowed to deviate by more than 2.5 degrees from true alignment above and below the horizontal plane. For all azimuth angles tested, the rate of rotation of the rotor was less than that obtained for the same meter when placed in true alignment.

ENGEL, P., and DEZEEUW, C. 1980. Performance of the Price 622AA, OTTC-1 and Marsh-McBirney 201 current meters at low speeds. Hydraulics Division, National Water Research Institute, Canada Centre for Inland Waters, Technical Note No. 80-14.

Abstract: Not available.

ENGEL, P., and DEZEEUW, C. 1981. Sensitivity of the Price current meter to the effects of Frazil Ice. Hydraulics Division, National Water Research Institute, Canada Centre for Inland Waters, Report No. 81-25, Sep., 7 p.

Abstract: The Hydraulics Division of the National Water Research Institute was requested to conduct some tests in their towing tank to assess the effects that frazil ice may have on the performance of the Price meter. In this report the problem is examined using theoretical analysis and some of the data from the tests conducted for the Water Survey of Canada.

ENGEL, P., and DEZEEUW, C. 1983. The effect of transverse velocity gradients on the performance of the Price current meter. Environment Canada, Canada Centre for Inland Waters, National Water Research Institute Contribution 83-15, Sep., 16 p.

Abstract: Theoretical analysis and experimental data are used to develop a mathematical model of the response of the Price meter rotor to a flow with a transverse velocity gradient. Application of the model showed that the Price meter over-registers when velocity gradients are positive and under-registers when such gradients are negative. In some cases, the error in a velocity measurement can be of the order of several percent. Some recommendations to reduce the effect of velocity gradients are made.

ENGEL, P., and DEZEEUW, C. 1984a. On the effect of changes in geometry and submerged weight of the Price meter rotor. Hydraulics Division, National Water Research Institute, Canada Centre for Inland Waters, Report No. 84-24, Jan., 17 p.

Abstract: Using dimensional analysis it was shown that the rotor response ao a meter with vertical axis can be expressed independently in term of a ratio of the drag coefficients of the of the driving elements and the submerged weight of the rotor. Experimentals results from tests on a conventional Price meter rotor and a modified plastic Price meter rotor were used to examine the effects of changing drag coefficients and submerged weight on general rotor performance and threshold velocity. The results indicate that considerable improvement in measuring low velocities may be obtained by using a rotor having the geometry of the conventional Price meter, and a substantially reduced submerged weight.

ENGEL, P., and DEZEEUW, C. 1984b. The effect of Columbus type sounding weights on the performance of the Price current meter. Environment Canada, Canada Centre for Inland Waters, National Water Research Institute Contribution 84-30, Aug., 31 p.

Abstract: Experiments were conducted in the towing tank at the National Water Research Institute to investigate the effect of the 15lb, 30lb, 50lb and 100lb Columbus type sounding weights on the performance of the Price 622AA current meter when used together with the WR2 hanger used by the Water Survey of Canada. The analysis showed that care must be taken that a meter is used with the same suspension configuration for which it is calibrated. Failure to do so may result in measurement errors of several percent at some speeds and errors in excess of ± 0.5% above the original measurement accuracy of the meter at almost all speeds. The results obtained for all the suspension configurations possible with the four sounding weights sizes and WR2 hanger used in this study are described in detail.

ENGEL, P., et al. 1985. Improvements to the low speed response of the plastic rotor for the Price current meter - Phase I. Environment Canada, Canada Centre for Inland Waters, National Water Research Institute Contribution 85-140, Nov., 15 p.

Abstract: This study has been conducted to develop a plastic rotor for the Price meter with the best possible low speed performance. Prelimanary designs have been obtained based on theoretical considerations and towing tank tests. indications are that threshold velocities of lass than 2 cm/s can be obtained. More extensive tests are planned to evaluate the consistency in the performance of the new rotor designs over a wide range of conditions.

ENGEL, P., et al. 1986. Improvements to the low speed response of the plastic rotor for the Price current meter - Phase II. Environment Canada, Canada Centre for Inland Waters, National Water Research Institute Contribution 86-121, Nov., 16 p.

Abstract: This study is a joint initiative of Water Survey of Canada and the Hydraulics Division of the National Water research Institute. Its purpose is to develop a plastic rotor for the Price meter with the best possible low speed performance. Preliminary designs have been obtained based on theoretical considerations and preliminary towing tank tests. Indications are that threshold velocities of less than 2 cm/s can be obtained. Extensive tests were conducted to evaluate the consistency in the performance of the new rotor designs over a wider range of conditions. Results indicate that a plastic rotor with improved response characterisitcs has been obtained.

ENGEL, P. 1987. Performance of float actuated water level recorder systems. Environment Canada, Canada Centre for Inland Waters, National Water Research Institute Contribution 87-67, May, 20 p.

Abstract: In this study the Stevens "A" series float type recorder system (for stage measurements) was evaluated to determone its performance under a range of conditions. For typical installations errors can be kept to less than ± 3 mm.

ENVIRONMENT CANADA 1980. Manual of Hydrometric Data Computation and Publication Procedures. Environment Canada, Inland Waters Directorate, Water Resources Branch, Ottawa, Canada, 51 p.

Abstract: This manual contains detailed instructions to ensure that national standards and uniformity are maintained throughout the Water Survey of Canada in the office procedures involved in the computation and compilation of hydrometric survey data, the preparation of manuscript for the regular series of data publications and the dissemination of streamflow and water level data in computer-compatible form.

FONTAINE, R.A. et al. 1983. Cost-Effectiveness of the stream-gaging program in Maine. U.S. Geological Survey, Open-File report 83-261, 81 p.

Abstract: This report documents the results of a study of the cost-effectiveness of the stream-gaging program in Maine.

The final part of the analysis involves the use of Kalman-filtering amd mathematical-programming techniques to define the strategies for operation of the necessary stations that minimize the uncertainty in the streamflow records for given operating budgets. Kalman-filtering techniques are used to compute uncertainty functions (relating the standard errors of computation or estimation of streamflow records to the frequencies of visits to the stream gages) for all station in the analysis. A steepest descent optimization program uses the uncertainty functions, information on practical stream-gaging routes, the various costs associated with stream-gaging, and the total operating budget to identify the visit frequency for each station that minimizes the overall uncertainty in the streamflow. The stream-gaging program that results from this analysis will meet the expressed water-data needs in the most cost-effective manner.

FORTIER, S., and HOFF, E.J. 1920. Defects in current meters and a new design. Engineering News-Records, Vol. 85, No. 20, Nov. 11, pp. 923-924.

Abstract: Discusses the inaccuracies of meters under field conditions and describes the new Hoff meter giving curves comparing the effect of friction in various types of meters.

The purpose of this brief article is to call attention to some of the defects in current meters, to outline the requirements of a meter suitable for irrigation and drainage ditches and to describe some features of a new design of meter which is being developed to meet the requirements of relatively low velocities and small channels. This new design is the result of experiments carried on by the the authors of this paper.

FRANCIS, J.R.D., and MILLER, J.B. 1968. The accuracy of calibration of model gauging structures. The Institution of Civil Engineers, Proceedings, Vol. 39, Feb., pp. 235-241.

Abstract: The systematic errors in calibrating hydraulic structure models were estimated by sending one model weir to several different laboratories. A narrow 4 in. weir showed a noticeably smaller scatter of the values of the discharge coefficient than a 12 in. model of the same cross section.

FRAZIER, A.H. 1967. Wiiliam Gunn Price and the Price current meters. U.S. National Museum Bulletin 252: Contributions from the Museum of History and Technology, Paper 70, Smithsonian Institution, pp. 37-68.

Abstract: This paper traces the history and development of an oustanding family of current meters, the Price family, which is interralated with the history of the United States Geological Survey. It also presents a biography of that remarkable 19th-century American inventor, William Gunn Price.

FREESTONE, H.J. 1983. The sensitivity of flow measurement to stage errors for New Zealand catchments (Note). Journal of Hydrology, New Zealand, Vol. 22, No. 2, pp. 175-181.

Abstract: Records from fifty automatic water-level recording stations representative of stations presently in operation within New Zealand were studied to determine the effect of water-level reading precision on the accuracy of flow records. the influence of stage-reading precisions of ± 1 mm, ± 3 mm and ± 10 mm on mean flow, median flow and the flow exceeded 95 % of the time were tested.

Basins with small flows are shown to be the most sensitive to stage measuring error. Gains from the installation of weirs and flumes do not usually result in increased accuracy sufficient to offset the decreased sensitivity due to the smaller range of stage that occurs with very small flows.

A precision of ± 1 mm in water level is required for very small catchments and ± 3 mm for most other catchments up to 500 km^2, for a precision of ± 5% flow measurement at median flow.

The study shows that the percentage error from measurement precision generally increases as flow decreases.

FTELEY, A. 1883. Current meter. American Society of Civil Engineers Transactions, Vol. 12, pp. 117-118.

Abstract: The flow in Sudbury River and in other channels which were measured frequently with current meters which were found very convenient, and, so far as could be determined by practical tests, very reliable. While observations were taken in the conduit to ascertain its flow, these instruments were accurately tested by comparing the velocities of the water, as indicated by them, with the correct velocities calculated from the weir measurements.

FULFORD, J.M., SAUER, V.B. 1986. Comparison of velocity interpolation methods for computing open-channel discharge. Selected Papers in the Hydrological Sciences, U.S. Geological Survey, Water-Supply Paper 2290, January, pp. 139-144.

Abstract: The Dutch members of a subcommittee of the ISO have suggested the use of the ratio $V/h^{1/2}$ to interpolate the horizontal velocity profile from a small number of measured velocities. This method (the ratio interpolation method) and two other discharge computation methods, a modified ratio interpolation method and a linear velocity fit method, were tested on data from the Mississippi and Ohio Rivers and seven smaller rivers in Georgia and South Carolina. Results from all the methods are compared with a "true" discharge computed by the standard mid-section method. Absolute mean error for the methods using all the measured cross section depths with a velocity approximation scheme ranged from 10.2 percent to 1.1 percent. Results from the study indicated that the use of five velocity measurements in a known cross section might be adequate to compute discharges by using the ratio interpolation method or a more simple linear interpolation scheme.

GORDON, R.L. 1989. Acoustic measurement of river discharge. Journal of Hydraulic Engineering, Vol. 115, No. 7, July, pp. 925-936.

Abstract: This paper presents a new moving-boat method for rapidly measuring river discharge using an acoustic Doppler current profiler (ADCP). The method uses an ADCP to measure current profiles and boat velocity along transects across a river. Measurements from the River Elbe, near Hamburg, Germany, are presented to illustrate the method and its associated uncertainties. Uncertainties in discharge from random errors, biases, and missed data near the surface, bottom, and sides of the river is investigated. Missed data near the surface and bottom are the largest source of error unless the data are corrected by assuming model profiles. With correction, the error in estimation of total discharge is dominated by flow in the shallow water at the sides of the river; for the

River Elbe, the total error appears to be about 5%.

GRAY, D.M. 1973. Handbook on the principles of hydrology. Water Information Center, Inc., N.Y., Reprinted. Section 8.7 River Hydraulics and Flow Measurement, pp. 8.65-8.73.

Abstract: Velocity distributions in natural channels are presented. Theoretical velocity distributions are also discussed.

GRINDLEY, J. 1970. The calibration of current meters: Method of calibration. Hydraulics Research Station, Wallingford, Berkshire, England, Report INT 80.

Abstract: Not available.

GRINDLEY, J. 1971a. The calibration of current meters: Effect of suspension. Hydraulics Research Station, Wallingford, Berkshire, England, Report INT 93.

Abstract: Not available.

GRINDLEY, J. 1971b. The calibration of current meters: Accuracy. Hydraulics Research Station, Wallingford, Berkshire, England, Report INT 95.

Abstract: Not available.

GRINDLEY, J. 1971c. Calibration and behaviour of current meters: Effect of oblique flow. Hydraulics Research Station, Wallingford, Berkshire, England, Report INT 87, 16 p.

Abstract: Almost 40 years ago Yarnell and Nagler (A.S.C.E. Vol. 96, 1931, pp. 766-860) investigated the effect of turbulence on the registration of current meters. The work included a study of oblique flow. The current meters now used for river flow measurements in the United Kingdom bear little ressemblance to those studied in the United States by Yarnell and Nagler. This is particularly so in the case of the propeller type meter. It was considered important to study the behaviour of these modern meters.

The present investigation differed in many ways from that of the Americans who made their tests in running water in a flume whereas the tests described in the following paragraphs were made in the current meter rating tank where the meters were towed through still water. In the American tests the tail fins of the cup type meters were removed and the meters were clamped rigidly to a fixed support. In the present tests all the meters were clamped rigidly at right angles to their supporting rodes but the tail fins were not removed from the cup type meters.

GRINDLEY, J. 1971d. Calibration and behaviour of current meters: Drag. Hydraulics Research Station, Wallingford, Berkshire, England, Report INT 96, 6 p.

Abstract: When a current meter is suspended by cable from a cableway at a gauging site the accuracy with which it can be positioned in the water depends on the cable and the vertical. If this angle is large the current meter may be well downstream of the cross-section and the vertical distance from the pulley block down to the meter will be less than the length of cable from the pulley block to the meter.

Corrections for the lengths of cable in air and underwater for various vertical angles are given in U.S. Geological Survey Water Supply Paper 888.

The present paper indicates the vertical angle of the cable when some current meters are used in combination with some sinker weights and enables the user to choose a suitable weight.

GRINDLEY, J. 1972. Calibration and behaviour of current meters: Test in flowing water. Hydraulics Research Station, Wallingford, Berkshire, England, Report INT 99, 6 p.

Abstract: In the rating tank the water is practically still and free from turbulence whereas the flowing water in a flume or stream has turbulence which might affect the performance of a current meter.

The short investigation described in this report is a preliminary step to a much larger investigation carried out in the summer of 1971 in Yorkshire rivers. These latter tests invilved the simultaneous use of up to 40 current meters in each cross-section of river investigated.

It was thought worthwhile to make the preliminary investigation with two current meters, used one at a time, in conditions which were as good as could be managed and with counting and timing equipment which enabled the uncertainty of measurement to be assessed over a wide variety of periods ranging from a few seconds up to 20 minutes.

GROAT, B.F. 1913. Characteristics of cup and screw current meters: Performance of these meters in tail-races and large mountain streams; statistical analysis of discharge curves. American Society of Civil Engineers, Transactions, Vol. 76, Paper no. 1259, pp. 819-840, 852-870.

Abstract: Describes tests made with Haskell and Price current meters and Pitot tube at Massena, N.Y., concluding that cup meters over-register (on the average 6%) more than screw meters under-register (the average for Haskell was about 1 per cent). States that current-meter measurements in pertubed water should be made with caution. Results of experiments given in which meters were oscillated longitudinally and transversely through a small amplitude in a still-water rating, and also some ratings from a skiff with oscillations caused by rocking the boat. An addendum states that experience on some mountain streams indicates that cup meters will over-register three to six times the amount which the screw meter under-registers. In discussion: W.G. Price (pp. 841-844); E.E. Haskell (pp. 844-846); C.H. Miller (pp. 846-848); and J.C. Hoyt (pp. 848-852).

During the summer and autumn of 1911 the writer ran a number of efficiency tests on two of the 6000-h.p. hydraulic turbine units recently installed in the power-house of the St. Lawrence River Power Company, at Massena, N.Y.

In all, about 40 000 instrumental readings, including gauge readings, were made. Of these, 7 000 were complete velocity observations by current meters (screw and cup types), and 4 000 additional readings on a Pitot tube furnished about 100 complete velocity observations for comparison with simultaneous readings by the current meters.

GROAT, B.F. 1914-15. Pitot tube formulas, facts and fallacies. Proceedings, Engrs.' Society of Western Pennsylvania, Vol. 30, pp. 323-383.

Abstract: Paper devoted mostly to Pitot tube, but on pages 351-366 gives results of ratings of large Price and Haskell current meters from boats under ideal conditions and with boat rocking; describes use of these meters in turbine tests at Massena, N.Y. Concludes that cup meter was accelerated by rocking and screw meter retarded.

GROAT, B.F. 1916. Chemi-Hydrometry and its application to the precise testing of hydro-electric generators. American Society of Civil Engineers, Transactions, Vol. LXXX, pp. 1231-1271.

Abstract: Describes still-water rating experiments on Haskell, Ott, and Price meters at University of Michigan, in which the meters were oscillated at various periods through arcs of various lengths in a horizontal, vertical, and longitudinal direction. Longitudinal oscillations showed that water pulsations affect meters but little, while lateral disturbances made the Price meter over-register, whereas the Ott and Haskell meters under-registered, the under-registration of the Haskell meters exceeding that of the Ott type. In discussion: R.E. Horton (pp. 1283-1285); and W.S. Richmond (p. 1287).

GROAT, B.F. 1927. In defense of current meters. Engineering News-Records, Vol. 98, No. 9, p. 370.

Abstract: Discussion on Mr. Hoyt's letter, p. 1010 of Dec. 16, 1926 issue of Engineering News-Records. Letter defends current meter as a valuable measuring device, and mentions characteristics of different types.

GROVER, N.C. 1916. Effect of channel on stream flow. Boston Society of Civil Engineers, Vol. III, No. 9, Nov., pp. 465-476.
Abstract: On the character of channel depends largely the cost and accuracy of a record obtained at any site. The gaging station will determine largely the accuracy of current-meter measurements and therefore the accuracy of the rating curve. The shape of the control will determine the sensitiveness of the station and therefore the accuracy with which a record of stage may be translated into a record of discharge. The permanence of the control will determine the permanence of the stage-discharge relation and therefore the dependability of the rating curve and the number of current meter measurements required as a foundation for the rating curve or succession of rating curves needed for interpreting the record of stage.

GROVER, N.C., and HOYT, J.C. 1916. Accuracy of stream-flow data. United States Geological Survey, Water Supply Paper 400-D, pp. 53-59.

