MANUAL ON PROCEDURES IN OPERATIONAL HYDROLOGY

VOLUME 3

STREAM DISCHARGE MEASUREMENTS
BY CURRENT METER
BY DILUTION AND BY THE SLOPE-AREA METHOD

SECOND EDITION

NORWEGIAN WATER RESOURCES AND ENERGY ADMINISTRATION
HYDROLOGY DEPARTMENT

1997

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STREAM DISCHARGE MEASUREMENTS BY CURRENT METER BY DILUTION AND BY THE SLOPE-AREA METHOD

SECOND EDITION

ØSTEN A. TILREM

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This manual consists of five volumes dealing with:

1. Establishment of Stream Gauging Stations
2. Operation of Stream Gauging Stations
3. Stream Discharge Measurement by Current Meter, by Dilution and by the Slope-Area Method
4. Stage-Discharge Relations at Stream Gauging Stations
5. Sediment Transport in Streams—Sampling, Analysis and Computation

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PREFACE

This Manual on Procedures in Operational Hydrology is a second, revised and enlarged edition of the original Manual, which was prepared jointly by Tanzanian and Norwegian authorities, when the author, Østen A. Tilrem, served as hydrologist in Western Tanzania. The first edition of the Manual was financially supported by the Norwegian Agency for International Development (NORAD). Mr. Tilrem has extensive experience in senior positions within hydrological co-operative programmes in both Latin America, Africa, and Asia.

The present edition of the Manual is produced by the Norwegian Water Resources and Energy Administration. It is intended for the use of field hydrologists and technicians, working under varying conditions in all parts of the world. The Manual should be useful as a reference book, which also provides textual depth for many topics.

Since the late seventies the micro-electronics field has developed rapidly, resulting in new possibilities for advanced capture and transmission of water-related data. Such advances are treated in the manual. The benefits of new technology are unfortunately often difficult to harvest, because of high costs, rapid changes in equipment design, or lack of supporting infrastructure. The field hydrologist should therefore also be familiar with traditional methods, which still have to be used in many parts of the world. Those traditional approaches may even have the additional benefit of providing a more direct insight in the hydrological processes taking place in the river or aquifer.

It is my sincere belief that users of the Manual will find it useful in their assessment of water resources.

Arne Tollan
Director

CONTENTS

Chapter 1 INTRODUCTION 13

1.1 General 13

1.2 The current meter method 13

1.3 Dilution gauging 13

1.4 The slope-area method 14

Chapter 2 THE CURRENT METER METHOD 15

2.1 Instruments and equipment 15

2.1.1 Current meters 15

2.1.1.1 The cup-type current meter 15

2.1.1.2 The propeller-type current meter 15

2.1.1.3 Rating of current meters 16

2.1.1.4 The spin test 17

2.1.1.5 Care and maintenance of current meters 17

2.1.2 Timers and revolution counters 17

2.1.2.1 Timers 17

2.1.2.2 Revolution counters 17

2.1.3 Sounding and suspension equipment 18

2.1.3.1 Sounding and suspension rods 18

2.1.3.2 Sounding and suspension lines 19

2.1.3.3 Weights 19

2.1.3.4 Gauging reels 19

2.1.3.5 Handlines 19

2.1.4 Width measuring equipment 20

2.1.5 Equipment for wading measurements 20

2.1.6 Equipment for measurements from boats 20

2.1.7 Equipment for measurements from cableways 24

2.1.8 Equipment for measurements from bridges 24

2.1.8.1 Bridge cranes 24

2.1.8.2 Bridge boards 24

2.1.9 Equipment for measurement from ice-cover 24

2.2 Current meter measurement sites 25

2.3 Current meter measurement procedures 27

2.3.1 General 27

2.3.2 Measurement of width 27

2.3.3 Spacing of verticals 27

2.3.4 Measurement of depth 28

2.3.4.1 Depth corrections 28

2.3.5 Methods of measuring mean velocity in the vertical 29

2.3.5.1 The 0.2 depth method 29

2.3.5.2 The 0.6 depth method 30

2.3.5.3 The 0.2 / 0.8 depth method 30

2.3.5.4 The 0.2 / 0.6 / 0.8 depth method 30

2.3.5.5 The Five-point method 30

2.3.5.6 The Six-point method 31

2.3.5.7 The Vertical velocity-curve method 31

2.3.5.8 The Surface velocity method 31

2.3.5.9 Typical vertical velocity curves 31

2.3.5.10 Velocity corrections 31

2.3.6 Current meter measurements 32
2.3.6.1 Measurement by wading 32
2.3.6.2 Measurement from boat 34
2.3.6.3 Measurement from cableway 36
2.3.6.4 Manned cableway 36
2.3.6.5 Cableway with instrument carriage 37
2.3.6.6 Measurement from bridge 37
2.3.6.7 Rod suspension from bridge 37
2.3.6.8 Cable suspension from bridge 37
2.3.6.9 Measurement from ice-cover 38
2.4 Computation of current meter measurements 39
2.4.1 Arithmetical mid-section method 39
2.4.2 Arithmetical mean-section method 39
2.4.3 Graphical integration method 39
2.4.4 Mean gauge height during current meter measurements 40
2.5 Factors affecting the accuracy of current meter measurements 42
2.5.1 Use and care of the equipment 42
2.5.2 The measuring cross-section 42
2.5.3 Spacing of the verticals 42
2.5.4 Measurement of depth and width 42
2.5.5 Oblique flow 42
2.5.6 Turbulent and pulsating flow 43
2.5.7 Vibration of suspension rod 43
2.5.8 Insufficient weight of sinker 43
2.5.9 Low temperatures 43
2.5.10 Wind 43
2.5.11 Vertical and horizontal motion of current meter 43
2.5.12 Drift and aquatic growth in stream channels 43
2.5.13 Bedload 43
2.5.14 Effects of piers, piling, and eddies 44
2.6 Accuracy of current meter measurements 44
2.6.1 Personal error (The Human factor) 44
2.6.2 Instrumental error 44
2.6.3 Methodic error 44
2.6.4 Velocity-pulsation error 44
2.6.5 Velocity-depth error 45
2.6.6 Velocity-width error 45