Abstract: The following topics are covered in this paper: (1) degree of accuracy required; (2) conditions affecting accuracy of records of daily discharge, including: permanence of the stage-discharge relation, precision of the discharge rating curve, refinement of gage readings, frequency of gage readings, and methods of applying the daily gage heights to the rating table; and (3) accuracy of monthly or yearly discharge.

GUNN, J.R. 1922. A study of the fundamental principles of current meters. Thesis for M.Sc. in Mechanics, University of California, 88 p.

Abstract: Not available.

GURLEY, W. & L.E. 1893. The Price current meter. Engineering News, 29, No. 9, Mar. 2, pp. 196-197.

Abstract: Article describes the Price current meter and its application on the Niagara River. The weight assembly (made of wood and lead, 60 lbs) is also described.

GUTMANN, I. 1926. Glorifying the current meter by Prof. A. Staus. Engineering News-Records, Vol. 97, No. 21, Nov., pp. 840-841.

Abstract: Review of Dr. Staus pamphlet (DER GENAUIGKEITSGRAD VON FLUGELMESSUNGEN BEI WASSERKRAFTANLAGEN, 35 p., Julius Springer) which discusses the precision of current meter gagings of canals and closed conduits. It is not a manual of instructions or descriptions but a critical review of instruments and methods of measurement and computation pointing out potential errors and their bearing on the precision of the final result.

The propeller type of meter is shown to be more reliable than the cup type.

HALL, W.G. 1953. The study of the Price current meter in low velocity flow. State University of Iowa, M.S. Thesis, 24 p.

Abstract: The following conclusions may be drawn from this investigation of the Price current meter at low velocities: the six-cup bucket wheel, with the smallest distance travelled per revolution and the lowest point of constant revolution is considered to be the most efficient wheel tested; bearing friction, rather that the number of cups on the wheel, determines the stalling velocity of the meter. Recommendations for further study of the meter at low velocities are to reduce the bearing friction of the meter by a re-design of the bearings; and to construct and test a light plastic bucket wheel.

HALL, M.J., and JOHNSTON, P.M. 1971. Stochastic analysis of velocity fluctuations in a natural stream channel. Proc. Warsaw Symp. on Mathematical Models in Hydrology, Vol. I, Unesco Stud. Rep. Hydrol., No. 15, pp. 26-38.

Abstract: One of the major errors in current meter measurements of flow velocities in natural stream channels arises from the effect of low-frequency turbulent velocity fluctuations. The magnitude of this error has generally been estimated on the assumption that the velocity fluctuations rae random in time. A study has been carried out at a gauging station in the North of England during which two-hour long series of velocity measurements were obtained at three depths in the same vertical of the cross-section. Analysis of these data has revealed a concentration of variance at low frequencies, but no obvious periodic components. This correlation structure should be taken into account when quantifying the likely error in a limited-exposure point measurement of velocity.

HALLIDAY, R.A., et al. 1975. The Niagara River acoustic streamflow measurement system. Environment Canada, Water Resources Branch, Technical Bulletin No. 86, 11 p.

Abstract: Work conducted in other countries in the 1960's demonstrated the feasibility of using acoustic velocity measurement devices for determining flow in open channels. Accordingly, a decision was made to install one such instrument, the Westinghouse Leading Edge (LE) Flowmeter, on a large Canadian river where there was a demand for "real time" streamflow data and where the stage-discharge relationship was affected by backwater. Results obtained would be used to determine the feasibility of operating an acoustic streamflow measurement system under Canadian conditions. A flow meter having a 1700-foot (530-metre) long acoustic path was installed in 1971 and, despite some installation and operational problems, is providing accurate streamflow data. The plans for the future include telemetry of the data to users and further calibration of the instrument.

HARDING, S.T. 1915. Experiments in the use of current meters in irrigation canals. Journal of Agricultural Research, Vol. V, No. 6, Nov., pp. 217-232.

Abstract: Comparisons of the relative accuracy of measurement made in irrigation canal with current meters using different methods are made in the discussion. In connection with field experiments made on the flow in various types of canals in order to determine the value of the coefficient n of Kutter's Formula, detail current-meter gagings were necessary. These details gaigns and other observations made at the same time have been used to compare the results obtained by the standard two-point, single-point, and integration methods, as well as by floats and various selected points of measurements. Much experience is now available in regard to the various methods of current-meter observations used in natural channels. the results given here apply to the more regular artificial channels used in irrigation for which there are fewer available data.

HARDISON, C.H., and MOSS, M.E. 1972. Accuracy of low-flow characteristics estimated by correlation of base-flow measurements. Manual of Hydrology, Part 2, Low-Flow Techniques, Geological Survey Water Supply Paper 1542-B, pp. 35-55.

Abstract: The number of discharge measurements required to define an acceptable relation between the base flow at a stream gaging station and that at an ungauged site depends on the statistics of the regression, the accuracy goal, and the lenght of record at the gauging station used in the regression. Equations and graphs are presented for evaluating the accuracy of a low-flow characteristic estimated from such a relation in terms of the number of years of record that would be required at the ungauged site to give an estimate of comparable accuracy. An outline of the derivations of basic equations is presented in a separate section of the report.

HARP, J.F. 1974. An innovative automatic stream gaging method. Journal of Hydrology, Vol. 21, pp. 27-31.

Abstract: This brief paper presents an extension of the moving boat method whereby intermediate sized streams may be gaged automatically, by means of a moving meter, by remote control with no operator at the point of the velocity measurement. The paper is clearly innovative in that no velocity magnitude measurement is required, only an angle measurement and a known input constant velocity of traversing meter. The technique presented here is most unusual in that a new technique is combined with classical methodology to produce a reliable field measurement of streamflow rates in a remarkably short time.

HENRY, D.G. 1871. On the flow of water in rivers and canals. Jour. Franklin Inst., Vol. 92, pp. 167-389.

Abstract: The errors in river flow determination are discussed, including the error of cross-section; the pulsation of the current; the uncertainty of location; floating bodies move faster that the water in which they are immersed; the upper float drags the lower, the effect of the current on the connecting cord.

HERSCHY, R.W. 1969. The evaluation of errors at flow measurement stations. Water Resources Board, Technical Note No. 11, pp. 1-31.

Abstract: The paper outlines the evaluation of error of British Standard flow measurement stations by simple statistical methods. These methods are discussed in the relevant Standards. The paper is in two sections: 1. Weirs and Flumes and 2. Velocity Area Stations.

In both sections it is shown that the largest single error is in the recording of head or stage. Nevertheless, in the case of weirs and flumes, it is shown that an overall accuracy of ± 2 per cent may be obtained for heads larger than 600 mm (2.0'). For heads as low as 60 mm (0.2') however, the error may be as much as ± 8 per cent. In the case of the velocity area stations it is shown that similar accuracies may be obtainable, depending mainly on the standard error of the stage-discharge relation for the particular station. A method of obtaining this standard error is demonstrated.

HERSCHY, R.W. 1970. The magnitude of errors at flow measurement stations. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. no. 99, pp. 109-131.

Abstract: An assessment of the accuracy of hydrometric data produced from flow measurement stations is important to the users of the data. This is particularly so in the case of water resources development. the paper uses statistical approach and outlines simple statistical methods for obtaining the error in a single determination of discharge at both velocity-area stations and at weirs and flumes. In connexion with velocity-area stations, a method of obtaining the standard error of the stage-discharge curve is discussed and a statistical test for significance of check gaugings is demonstrated. Statistical definitions as they apply to hydrometry are included in an appendix.

HERSCHY, R.W. 1975a. The effect of pulsations in flow on the measurement of velocity. Proceedings of the International Seminar on Modern Developments in Hydrometry, Padova. World Meteorological Organization, Geneva, pp. 389-396

Abstract: The paper describes an investigation carried out into the effects of pulsations in the flow on the accuracy of velocity measurements. Up to 40 current meters on 8 verticals were operated simultaneously over a continuous period of 24 hours at each of 3 river sites. The computed uncertainties were plotted against corresponding point velocities and the relations tabulated for exposure times of 30 sec, 1 min, 2 min and 3 min. It was found that the uncertainties in velocity due to pulsations were related to both depth and velocity and were highest at low velocities and lowest at high velocities no matter what position in the vertical these velocities occured. Uncertainties were expressed at the 95 per cent confidence level and varied from 5 per cent for an exposure time of 3 min and a velocity of 0.3 m/s to 80 per cent for an exposure time of 30 sec and a velocity of 0.05 m/s. Since the equation for the estimation of the uncertainties in a single determination of discharge randomizes the contributing uncertainties, it is suggested that the tabulated values are suitable for general application for similar rivers.

HERSCHY, R.W. 1975b. The accuracy of existing and new methods of river gauging (Ph.D. Thesis). Department of geography, University of Reading, March, 485 p.

<u>Abstract</u>: The object of the research was to estimate the uncertainties in the measurement of river discharge by the following techniques:
1. The uncertainty in a single determination of discharge, X_o, by current meter by investigating the contributing uncertainties in a modified error equation which relates X_o to uncertainties in : width, depth and velocity and the number of verticals used. Particular attention has been given to the uncertainty in the measurement of velocity caused by the uncertainties due to pulsations in flow, to the number of current meter observations made in the vertical, to the current meter rating.
2. The uncertainty in the stage-discharge relation by a statistical analysis of the stage-discharge curve using standard error of estimate and standard error of the mean. The method has been successfully tested on a random sample of national network stations.
3. The uncertainties in the daily mean discharge, monthly mean discharge and annual discharge, by relating these uncertainties to the standard error of the mean, the stage and the slope of the stage-discharge curve.

The uncertainties into the ultrasonic and electromagnetic methods of river gauging are described and the uncertainties estimated form these investigations. The research suggests that the upper limit of these uncertainties can be conveniently set as follows (95 oer cent confidence limits):

recording stage (or head) by punched tape = ± 3 mm
single current meter gauging = ± 7 %
standard error of estimate of the stage-discharge relation= ± 10%
standard error of the mean of the stage-discharge relation= ± 5%
uncertainty in the daily mean discharge = ± 2%
ultrasonic method - uncertainty in a single gauging = ± 2%
electromagnetic method-std error of estimate of rating eq.= ± 10%
electromagnetic method-std error of the mean of rating eq.= ± 2 %

The methods employed may also be used to determine the uncertainty with which the variables should be measured in order to attain a desired accuracy.

Whilst the velocity-area mehtod and new methods form the predominant part of the thesis, a review is made of the uncertainties in measurement of river discharge by the use of measuring structures and corresponding expressions developed for estimating the uncertainties in the daily mena, monthly and annual discharges.

A review is made of existing literature and in particular the work done in this field by Carter & Anderson, Dementev, Grindley, Lambie, Robertson, Smoot and Carter, British Standards Institution and International Standards organization.

HERSCHY, R.W. 1978a. The accuracy of current meter measurements. Proc. Instn Civ. Engrs, Part 2, June, 65, pp. 431-437.

Abstract: The uncertainty in a current meter measurement due to the restricted number of verticals used is investigated. In the sample of 193 special current meter measurements examined the uncertainty is shown to be random. Values of the uncertainty for 5-50 verticals are presented.

HERSCHY, R.W. 1978b. Accuracy. Hydrometry: Principles and Practices: Chapter 10, John Wiley and Sons, pp. 353-397.

Abstract: The chapter is divided into the following sections: introduction; statistical terms and definitions as applied to river gaugings; nature of errors; theory of errors; the error equation; values of uncertainties; and conclusions.

HERSCHY, R.W. 1982. Current meter calibration - individual rating versus group rating. Advances in Hydrometry, Proceedings of the Exeter Symposium, July, IAHS Publ. no. 134, pp. 25-36.

Abstract: The cost of the individual rating of current meters is expensive and is likely to increase substantially in the future. Both International and British Standards make provision for current meters to be used with either an individual rating or a group rating. Previous work in this field is summarized and new information presented. The paper concludes that the adoption of a group rating need not reduce the accuracy of current meter gaugings; the cost saving of a group rating however is significant.

HERSCHY, R.W. 1985. Accuracy. Streamflow Measurement: Chapter 14, Elsevier Applied Science Publishing, pp. 474-510.

Abstract: The chapter is divided into the following sections: introduction; standard deviation; nature of errors; theory of errors; the error equation; values of uncertainties; examples in the calculation of uncertainties; and estimation of length of record required at a streamflow station.

HERSCHY, R.W., et al. 1978. The effect of pulsations on the accuracy of river flow measurement (technical memo). Department of the Environment, Reading (England), Water Data Unit, 50 p.

Abstract: The investigation included the operation of up to 40 current meters simultaneously at 5 points in each of 8 verticals at 3 different river sections in Yorkshire. Readings of velocity were taken every 30 seconds for periods of over 24 hours. The 5-point, the 2-point and the single point methods of gauging under the effect of pulsations were examined by computer analysis of field readings. The 5-point method gave the best results followed by the 2-point and single point methods in that order. The values of discharges computed from simultaneous observations of velocity were generally no better than those computed from consecutive observations. The uncertainties in point velocities due to pulsations varied from about 5% at a velocity of 0.3 m/s to 80% at a velocity of 0.05 m/s, at the 95% level.

HERSCHY, R.W., and NEWMAN, J.D. 1982. The measurement of open channel flow by the electromagnetic gauge. Advances in Hydrometry, IAHS Publ. no. 134, pp. 215-227.

Abstract: Since the previous symposium in Padova in 1975 significant improvements have been made to the electromagnetic gauge for measuring flows in open channels. These improvements have been mainly in the instrumentation and they are described together with a summary of the principle, site requirements and applications. A brief introduction of the application of the gauge to the measurement of flow in sewers and culverts is also presented.

HOFF, P.E. 1927. Current meter investigations needed. Engineering News Record, 99, No. 1, Jul. 7, p. 28.

Abstract: Request for an official investigation into current meters.

HOLMES, D.K., et al. 1970. LE (Leading Edge) flowmeter - a unique device for open channel discharge measurement. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. no. 99, pp. 432-443.

Abstract: This paper describes the capability of LE acoustic flow meters to measure open channel volumetric flow. Problems associated with the inhomogeneity of the medium have been overcome, as evidenced by the successful operation of the LE flowmeter on various rivers and canals in the United States.

Using the time differences resulting from transmitting signals between transducer pairs, average path velocities are calculated. Volume flow is computed by appropriately weighting the individual path velocities. Minimum resolvable flow, which is inversely proportional to path length, is about 0.2 m/sec for a 1m path.

For maximum accuracy, multiple paths are required. In channels with constant stage, flow is obtained by quadrature integration independent of the velocity profile. With variable stage, a water level sensor is also required. A typical flow with stage changes of +21 per cent, - 7 per cent has been integrated to better than 1 per cent accuracy.

HORNBECK, J.W. 1965. Accuracy in streamflow measurements on the Fernow Experimental Forest. U.S. Forest Service Research Note NE-29, U.S. Dept. of Agriculture, Northeastern Forest Experiment Station, 8 p.

Abstract: Measurements of streamflow from small watersheds on the Fernow Experimental Forest at Parsons, West Virginia was begun in 1951. Stream-gaging stations are now being operated on 9 watersheds ranging from 29 to 96 acres in size; and 91 watersheds-years of record have been collected. To determine how accurately streamflow is being measured at these stations, several of the important factors that influence the accuracy of the records have been studied.

The factors studied were grouped into the following four categories: (1) stream-gaging instrumentation, (2) stage-dsicharge relation, (3) manual checking of stage, and (4) compilation of data.

HORTON, T. 1901. Flow in the sewers of the North Metropolitan Sewerage System of Massachusetts. Trans. ASCE, Vol. 46, pp. 78-92.

Abstract: An Ellis current meter, with four vanes, was used to conduct measurements. Prior to eash series of observations (three), the meter was rated over a course varying between in length from 500 to 1000 ft., and for varying speeds.

HOYT, J.C. 1907. A universal current meter. Engineering News, Vol. 57, p. 263.

Abstract: Describes adaptability of small Price meter to stream gauging, and gives rating curves for for Fteley, Warren, Haskell, small Price, large Price, and Lallie current meters.

HOYT, J.C. 1908. Recent changes of Methods and equipment in the water resources work of the United States Geological Survey. Engineering News, Vol. 60, pp. 15-16.

Abstract: Describes refinements which were made in construction and use of Price meter, referring to pentacount registering device, torpedo weights, rods, etc.

HOYT, J.C. 1910. The use and care of the current meter, as practiced by the United Geological Survey. American Society of Civil Engineers, Transactions, Paper No. 1133, Vol. 66, pp. 69-134.

Abstract: Gives history of current-meter development, plates showing Price, Haskell, Fteley, Ellis, Richards, Woltman, Ott, and Amster meters. The use, care, and rating of the Price meter is thoroughly discussed.

In discussion: A.H. Dramont (pp. 106-107); E.C. Murphy (pp. 107-108); H.K. Barrows (pp. 108-110); C.E. Grunsky (pp. 110-126); E. Kuichling (pp. 126-128); G.H. Matthes (pp. 128-129); W. Pearl (p. 130); and C.M. Allen (pp. 130-132).

HOYT, J.C. 1913. The effect of ice on streamflow. U.S. Geological Survey, Water-Supply Paper 337, 77 p.

Abstract: With a view to standardizing, this paper presents the available information on the sucbject, discussing the factors that influence the run-off during the periods of low temperature, the varieties of ice and their effect on the applicability of the laws of open-channel flow, and the collection and interpretation of necessary data.

HOYT, J.C., and GROVER, N.C. 1907. River discharge. John Wiley & Sons, New York, 137 p.

Abstract: Book that brings together all available sources of information on river discharge.

HOYT, K.K. 1926. Defense of the Price current meter. Engineering News-Records, Vol. 97, No. 25, p. 1010.

Abstract: Letter defends the use of Price meter by the U.S. Geological Survey, comparing the behavior of same with screw meters advocated by Dr. Ing. A. Staus.

HOYT, K.K. 1928. Accuracy of stream-flow measurements. Engineering News Record, 101, No. 5, Aug. 2, pp. 167-168.

Abstract: It is shown that the price meter, when employed by experiences personnel, can give consistent results under different channel conditions and that it checks the much-praised Gibson method.

HULSING, H., et al. 1966. Velocity-head coefficients on open channels. Geological Survey Water-Supply Paper 1869-c, 45 p.

Abstract: This report presents the results of a detailed study of the velocity-head coefficients, alpha, in natural channels. It is based upon an analysis of point velocities obtained from discharge measurements made by multiple-point method or by the two-point (0.2d/0.8d) method.

HURST, H.E. 1920. Short report on Nile gauge readings and discharges. Cairo, Physical Department Paper No. 1, 43 p. Addendum: The effect of turbulence on river discharge measurements, 8 p.

Abstract: Not available.

ISO 2357 1974. Liquid flow measurement in open channels - Cup-type and propeller-type current meters. International Organization for Standardization, 4 p.

Abstract:

ISO 3455 1976. Liquid flow measurement in open channels - Calibration of rotating-element current-meters in straight open tanks. International Organization for Standardization, 8 p.

Abstract: The IS specifies the procedure to be used for the calibration of current-meters, i.e. for the experimental determination of the relationship between liquid velocity and rate of revolution of the rotating element. It also specifies the type of tank and equipment to be used and the method of presenting the results.

ISO DATA 2 1978. Investigation on the total error in measurement of flow by velocity-area methods. International Organization for Standardization.

Abstract:

ISO 772 1978. Liquid flow measurement in open channels - Vocabulary and Symbols. International Organization for Standardization, 35 p.

Abstract:

ISO 5168 1978. Measurement of fluid flow - Estimation of uncertainty of a flow-rate meassurement. International Organization for Standardization, July, 26 p.

Abstract: This International Standard describes the calculations required in order to arrive at a statistical estimate of the interval within which the true value flow-rate may be expected to lie. These calculations are presented in such a way as to be applicable to any flow measurement method. This International Standard should be used for guidance on the general techniques to be applied.

ISO 748 1979. Liquid flow measurement in open channels -

Velocity-area methods. International Organization for Standardization

Abstract: This International Standard specifies method for determining the velocity and cross-sectional area of water flowing in open channel (with or without ice cover), and or computing the discharge therefrom.

ISO TC 113 1981. Measurement of Liquid Flow in open channels, Subcommittee 1- Velocity-area methods - Computation of discharge in velocity-area methods by the Netherlands. Dutch members of Subcommittee One of Technical Committee 113 of the International Organization for Standardization, (ISO/TC113/SC1 N345), unpublished report, 12 p.

Abstract: To reduce the error for a small number of verticals, a method of discharge computation has been investigated, in which the horizontal velocity profile is computed by interpolation between measured verticals and extrapolation to the banks according to $v/h^{1/2}$ = constants.

Based on the results of an arbitrary discharge measurement in the river Rhine this "interpolation method" is compared to the standardized "mid-section method" (ISO 748). It appears that the method of computation has a significant influence on the accuracy of the discharge. The "interpolation method" gives considerably better results and espacially for a restricted number of verticals the mid-section method is even unreliable.

The error-investigation as presented in TR 7178 holds specifically for the mid-section and does not fit as such for other methods of discharge computation.

ISO 1100 1982. Liquid flow measurement in open channel - Part 2: Determination of the stage-discharge relation. International Organization for Standardization, 33p.

Abstract: This International Standard specifies methods of determining the satge-discharge relation for a gauging station. A sufficient number of discharge measurements complete with corresponding stage measurements is required to permit the stage-discharge relation to be determined to the accuracy required by this International Standard.

An analysis is included of the uncertainties involved in the preparation and the use of the stage-discharge relation.

ISO 7178 1983. Liquid flow measurement in open channels - Velocity-area methods - Investigation of total error. International Organization for Standardization, Technical Report 7178, July, 27 p.

Abstract: This technical report summarizes the results of investigations of the total error in measurement of flow by velocity-area methods. It describes the procedure used and types of errors (section one), and gives recommendation for the collection of data for investigations of errors (setion two) with a view to supplementing the information given in ISO 1088.

ISO 1088 1985. Liquid flow measurement in open channels - Velocity-area mehtods - Collection and processing of data for determination of errors in measurement. International Organization for Standardization, January, 21 p.

Abstract: This International Standard specifies a standard basis for the collection and processing of data for the determination of individual components of error in the measurement of liquid flow in open channels by velocity-area methods.

ISO 8363 1986. Liquid flow measurement in open channels - General guidelines for the selection of methods. International Organization for Standardization, November, 6 p.

Abstract: This International Standard gives general guidelines for the selection of a suitable method for liquid flow measurements in open channels.

IONIDES, M.G. 1934. River stage-discharge curves. Engineering, Vol. CXXXVIII - from July to December 1934, London, Oct. 12, p. 396.

Abstract: A new simple method is described which takes into account the effect of changing stage on stage-discharge curves for rivers.

JARRETT, R.D. 1987. Errors in slope-area computations of peak discharges in mountain streams. Journal of Hydrology, Elsevier Science Publishers B.V., Amsterdam, 96, pp. 53-67.

Abstract: During an evaluation of 70 slope-area measurements on higher-gradient streams (stream slopes greater than 0.002) throughout the United States, peak discharges measurements were found to be affected by n values, scour, expansion and contraction losses, viscosity, unsteady flow, number of cross sections, state of flow and stream slope. Problems due to measurement error can often be as great as or greater than 100% and leads to overestimation of the actual peak discharge. This can result in misleading maximum flood values, erroneous flood-frequency analyses and overdesign of flood-plain structures.

A brief discussion of these problems, tentative solutions and research needs is presented. The critical-depth method of computing peak discharge provides the most reasonable results in higher-gradient streams.

JEPSON, P. 1967. Current meter errors under pulsating flow conditions. J. Mech. Engng. Sci. 9, pp. 45-54.

Abstract: Not available.

JOHNSON, D. 1971. Velocity oscillations of current meter measurements. Proc. Inst. Civ. Engrs., 49, pp. 405-406.

Abstract: Paper presents a summary of data collected (velocity measurements) in 1968 which revealed a complex series of periodicities varying in wavelength from 2 or 3 min to an hour or more. To enable the behaviour of these periodicities to be examined in more detail, the various harmonic components in each time series were isolated by means of a series of band pass filters.

JOHNSON, D., and TATTERSALL, K.H. 1971. Hydrological data analysis for water resources problems. J. Instn. Wat. Engrs., 25(4), pp. 181-200.

Abstract: A series of consecutive velocity measurements made at 30 sec. intervals at a single point in a cross-sections is statistically analyzed.

KALINSKE, A.A. 1945. Application of statistical theory to measurements of velocity ans suspended sediment in rivers. Transactions, American Geophysical Union, Vol. 26, No. II, Oct. pp. 261-265.

<u>Abstract</u>: To obtain a proper mean mesure of velocity or suspended sediment-concentration in a turbulent stream, it is necessary to make observations or take data over a period of time because of the fluctuating nature of the measured quantity. Measurements of velocity with vane-type current-meters, and sediment-concentration determinations by sampling techniques are the important examples of the problem to be considered: namely, over what period of time must a measurement be made in order that a deisred accuarcy can be obtained for the mean value of velocity or sediment-concentration, and on what factors does this necessary time depend. The purpose of this paper is to apply the statistical theory of random sampling to the solution of this problem.

KALLIO, N.A. 1966. Effect of vertical motion on current meters. United States Geological Survey, Water-Supply Paper 1869-B, pp. B1-B20.

<u>Abstract</u>: The effect of vertical motion on the performance of current meters at varoius stream velocities was evaluated to determine whether accurate discharge measurements can be made from a bobbing boat.

Three types of current meters - Ott, Price, and vane types- were tested under conditions simulating a bobbing boat. A known frequency and amplitude of vertical motion were imparted to the current meter, and the related effect on the measured stream velocity was determined. One test of the Price meter was made under actual conditions, using a boat and standard measuring gear. The results of the test under actual conditions verified those obtained by simulating the vertical movements of a boat.

The test show that for stream velocities below 2.5 feet per second the accuracy of all three meters is significantly affected when the meters are subjected to certain conditions of vertical motion that can occur during actual field operations. Both rate of vertical motion and the frequency of vertical oscillation affect the registration of the meter.

The results of these tests, presented in the form of graphs and tables, can be used as a guide to determine whether wind and stream flow are within an acceptable range for a reliable discharge measurement from a boat.

KARASEV, I.F. 1978. Improved water-discharge models and estimate of water-discharge measurement in the "velocity-area" method. Soviet Meteorology and Hydrology, No. 12, March, pp. 65-73.

<u>Abstract</u>: This paper presents analytic relationships obtained on a correlation-hydraulic basis for new water-discharge models and the errors of water-discharge measurement.

KARASEV, I.F. 1980. More on error estimation for streamflow measurements. Soviet Meteorology and Hydrology, No. 11, pp. 91-94.

<u>Abstract</u>: It is shown that the maximum-error method and certain relationships of particular form are invalid for estimation of the error of measurement of discharge volumes in channel flows.

KARASEV, I.F., and CHIZHOV, A.N. 1970. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. No. 99, pp. 382-387.

<u>Abstract</u>: In measuring discharge by current meter, the so-called errors of the method, both random and systematic, are of primary importance; the errors of depth and velocity measurements should be considered first of all. The latter error is due to turbulent pulsation of velocity and depend slightly on the instrumental error.

Areal averaging of depth and velocity from a series of verticals decreases the error of discharge measurements. It allows a certain increase of error in velocity measurement without considerable increase in the error of discharge. It also permits a reduction in the duration of current meter exposure at a given point, which in turn accelerates the discharge measurements. This averaging in space and time is most useful for the integration methods of discharge measurements, particularly for the integration of velocities down the vertical. Suffcient accuracy is provided by the use of a current meter with a contact every other revolution, which eliminates the influence of marginal effects.

KASUGAYA, N. 1958. On the accuracy of the calculating formulas for the vertical mean velocity. Trans. of the Soc. of Civ. Eng. of Japan, (in japanese), No. 54, Feb., pp. 26-34.

<u>Abstract</u>: The author, at first, theoretically argues about the accuracy of the calculating formulas for the vertical mean velocity, connecting them with the various theories with respect to the vertical velocity distribution in an open channel. Then, applying those formulas to the data obtained in the River Tone, he concludes that is is desirable to adopt the two-point method or the three-point new one, which is introduced by the mean value theorem, in the ordinary condition, and the four-point new method at the place where the flow is exceedingly turbulented. Among the formulas having prevailed up to this time, the three-point method and the four-point one except the two-point one are not valuable at all.

KASUGAYA, N. 1958. Inducement of a new mean value method and calculating formulas for discharge in natural streams. Trans. of the Soc. of Civ. Eng. of Japan, (in japanese), No. 55, May, pp. 1-9.

<u>Abstract</u>: The author induces a new mean value method to be most effectively applied to the continuous curve which intersects a horizontal axis at both ends of defined interval. According to this new method, some calculating formulas of discharge in natural streams are obtained. When we apply these formulas to stream gaging, the smallest number of the verticals, consequently of the measuring points, may be sufficient. Therefore, we can measure the most accurate value of discharge, because we can prolong the period of velocity measurement at every points to eliminate the effect of pulsations of moving water, and moreover the shortening of the total period of gaging makes the effect of changing stage as little as possible.

KASUGAYA, N. 1958. Accuracy of the calulating formula for river discharge and proposal of a stream-gaging procedure. Trans. of the Soc. of Civ. Eng. of Japan, (in japanese), No. 57, Jul., pp. 12-19.

<u>Abstract</u>: For purpose of studying the accuracy of the calculating formulas for the rate of discharge in natural streams, twenty data obtained in the River Tone are used. Then the author concludes that the number of verticals are six at most, which vary with the degree of

unvenness of the transverse curve of the river bed, and are seasonally varied, therefore, with the hydrological conditions, i.e. precipitation, runoff, scoring, sedimentation, etc. To conclude, he proposes a stream-gaging procedure and mentions some remarks when his formulas are accepted.

KENNEY, B.C. 1977. Response characteristics affecting the design and use of current direction vanes. Deep-Sea Research, Vol. 24, pp. 289-300.

Abstract: A second order linear equation describing the motion of a current direction vane is derived and parameters important to the design of such vanes discussed. It is shown that serious error may result from the use of a direction vane to orient a velocity sensor into the "mean" current.

KERR, S.L. 1935. Research investigation of current-meter behaviour in flowing water. Transactions of the American Society of Mechanical Engineers, Vol. 37, pp. 295-301.

Abstract: This paper investigates the inconsistencies of flow measurements in closed flumes by means of current meters. It describes (a) the construction of a flume in which two meters were installed side by side and tested under varying conditions of flow, (b) the velocity distribution in the flume, and (c) the establishment of the true velocity plane across the face of the meters by means of a pitot tube. The pitot-tube coefficient was established for each flow condition, thus providing an accurate means of establishing the actual velocity existing in front of the current meter.

KINNISON, H.B. 1930. Stream-flow data - Its collection and use. Journal of the Boston Society of Civil Engineers, Vol. XVII, No. 5, May, p. 183.

Abstract: Current meter measurements are compared to salt-velocity measurements at Bellow Falls, Vt.

KINOSITA, T. 1970. Ultrasonic measurement of discharge in rivers. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. No. 99, pp. 388-399.

Abstract: Progress in improvement of ultrasonic flowmeters in Japan since 1964 id reported. Data obtained by ultrasonic flowmeters are compared with those from rotating current meters; agreement is vey good. Some limitations were experienced during field tests. If these limitations are resolved, the author believes that it will be a most useful instrument for flow measurement.

KINOSITA, T. 1982. Improvement of ultrasonic flowmeter in rivers in Japan. Advances in Hydrometry, Proceedings of the Exeter Symposium, July, IAHS Publ. no. 134, pp. 187-202.

Abstract: The author has already reported on the successful implementation of ultrasonic flowmeters in rivers in Japan. Subsequently he has made further efforts to improve them. But missing data and other problems were sometimes experienced during periods of operation. The causes of the problems were carefully investigated, and the paper discusses these problems and their solution. It is concluded that the ultrasonic flowmeter is a unique method of measuring discharge automatically at a site where a stable stage-discharge relation is not available, for instance on a tidal river. Hydraulic characteristics of river flow based on continuously measured discharge are also discussed and these characteristics are useful in providing guidelines for hydrometric network systems.

KIRBY, W.H. 1987. Linear error analysis of slope-area discharge determinations. Journal of Hydrology, Elsevier Science Publishers B.V., Amsterdam, 96, pp. 125-138.

Abstract: The slope-area method can be used to calculate peak flood discharges when current meter measurements are not possible. Thsi calculation depends on several quantities, such as water-surface fall, that are subject to large measurements errors. Other critical quantities, such as Manning's n, are not even amenable to direct measurement but can only be estimated. Finally, scour and fill may cause gross discrepancies between the observed condition of the channel and the hydraulic conditions during the flood peak.

The effects of these potentials errors on the accuracy of the computed discharge have been estimated by statistical error analysis using a Taylor-series approximation of the discharge formula and the well-known formula for variance of a sum of correlated random variates. The resultant error variance of the computed discharge is a weighted sum of covariances of the various observational errors. The weights depend on the hydraulic and geometric configuration of the channel.

The mathematical analysis confirms the rule of thumb that relative errors in computed discharge increase rapidly when velocity heads exceed the water-surface fall, when the flow field is expanding and when lateral velocity variation (alpha) is large. It also confirms the extreme importance of accurately assessing the presence of scour or fill.

KITANIDIS, P.K., et al. 1984. Evaluation of the efficiency of streamflow data collection strategies for alluvial rivers. Journal of Hydrology, Elsevier Science Publishers, Amsterdam, Vol. 72, No. 1/2, April, pp. 85-103.

Abstract: Streamflow discharge is usually determined indirectly from measurements of the river stage at gaging stations and through the use of stage-discharge relationships (rating curves). However, in alluvial streams, stage-discharge relationships change continually and, sometimes, quite markedly. Such changes may be caused by major floods, seasonal variations, or long-term secular trends associated with changes in the river channel. Consequently, reliable estimates of discharge using rating curves are not possible unless frequent direct measurements of discharge are made. Such measurements involve appreciable costs, and it is important to evaluate their contribution in increasing the accuarcy of estimation of quantities of interest such as mean daily, monthly or annual flow. A methodology for the evaluation of the efficiency of data-collection strategies for alluvial rivers is developed and applied to stations on the Missouri River, U.S.A. A flexible and expedient model describing the variability of discharges and shifts in the stage-discharge relationship is developed. Procedures for the estimation of parameters and the validation of the model using actual data are presented. The

calibrated and validated model is then employed in simulations to evaluate the effect of sampling strategies (such as frequency and accuracy of discharge measurements) on the accuracy of estimated daily, monthly and annual flow. Curves relating the cost of sampling to the achieved accuracy can be generated, and the optimization of sampling strategies given accuracy or budget objectives or constraints can be achieved.

KITANIDIS, P.K., et al. 1984. Effects of visitation frequency and instrument reliability on the accuracy of estimation of river discharges. Hydrological Sciences Journal, IAHS, Vol. 29, No. 3, Sep., pp. 255-269.

Abstract: The process of failures of a gauging station can be modelled as Poisson with time to the first failure distributed exponentially. The process is restarted when the station is visited and serviced. The probability distributions of the number of failures and the length of the missing record associated with gauging-stations failures are derived as functions of the average time to failure, t_o, and the pattern and frequency of visits. A maximum likelihood method of estimation of t_o from readily available data is proposed and analysed. This method gives estimates of t_o which, for samples containing a reasonably large number of failures, are approximately unbiased, efficient and normally distributed. A moment method of estimation of t_o is also proposed. Methods for validation of the assumed model and for testing the uniformity between stations or groups of stations are presented. The proposed methodology has been applied to study the performance of a network of 168 gauging stations.

KLEIN, G.S., and YUFIT, G.A. 1983. A doppler meter for river surface water speed. Soviet Meteorology and Hydrology, Allerton Press, No. 1, Jan., pp. 95-99.

Abstract: The use of a doppler surface-velocity meter is considered. The main factors governing the error of measurement are considered, and measurements are reported for the speed range 0-3 m/sec. A comparison is made with the results obtained with a hydrometric propeller.