Chapter 3 LEVEL AND DISCHARGE MEASUREMENT UNDER DIFFICULT CONDITIONS 46
3.1 General 46
3.2 Unstable stream channel 46
3.2.1 Cases 46
3.2.2 Problems 46
3.2.3 Solutions 47
3.2.3.1 Relocation of gauging station 47
3.2.3.2 Stabilization of banks and streambed 47
3.2.3.3 Prevention of silting of intakes and stilling well 47
3.2.3.4 Desilting methods 48
3.2.3.5 Soundings 48
3.2.3.6 Discharge measurements 48
3.2.3.7 Shifting stage-discharge relations 48
3.2.3.8 Intercomparison between gauging stations 49
3.2.3.9 Change of variables 49

3.3 Flash floods 49
3.3.1 Cases 49
3.3.2 Problems 49
3.3.3 Solutions 50
3.3.3.1 Maintenance and service of recording instruments 50
3.3.3.2 Adaption of standard design to meet adverse conditions 50
3.3.3.3 Flood-crest gauges 50
3.3.3.4 Advance warning 50
3.3.3.5 Optimized current-meter measurements 50
3.3.3.6 Indirect discharge measurements 50
3.3.3.7 The velocity-index method 50
3.3.3.8 River-model analysis 50
3.3.3.9 Dilution methods 51
3.3.3.10 Float measurements 51
3.3.3.11 Regionalization 51
3.3.3.12 Pulsating flow (roll waves) 51
3.3.3.13 Plan of operation 51
3.4 Inability to define stage-discharge relation 51
3.4.1 Cases 51
3.4.2 Problems 52
3.4.3 Solutions 52
3.4.3.1 Variable backwater 52
3.4.3.2 Looped discharge rating 52
3.4.3.3 Unstable flow and variable backwater combined 52
3.4.3.4 Shifts and aquatic vegetation 52
3.5 River channel affected by aquatic growth and weeds 52
3.5.1 Cases 52
3.5.2 Problems 52
3.5.3 Solutions 53
3.5.3.1 Shifting control corrections 53
3.5.3.2 Family of stage-discharge curves 53
3.5.3.3 Electromagnetic method 53
3.5.3.4 Anti-growth measures 53
3.6 Bank overflow—flood plain 53
3.6.1 Cases 53
3.6.2 Problems 54
3.6.3 Solutions 54
3.6.3.1 Clearance of a discharge measuring section across the flood plain 54
3.6.3.2 Width constriction of the flood plain 54
3.7 Large interchange between surface water and groundwater 54
3.7.1 Cases 54
3.7.2 Problems 54
3.7.3 Solution 54
3.7.3.1 Water-balance analysis 54
3.8 Arid conditions 54
3.8.1 Cases 55
3.8.2 Problems 55
3.8.3 Solutions 55
3.8.3.1 Siting of gauging stations 56
3.8.3.2 Stabilization of the streambed 56
3.8.3.3 Recess staff gauge 56
3.8.3.4 Stilling well 56
3.8.3.5 Recording instruments 56

3.8.3.6 Gauging structures 57
3.8.3.7 Discharge measurements 57
3.8.3.8 Measurement of changes in streambed level during floods 57
3.9 River channel and estuary affected by tides 58
3.9.1 Cases 58
3.9.2 Problems 58
3.9.3 Solutions 59
3.9.3.1 Direct measurement 59
3.9.3.2 Empirical methods 59
3.9.3.3 Velocity-area method 60
3.9.3.4 Unsteady flow mathematical modelling method 60
3.10 River channel affected by wind 60
3.10.1 Cases 61
3.10.2 Problems 61
3.10.3 Solutions 61
3.10.3.1 Correct location and siting of gauging station 61
3.10.3.2 Orientation of gauging sites on rivers 61
3.10.3.3 Gauge and control separated by a distance 62
3.10.3.4 Conditions for discharge measurements 62
3.10.3.5 Special cases 62
3.11 River channel affected by ice 62
3.11.1 Cases 62
3.11.2 Problems 63
3.11.3 Solutions 63
3.11.3.1 In temperate climates—Siting of the gauging stations so that variable backwater effects are eliminated or reduced 63
3.11.3.2 In cold climates—Installation of gauging stations so that they are kept reasonably free of ice 63
3.11.3.3 Prevention of formation of ice in autographic recorders and at other gauges 64
3.11.3.4 Determination of the magnitude of backwater caused by ice and computation of discharge during periods of backwater 64
3.11.3.5 Special procedures and equipment used for measurement of discharge under ice cover 64
3.12 Steep mountain streams 65
3.12.1 Cases 65
3.12.2 Problems 65
3.12.3 Solutions 66
3.12.3.1 Construction of artificial control with upstream and downstream apron 66
3.12.3.2 Construction of standard Crump weir or Flat V-weir 66
3.12.3.3 Construction of upstream check-dam 66
3.12.3.4 Construction of critical-depth flume 66
3.12.3.5 Discharge measurements by dilution method 66

Chapter 4 THE RELATIVE SALT-DILUTION METHOD 67
4.1 General 67
4.2 Theory 67
4.3 Measuring procedure 68
4.3.1 The measuring reach 68
4.3.2 Preparation of the salt solution 68
4.3.3 Observation of the salt solution wave 69
4.3.4 The calibration curve 70

4.4 Calculation of the discharge 72
4.5 Sources of errors 73
4.6 Computerized calibration, sampling and computation..... 73

Chapter 5 MEASUREMENT OF PEAK DISCHARGE BY THE SLOPE-AREA METHOD ... 75
5.1 General 75
5.2 Uniform flow equations 75
5.2.1 The Manning equation 75
5.2.1.1 The friction slope 75
5.2.1.2 Values of the Manning coefficient 76
5.2.1.3 The conveyance factor 76
5.3 Calculation of the discharge 77
5.3.1 Truly uniform channel 77
5.3.2 Channel not truly uniform 77
5.3.3 Significantly non uniform channel 77
5.4 Characteristics of the channel 77
5.4.1 Length of a channel reach 77
5.4.2 Wetted perimeter of a cross section 77
5.4.3 Hydraulic radius of a cross section 77
5.5 Selection of the channel reach for slope-area measurements 77
5.5.1 Minimum length and slope of the reach 77
5.5.2 The cross sections 78
5.5.3 Reference gauges 78
5.6 Field survey of the channel reach 78
5.7 Accuracy of the slope-area method 78
5.8 Simplified slope-area method 78