KOLUPAILA, S. 1949. Technical Note: Recent developments in current-meter design. Transactions, American Geophysical Union, Vol. 30, No. 6, Dec., pp. 916-918.

Abstract: Paper outlines recent developements in current meters, i.e. improvements of the screw-type meter (OTT), significance of the component runner, and problem of angular flow are also discussed.

KOLUPAILA, S. 1958. Discussion: Common errors in measurement of irrigation water by C.W. Thomas. Journal of the Irrigation and Drainage Division, Proc. of the American Society of Civil Engineers, Vol. 84, No. IR2, Part 1, Apr., pp. 27-28.
Abstract: Author states that European studies indicated that a most dangerous error is caused by different velocity distribution before the weir.

KOLUPAILA, S. 1958. Use of current meters in turbulent and divergent channels. IAHS General Assembly of Toronto, Vol. 1, Publication No. 43, pp. 437-444.

Abstract: The current meter is still the most reliable instrument for flow investigation and discharge measurements in natural and artificial channels. The greatest obstacle in these operations is the irregular pulsation of turbulent flow and obliquity of streams lines. The usual blades of screw type current meters dont comply with the required cosine law, when the direction of stream is not parellel with their axis of rotation.

A new design of the component runner, recently introduced into the modern current meters, offers a valuable improvement: it assures a correct cosine law for angle up to 45°. This important innovation has been investigated in laboratories and checked during tests of power plants. The results are very favorable, the grade of accuracy obtained was more than satisfactory. Merits of component runners are particularly evident in inlets or casings of large turbines where the stream lines are inevitably curved.

This new invention promises the same efficiency in turbulent natural streams; there the angular pulsation introduces a distinctive error, because velocities fluctuate in magnitude and direction, and projections of these velocities are to be integrated. The component runner is particularly significant in large and shallow rivers with complex cross-section and relatively slow flow, distorted by piers, isles, stones, weeds, ice jams, etc.

KOLUPAILA, S. 1960. Early history of hydrometry in the United States. Proc. ASCE, Vol. 86, HY1, pp. 1-51.

Abstract: The history of hydrometry (stream flow measurements) in the United States is presented.

KOLUPAILA, S. 1961. Bibliography of hydrometry. University of Notre Dame Press, Notre Dame, Indiana, 975 p.

Abstract: This outstanding bibliography includes 7370 titles of papers in 38 languages, by 4500 authors.

KOLUPAILA, S. 1964. Discussion of accuracy of current meter measurements. American Society of Civil Engineers, Hydraulics Division Journal, Vol. 90, #HY 1, Jan., pp. 352-355.

Abstract: The paper contains results of series of special investigations : (1) rating of a current meter in two towing basins; (2) discharge measurement by current meters of cup and screw type; (3) observation of flow pulsation at 23 hydrometric stations; (4) data on velocity distribution in 100 cross sections; and (5) significance of the number of verticals across a river. The authors presneted only final averages, but the amount of collected important material deserves more exetensive publication.

KOVACS, G. 1976. Methods for the computation, space interpolation and mapping of river run-off. Water Balance of Europe, Technical reports in hydrology, Bulgaria Workshop, Oct., pp. 31-32.

Abstract: World Meteorological Organization (WMO) definition of the word accuracy.

KRAJEWSKI, W.F. and KRAJEWSKI, K.L. 1989. Real-time quality control of streamflow data - a simulation study. Water Resources Bulletin, AWRA, Vol. 25, No. 2, pp. 391-399.

Abstract: The problem of real-time quality control of streamflow data is addressed. Five methods are investigated via a Monte-Carlo simulation. experiment based on streamflow data from Bird Creek basin in Oklahoma. The five methods include three deterministic approaches and two statistical approaches. The relative performance of the investigated methods is evaluated under hypothesized random mechanism generating isolated outliers. The detrministic method based on streamflow gradient analysis and the statistical method based on forecast residual analysis perform best in detecting such outliers.

KULIN, G. 1977. Some error sources in Price and Pigmy current meter traverses. National Bureau of Standards Special Publication 484, Proceedings of the Symposium on Flow in Open Channels and Closed Conduits, Gaithersburg, MD, February 23-35.

Abstract: The author reports that errors of several percent are possible when measuring flows with badly skewed profiles if the sum of the horizontal gradients across the measuring cross-section is not zero (Engel, 1983).

LAENEN, A. 1985. Acoustic velocity meters. U.S. Geological Survey, Techniques of Water-Resources Investigations, Chapter A17, Book 3, 38 p.

Abstract: This report provides methods for computing the effect of various conditions on the accuracy of a record obtained from a acoustive velocity meter.

LAENEN, A., and SMITH, W. 1982. Acoustic systems for the measurement of streamflow. U.S. Geological Survey, Open-File Report 82-329, 45 p.

Abstract: The purpose of this report is to consolidate information on acoustic velocity meters.

LAMBIE, J.C. 1966. The rating and behaviour of a group of current meters. ICE (Institution of Civil Engineers-Scottish Hydrological Group), Glasgow, Unpublished Report, 1966.

Abstract: Not available.

LAU, Y.L. 1982. Velocity distributions under floating covers. Canadian Journal of Civil Engineering, Vol. 9, No. 1, pp. 76-83.

Abstract: The k-e turbulence model has been used to calculate the velocity distributions for a large number of channel flows with different top and bottom boundary roughnesses. The resulting distributions are used to review the standard procedures for stream gauging of ice-covered flows. It is found that the average of the velocities at 2/10 and 8/10 of the depth is indeed very nearly equal to the overall mean velocity. Examination of the velocity profiles shows that the profiles deviate from the logarithmic distribution for about 40% of the flow depth. Other flow properties, such as the location of the maximum velocity and the mean velocities in the top and bottom layers, are also examined.

LAURENT, J. 1927. Mesures à prendre pour augmenter la précision des jaugeages des cours d'eau. Union Géodésique et Géophysique Internationale, Assemblée Plénière de Prague, Sep., Pithiviers.

Abstract: Not available.

LAWSON, D.E., et al. 1986. Morphology, hydraulics and sediment transport of an ice-covered river - Field techniques and initial data. U.S. Army Corps of Engineers, Cold Regions Research & Engineering Laboratory (CREEL), Report 86-11, 37 p.

Abstract: This initial study of the ice-covered Tanana River, near Fairbanks, Alaska, attempted to 1) establish field methods for systematic and repetitive quantitative analyses of an ice-covered river's regime, 2) evaluate the instruments and equipment for sampling, and 3) obtain the initial data of a long-term study of ice cover effects on the morphology, hydraulics and sediment transport of a braided river. ... Preliminary results indicate that water flow below the ice cover occurs in distinct channels that are generally separated from each other by stagnant deposits of frazil ice.

LEAF, C.F. 1970. Precision and accuracy in stream gaging. IHD Experimental Basin Workshop, Kananaskis Research Forest, Alberta, Canada, Sep., 19 p.

Abstract: Partial literature review on accuracy of streamflow measurement.

LEUPOLD & STEVENS, INC. 1978. Errors in float operated devices (Chapter 8). Stevens water resources data book. Stevens Water resources products, Leupold & Stevens , Inc., 3rd edition, Apr., pp. 73-90.

Abstract: Describes errors involved in the records made by float operated recorders, i.e. float lag; line shift; submergence of counterweight; temperature and saturation; and humidity.

LIDDELL, W.A. 1927. Stream gaging. McGraw Hill Book Co., New York, First edition, p. 9 and pp. 136-150.

Abstract: Discusses experimental work done in the United States, the effects of turbulent flow, and the behavior of cup-shaped and screw-shaped meters when subjected to various tests.

LINSLEY, R.K. and FRANZINI, J.B. Water Resources Engineering. McGraw-Hill Book Company, 3rd Edition, p. 22.

Abstract: Gives the adjective classification of accuracy of streamflow data as used by the U.S. Geological Survey.

LOWELL, F.C., and HIRSCHFELD, F. 1979. Acoustic flowmeters for pipelines. Mechanical Engineering, Vol. 101, No. 10, October, pp. 29-35.

Abstract: The sources of error that have to be taken into account when acoustic flowmeters are employed are summarized, discussed and analysed.

MACKENZIE, A. 1884. Report on current meter observations in the

Mississippi River, near Burlington, Iowa, during the month of Ocotober, 1879. Washington, Engineer Department, United States Army.

Abstract: Not available.

MAIN ADMINISTRATION OF THE HYDROMETEOROLOGICAL SERVICE 1975. Water discharge measurements. Manual for hydrometeorological area centers and stations: Chapter 9. Council Ministers of the U.S.S.R., pp. 103-146.

Abstract: Official manuals on stream gauging for the U.S.S.R.

MANLEY, R. 1977. Improving the accuracy of flow measurement at open channel sites. Water Services, Resources, Supply, Sewage & Effluent, Vol. 81, No. 982, Dec., pp. 741-744.

Abstract: The paper present a technique (rating curve equation) to improve the accuracy of streamflow record of a number of gauging sites in the Severn-Trent area.

MATALAS, N.C., and CONOVER, W.J. 1965. Derivation of the velocity profile from a statistical model of turbulence. Water Resources Research, Vol. 1, No. 2, pp. 235-261.

Abstract: A statistical model of turbulence for tw-dimensional uniform flow in open channels is developed, and this model is used to derive the vertical velocity profile. This profile is defined by a three-parameter hyperbolic function, with two parameters reflecting the effect of bed roughness and fluid viscosity on the shape of the profile. The third parameter is the mean velocity in the vertical. The hyperbolic function is fitted to velocity data for water in natural channels, a laboratory flume, and air in a wind tunnel. A brief comparison of the hyperbolic function with the logarithmic function is given.

MATTHES, G.H. 1927. Price Current Meter: serviceability vs. scientific design. Engineering News-Record, Vol. 98, No. 3, p. 126.

Abstract: Letter stresses the fact that the hydrographers of the U.S. Geological Survey during the early existence of the Bureau found the Price meter to be more serviceable than other types.

MAXWELL, W.H.C. 1968. Discussion: The accuracy of calibration of model gauging structures by J.R.D. Francis & J.B. Miller. The Institution of Civil Engineers, Proceedings, Vol. 40, July, pp. 397-402.

Abstract:

MOFFATT, R.L. 1978-79. Comparison of discharge measurements made with the Ott cosine and Price AA current meters. Water Resources Division Bulletin, U.S. Geological Survey, Oct.-Dec. 1978 Jan.-June 1979, pp. 32-34.

Abstract: To determine the effects from horizontal and vertical components of velocity under certain conditions (high velocities, deep cross-section, and turbulent flow) a comparison study was made using the Ott cosine and Price AA standard-rated current meters.

MOODY, L.F. 1914-15. The measurement of the velocity of flowing water. Proceedings, Engrs.' Society of Western Pennsylvania, Vol. 30, pp. 280-323.

Abstract: Paper devoted mostly to Pitot tube, but on pages 320-322, the results of comparative ratings of a Pitot tube, Price meter, and Fteley and Stearns meter are compared with the meters turned through various horizontal angles up to 70 degrees. Also gives results of an experimental screw meter with good characteristics. Concludes cup meter over-registers and registers velocities from right differently from those from left; screw meter under-registers.

MOODY, W.J. 1982. Errors in velocity measurement made with a 622AA Price Current Meter from a boat. National Water Research Institute, Hydraulics Research Division, Technical Note, Report No. 82-28, Feb., 4 p.

Abstract: The purpose of the paper were to 1) investigate the magnitude and location of flow disturbance in the immediate proximity of an inflated boat, and 2) assess the influence of the flow disturbance on current meter velocity observations.

MOREL, H. 1966. Sur les courbes de réponse des moulinets, aux faibles vitesses et en canal d'étalonnage. International Current Meter Group, ICMG Report No. 19, 1966, 9 p.

Abstract: The torque of the propeller is expressed in analytical form and compared to expressions of the breaking torques. Analytical expressions for the speed of rotation 'n' and the constant term 'a' are then deducted. According to the type of boundary layer on the blades, the torque expression changes and so does the value of 'a' in relation to 'n'.

The shape of the curves that can be predicted according to this analysis fits well with observed curves and makes some unusual results understandable.

MORTON, G.H. 1983. Peace River and Slave River Studies - Artic Rivers Work Group. Water Resources Branch, Environment Canada, Calgary (Alberta), Dec., 56 p.

Abstract: To gain a better understanding of the factors affecting winter streamflow measurements, the accuracy of discharge computations, and to standardize procedures and improve field and office methods and equipment, the Artic Rivers Work Group was established.

This report addresses the studies carried out by the Water Survey of Canada, Calgary District, on the Peace River at Peace Point and Slave River at Fitzgerald during the winters of 1965-66 and 1966-67. Studies carried out on other rivers which have significance to the study but which were not carried out under the direction of the Artic Rivers Work Group, are also analyzed.

Discharge measurements under ice cover were carried out by the standard method of 0.2 and 0.8 velocity observations using a Price current meter. Tests were carried out to ascertain if fluorometric dyes could be used to determine the discharge during periods of freeze-up and break-up. Studies were made on velocity distribution under ice cover and relating a point velocity to the mean river velocity. During the winter of 1966-67 simultaneous measurements were carried out on a section free of frazil ice and a section with considerable frazil ice on the Peace River at Peace Point.

The simultaneous discharge measurements on the Peace River at Peace Point gave results of up to 18 per cent less discharge being measured at the section influenced by frazil ice than measured at the section free of frazil ice. The effective gauge height method of computing discharge under ice cover was determined to be the best overall method for the type of stream studied. Also, the normal backwater, adjusted discharge and interpolated discharge methods all had merit for both streams. A method developed employing a two-part winter rating curve was the least accurate of the methods investigated.

Recommendations are made to continue taking discharge measurements on a monthly basis during the winter period and compute the dischrage using the effective gauge height method; conduct further studies on the flow through frazil ice; use of an Ott current meter where flowing frazil ice is encountered; and conduct simultaneous measurements under ice cover using the Price, Ott and Vane current meters.

MOSS, M.E., and GILROY, E.J. 1980. Cost effect stream-gaging strategies for the Lower Colorado River Basin; the Blythe Field Office Operations. U.S. Geological Survey, Open-File Report 80-1048, Dec., 112 p.

Abstract: This report describes the theoretical developments and illustrates the applications of techniques that recently have been assembled to analyze the cost-effectiveness of federally funded stream-gaging activities.

The cost-effectiveness of the current operation of 19 stream gages of the hydrologic network that supports the Colorado River compact and subsequent adjudications is found to be relatively close to the theoretical limits when the total uncertainty in annual-mean-discharge estimates is considered.

MURPHY, E.C. 1901. Tests to determine accuracy of discharge measurements of New York State Canals and Feeders. U.S. Geological Survey, Water Supply and Irrigation Paper No. 47, pp. 18-29.

Abstract: Describes comparitive measurements by rods and meter on New York State canals and also experiments made in 1900 with rods, small Price meters, and weir at Cornell University Hydraulics Laboratory.

MURPHY, E.C. 1902a. Current meter and weir discharge comparisons. American Society of Civil Engineers, Transactions, Paper No. 912, Vol. XLVII, April, pp. 370-391.

Abstract: Describes fifty discharge measurements with Haskell and Price meters in testing canal at Cornell University with agreement between meters closer than with weir, but in every case variations were less than 4.8%; twenty of the tests showed differences less than 1 per cent. In discussions: C.H. Miller (pp. 379-380); J.B. Lippincott (pp. 383-387); and E.E. Haskell (pp. 387-388).

MURPHY, E.C. 1902b. Accuracy of stream measurements. U.S. Geological Survey, Water-Supply and Irrigation Paper No. 64, pp. 11-95.
Abstract: Discusses difficulties, and instruments used in measuring

stream velocities, giving history of current meter, describing various types, and stating their advantages and disadvantages. Discusses the effect of pulsation of velocities of moving water on measurements. Extracts results of Ellis, Marr, Henry, Gordon, New York State Canal Survey, Fteley and Stearns, comparing float measurements with weir. Describes in detail his own experiments at Cornell University and Chevy Chase, Md., in 1900-1901. Compares measurements with Price, Haskell, and Fteley meters with weir measurements. Concludes that small Price current meters under ideal conditions can measure discharge within 1 or 2%; is more accurate when held rigidly on a rod rotating faster under this condition; will under-register current meter velocities closer to the water surface than 0.5 ft., etc. Some experiments under abnormal conditions showed results departing as much as 40% from the weir discharge. Haskell meter registered velocities near the surface more accurately than Price meter, not as accurate in low velocities.

MURPHY, E.C. 1904. Accuracy of stream measurements. U.S. Geological Survey, Water-Supply and Irrigation Paper No. 95, Second (Enlarged Edition), 169 p.

Abstract: Revision of Water Supply Paper No. 64 with additional experimental data comparing Price and Fteley meters in shallow streams of varying roughness with weir measurements. The part giving the data on vertical velocity curves has been augmented by additional data.

MURPHY, E.C., et al. 1904. Hydrographic Manual of the United States Geological Survey. U.S. Geological Survey, Water Supply and Irrigation Paper No. 94, pp. 19-31.

Abstract: Discusses use of meters in obtaining discharge measurements, and describes Price meters in detail.

MUSZKALAY, L. 1970. Relation entre la pulsation et la précision du jaugeage par moulinets. International Symposium on Hydrometry, Koblenz, Sept., IAHS Publ. No. 99, pp. 132-141.

Abstract: Based on measurements carried out in a square section of the channel, it has been shown that behind the stilling grid the pulsation of the water movement decreases hyperbolically with the distance. Simultaneously, the measured discharge and the relative error of the discharge measurement decreases approximately linearly with the distance. The measured discharge increases parabolically with the average variance and with the relative variance. The relative error of the discharge measurement is proportional to the second power of variance and relative variance, that is, the measurement error is related in linear proportion to the turbulent energy. With 4 per cent average relative variance, the caused error reaches, under given conditions, 3 per cent. Therefore the measuring places must be selected so that the relative variance does not exceed 4 per cent.