BIBLIOGRAPHY AND REFERENCES 79

APPENDIX A – Current meter measurement notes 83

APPENDIX B – The mid-section method of computing current meter measurements 87

APPENDIX C – The mean-section method of computing current meter measurements 93

APPENDIX D – Rating of current meters 99

Table 1 – Air-line correction 29

Table 2 – Wet-line correction 29

Table 3 – Observation of the solution wave in the stream 69

Table 4 – Developing the calibration curve 71

Table 5 – List of equipment for the relative Salt Dilution Method (manual version) 73

Table 6 – Values of the Manning Roughness Coefficient..... 78

Table D.1 – Observed and calculated data of a current-meter rating 102

Table D.2 – Calculations to determine the current-meter rating equations 102

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Østen A. Tilrem

CHAPTER 1

INTRODUCTION

1.1 General

The discharge of a stream is the volume of water flowing through a cross section of the stream per unit of time. Stream discharge is normally expressed in cubic metres per second (m^3/s). Discharge is the most important parameter in hydrology, its measurement normally involves consideration of both stage and velocity of flow.

When a gauging station has been set up on a stream, a continuous record of stage (i.e. gauge height) can be observed only. A continuous record of discharge is obtained by converting the gauge height readings into discharge by means of the stage-discharge relationship for the station site. To establish the relation between the stage and the volume of water flowing in the stream, a sufficient number of discharge measurements is made at various stages. The measurements are plotted on graph paper against their corresponding gauge heights to produce the stage-discharge relation, or the discharge rating curve as it is called. After having been established, the gauge height readings that have been taken at regular intervals, such as daily or more often, are applied to the rating curve and the corresponding discharges thereby determined.

The necessity for making discharge measurements depends on the circumstances at each individual gauging station. In the case of new stations, gaugings should be done without delay in order to complete the discharge rating curve in the shortest possible time. At stations where the rating curve has been established, regular gaugings are required to check for any changes that may have occurred in the stage-discharge relation. The first indication of any change will normally appear through deviation of the check measurements from the established rating curve. At some stations, where the control is permanent, the initial rating curve may apply throughout the entire period of operation of the station and check measurements only will be required. Stations with poor and shifting controls normally require complete re-rating at intervals, generally after major floods.

1.2 The Current Meter Method

Most discharge measurements are made by the conventional Current Meter Method. This method is adaptable to a wide range of flow velocities and is practically unlimited with respect to the total discharge which can be measured, provided the flow is not too turbulent. Stream discharge is by definition the product of velocity and cross-sectional area of the flow and this method evaluates these two terms for a particular cross section. The current meter method belongs to the area-velocity group of discharge gauging methods.

Essentially, the method consists of: (a) dividing the stream cross section into a number of parts for each of which the area and the mean velocity of flow are determined separately, (b) computing the discharge in each part as the product of the velocity and the area, and (c) summing up the partial discharges to obtain the total. It is evident that velocity observations must be made at a sufficient number of points in order to eliminate the effect of variations in the velocity of flow across the stream.

1.3 Dilution Gauging

Dilution Gauging is often used as an alternative to the current meter method at sites where excessive turbulence, high velocities and rocky or shallow sections would make the operation of a current meter difficult. The principle involved is that the discharge is calculated from the degree of dilution in the flowing water of an added tracer solution. There are upper limits on the size of a river that may be gauged, because the injected solution must mix uniformly with the flow and the degree of dilution must be within the detectable range of the tracer.

Sodium Chloride (common salt) has been widely used as a tracer. However, its use is limited to smaller streams and rivers because it can not be accurately detected at concentrations lower than 1 part per million (ppm or mg/l). Thus, in large bodies of water, the quantity required would be prohibitive. Salt's greatest advantage is its low cost

and the simple and inexpensive instrumentation required.

Fluorescent dyes, as for example *Rhodamine B,* can be detected at concentrations of less than 1 part per billion (ppb). It is readily separated from naturally occurring substances, it is relatively cheap and not harmful to aquatic life.

Radioisotopes can be applied as tracers. However, their use is limited because of the high cost involved, the need for specially trained personnel, and the associated contamination-hazards. On the other hand, in many cases the high cost may be offset to a large degree by the extremely small concentration of a radioactive substance that can be detected.

1.4 The Slope-Area Method

The Slope-Area Method provides an approximate estimate of the discharge in a stream and is used when gauging of the discharge by more accurate methods, like the current meter method, is not possible. Thus, the slope-area method is commonly used to define the extreme flood-stage end of the discharge rating curve because the magnitude of extreme floods is often such that other methods of gauging the discharge can not be used. The slope-area method can be used with accuracy in uniform channels with stable boundaries such as rock and coarse bed material.

It is, however, not advisable to use this method in the case of very large rivers or rivers with high sediment concentration, or channels with significant curvature.

Bibliography

Chapter 1: [1], [11], [39].

CHAPTER 2

THE CURRENT METER METHOD

2.1 Instruments and Equipment

Current-meter measurements are classified into five types in terms of the means the hydrologist uses to cross the stream when making the measurement. The five types are (a) by wading, (b) from boat, (c) from cableway, (d) from bridge, and (e) from ice-cover.

Current meters, revolution indicators and timers, measuring tapes and tag lines are equipment used in all types of discharge measurements. Other equipment used depend on the type of measurement being made. Instruments and equipment are described under the following categories in this section:

a) Current meters,
b) Timers and revolution counters,
c) Sounding and suspension equipment,
d) Width measuring equipment,
e) Equipment for wading measurements,
f) Equipment for boat measurements,
g) Equipment for cableway measurements,
h) Equipment for bridge measurements,
i) Equipment for measurements from ice-cover.

2.1.1 Current Meters

A current meter is a device with a rotor which revolves at a speed which is a function of the local velocity of flow. By placing the current meter at a point in the stream and recording the number of revolutions over a known period of time, the velocity at that point can be determined from the revolution-velocity rating of the current meter.