MUSZKALAY, L. 1979. Three dimensional turbulence in streams and its role in mixing. Hydraulic Engineering in Water Resources Development and Management Proceedings, International Association for Hydraulic Research, 1st Congress, Cagliari, Italia, Paper BA7, pp. 154-156.

Abstract: Results of current measurements extending to three dimensions and performed in natural streams of different magnitude have shown the transverse components of the velocity vector, the spatial and temporal variations thereof, to play an important part in the mixing process of substances entering the streams.

The temporal variations in the components of the velocity vector may be random in character (pulsating movement of variable frequency), periodic (regularly variable movement of very low frequency), or a resultant combination of the two.

MUSZKALAY, L., and STAROSOLSZKY, O. 1981. Intercomparison of principal hydrometric instruments. International Association for Hydraulic Research, XIX IAHR Congress, New Delhi, India, Proc. Subject A, Volume II, pp. 139-153.

<u>Abstract</u>: The Commission for Hydrology of the WMO launched an international project for the intercomparison of the principal hydrometric instruments. In the first phase 48 water level recorder types and 28 current meter types were tested by eight countries according to common specifications. The results related to sensitivity, linearity, hysteresis and repeatability of water level recorders and rating curve characteristics, sensitivity to oblique flow, effect of friction, size of channel and pulsation were evaluated.

NAGLER, F.A. 1935. Use of current meters for precise measurement of flow. Transactions of the Emerican Society of Mechanical Engineers, Vol. 57, HYD-57-1, pp. 59-67.

<u>Abstract</u>: In this paper the author deals with the art of flow determination by current meter, compares the accuracy of this method with that of other means of water measurement, and draws attention to a number of precautions which should be observed in order to minimize error. He compares also the characteristics of cup and screw meters, discusses meter ratings, the effects of turbulence and angularity of flow, describes the channel sections best suited to accurate gaging, and covers in some detail the technique of flow determination under varying conditions in the field.

NEWELL, F.H. 1901. Methods of stream measurements. USGS Water-Supply and Irrigation Papers 56, 51 p.

<u>Abstract</u>: Velocity measurements using current meters are discussed, including unit meausrements, multiple measurements, and integration method.

NEWMAN, J.D. 1976. Electronic methods of river gauging. Systems Technology, December, No. 25, pp. 24-31.

<u>Abstract</u>: This paper describes two electronic techniques (electromagnetic and ultrasonic methods) which have been developed to overcome some of the limitations of traditional methods of continuous flow measurement in open channels.

NEWMAN, J.D. 1982. Adavances in gauging open channels and rivers using ultrasonic and electromagnetic methods. International Symposium on Hydrometeorology, AWRA, pp. 15-26.

<u>Abstract</u>: This paper describes two electronic methods of flow measurement

(electromagnetic and ultrasonic techniques) which have been developed to overcome some of the limitations of traditional methods of continuous flow measurement.

O'BRIEN, M.P., and FOLSOM, R.G. 1948. Notes on the design of current meters. Transactions American Geophysical Union, vol. 29, No. 2, April, pp. 243-250.

Abstract: A perfect current meter is defined and a general discussion of departures of real current meters from the ideal is presented. The Price current meter has been shown to overregister due to turbulence and angularity of the fluid stream. The propeller type of meter shows less sensitivity due to flow stream characteristics when it is properly designed. The effects on accuracy of turbulence, Reynolds number, and meter inertia are included. Methods of rating current meter are discussed with some indication of the deficiencies of present standard procedures. The work results in a series of recommendations and design specifications for an improved propeller type of current meter.

OTT, L.A. 1935. Observations on the use of current meters for precise flow measurement. Transactions of the American Society of Mechanical Engineers, Vol. 57, HYD-57-6, pp. 227-228.

Abstract: This paper discusses the circumstances surrounding the development of current meters in Central Europe, and the application of these meters in the testing of large water-power plants. Among the important steps presented in the application of these instruments are, the use in parallel of a plurality of meters, the adoption of simultaneous electric recording by a chronograph, the consequent adoption of the municipality of meter types, and standardization of practice.

Reference is made to the practice of attempting to avoid the necessity for properly cconverting unfavorable measuring sections by using two types of meter having different degrees of error in resolving oblique flow. It is pointed out that precise rating of meters with duplication of the exact supporting means used in field tests. Standard values for the degree of accuracy of the instruments used in Germany are given, and the accuracy actually obtainable in practice is discussed in the light of comparative tests which have been made.

PARDOE, W.S. 1916. Methods of stream gaging. Eng. News., Vol. 75, No. 19, May 11, p. 889.

Abstract: The author states that (1) the one point method (0.6 depth) is only very approximate, (2) the two-point method (0.2 and 0.8 depth) is vey nearly theoretically correct and gives correct results, (3) the three-point method (0.2, 0.6, and 0.8 depth) is not as accurate as the two-point method.

PAULE, D.J. 1965. Accuracy in instrumental measurement and calibration - Part 1. Australian Journal of Instrument Technology, Nov., pp. 122-128.

Abstract: This paper evaluates the forms of error and their occurrence in instruments and their environment and, in establishing a rationalised basis for the combination of the separate sums for systematic and random errors, characterises the sum by a multiple of the standard deviation.

A discussion of dispersion indices concludes that "probable error" is often wrongly quoted. The practice of metering with pairs of like instruments to achieve a better result than with one is shown to be fallacious. Formulae are given for the summation of errors.

PAULE, D.J. 1966. Accuracy in instrumental measurement and calculation - Part 2. Australian Journal of Instrument Technology, Feb., pp. 5-12.

Abstract: This paper evaluates the forms of error and their occurrence in instruments and their environment and, in establishing a rationalised basis for the combination of the separate sums for systematic and random errors, characterises the sum by a multiple of the standard deviation. A discussion of dispersion indices concludes that "probable error" is often wrongly quoted. The practice of metering with pairs of like instruments to achieve a better result than with one is shown to be fallacious. Formulae are given for the summation of errors.

PELLETIER, P.M. 1989. Uncertainties in streamflow measurement under winter ice conditions - A case study: the red River at Emerson, Manitoba, Canada. Water Resources Research, Vol. 25, No. 8, pp. 1857-1867.

Abstract: Summary of the report published by the same author in 1988, with some wider conclusions.

PELLETIER, P.M. 1988a. Techniques used by Water Survey of Canada for measurement and computation of streamflow under ice conditions. Proceedings of the 5th Workshop on Hydraulics of River Ice/Ice Jams, June 22-24, Winnipeg, pp. 255-276.

Abstract: In this paper, the field methods and instruments, and computational methods used by Water Survey of Canada for streamflow measurement and computation under ice conditions are reviewed. Factors affecting the accuracy of discharge measurements performed under ice conditions are discussed. Newly developed instruments for use under ice conditions are described and their advantages discussed. A comparison between techniques used by Canada and other northern countries is also given. Areas of research and investigations for improvement in the overall quality of data are suggested.

PELLETIER, P.M. 1988b. Uncertainties in the determination of river discharge: a literature review. Canadian Journal of Civil Engineering, Vol. 15, No. 5, pp. 834-850.

Abstract: This paper presents the results of a literature review of more than 140 publications on the uncertainties in the determination of river discharge. The uncertainties in a single determination of discharge, which includes uncertainties in sampling the cross-sectional area and the mean velocity in time and in space, and in the current meter, are emphasized. The objectives of the literature review were to determine all the possible sources of uncertainties in a current meter measurement, to quantify these uncertainties based on past investigations, and to determine if additional research was required to improve the overall accuracy of hydrometric data in Canada. Because of lack of available information on the performance of the current meter in combination with the velocity-area method under conditions of small streams or low velocities, research is required. Research is also required to assess the uncertainties in the determination of discharge under ice conditions.

PELLETIER, P.M. 1988c. An investigation of the measurement of streamflow under winter conditions: International hydrometric gauging station on the Red River at Emerson, Manitoba, Canada. Environment Canada, Water Resources Branch, Report no. IWD-WNR(W)-WRB-HI-88-1, Winnipeg, 166p.

Abstract: Computed streamflows on the Red River at Drayton in North Dakota, U.S.A. have been found to be generally higher, under winter conditions, than computed streamflows on the Red River at Emerson in Manitoba, Canada. The station at Drayton is located 85 km upstream of Emerson. These differences have been noted through the international joint review and approval of the Red River at Emerson International Gauging Station streamflow record. Moreover, historically the U.S. Geological Survey measures higher streamflows under ice conditions than Water Survey of Canada, on the Red River at Emerson. The difference between USGS and WSC discharge measurements under ice conditions is generally between +10 to 20%.

To explain these differences, field and laboratory experiments were conducted in 1986, which included an international field metering program at Drayton and at Emerson; rating of current meters and suspension equipment at National Calibration Services in Canada, and in the United States; and testing of current meters in flowing water.

The techniques used by WSC and USGS for measurements under ice cover were reviewed and no significant differences noted except in the metering equipment. The USGS uses a vane-type meter on rod suspension compared to a cup-type meter on rod or cable suspension for WSC.

Through the analysis of the field and calibration data it was determined that significant differences exists between a current meter rated on rod and on cable suspension. This suspension effect being responsible for the large differences between USGS and WSC.

Small differences in depth measurements were observed between USGS and WSC, and found to be reducible by change in practices of technicians of both agencies. Differences in current meter rating procedures between United States and Canada were noted, and found to be small for velocities higher than 0.3 m/s, but to increase rapidly as the velocities decrease below 0.3 m/s. The vane-type meter was found to give consistently higher velocity than cup-type meter, even under controlled conditions, i.e. one meter flume. The cup-type meter, based on limited flume experiments, was found to be more accurate than the vane-type.

Changes in discharge measurements techniques under ice conditions are also recommended, including the sampling of vertical velocity curves, and an increased time of exposure for current meter observations. To improve the overall quality of streamflow records for winter ice period several investigations are recommended.

PENTLAND, R.L. 1965. How long should you run your meter? Water Ways, Water Resources Branch, Department of Northern Affairs and National Resources, no. 5, pp. 13-15.

Abstract: A method to determine the optimum duration of velocity observations is given.

PETERS, F.H. 1912. The current meter rating station at the Irrigation Office, Dept. of Interior, Alberta. Trans. of the Canadian Society for

Civil Engineers, 26, Paper No. 329, pp. 267-277.

Abstract: The main features of the current meter rating stattion in Calgary are given. Some statements on current meters are made, e.g. experience in rating nine current meters has indicated that after considerable use, the meters runs faster. Standard rating (as given by Gurley) versus individual rating are also discussed.

PETERSON, E.R. 1969. Instrumentation and observation techniques. Proceedings of Hydrology Symposium No. 7, Victoria, B.C., May, pp. 59-80.

Abstract: This paper briefly summarizes the varoius types of equipment and techniques presently employed in the data accumulation process, what is being developed and some of the possibilities and requirements for the future.

PETTERSSON, L.E., and SKOFTELAND, E. 1986. Winter discharge measurements and the routine processing of winter stage and discharge records in Norway. Proceedings of Sixth International Northen Reasearch Basins Symposium - Workshop, "Field Measurements under winter conditions", Michigan Technological University, Houghton, Michigan, Jan. 26-30, pp. 11-23.

Abstract: In Norway, about 60 per cent of the 700 stream-gauging stations are affected by backwater every winter due to ice at the control, either permanently or sporadically. The backwater effect has a marked regional variation closely related to the variation of climate. To obtain discharge records for the winter season, one winter discharge measurement is taken at as many of these stations as possible. This frequency is not satisfactory from a hydrometric point of view.

The special problems connected to winter discharge measurements by current meter from an ice-cover often make these measurements less reliable than measurements under open-water conditions. The ice conditions may in extreme cases make it impossible to carry out a measurement.

In Norway, the so-called "backwater method" is used to obtain records of stage and discharge for stations affected by ice. This graphical method, based on daily data, requires values of the observed gauge height, a direct measurement of discharge, the open-water rating curve, and available information on ice conditions, air temperature and precipitation. A graphical comparison with hydrographs unaffected by ice from nearby stations is extensively used when adjusting for the backwater effect.

The consequences of the considerable uncertainties in winter flow records depend on the application of data. Daily values may in some cases have a relative error of more than 100 per cent, but the effect on the computed annual mean discharge may be negligible, due to the fact that winter is the low-water season in most areas.

PIERCE, C.H. 1941. Investigations of methods and equipment used in stream gaging. Part 1. Performance of current meters in water of shallow depth. United States Geological Survey, Water-Supply Paper 868-A, 35 p.

Abstract: The investigation of the performance of current meters in measuring the velocity of water in shallow depths, recently made by Geological Survey at the National Hydraulic Laboratory, National Bureau

of Standards, Washington, D.C., was arranged primarily for the purpose of determining coefficients to be applied as correction factors to velocities obtained by current meters when used under the adverse conditions of very shallow water. The scope of the investigation covered measurements of discharge in the 12-foot flume with standard-size cuurent meters and with cup-type pygmy current meters that have a bucket wheel 2 inches in diameter. The investigation was limited to water
between depth of 0.2 foot and a maximum depth of 1.5 feet. The velocity ranged from 0.1 foot to 1.5 feet per second. Coefficients for the 0.6 depth method and for the 0.2- and 0.8-depth method, where standard-size current meters were used, were determined for the entire range of velocities. For the 0.5-depth method where standard-size current meters were used for all methods where pygmy meters were used coefficients were determined for the entire range of velocities except for those below 0.2 foot per second. The depths of water in which measurements were made by the various methods are shown by the depths for which coefficients are given in the diagrams.

The depth of water in the flume was regulated by needle gates a short distance below the place of measurement, the needle gates being adjusted so as to obtain the desired depth and velocity for a given discharge. An 8-inch or a 4-inch venturi meter calibrated in place was used for determining discharges less than 3.5 second-feet. Discharges greater than 3.5 second-feet were measured by a sharp crested weir calibrated in place. The discharge as measured by the current meter was compared with the weir or venturi-meter discharge measurement to obtain the correction factor for the current meter measurement. Conditions of beds of smooth concrete, 3/4-inch gravel, and coarse gravel were investigated. The coarse gravel was run-of-bank gravel, all retained on a 1-inch screen but passing through a 5-inch screen.

Other phases of the investigation, such as studies of pulsations, vertical velocity curves, distribution of velocities near the side walls of the flume, and performance of current meters when used near the water surface and near the flume walls, were incidental to the main purpose of the investigation. The information obtained from these studies was used in analysing and interpreting the results of the discharge measurements.

PRICE, W.G. 1895. A new current meter and a new method of rating current meters. Engineering News, Vol. XXXIII, Jan. 10, p. 27.

Abstract: Describes Price acoustic current meter and method of rating skiff in still pond.

POTTER, K.W., and WALKER, J.F. 1981. A model of discontinuous measurement error and its effect on the probability distribution of flood discharge measurements. Water Resources Research, American Geophysical Union, Vol. 17, No. 5, Oct., pp. 1505-1509.

Abstract: Above a given threshold an indirect method is usually used to estimate flood discharges. This results in a significant increase in the standard deviation of the measurement error, a phenomenon which the authors have termed discontinuous measurement error. An error model reveals that the coefficients of variation, skewness, and kurtosis of the distribution of the measured flood discharges are significantly higher that the corresponding coefficients of the parent flood distribution. This bias has important implications with regard to flood frequency analysis.

PROCHAZKA, J. 1960. Notes on the question of accuracy of discharge measurement with a current meter. General Assembly of Helsinki, IAHS Publ. No. 53, Aug., pp. 498-509.

Abstract: In the determination of water discharges in open channel streams it is necessary to know the accuracy and the reliability of the value that has been found.

It is supposed that in the case of point velocity measurement by means of current meter mounted on a rod or freely suspended in water or in the case of graphical or numerical evaluation of water discharges the final result is influenced by a whole series of random and mutually dependent and independent factors.

These are for example: the construction of the current meter, the influence of the water and turbidity of water, the inaccurate measurements of time for selected number of signals (revolutions) of the current meter, the turbulent pulsation of the velocity on the individual points of the cross-section, the deviation of the calculated mean vertical velocity from the actual one, the deviation of the calculated mean cross-section velocity from the actual one, inaccurate sounding (the profile depth measurement), the inaccurate profile width measurement at water level, the deviation of the computed cross-section area from the actual one - and other factors.

On the basis of experimental discharge measurements in the streams of Slovakia the standard deviations (variation coefficients) of random factors from the actual (i.e. expected) values are evaluated.

The final expression for the accuracy of hydrometering (in the selected reliability) depends on the basic parameters such as the number of measured verticals in the cross-section, the number of sounding verticals, number of points on one measured vertical, the number of signal observed (number of revolutions) of the current meter in each point, the mean cross-section velocity, the average depth of the cross-section, the profile width on the water surface, the type of current meter, etc.

For the computation simplification and clarifying the influence of individual values on the accuracy of the resulting value, the final expression is plotted by a combined nomogramm.

The solution enables the comparison and evaluation of the discharge measurements performed in various streams cross-sections of the region under observation. It forms the basis for the establishment of directions for the carrying out of the hydrometering with selected tolerance of the discharge value in advance.

QUINN, F.H. 1979. Relative accuracy of connecting channel discharge data with application to Great Lakes Studies. Journal of Great Lakes Research, Vol. 5, No. 1, pp. 73-77.

Abstract: The flows in the Great Lakes connecting channels are a major component in the water balance of the Great Lakes Basin. The increased emphasis on Great Lakes water quality and quantity requires an assessment of the accuracy of both measured and computed connnecting channel discharge data. In this study, the standard error of typical discharge measurements was found to be approximately 3 to 5 percent, depending upon the number of panels used in the cross-section. Measurement sets were found to have a practical limit of about 25 measurements. The standard error of a set of measurements was found to be on the order of 1 percent. The procedure used to compute the published flows of the Niagara River was

found to have an apparent bias of about 2 percent on the high side. It is recommnended that the published Niagara River flows be adjusted prior to use the detailed water balance studies.

RANTZ, S.E. 1982a. Measurement and computation of streamflow: Volume 1. Measurement of stage and discharge. U.S. Department of the Interior, Geological Survey Water-Supply Paper 2175, pp. 179-183

Abstract: A summary of factors affecting the accuracy of a discharge measurement are presented (re. Corbett), and the accuracy of a discharge measurement made under average conditions is outlined. The assumptions made by Carter and Anderson (1963) are outlined.

RANTZ, S.E. 1982b. Measurement and computation of streamflow: Volume 2. Computation of discharge. U.S. Department of the Interior, Geological Survey Water-Supply Paper 2175, pp. 346-348.

Abstract: Criteria for a check discharge measurement is outlined, i.e. if discharge measurement is outside ± 5% of the rating curve, an additional measurement is required.

REID, I.A., and PENTLAND, R.L. 1964. The duration of velocity observations. Water Ways, Water Resources Branch, Department of Northen Affairs and National Resources, No. 1, Mar., pp. 6-9.

Abstract: Velocity measurements for periods varying from one to four minutes were made in the Ottawa River in 1963. Standard deviation of velocity observation are computed, and it is found that if measurement of extreme accuracy are required (re. Ottawa River), a period of two minutes should be used.

RODDA, J.C. 1976. Facets of Hydrology. John Wiley & Sons, in Chapter 5 "New methods of river gauging" by R.W. Herschy, pp. 119-161.

Abstract: The moving boat, ultrasonic, and electromagnetic methods are discussed, and their relative accuracy determined.

ROBSON, A.D. 1954. The effect of water temperature upon the calibration of a current meter. Transcations Americal Geophysical Union, Vol. 35, pp. 647-648.

Abstract: Four ratings of a current meter made over a wide range of water temperatures gave no indication of change in calibration within the limits of accuracy of the ordinary current meter rating table.

ROSENBERG, H.B. 1966. Evaluation of streamflow detreminations under an ice cover. Workshop Seminar on Ice Formation and Breakup in Lakes and Rivers, Nov., 15 p.

Abstract: MAny factors must be considered in evaluating the accuracy of streamflow records. This is especially true if a continuous record is required in which winter discharge have a prominent place. Before progressing to the more difficult part of the problem, i.e. the ice period, I would like to spend a few minutes discussing some of the factors we must consider in evaluating discharges under open water conditions. Discharges under ice conditions them will be superimposed upon the open channel conditions giving us a better appreciation of accuracy of our winter records.

ROSENBERG, H.B., and PENTLAND, R.L. 1983. Accuracy of winter streamflow records. Environment Canada, Inland Waters Directorate, Reprint (originally presented to the Eastern Snow Conference, 1966), pp. 51-72.

Abstract: The accuracy of winter streamflow records is being examined in a Canada-wide research program. This paper presents interim results of the program; reviews methods of calculating discharge under ice cover; and presents an analysis of various factors contributing to probable error in winter streamflow data. Suggested methods are derived for improving accuracy.

ROTHACHER, J., and MINER, N. 1965. Accuracy of measurement of runoff from experimental watersheds. Forest Hydrology, Proceedings of a National Science Foundation Advanced Science Seminar, Sep., pp. 705-713.

Abstract: Errors in field measurement of streamflow from experimental watersheds vary with (1) the design of the control section, (2) measurement of flowing water (area times velocity) to obtain rating tables and formulas, and (3) with the type and installation of the recorder. Errors in compilation of data are results of conversion from a record (trace on a chart or punched tape) of depth of water in a weir to volume of flowing water for a period of time. Charts can be read both manually and mechanically with errors of only a few percent. Automated equipment coupled with computers eliminates human errors and minimizes recording and conversion errors. Minimum error obtainable under the best conditions is probably about 3 to 5 percent.

ROUSE, H. 1959. Engineering Hydraulics. Proceedings of the Fourth Hydraulics Conference, Iowa Institute of Hydraulic Research, June 12-15, pp. 222-225.

Abstract: Discusses accuracy of velocity integrations using the 1- and 2-point velocity method.

RUMPF, C.P. 1914. An investigation of the use and rating of the current meter. Engineering News, Vol. 71, No. 20, May 14, pp. 1083-1084.

Abstract: Gives results of tests on cup and screw meters holding meters at various angles with the current.

RUMYANTSEV, V.A. 1981. Errors of water-discharge measurement by the "velocity-area" method. Soviet Meteorology and Hydrology, Allerton Press, pp. 70-77.

Abstract: Expressions that can be used to establish the systematic errors and accidental-error variances of determination of unit water discharge volumes and measurement of total water discharge by the "velocity-area" method are presented.

RUSINOV, M.I. UNDATED. Measurements under difficult conditions. pp. 260-274b.

Abstract: In the report the methods of hydrometric measurements under difficult conditions used at present are presented (in artic and tropical climates, during winter period, in case of unstable channel, unsteady motion, etc.).

SAVINI, J., and BODHAINE, G.L. 1971. Analysis of current meter data at Columbia River gaging stations, Washington and Oregon. U.S. Geological Survey, Water-Supply Paper 1869-F, 59 p.

Abstract: The U.S. Geological Survey developed equipment to measure stream velocity simultaneously with 10 current meters arranged in a vertical and to measure velocity closer to the streambed than attainable with conventional equipment.

With the 10 current meters, synchronous velocities were recorded for a period of 66 minutes at 10 different depths in one vertical of one gaging-station cross-section. In addition, with a current meter installed on a special bracket to allow measurements to 0.5 foot above streambed, data were obtained at two to four verticals in four gaging-station cross-sections.

The standard deviation, expressed as a percentage of the mean velocity, ranged from about 4 per cent near the surface to 1 percent at 0.95 depth. In spite of fluctuation in mean velocity that occured during the 66 minutes, an observation period of 4 minutes yields a mean velocity that differs from the 66-minute mean by less than one-half of a percent.

SCHNEIDER, V.R., and FUTRELL II, J.C. 1984. Performance of ice meter and weight assemblies. U.S. Geological Survey, Water Resources Investigations Report 84-4035, NSTL, 23 p.

Abstract: The performance of three ice meters and weight assemblies nwas evaluated in a towing tank. Each meter was rated individually on a rod suspension. Each meter was then re-rated on a cable suspension, with the appropriate weight assembly. Vertical and veer cable angles were measured along meter yaw angle. The effect of the weight assembly on the rod-suspension rating for each meter was illustrated by computing a correction coefficient which ranged between 0.88 and 1.10 depending on the weight system used and the fluid velocity. A slush-n-all type weight assembly least affected the meter rating and was the most stable in all flow conditions.

SCHOOF, R.R. 1965. Stream gaging precision related to meter suspension and procedural error. Oklahoma State University, M.S. Thesis, 68 p.

Abstract: An intensive review of the stream gaging literature was made to determine the exact procedure for accurate and precise measurement of open channel flow and the accuracy and precision that is expected in random discharge measurements by experienced hydrographers. Literature from previous studies indicated that the standard deviation of random discharge measurements is about three percent and that "good" records of mean daily flow are generally within five percent of the true value.

Two tests were conducted to determine the relationship of flow velocities measured with a Price meter on cable and rod suspension and to detect and determine the effect of incorrect gaging procedure. The tests were conducted at Agricultural Research Service gaging stations on the Washita River near Chickasha and at Anadarko, Oklahoma. Seventeen comparisons were made of discharge estimates made with meter on rod suspension and on cable suspension. The discharge estimated by cable measurements averaged 4.3 percent greater than that estimated by the rod measurements. Apparently the difference was not caused by consistent errors in measurements of width or depth.

Registrations of a Price meter on rod and cable suspension were compared. Depth of flow in the vertical tested was 2.6 feet. registration of the meter varied little with size of weight and blocking of the meter to prevent tipping. At 0.6 and 0.8 depth, there was no significant difference between velocities registered by the meter on rod suspension and cable suspension. However, at 0.2 and 0.4 depth, the cable suspended meter registered about 9 percent greater velocity than did the rod suspended meter.

One hundred and sixty-eight discharge measurements at five weir control gaging stations were used to determine a probable error or average deviation of measurements from the respective station rating. The mean probable error of all these measurements was about 9.2 percent. The mean probable error for measurements greater than one cubic foot per second, however, was only 6.2 percent.

SCHUBAUER, G.B., and MASON, M.A. 1937. Performance characteristics of a water current meter in water and in air. U.S. Department of Commerce, National Bureau of Standards, Research Paper RP981, Part of Journal of Research of the National Bureau of Standards, Volume 18, Mar., pp. 351-360.

<u>Abstract</u>: The effect of density on the performance of a water current meter of the cup-wheel type, known as the small Price meter, was investigated by calibrating the meter first in water by towing it in a rating tank, and second in air by placing the meter in wind tunnel. The change from water to air produced a change in density by a factor of approximately 800. It was found that the revolutions of the cup wheel during 1 foot of travel of the fluid was a function of the product of velocity by the square root of the density and that Reynolds number and turbulence have no measurable effect. It was concluded that changes of density occuring in field can cause no appreciable error.

SCOBEY, F.C. 1914. Behavior of cup meters under conditions not covered by standard ratings. Journal of Agricultural Research, May 25, pp. 77-83.

<u>Abstract</u>: Gives results of experiments on Price current meter rated in still water on rod and acble, tipped varying amounts to 30° upward and downward, also near water surface, bottom, and channel sides, with dull pivot, and vertical oscillation of meter. Concludes meter should be held horizontal, channel sides have little effect, but bottom and surface readings are in error: dull pivot has inappreciable effect for velocities greater than 1 ft. per sec.; vertical meter movement rotates the meter in the same direction as moving water.

SERGUTIN, V.E. 1976. A hydraulic-hydrometric method for determination of water flow in open streams. Soviet Meteorology and Hydrology, No. 6, pp. 72-76.

<u>Abstract</u>: A method is proposed for determination of the correction factor in the approximate formula for the discharge in an open stream without intermediate calculation of the effective cross-sectional area. The initial base quantities are the width of the river at water level, its

maximum depth, and the maximum surface velocity. The correction factor is determined and then processed statistically on the basis of actual data given in the Hydrological Yearbook of the USSR Hydrometeorological Service for specific streamflows.

SHUZHENG, C. and YINBO, X. 1987. The effect of discharge measurement error in flood frequency analysis. Journal of Hydrology, Elsevier Science Publishers, 96, pp. 237-254.

Abstract: The major emphasis of this study was to demonstrate the effects of measureemnt error on the results of a flood flow frequency analysis. Results from the Monte Carlo method of generating sequentially synthetic hydrological records indicate that in the absence of historical outliers, the effects of small measureemnt errors are themselves small and may be neglected. When a historical outlier whose error parameter is smaller than 0.3 is included in the analysis, the resulting frequency curve is improved.

SMOOT, G.F., and CARTER, R.W. 1968. Are individual current-meter ratings necessary? Journal of the Hydraulics division, Proceedings of the American Society of Civil Engineers, Vol. 94, No. HY2, Mar., pp. 391-397.

Abstract: Price current meters used by the Geological Survey for streamflow measurements are rated individually at the National Bureau of Standards by towing the meters at known velocities in a tank of still water, and recording the rates of revolution of the rotors. The practice of rating each meter individually was adopted in the early days of stream gaging, when the tolerance allowed in the manufacture of meters was much greater than it is today.

If identical meters could be produced by rigid control in manufacturing, a standard rating could be used and the need for calibrating each meter would be eliminated. To determine the feasibility of this procedure, three groups of Price current meters from different manufacturers were selected for study. Variances of the calibration data were determined from individual ratings and an average rating for each group. The investigation also included tests to determine the effect of physical changes in various components of the meter and tests to determine the stability of rating during prolonged use of meters in the field.

STAROSOLSZKY, O. 1958. Discussion: Common errors in measurement of irrigation water by C.W. Thomas. Journal of the Irrigation and Drainage Division, Proc. of the American Society of Civil Engineers, Vol. 84, No. IR2, Part 1, Apr., pp. 23-27.

Abstract: Gives probable error for head observation for several types of measuring device (e.g. weir and flume).

STAROSOLSZKY, O. 1983. Trends in the development of hydrometry. Hydrological Sciences Journal, iahs, Vol. 28, No. 1, Mar., pp. 103- 123.

Abstract: Operational hydrology requires reliable and accurate instruments and methods of observation. It is useful to review developments, particularly those of the last decade. Two milestones of this development may be mentionned, both actively supported by the IAHS International Commission on Surface Water, namely the IAHS/UNESCO/WMO (1970) Symposium in Koblenz, and the WMO Seminar in Padova 1975 (WMO, 1975). In assessing the trends, the interconnections of hydrometry with network design and data processing are discussed. Suggestions are also submitted for further developments including research and the potential applications in one particular field, where new instruments and methods are badly needed, specifically the measurement of three-dimensional turbulent flow in streams and lakes. Problems and results are introduced in connection with three-dimensional flow measurement to give an example for the trend of development.

STEARNS, F.P. 1883. On the current-meter, together with a reason why the maximum velocity of water flowing in open channels is below the surface. Transactions, American Society of Civil Engineers, Vol. XII, Aug., pp. 301-338.

Abstract: Illustrates and describes the Fteley and Stearns screw type of current meter. Gives result of rating experiments in which an irregular and variable velocity was created by oscillating the meter; and experiments during which the axis of the meter was turned at various angles with the direction of motion of the rating car up to a maximum of 41°, in which position the meters under-registered about 10 per cent. Results of twenty-seven experiments are given in which the discharge of the Sudbury Conduit was measured both by current meter and weir with varying degrees of agreement depending mostly on the method used in taking the velocity observations by current meter.

STEPHENS, S.K., and STARK, H.L. 1970. Hydraulic model study to determine a stage-discharge relationship. International Symposium on Hydromtry, Koblenz, IAHS Publ. NO. 99, Sep., pp. 412-422.

Abstract: A large part of the runoff in the Burdekin River at Burdekin Falls in Queensland, Australia, is derived from flood flows which can exceed two million cusecs (57,000 m^3/sec). Because of the difficulty of gauging flows of this order by conventional means, it was decided to derive the stage-discharge relationship by a hydraulic model study.

A model was construct based on a photogrammetreic survey of approximately 3 miles (4.8 km) o fthe river to an undistorded scale of 1:100. Data necessary for model verification were provided from current meter gaugings for relatively low flows of up to 16,000 cusecs (460 m^3/sec) and flood slopes at discharges of up to about 700,000 cusecs (20,000 m^3/sec) from observations at two stage recorder sites.

The study indicated that the model could produce a stage-discharge relationship to an accuracy of about ± 5 per cent for flows up to 1,000,000 cusecs (28,500 m^3/sec).

STEVENS, J.C. 1908. Comparison of formulas for computation of stream discharge. Engineering News, Vol. 59, No. 26, Jan., pp. 682-684.

Abstract: The following discussion has for its object the examination of several formulas for computing stream discharge, with a view to the adoption of one as a standard which will give reliable results under all field conditions.

Discusses errors involved in various method of using current-meter data in obtaining the discharge of a stream. Recommends the method adopted by the U.S. Geological Survey, and also multiplying each depth by its corresponding velocity.

STEVENS, J.C. 1911. Hydrometry as an aid to the successful operation of an irrigation system. Transactions, American Society of Civil Engineers, Vol. LXXI, p. 323.

Abstract: Gives results of twelve measurements made fot the purpose of comparing the small Price pentacount head with the single count head. The maximum difference was 1.8 per cent.

STEVENS, J.C. 1919. The accuracy of water-level recorders and indications of the float type. Transactions, American Society of Civil Engineers, Paper No. 1444, Vol. 83, pp. 894-903.

Abstract: This paper in an inquiry into the degree of accuracy that may be expected from the use of automatic recorders and indicators of the float type. It shows that standard instruments now on the market are, in general, sufficiently accurate for most practical purposes, but that where an extraordinary degree of accuracy is required, certain corrections may be applied to the indicated or recorded heights, by which the true heights may be ascertained.

TAMBURI, A., and LYE, L. 1985. Discharge measurements at non-ideal sites. Proceedings, Canadian Society for Civil Engineers Annual Conference and the 7th Canadian Hydrotechnical Conference, Volume 1A, May, pp. 169-189.

Abstract: The common Price or Gurley meter, used in conjunction with the velocity-area method is considered to provide discharge measuremnts accurate to ± 2% at good sites (Carter 1963). However, most Canadian measurement sites do not even approach the ideal site conditions described by Lambie (1980). These non-ideal sites typically introduce significant errors of both the random and non-random variety.

Typical significant sources of errors introduced at non-ideal sites are discussed and examples of the introduced errors at non-ideal sites in Western Canada are presneted.

An inexpensive modification of the Price meter and velocity-area method is proposed. The proposed modification awaits testing but should significantly reduce errors at non-ideal sites.

TERZI, R.A. 1981. Hydrometric field manual - Measurement of streamflow. Environment Canada, Inland Waters Directorate, Water Resources Branch, 37 p.

Abstract: River discharge can be obtained by either direct or indirect methods of measurement. In this section of the field manual, the techniques used by the Water Resources Branch for making direct discharge measurements by current meter are described in detail since this is the fundamental method for measuring streamflow.

A portion of this manual deals specifically with the care, adjustment and maintenance of the Price current meter inasmuch as it is the principal instrument used in the determination of river discharge. Other items of equipment and equipment assemblies required for making the various types of direct discharge measurement are also described.

TEUBER, W. 1987. Influence de l'étalonnage des moulinets hydrométriques sur l'incertitude des déterminations de débit - Résultats d'une étude comparative. Commission international de l'hydrologie du

bassin du Rhin, (in Frecch and in German) Rapport no. I-6 de la CHR, 67 p.

Abstract: The preent report contains the results of an intercomparison exercise organized by the Federal Institute of Hydrology concerning the calibration of current meters. The exercise was carried out between August 1984 and August 1985 in the four Rhnine basin countries Switzerland, Austria, Federal Republic of Germany, and the Netherlands.