The number of revolutions of the rotor is obtained by an electric circuit through a contact which completes the circuit at a selected number of revolutions. The electric-impulse produces an audible signal in a buzzer or is registered on an electric-counter. The time is determined by a stop watch, or better by an electronic counter and timer combined into one single instrument. These small lightweight instruments have been available for a number of years.

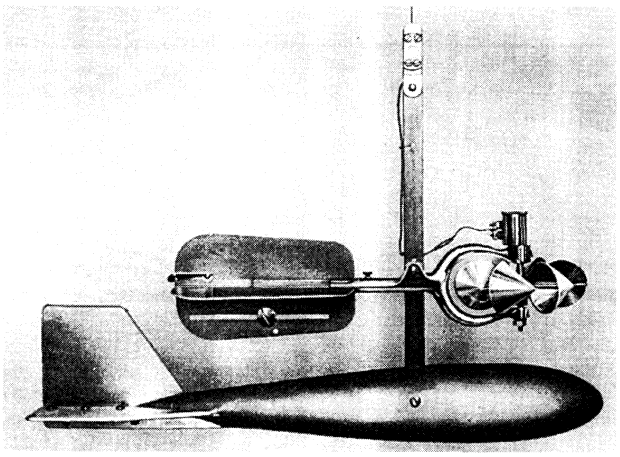

Figure 1. The PRICE vertical-shaft cup-type current meter with hanger bar and streamlined weight, suspended on cable (courtesy of the US Geological Survey).

2.1.1.1 The Cup-type Current Meter

There are two common types of current meters, the cup-type and the propeller-type. The cup-type current meter consists of a rotor revolving about a vertical shaft and hub assembly, bearings, the main frame, a contact chamber containing the electric-contact, tail fin, and a means of attaching the instrument to a rod or cable (Fig. 1). The rotor is generally constructed of six conical cups fixed at equal angles on a ring mounted on the vertical shaft. The assembly is retained in the main frame by means of an upper shaft-bearing and a lower pivot-bearing.

2.1.1.2 The Propeller Type Current Meter

The propeller-type current meter consists of a propeller revolving about a horizonal shaft, two ball-bearings in an oil chamber, the current-meter body containing the electric-contact, a tailpiece with a vane, and a means of attaching the instrument to the suspension equipment (Fig. 2). The current meter may be supplied with one or more propellers which differ in pitch and diameter to be used for various flow velocities.

Figure 2. The OTT Horizontal-shaft propeller-type current meter suspended on wading rod (courtesy of A. Ott).

The ideal current meter, when held rigidly at right angles to the measuring cross section, will register the normal flow component when subjected to oblique flow. Only the propeller-type current meter can meet such a design requirement and component propellers are available which register the velocity normal to the measuring cross section when held rigidly by rod suspension at right angles to the section.

Since the cup-type current meter is not sensitive to the flow direction it always measures the maximum horizontal velocity regardless of whether this is normal or oblique to the measuring cross section. Thus, it tends to over-estimate the velocity if the flow is not normal to the measuring cross section.

The comparative characteristics of the cup-type and the propeller-type current meters can be summarized as follows.

Cup-type current meter:

a) It operates at lower velocities than the propeller-type current meter.
b) The bearings are well-protected from silty water.
c) A single rotor serves for the entire range of velocities.
d) The rotor is reparable in the field without adversely affecting the rating of the current meter.

Propeller-type current meter:

a) The propeller disturbs flow less than the vertical-shaft cup-type rotor.
b) The propeller is less likely to become entangled with debris than the cup-type rotor.
c) Bearing friction is less than for vertical-shaft rotors because any bending moment on the rotor shaft is eliminated.

2.1.1.3 Rating of Current Meters

In order to determine the velocity of the water from the revolutions of the rotor of a current meter, a relation must be established between the angular speed of the rotor and the velocity of the water which causes it to turn. The establishment of this relation is known as *rating the current meter.*

Current meters differ in their ratings principally because of slight variations in each individual rotor. Also, different sizes or shapes of weights suspended below the current meter may affect the rating as does a too short distance between the current meter and the weight. Because of these effects upon the rating, each current meter is rated individually for at least one suspension, generally the rod suspension, and coefficients based on the analysis of several comparative ratings are applied to the rod-suspension rating to obtain the rating for other suspensions.

The rating is checked after hard usage, when the current meter has been accidentally damaged and about once a year under ordinary use.

The usual method of rating a current meter is to pull it through still water and observe the time of travel and the number of revolutions made as the current meter travels a given distance. The number of revolutions per second and the corresponding velocity are then computed. When these two quantities are plotted one against the other on ordinary graph paper, a straight line will usually fit the points closely. Generally, however, there is a change in the slope of the line at a certain velocity, that varies for different meters, so that two equations must be derived for the relationship, one for the higher velocities and the other for the lower.

These two equations are then solved for different velocities and a rating table made up.

Practical hints for rating current meters and an illustrative computation of the rating equations are given in Appendix D.

2.1.1.4 The Spin Test

The spin test is a simple method for checking the condition of the current meter. When making the test, the rotor is protected from air currents. It is then given a quick turn by hand to start it spinning and the duration of the spin is timed with a stop watch. As the rotating rotor approaches its stopping point, the motion should be carefully watched to see whether the stop, is abrupt or gradual. Regardless of the duration of the spin, if the rotor comes to an abrupt stop the reason for this should be found and corrected before the current meter is used. The normal spin time for a propeller-type current meter should be from 60 to 100 seconds for the heavier propellers made of metal. For a cup-type rotor, the spin time is considerably longer.

For light rotors made of plastic or aluminium, the best way is to hold the rear end of the meter against one's ear and listen for crunching and grinding sounds, which will indicate that the bearings are fouled by silt or other impurities.

2.1.1.5 Care and Maintenance of Current Meters

To ensure reliable functioning of the current meter, it is necessary that the meter be kept in good condition.

Before and after use, the current meter is tested for proper functioning by the spin test. Also, by turning the rotor slowly, the number of rotations is compared with the number indicated by the counter or audible signals. Further, the current meter is examined for worn or damaged bearings, proper shaft alinement and for deformation of the rotor. After each discharge measurement, all bearing surfaces must be thoroughly cleaned and oiled. The oil must have the same specifications as those recommended by the manufacturer.