In the present report, the results of the meter calibrations are compared for each combination and their dispersion examined. For all six meter combinations (two types of Ott meters, with two types of propellers, on rigid rod and on cable suspension) the corresponding calibration curves of three participating institutions are relatively close together, while the results of the other two institutions show somewhat more deviation (up to 3%). On the basis of the calibration results, sources on inaccuracy in calibration are analysed. The folloing sources are discussed: problems in the registration of measurement values; influence of the number of measurement points and their distribution over the measurement area; the method used for the determination of the equations of the curves; whether or not the "Epper effect" is taken into account in the determination; influence of the way the meter is attached during the calibration; hydraulic differences in the calibration of meters suspended from a cable and from a rigid rod; and hydraulic differences in the calibration in tow tanks and in closed circular tanks.

THIBODEAUX, K.G. and FUTRELL, J.C. 1987. The effects of vertical motion on the performance of current meters. U.S. Geological Survey, Water Resources Investigations Report 87-4147, 50p.

Abstract: A series of tests to determine the correction coefficents for Price type AA and Price type OAA current meters, when subjected to vertical motion in a towing tank, has been completed. During these tests, the meters were subjected to vertical travel that ranged from 1.0 to 4.0 feet and vertical rates of travel that ranged from 0.33 to 1.20 feet per second while being towed through the water at speeds ranging from 0 to 8 feet per second. The tests show that type AA and type OAA current meters are affected adversely by the rate of vertical motion and the distance of vertical travel. The results of these tests show that when current meters are moved vertically, correction coefficients must be applied to the observed meter velocities to correct for the registration errors that are induced by the vertical motion. The type OAA current meter under-registers and the type AA current meter over-registers in observed meter velocity. These coefficients for the type OAA current meter range from 0.99 to 1.49 and for the type AA current meter range from 0.33 to 1.07. When making a current-meter measurement from a boat or a cableway, errors in observed current-meter velocity will occur when the bobbing of a boat or cableway places the current meter in vertical motion. These errors will be significant when the flowing water is less than 2 feet per second and the rate of vertical motion is greater than 0.3 foot per second.

THOMAS, C.W. 1957. Common errors in measurement of irrigation water. Journal of the Irrigation and Drainage Division, Proc. American Society of Civil Engineers, Paper 1362, No. IR2, Sep., pp. 1-24.

Abstract: Devices and structures in general use in the United States for measuring irrigation water are usually subjected to changes in water levels upstream, and perhaps downstream, from the point of measurement.

The generally accepted approach to meet this problem is standardization and calibration of the measuring equipment. Use of tables, graphs, or charts developed from the calibration for determining discharge in the field structure is a replica of the device from which the data were derived and that the flow conditions are identical. Deviations from these standards will result in errors. The magnitude of errors resulting from changes in certain dimensions, incorrect settings, changes in flow patterns, and other deviations is evaluated for some of the commonly used measuring devices. It is concluded that measurements obtained from equipment which is capable of operating with a high degree of accuarcy may be subjected to gross errors unless due care is exercised in fabrication, installation, operation, and maintenance.

THOMAS, C.W. 1959. Errors in measurement of irrigation water. Transactions, American Society of Civil Engineers, Vol. 124, Paper 2980, pp. 319-340.

<u>Abstract</u>: Devices and structures for measuring irrigation water are subjected to changes in water levels upstream and downstream from the point of measurement. The generally accepted approach to meet this problem is standardization and calibration of the measuring equipment. The use of tables, graphs, or charts developed (from the calibrations) for determining discharge in the field is based on the criteria that the field structure is a replica of the device from which the data were derived and that the flow conditions are identical. Deviations from these standards will result in errors. The magnitude of errors resulting from changes in certain dimensions, incorrect settings, changes in flow patterns, and other deviations is evaluated for some of the commonly used measuring devices. Measurements obtained from equipment capable of operating with a high degree of accuarcy may be subjected to errors unless care is exercised in fabrication, installation, operation, and maintenance.

THORNE, C.R, and HEY, R.D. 1979. Direct measurements of secondary currents at a river inflexion point. Nature, Vol. 280, No. 5719, July, pp. 226-228.

<u>Abstract</u>: Secondary currents are defined as currents which occur in a plane normal to the local axis of primary flow. They may develop in pipes or open channels as a result of non-equal distribution of boundary shear stress or by skewing of cross-stream vorticity into a long stream direction. Secondary currents distort the distributions of primary isovels and boundary shear stress from those found in simple flows and have important effects on sedimentary processes of erosion and deposition. Direct measurements of secondary currents in river bends were reported recently. Further data have been obtained for the reach around the inflexion point between bends and are reported here.

TOWNSEND, F.W., and BLUST, F.A. 1960. A comparison of stream velocity meters. Journal of the Hydraulics Division, Proc. American Society of Civil Engineers, Vol. 86, No. HY4, April, Part 1, pp. 11-19.

<u>Abstract</u>: A description of the U.S. Lake Survey method of making stream flow measurements is given, and comparisons of current velocities simultaneously measured by cup and screw type current meters in the lower Niagara River are presented. The conclusion is reachaed that the two types of meters give identical results in Lake Survey flow measurements.

TROSKOLANSKI, A.T. 1960. Hydrometry: Theory and practices of hydraulic measurements. Pergammon Press, New York, 684 p.

Abstract: Hydrometric current meters are compared and theory of current meter outlined. Accuracy of current meter measurements is also discussed.

UNBEHAUEN, W. 1970. The intense evaluation of discharge measurements by the equations of the universal velocity distribution law. International Symposium on Hydrometry, Koblenz, Sep., IAHS Publ. No. 99, Vol. II, pp. 865-882.

Abstract: The most recent investigation of the author show that the assumptions made in obtaining the universal velocity distribution laws are valid also for the natural channels. These findings are the basis for the evaluation of discharge measurements by means of the velocity distribution laws.

With the help of the "wall law", the turbulent shear velocities and the effective roughness k_s may be computed. The value k_s represents the total hydraulic roughness produced by turbulent friction and further additional energy losses. The additional determination of the mean shear velocitiy of the cross-section will provide the initial data for the computation of the mean velocities and mean velocity of each vertical and the total cross-section. By means of the sectional area and the velocity, the total discharge of the cross-section is determined.

Compared with the conventional method this procedure for evaluation discharge also permits the determination of the hydraulic paramters.

UNESCO 1977. Hydrological maps. UNESCO/WMO, Studies and reports in hydrology 20, pp. 30-32.

Abstract: Definitions of errors.

UNITED NATIONS 1962. Field methods and equipment used in hydrology and hydrometeorology. Transactions of the interregional seminar on field methods and equipment used in hydrology and hydrometeorology, November 27 to December 11 1961, Bangkok, Thailand. Economic Commission for Asia and the Far East, World Meteorological Organization.

Abstract: Includes sections entitled: "Measurement and long distance recording of water stage by R.E. Oltman"; "Water discharge measurement by A.K. Proskurjakov and A.G. Kovzelj".

UNWIN, W.C. 1882-83. Current meter observations in the Thames. Proc. ICE (Inst. Civ. Engrs.), Vol. 71, pp. 338-349.

Abstract: This paper contains the record of a series of current meter observations, partly in the tidal, partly in the non-tidal, waters of the Thames.

UNITED STATES GOVERNMENT (Agencies) 1977. National handbook of recommended methods for water-data acquisition. Office of Water Data Coordination, Geological Survey, U.S. Department of the Interior, Chapter 1, p. 3

Abstract: Uncertainty in data acquisition methods.

VAN DER SCHAAF, S. 1984. Errors in level recorder data: prevention and detection. Journal of Hydrology, Elsevier Science Publishers, 73, 373-382.

Abstract: The occurence of errors in water-level recorder data can be reduced by both prevention and detection with subsequent correction. For effective prevention, the error sources should be known; for effective detection, knowledge of error symptoms and their relationship with error sources is essential. The effectiveness of both error prevention and detection depends on field precautions, the quality and frequency of field checks and field check reports, on the quality of equipment maintenance and, as far as detection-correction is concerned, on the sampling interval.

Errors in the data should be detected by a computer program, not manually. A computer-produced error report and field-check reports are necessary for errors in the data to be corrected.

VAN DER MADE, J.W. 1982. Determination of the accuracy of water level observations. Advances in hydrometry, Proceedings of the Exeter Symposium, IAHS Publ. no. 134, July, pp. 173-184.

Abstract: The accuracy of a water level observation, expressed by its standard deviation, is influenced not only by the recording instrument itself but also by the situation and the conditions at and around the station. The standard deviation cannot be derived from local observations only, because of the real movements of the water stage, i.e. the very phenomena we want to observe (signal). Methods of deriving the standard deviation (inaccuracy) from neighbouring stations, using simple multiple regression, are discussed. It appears that the standard deviation of water level observations in rivers can amount to several centimetres.

VANONI, V.A. 1941. Velocity distribution in open channels. Civil Engineering, Vol. 11, No. 6, June, pp. 356-357.

Abstract: Uses of the Von Karman universal logarithmic velocity distribution law for pipes, modified for the case of uniform two-dimensional open-channel flow.

VENETIS, C. 1970. A note on the estimation of the parameters in logarithmic stage-discharge relationships with estimates of their error. Bulletin of the International Association of Scientific Hydrology, International Union of Geodesy and Geophysics, XV, 2, June, pp. 105-111.

Abstract: Under certain assumptions the stage-discharge relationship of a channel cross-section can be approximated by a logarithmic relationship. Observational pairs of stage and discharge plotted on log-log paper often cluster around a straight line and this suggests that the assumptions involved are often approximately satisfied.

In such cases the parameters of the logarithmic relationship are usually estimated graphically from the position and slope of the straight line on the log-log paper. In this paper principles and methods are outlined fro the estimation of the parameters with estimates of their standard error, via regression analysis. Because the water level of zero flows is usually one of the unknown parameters, the regression is non-linear and least squares optimal estimates can be obtained from the dispersion matrix of the joint distribution of the least squares estimators via the maximum likelihood function. An estimate of the error in predictions of the discharge depending on the corresponding stage may be obtained.

WAHL, K.L. 1977. Accuracy of channel measurements and the implications in estimating streamflow characteristics. Journal Research U.S. Geological Survey, Vol. 5, No. 6, Nov.-Dec., pp. 811-814.

Abstract: Regional relations between flow characteristics and stream-channel size offer a promising alternative to available methods of estimating flow characteristics for ungauged sites, particularly in semiarid regions. The reliability of such relations and of flow estimates made from them is partly dependent on the user's ability to recognize a suitable reach and the reference levels in that reach. A test was made in northen Wyoming to determine how consistenly trained individuals could measure channel size for three different reference levels. Seven participants independently visited 22 sites and measured channel dimensions in sections of their choosing. Assuming that the functional relation between a discharge characteristic (Q) and channel width (W) is log Q=f(1.5 log W) and that the average log W from seven measurements is the best estimate of log W at a site, an average standard error for discharge of about 30 percent was attributed to differences in width measurements alone.

WALKER, J.F. 1988. General two-point method for determining velocity in open channel. Journal of Hydraulic Engineering, ASCE, Vol. 114, No. 7, July, pp. 801-805.

Abstract: This paper presents a general two-point method that can be used to determine the depth-averaged velocity when measurements at two arbitrary but known depths are available. In addition, the accuracy of the method is examined.

WEIYA, G., et al. 1982. The method for uniformizing the stage-discharge relations of stable river beds and its application. Advances in hydrometry, Proceedings of the Exeter Symposium, July, IAHS Publ. no. 134, pp. 49-61.
Abstract: The object of uniformizing the complex rating curves for stable river beds are those of giving a clear conception, of providing a simple appropriate adjusting method, and of taking this method as a basis for solving the principle problems concerned in automatic processing.

However, the significance of uniformizing the rating curve of a stable river bed is not only limited to the application of automatic processing, but also to a widening view of the characteristics of gauging-stations. the method provides a basis for reducing the number of measurements and makes continuous-record stations obsolescent, or changes them into partial-record stations where data at yearly intervals are collected. Uniformization makes it possible to improve the measurement of discharge and allows gauging stations to be visited only periodically in sequence. It also provides a new way of simplifying the complex loop rating for hydrological design and forecasting. The method has been named Uniformization.

WILLIAMS, G.S. 1912. Measurements of water. Jour. West. Soc. Engrs., Vol. 17, pp. 22-34.

Abstract: The author discusses the accuracy of the hook gauge, weir, rod floats.

WILM, H.G. 1944. Statistical control of hydrologic data from experimental watersheds. American Geophysical Union, Transactions of 1943, National research Council, Papers, Section of Hydrology, Part II, Jan., pp. 618-624.

Abstract: Covariance-method of analysis is proposed for hydrologic investigations.

WINTER, T.C. 1981. Uncertainties in estimating the water balance of lakes. Water Resources Bulletin, American Water Resources Association, Vol. 17, No. 1, Feb., pp. 82-115.

Abstract: Evaluation of hydrologic methodology used in anumber of water balance studies of lakes in the United States shows that most of these studies calculate one or more terms of the budget as the residual. A literature review was made of studies in which the primary purpose was error analysis of hydrologic measurement and interpretation.

Errors in estimates of stream discharge are often considered to be within 5 percent. If the measuring section, type of flow profile, and other considerations, such as the stage discharge relationship, are less than ideal, errors in estimates of stream discharge can be considerably greater than 5 percent.

WOOD, G.K. 1945. Accuracy of stream-flow records. American Geophysical Union, Transactions of 1944, Papers, Section of Hydrology, Part VI, pp. 985-989.

Abstract: With the expansion of the stream-gaging program, there has been a continual improvement in the accuracy of the stream-flow records. It is the purpose of this paper, first, to discuss briefly the various factors influencing or affecting the accuracy of these records as a whole, without special reference to the accuracy of records of floods or droughts, complete coverage of which would require a separate paper and, second, to present examples illustrating the accuracy of discharge data obtained by methods of the Survey as determined by comparison with stream-flow records computed by other methods of recognized accuracy.

WMO 1980. Manual on stream gauging. Volume I - Fieldwork. Secretariat of the World Meteorological Organization, Operational Hydrology Report No. 13, WMO - No. 519, 308 p.

Abstract: Three major topics are discussed in Volume I, namely selection of gauging-station sites, measurement of stage and measurement of discharge.

WMO 1980. Manual on stream gauging. Volume II - Computation of Discharge. Secretariat of the World Meteorological Organization, Operational Hydrology Report No. 13, WMO - No. 519, 258 p.

Abstract: Volume II deals primarly with computation of the stage-discharge relation and computation of daily mean discharge.

YANG, M.H. 1967. Effect of turbulence characteristics upon the registration of a Price current meter. Master's Thesis, Dept. of Mechanics and Hydraulics, University of Iowa, Aug., 25 p.

Abstract: Usually turbulent characteristics are described in terms of an intensity and a scale. When a Price current meter is held in a turbulent flow, the registered velocity in turbulent flow has been found to be different from the velocity obtained in non-turbulent flow (Yarnell and Nagler, 1931); any errors in registration should be related to these two quantities or their combination. The effects of the two parameters upon registration of the Price current meter are presented in this experiment.

YARNELL, D.L., and NAGLER, F.A. 1931. Effect of turbulence on the registration of current meters. Transactions of the American Society of Civil Engineers, Vol. 95, Paper 1778, pp. 766-795.

Abstract: This paper describes a series of experiments which were conducted on several types of current meters for the purpose of determining the effect of turbulence, or variations in direction, and rapid changes in speed of flow, on their registration. In contrast with experiments hitherto made by moving the meter in still water, these tests were made by holding the meter stationary in a controlled stream of water.

The results of the tests are shown in diagrams and the conclusions are given at the end of the paper.

YOUNG, K.B. 1950. A comparative study of mean-section and mid-section methods for computation of discharge measurements. U.S. Geological Survey, Water Resources Division, Feb., Washington, 52 p.

Abstract: Not available.