The manufacturer's recommendations for use and maintenance of the current meter must be followed. A log-book showing the actual details of the current meter and any repairs and changes it has undergone should be maintained for each meter. The hours of use are also recorded in the log-book.

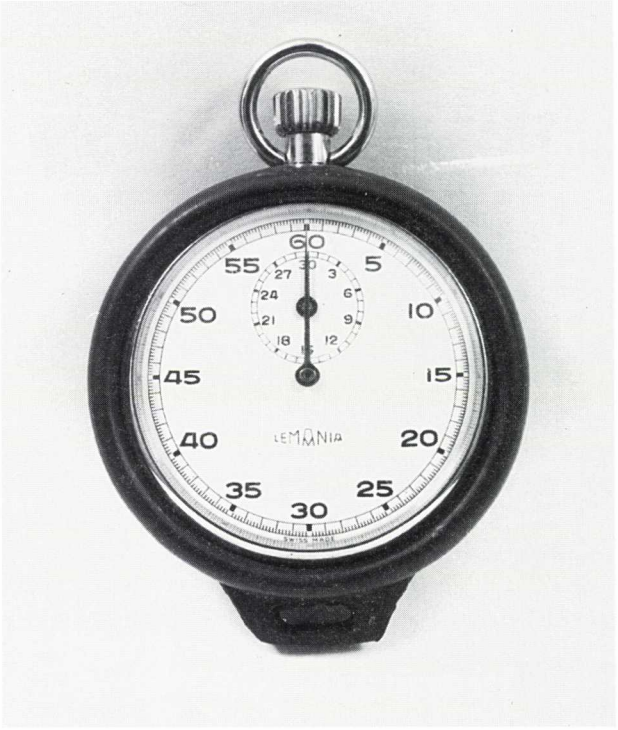

Figure 3. Stopwatch in protective rubber covering.

2.1.2 Timers and Revolution Counters

2.1.2.1 Timers

In order to measure the velocity at a point with a current meter, it is necessary to count the revolutions of the rotor during a certain interval of time, normally not less than 60 seconds. The velocity is then obtained from the current meter rating equation or rating table. The time interval is measured to one fifth of a second with a stopwatch.

The stopwatch commonly used is a still-movement type graduated to the fifth of a second (Fig. 3). One complete revolution of the large hand is made in 60 seconds. A smaller dial on the face of the watch indicates the number of minutes the watch has been running limited up to 30 minutes. Depressing the stem of the watch starts it, a second depression will stop it, and a third depression resets the watch to zero. Watches should be checked periodically to be certain that they give correct time.

2.1.2.2 Revolution Counters

The revolutions of the current-meter rotor are counted during the observation of velocity. An electric-circuit built into the meter closes each time the rotor of the meter has made one revolu-

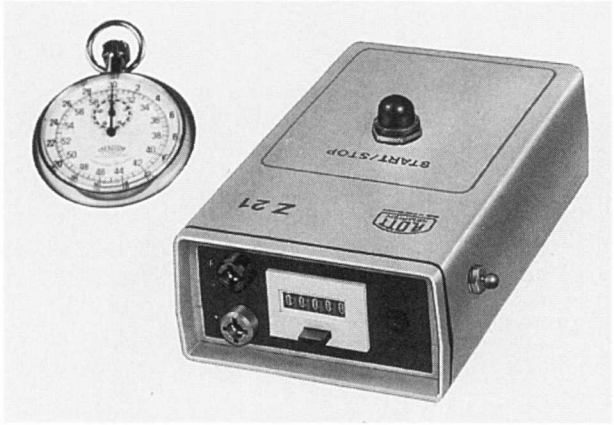

Figure 4. Revolution counter used with stopwatch for counting current-meter propeller impulses, every pulse generated is counted (courtesy of A. Ott).

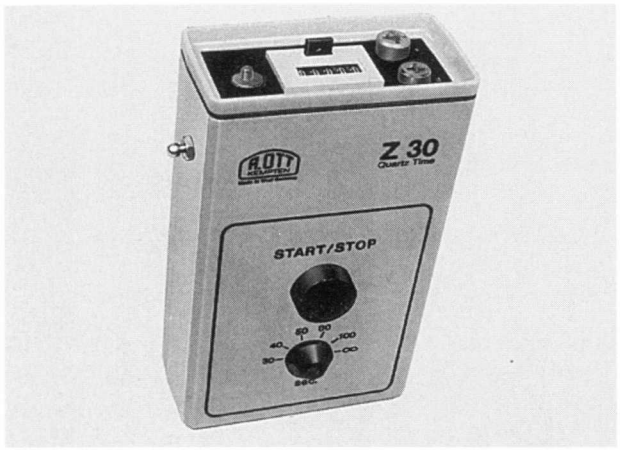

Figure 5. Revolution counter/timer with built in timer for counting propeller impulses at pre-set or any desired time interval (courtesy of A. Ott).

tion. An automatic counter is part of the electric-circuit and each closure of the circuit is thus counted or registered.

There are various types of revolution counters, with or without built-in timers:

a) Counter used with a stop watch to count and time any desired number of propeller impulses (Fig. 4).
b) Counter with built in timer for counting/timing propeller impulses at pre-set or any desired time interval (Fig. 5).
c) Counter/timer for counting and timing pre-set time intervals or pre-set number of pulses (Fig. 6).

Figure 6. Revolution counter/timer for pre-set time interval or pre-set number of impulses. Display shows simultaneously number of impulses and time (courtesy of A. Ott).

2.1.3 Sounding and Suspension Equipment

Determination of stream depth (soundings) is always done when making current-meter measurements. Therefore, suspension equipment as used in stream gauging serves the dual purpose of measuring the total depth of water and suspending the current meter at the desired points in the measuring cross section.

Sounding is commonly done mechanically, the equipment used depending on the type of measurement being made. The depth of water and the position of the current meter below the water surface are measured by means of a rigid rod or by a line attached to a weight and controlled by a gauging reel.

Soundings may also be done by means of echo-sounders. The echo-sounder is an electro-acoustic instrument which gives the depth of water by measuring the transmission time of a burst of acoustic energy from just below the surface of the water and to the reception of the echo back from the streambed. Echo-sounders are particularly useful for making rapid and accurate soundings in streams. Also, they are useful where the velocity of flow is so high that other means of sounding are difficult.