APPENDIX B

LISTINGS OF PROGRAMS

PROGRAM "ELECTRE I"

```
C
C     PROGRAM - ELECTRE I
C
C
C     DECLARATION OF VARIABLES
C
      REAL V(75,75), X(150), Y(150), LARGEP, LARGEQ, PC(75)
      REAL C(75,75),D(75,75),U(75,75), MAX, MM, MAXINT
      REAL QC(75)
      INTEGER P, Q, FLAG1, FLAG2, B(75), MSI(75), CW(75)
      INTEGER REA, WR
      INTEGER L(75,75), PRE(75,75), KER(75)
      CHARACTER*13 INPFIL,OUTFIL
C
C     INPUT AND OUTPUT FILES
C
      WRITE(*,'('' INPUT FILENAME:'',\)')
      READ(*,'(A)')INPFIL
      WRITE(*,'('' OUTPUT FILENAME:'',\)')
      READ(*,'(A)')OUTFIL
      OPEN(5,FILE=INPFIL,STATUS='OLD')
      OPEN(6,FILE=OUTFIL,STATUS='NEW')

      REA=5
      WR=6
C
C     ENTER THE NUMBER OF CRITERIA TO BE CONSIDERED
C
      READ(5,*) M
C
C     ENTER THE NUMBER OF PROPOSED ALTERNATIVES
C
      READ(5,*) N
C
C     ENTER THE MAXIMUM SCALE INTERVALS FOR THE "M" CRITERIA
C
      READ(5,*)  (MSI(I),I=1,M)
C
C     ENTER THE WEIGHT FOR EACH OF THE "M" CRITERIA
C
      READ(5,*)  (CW(I),I=1,M)
C
C     FOR CRITERION NUMBER "I" ENTER THE POINT VALUE
C     ASSIGNED TO EACH ALTERNATIVE
C
C     IF LOWER POINT VALUES ARE PREFERED FOR CRITERION "I"
C     ENTER -1, IF HIGHER POINTS ARE PREFERED FOR THIS
C     CRITERION ENTER 1
C
      DO 99 I = 1,M
         READ(5,*)  (V(I,J),J=1,N)
         READ(5,*) B(I)
   99 CONTINUE
C
C     PRINTOUT OF INPUT VALUES
C
      WRITE (6,*) 'M: ',M
      WRITE (6,*) 'N: ',N
      WRITE (6,666)  (MSI(I),I=1,M)
      WRITE (6,666)  (CW(I), I=1,M)
  666 FORMAT(20I4)
      DO 11 I=1,M
        WRITE (6,667)  (V(I,J),J=1,N)
  667   FORMAT(12F6.1)
        WRITE (6,*) B(I)
   11 CONTINUE
C
C     ENTER 1 IF WANT TO USE OWN MINIMUM CONCORDANCE CONDITONS
C             (P) AND MAXIMUM DISCORDANCE CONDITIONS  (Q)
C
C     ENTER 2 IF WANT THE PROGRAM TO GENERATE A SERIES OF P
C             AND Q VALUES
C
C     ENTER 3 IF BOTH ARE DESIRED
C
```

```
      READ(5,*)ICON
      WRITE(6,*) 'P AND Q OPTION: ',ICON
      IF (ICON.EQ.2) GO TO 420
C
C     ENTER THE SET OF CONDITIONS (P AND Q)
C     HOW MANY OF YOUR OWN SETS OF CONDITIONS WOULD YOU
C     LIKE TO INPUT
C
      READ(5,*)ISET
      WRITE(6,*) ISET
C
C     FOR SET "I", ENTER VALUES OF P AND Q
C
      DO 410 I=1,ISET
         READ(5,*)PC(I),QC(I)
         WRITE(6,*) PC(I),QC(I)
  410 CONTINUE
C
C
C START OF CALCULATIONS
C
C
  420 DO 10 P=1,M
      JJ=-1
      DO 12 Q=1,N
      JJ=JJ+2
      X(JJ)=V(P,Q)
      X(JJ+1)=Q
   12 CONTINUE
   14 FLAG1=0
   15 I=1
   16 I=I+2
      IF(X(I-2).GT.X(I)) GO TO 18
   17 II=(I+1)/2
      IF(II.EQ.N) GO TO 20
      GO TO 16
   18 T=X(I)
      TT=X(I+1)
      X(I)=X(I-2)
      X(I+1)=X(I-1)
      X(I-2)=T
      X(I-1)=TT
      FLAG1=1
      GO TO 17
   20 IF(FLAG1.EQ.0) GO TO 30
      GO TO 14
   30 IF (B(P) ) 35,40,40
   35 NN = N+N
      DO 36 I=1,N
      II = I+I
      Y(II-1) = X(NN-1)
      Y(II) = X(NN)
      NN = NN-2
   36 CONTINUE
      NN = N+N
      DO 37 I = 1,NN
      X(I) = Y(I)
   37 CONTINUE
   40 K = 1
      FLAG2 = 0
      KK = K+K
      J = X(KK)
      L(P,J) = K
   45 K = K+1
      KK = K+K
      IF(X(KK-1).EQ.X(KK-3) ) GO TO 47
      FLAG2 = 0
      J = X(KK)
      L(P,J) = K
   46 IF(K.EQ.N) GO TO 10
      GO TO 45
   47 IF(FLAG2.EQ.1) GO TO 48
```

```
      J = X(KK)
      K = K-1
      L(P,J) = K
      LL = L(P,J)
      K =K+1
      FLAG2 = 1
      GO TO 46
   48 J = X(KK)
      L(P,J) = LL
      FLAG2 = 1
      GO TO 46
   10 CONTINUE
      WRITE (6,102)
  102 FORMAT (///////,15X,'MATRIX OF LEVELS')
      DO 100 I=1,M
      WRITE (6,101) (L(I,J), J=1,N)
  101 FORMAT ('-',75(2X,I4))
  100 CONTINUE
C
C     CALCULATION OF CONCORD MATRIX
C
      DO 60 I=1,N
      DO 60 J=1,N
      C(I,J) = 9.99
   60 CONTINUE
   50 SCW = 0
      DO 51 I=1,M
      SCW = SCW + CW(I)
   51 CONTINUE
      DO 53 J=1,N
      DO 53 K=1,N
      SUM = 0.0
      IF(K.EQ.J) GO TO 53
      DO 55 I=1,M
      IF (L(I,J) - L(I,K)) 55, 58, 57
   58 SUM = SUM + CW(I) / 2.
      GO TO 55
   57 SUM = SUM + CW(I)
   55 CONTINUE
      C(J,K) = SUM / SCW
      C(K,J) = 1. - C(J,K)
   53 CONTINUE
      WRITE(6,106)
  106 FORMAT (///////15X,'CONCORD MATRIX')
      DO 105 I = 1,N
      WRITE (6,108) (C(I,J), J = 1,N)
  108 FORMAT ('-', 75(2X,F3.2))
  105 CONTINUE
      MAX = 0.0
      DO 61 I = 1,M
      DO 62 J = 1,N
      IF (V(I,J).GT.MAX) MAX = V(I,J)
   62 CONTINUE
      DO 63 J = 1,N
      U(I,J) = MSI(I) * V(I,J) /MAX
   63 CONTINUE
      MAX = 0.0
   61 CONTINUE
      WRITE (6,109)
  109 FORMAT (///////15X,'UNITS MATRIX')
      DO 110 I = 1,M
      WRITE (6,111) (U(I,J), J = 1,N)
  111 FORMAT ('-',2X,12(F6.1))
  110 CONTINUE
      DO 121 I = 1,N
      DO 121 J = 1,N
      D(I,J) = 999.99
  121 CONTINUE
      GO TO 70
   70 MM = 0.0
      DO 71 I = 1,M
      IF (MSI(I).GT.MM) MM = MSI(I)
   71 CONTINUE
      DO 73 J = 1,N
      DO 73 K = 1,N
```

```
      IF (K.EQ.J) GO TO 73
      MAXINT = 0.0
      DO 74 I = 1,M
      IF (L(I,J).LT.L(I,K)) GO TO 75
      GO TO 74
   75 T = U(I,J) - U(I,K)
      IF (T.LT.0) T = T*(-1)
      IF (T.GT.MAXINT) MAXINT = T
   74 CONTINUE
      D(J,K) = MAXINT /MM
   73 CONTINUE
      WRITE (6,115)
  115 FORMAT (//////15X,'DISCORD MATRIX')
      DO 116 I = 1,N
      WRITE (6,117) (D(I,J), J = 1,N)
  117 FORMAT ('-',13(2X,F4.2))
  116 CONTINUE
      IF (ICON.EQ.1) GO TO 540
C
C     CHOOSE THE SMALLEST C(I,J) = P, AND THE SMALLEST
C     D(I,J) = Q
C
      SMALLP = 10.0
      SMALLQ = 10.0
      DO 201 I = 1,N
      DO 201 J = 1,N
      IF (I.EQ.J) GO TO 201
      IF (C(I,J).LT.SMALLP) SMALLP = C(I,J)
      IF (D(I,J).LT.SMALLQ) SMALLQ = D(I,J)
  201 CONTINUE
C
C     CHOOSE THE LARGEST D(I,J) = Q AND THE LARGEST C(I,J) = P
C
      LARGEP = 0.0
      LARGEQ = 0.0
      DO 202 I = 1,N
      DO 202 J = 1,N
      IF (I.EQ.J) GO TO 202
      IF (D(I,J).GT.LARGEQ) LARGEQ = D(I,J)
      IF (C(I,J).GT.LARGEP) LARGEP = C(I,J)
  202 CONTINUE
C
C     BEGINS THE CALCULATION OF THE MATRIX OF PREFERENCES
C
      PP = SMALLP
  235 QQ = SMALLQ
C
C     WRITE THE CURRENT VALUES OF P AND Q FOR WHICH
C     THE PREFERENCES ARE CALCULATED
C
  240 WRITE (6,250)
      WRITE (6,251) PP,QQ
  250 FORMAT (////,2X,' THE PREFERENCES AMONG ALTERNATIVES',
     1' FOR THE VALUES')
  251 FORMAT (2X,' OF P = ',F5.2,'  AND Q = ',F5.2,'ARE :')
C
C     INITIALIZE THE MATRIX OF PREFERENCES PRE(75,75)
C
      DO 200 I = 1,75
      DO 200 J = 1,75
      PRE(I,J) = -1
  200 CONTINUE
C
C
C
      DO 255 I = 1,N
      K = 0
      DO 255 J = 1,N
      IF (I.EQ.J) GO TO 255
      IF (C(I,J).LT.PP) GO TO 255
      IF (D(I,J).GT.QQ) GO TO 255
      K = K + 1
      PRE(I,K) = J
  255 CONTINUE
C
```

```
C     WRITE MATRIX OF PREFERENCES
C
C     SEARCH ON VECTOR PRE(I,J)  FOR FINDING
C     THE LAST ALTERNATIVE ON WHICH I IS PREFERED
C
      DO 256 I = 1,N
      DO 257 J = 1,N
      IF (PRE(I,J).EQ.-1) GO TO 259
      IF (K.EQ.N) GO TO 267
  257 CONTINUE
  267 K = N
      GO TO 260
  259 K = J - 1
      IF (K.EQ.0) GO TO 261
  260 WRITE(6,262) I, (PRE(I,J), J = 1,K)
  262 FORMAT(/,1X,I2,' ==>  ',75(I2,'=='))
      GO TO 256
  261 WRITE (6,263) I
  263 FORMAT(/,1X,I2,'  ==>  NONE')
  256 CONTINUE
C
C     INITIALIZE KER(K) = -1
C
      DO 270 K= 1,N
      KER(K) = -1
  270 CONTINUE
      LL = 0
C
C     FORM THE KERNEL
C
      DO 271 I = 1,N
      DO 272 J = 1,N
      DO 273 K = 1,N
      IF (PRE(J,K).EQ.-1) GO TO 272
      IF (PRE(J,K).EQ.I) GO TO 271
  273 CONTINUE
  272 CONTINUE
      LL = LL + 1
      KER(LL) = I
  271 CONTINUE
      IF (KER(1).EQ.-1) WRITE (6,274) PP,QQ
  274 FORMAT (////,' FOR THE VALUES OF P = ',F4.2,' AND',
     1' Q =  ',F4.2,' THE KERNEL IS EMPTY')
      IF (KER(1).EQ.-1) GO TO 278
C
C     SEARCH FOR THE NUMBER OF ELEMENTS IN THE KERNEL
C
      DO 275 I = 2,N
      IF (KER(I).EQ.-1) GO TO 276
  275 CONTINUE
      K = N
      GO TO 279
  276 K = I - 1
  279 WRITE (6,277) PP,QQ
      WRITE (*,277) PP,QQ
  277 FORMAT (///,' THE KERNEL FOR VALUES OF P = ',F4.2,
     1' AND Q = ',F4.2,' IS:')
      WRITE (6,280) (KER(I),I=1,K)
      WRITE (*,280) (KER(I),I=1,K)
  280 FORMAT(/,1X,75(1X,I2,'=='))
C
C     WAS THE GREATEST VALUE OF Q ?
C
  278 IF (QQ.EQ.LARGEQ) GO TO 289
      IF (QQ.GT.LARGEQ) GO TO 289
C
C     IDENTIFY NEXT Q
C
      QQ = QQ + 0.10
      GO TO 240
  289 IF (PP.EQ.LARGEP) GO TO 530
      IF (PP.GT.LARGEP) GO TO 530
      PP  = PP + 0.10
      GO TO 235
  530 IF (ICON.EQ.2) GO TO 1000
```

```
  540 DO 900 LC = 1,ISET
      WRITE (6,550)
      WRITE (6,551) PC(LC),QC(LC)
  550 FORMAT (////,2X,' THE PREFERENCES AMONG ALTERNATIVES',
     1' FOR THE VALUES')
  551 FORMAT (2X,' OF P = ',F5.2,'  AND Q = ',F5.2,' ARE :')
      DO 500 I = 1,75
      DO 500 J = 1,75
      PRE(I,J) = -1
  500 CONTINUE
      DO 555 I = 1,N
      K=0
      DO 555 J=1,N
      IF (I.EQ.J) GO TO 555
      IF (C(I,J).LT.PC(LC)) GO TO 555
      IF (D(I,J).GT.QC(LC)) GO TO 555
      K = K+1
      PRE(I,K) = J
  555 CONTINUE
      DO 556 I = 1,N
      DO 557 J = 1,N
      IF (PRE(I,J).EQ.-1) GO TO 559
      IF (K.EQ.N) GO TO 567
  557 CONTINUE
  567 K=N
      GO TO 560
  559 K = J-1
      IF (K.EQ.0) GO TO 561
  560 WRITE(6,562) I, (PRE(I,J), J = 1,K)
  562 FORMAT(/,1X,I2,' ==>  ',75(I2,'=='))
      GO TO 556
  561 WRITE (6,563) I
  563 FORMAT(/,1X,I2,'  ==>  NONE')
  556 CONTINUE
      DO 570 K = 1,N
      KER(K) = -1
  570 CONTINUE
      LL = 0
      DO 571 I = 1,N
      DO 572 J = 1,N
      DO 573 K = 1,N
      IF (PRE(J,K).EQ.-1) GO TO 572
      IF (PRE(J,K).EQ.I) GO TO 571
  573 CONTINUE
  572 CONTINUE
      LL = LL + 1
      KER(LL) = I
  571 CONTINUE
      IF (KER(1).EQ.-1) WRITE (6,574) PC(LC),QC(LC)
      IF (KER(1).EQ.-1) WRITE (*,574) PC(LC),QC(LC)
  574 FORMAT (////,' FOR THE VALUES OF P = ',F4.2,' AND',
     1' Q =  ',F4.2,' THE KERNEL IS EMPTY')
      IF (KER(1).EQ.-1) GO TO 1000
      DO 575 I = 2,N
      IF (KER(I).EQ.-1) GO TO 576
  575 CONTINUE
      K = N
      GO TO 579
  576 K = I-1
  579 WRITE(6,577) PC(LC),QC(LC)
      WRITE(*,577) PC(LC),QC(LC)
  577 FORMAT(///,' THE KERNEL FOR VALUES OF P = ',F4.2,
     1' AND Q = ',F4.2,' IS:')
      WRITE(6,580) (KER(I),I=1,K)
      WRITE(*,580) (KER(I),I=1,K)
  580 FORMAT(/,1X,75(1X,I2,'=='))
  900 CONTINUE
 1000 STOP
      END
```

PROGRAM "COMPROMISE PROGRAMMING"

```
C
C       PROGRAM - COMPROMISE PROGRAMMING
C
        DIMENSION V(75,75),VMAX(75),S(75),IS(75),W(75),VMIN(75)
        DOUBLE PRECISION V,VMAX,S,W,WMAX,SUM,VMIN
        INTEGER KR,NO
        REAL P
        CHARACTER*13 INPFIL,OUTFIL
C
C     INPUT AND OUTPUT FILES
C
        WRITE(*,'('' INPUT FILENAME:'',\)')
        READ(*,'(A)')INPFIL
        WRITE(*,'('' OUTPUT FILENAME:'',\)')
        READ(*,'(A)')OUTFIL
        OPEN(5,FILE=INPFIL,STATUS='OLD')
        OPEN(6,FILE=OUTFIL,STATUS='NEW')
2       FORMAT(12F6.0)
C
C       READ INPUT DATA
C
        READ (5,*) KR,NO
        READ (5,*) P
C
C       WRITE INPUT DATA
C
        WRITE (6,4)NO,KR,P
4       FORMAT(/////8X,'MULTIOBJECTIVE COMPROMISE PROGRAMMING',
     1  //,8X,'NUMBER OF ALTERNATIVES = ',I3,//,8X,
     2  'NUMBER OF CRITERIA = ',I3,//,8X,'COEFFICIENT P = ',
     3   F6.1,//,8X,'INPUT  MATRIX',//)
C
        WRITE (6,5) (K,K=1,KR)
5       FORMAT(8X,'CR:',12I6)
C
C       READ & WRITE CRITERIA BY ALTERNATIVES
C
        DO 10 N=1,NO
        READ (5,*) (V(K,N),K=1,KR)
        WRITE (6,6) N,(V(K,N),K=1,KR)
6       FORMAT(8X,'ALT',I2,(12F6.2))
10      CONTINUE
C
C       READ & WRITE ASSOCIATED WEIGHTS
C
        READ (5,*) (W(K),K=1,KR)
        WRITE (6,7) (W(K),K=1,KR)
7       FORMAT(//8X,'WEIGHTING COEFFICIENTS'//
     1  13X,12F6.2//)
C
C       START OF CALCULATIONS
C
C       LOCATE MAXIMUM AND MINIMUM VALUES FOR EACH CRITERIA
C
        WMAX=0.
        DO 11 K=1,KR
        IF (W(K).GT.WMAX) WMAX=W(K)
        VMAX(K)=0.
        VMIN(K)=1E+25
        DO 12 N=1,NO
        IF (V(K,N).GT.VMAX(K)) VMAX(K)=V(K,N)
        IF (V(K,N).LT.VMIN(K)) VMIN(K)=V(K,N)
12      CONTINUE
11      CONTINUE
C
C       COMPUTE THE SUMMATION OF THE RATIO OF THE DIFFERENCES
C       FOR P < 100
C
        DO 13 N=1,NO
        SUM=0.
        IF (P.GE.100.) GO TO 20
        DO 14 K=1,KR
        SUM=SUM+((VMAX(K)-V(K,N))/(VMAX(K)-VMIN(K))*W(K)/WMAX)**P
14      CONTINUE
        S(N)=SUM**(1/P)
```

```
      GO TO 21
C
C     COMPUTE THE SUMMATION OF THE RATIO OF THE DIFFERENCES
C     FOR P > 100
C
20    CONTINUE
      DO 15 K=1,KR
      SN=(VMAX(K)-V(K,N))/(VMAX(K)-VMIN(K))*W(K)/WMAX
      IF (SUM.LT.SN) SUM=SN
15    CONTINUE
      S(N)=SUM
21    CONTINUE
13    CONTINUE
C
C     PRINT THE FINAL RESULTS
C
      WRITE (6,8)
8     FORMAT(//,8X,'FINAL TABLE'/8X,'ALT      L(ALT)   RANK'/)
      DO 16 N=1,NO
      IS(N)=1
      DO 17 M=1,NO
      IF (S(N).GT.S(M)) IS(N)=IS(N)+1
17    CONTINUE
      WRITE (6,3) N,S(N),IS(N)
3     FORMAT(6X,I4,F9.3,I6)
16    CONTINUE
      STOP
      END
```