2.1.3.1 Sounding and Suspension Rods

The sounding/suspension rod, also known as *measuring* rod, is a graduated and rigid rod with a detachable foot plate (Fig. 2). The rod is used for the measurement of water depths and as a support for the current meter when gauging by wading, or from a boat or bridge up to depths of 4–5 m in velocities up to 2 m/s. The current meter is made to slide on the rod and it is fixed in position with a clamp screw. The rod has a direction pointer that is fixed to the rod with a clamp screw.

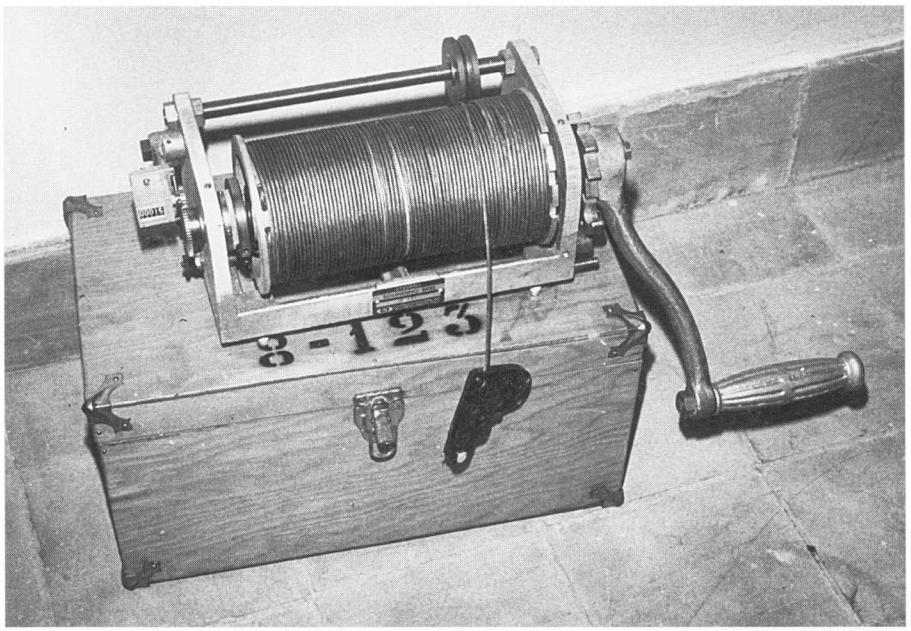

Figure 7. Gauging reel with depth counter (Stevens).

A standard rod is made of 20 mm diameter metal tubing in sections of 1 m or 2 m in length and is graduated at intervals of 10 cm. For smaller streams that can be waded, the lower 2 m portion of the rod is used only, it is then termed a *wading rod.*

2.1.3.2 Sounding and Suspension Lines

A suspension/sounding line is used when the stream is too deep and swift so a rod can not be used. The line is essentially a small calibre cable to which is attached a weight and current meter by means of a hanger bar. (Fig. 1).

Suspension and sounding lines are controlled by means of a gauging reel or a winch, or by a hand-line reel. Usually, the line also serves for the transmission of the electric-impulses from the current meter and the ground contact of the weight by an inner insulated two-conductor electric-cable.

2.1.3.3 Weights

The weight is suspended below the current meter. In this way it prevents damage to the current meter when the assembly is lowered to the streambed to determine the depth of the water. Weights are generally made in sizes of 10, 25, 50 and 100 kg and are usually made of lead. They are streamlined and furnished with tail vanes to orient them into the current. The weight may be equipped with a ground contact which produces an audible signal when the weight touches the streambed.

The higher the velocity and the greater the water depth, the heavier the weight required will have to be.

For guidance in the choice of weights, the following formula may be used

$$m = 5\bar{v}d \qquad (2.1)$$

where

m = weight of the sinker-weight (kg),
$\bar{v}$ = mean velocity (m/s),
d = depth (m).

2.1.3.4 Gauging Reels

A gauging reel consist of a drum for winding the suspension cable, a crank and ratchet for raising and lowering the current meter assembly and for holding it in a desired position, and a counting device indicating the length of line played out. (Fig. 7).

2.1.3.5 Handlines

Handlines are used for suspension of equipment and is a simple device operated by hand. It is em-

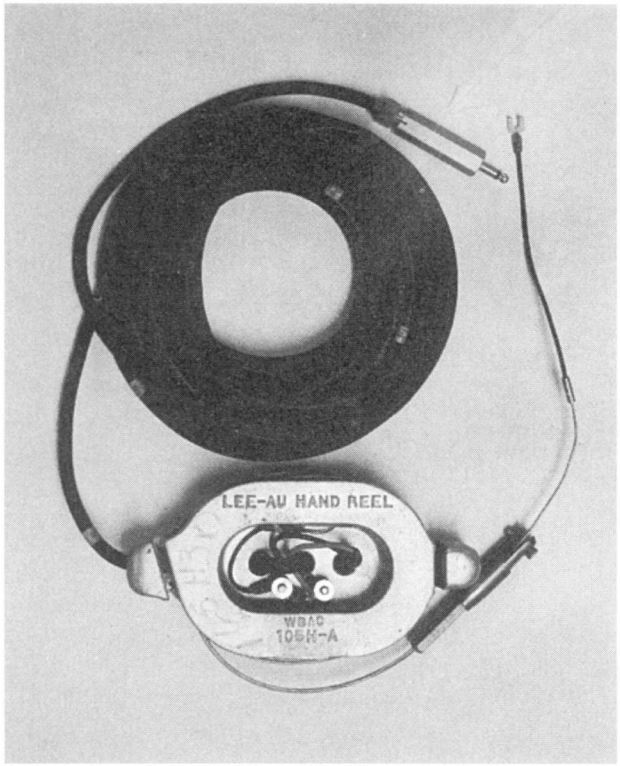

Figure 8. Handline (courtesy of the US Geological Survey).

ployed for making discharge measurements from bridges, using weights up to 20 kg and for velocities up to 2 m/s. The advantages of the handline are that it is easier to set up, eliminates the use of gauging reels and equipment to support the reel, and makes discharge measurements from bridges with vertical and diagonal members quicker and easier. The disadvantages of the handline are that it requires more physical effort, especially for deep streams, and there is a greater possibility of making errors in determining the depths. A handline consists of the following parts (Fig. 8):

a) A hand cable made up of a heavy rubber-covered two-conductor electric-cable, tagged at 0.5-metre intervals and about 10 m long,
b) Small hand reel,
c) A reverse-lay steel cable of diameter 2.5–3 mm with an inner insulated two-conductor electric-cable, about 12 m long,
d) Connector and plugs for the current meter,
e) Plugs for the electric revolution counter.

The hand cable is electrically connected to the steel cable at the hand reel. The connector joins the lower steel cable to the current-meter assembly. The steel cable in excess of the length needed to carry out the gauging is wound on the reel.

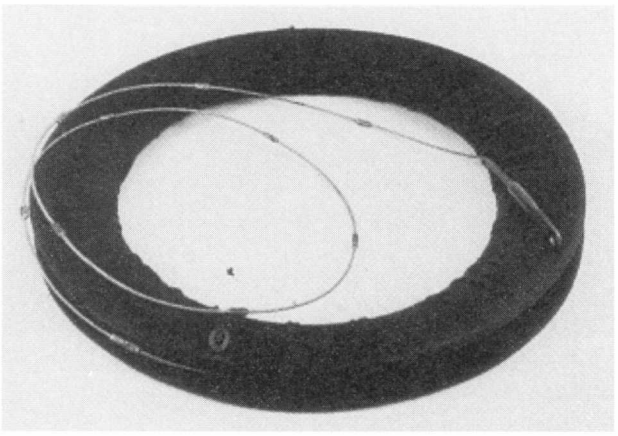

Figure 9. Tag line on canvas-reel.

2.1.4 Width Measuring Equipment

The spacing of the gauging verticals in a cross section is measured from an initial point on the bank of the stream. Cableways with manned cable car and bridges used regularly for making discharge measurements are commonly marked at 2,5 or 10 m intervals by point marks. Spacing of verticals between the markings is measured with a pocket tape. For measurements made by wading, from unmarked bridges or from boats, measuring tapes or tag lines are used.

The tag line is made of galvanised steel cable about 2 mm in diameter and brass tags at measured intervals are used to indicate the distances. The standard lengths are 25, 50, and 100 m, but other lengths can be obtained by special order. It is practical to wind the tag line on a canvas hand-reel of 20–30 cm diameter (Fig. 9).

2.1.5 Equipment for Wading Measurements

When doing wading measurements, life jacket and high boots or chest waders are required in addition to the current meter equipment, including current meter, revolution counter/timer, measuring rod, tag line, and measuring tape.

2.1.6 Equipment for Measurements from Boats

Measurements made from boats require some special equipment that is not used for other types of measurements:

a) A boat of sufficient size to support the gauging crew and the equipment,

Figure 10. Two river boats with platform laid across and tripod with winch, used for current-meter measurements and sediment sampling, powered by two 18HP engines (Karun River at Ahwas, Iran).

Figure 11. Current-meter measurement from light transportable aluminium boat using rod suspension (Halali River at Iyayi, Tanzania).

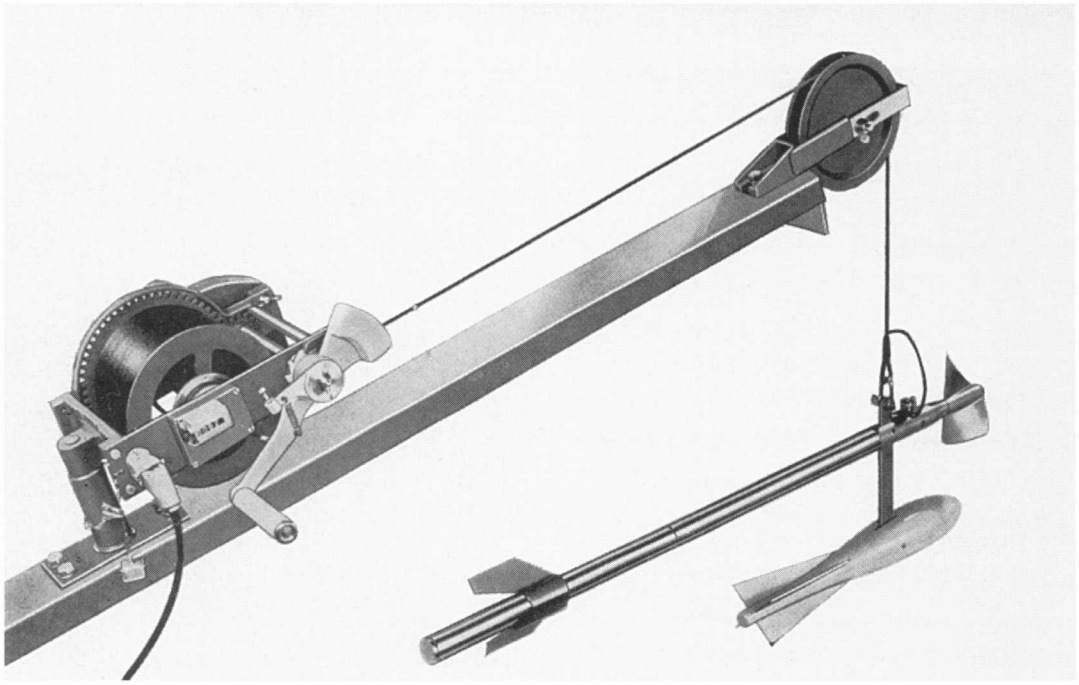

Figure 12. Small single-drum winch connected to jib for measurement from boat by cable-suspended current-meter assembly (courtesy of A. Ott).

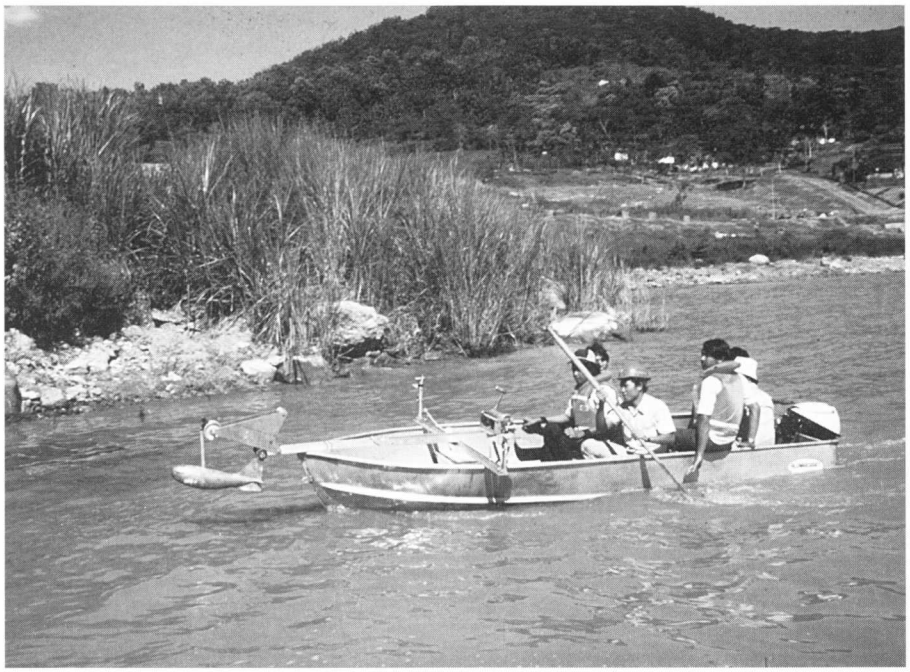

Figure 13. Small boat-crane with sediment sampler used from light aluminium boat (Cimanuk River at Jatiluhur Reservoir, Java, Indonesia).

b) Extra large tag-line reel for use on wide rivers,
c) Pair of oars,
d) Bailing device,
e) Outboard or inboard engine to power the boat.

An engine is required for gauging large rivers. The engine must be able to power the boat at a speed at least 25 % greater than the expected maximum speed of the flow. The length of the boat must be sufficient to ensure safe manoeuvrability. A simple rule for the selection of boat is

$$v = 1.3\, L^{1/2} \qquad (2.2)$$

where v is the maximum relative speed of the boat in m/s and L is the waterline length of the boat in m.

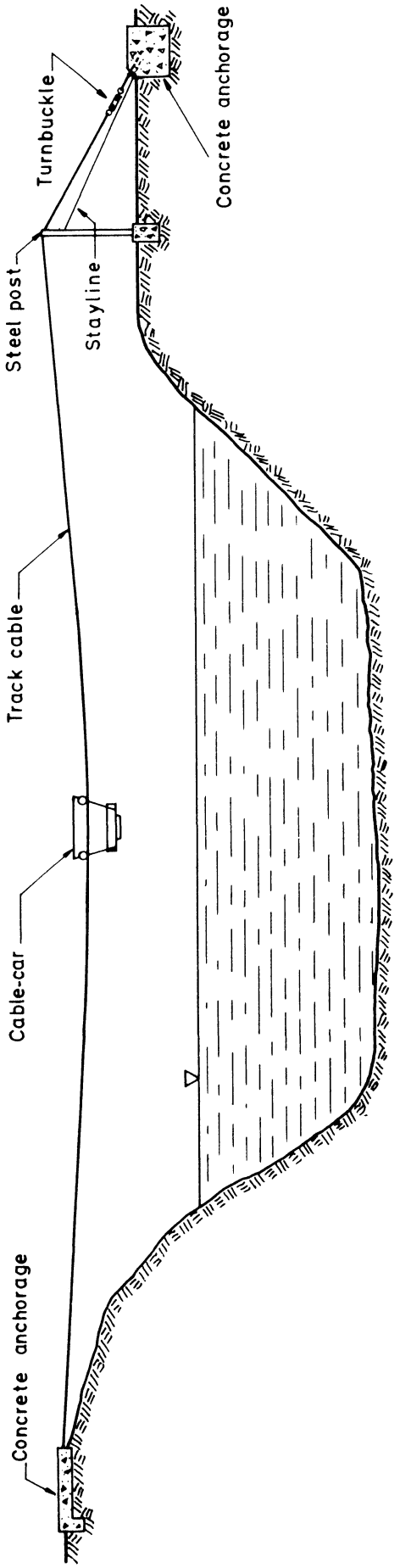

Figure 14. Large cableway with cable car for manned operation running on track cable. For current-meter measurements and sediment sampling.

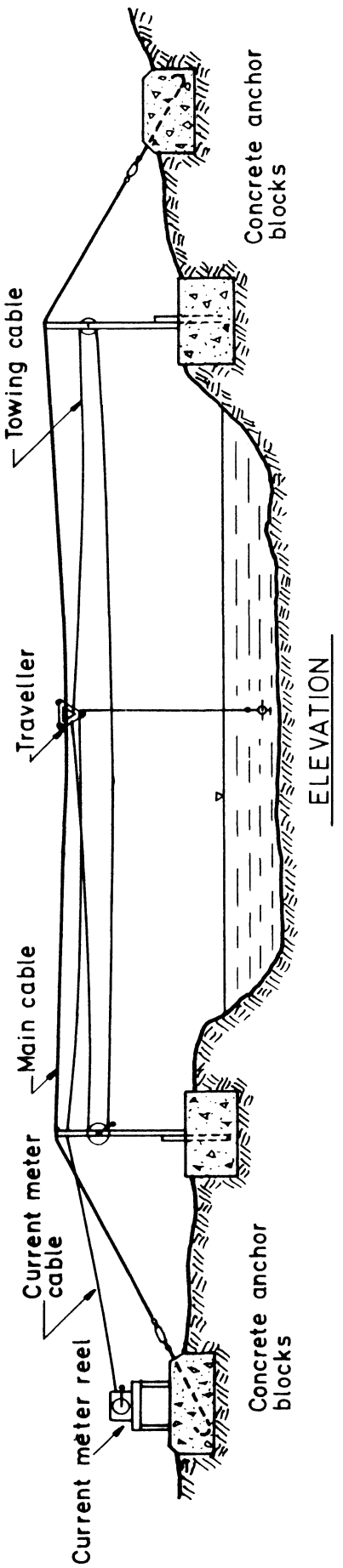

Figure 15. Large cableway operated from river bank. Current-meter is suspended from small carriage running on track cable.

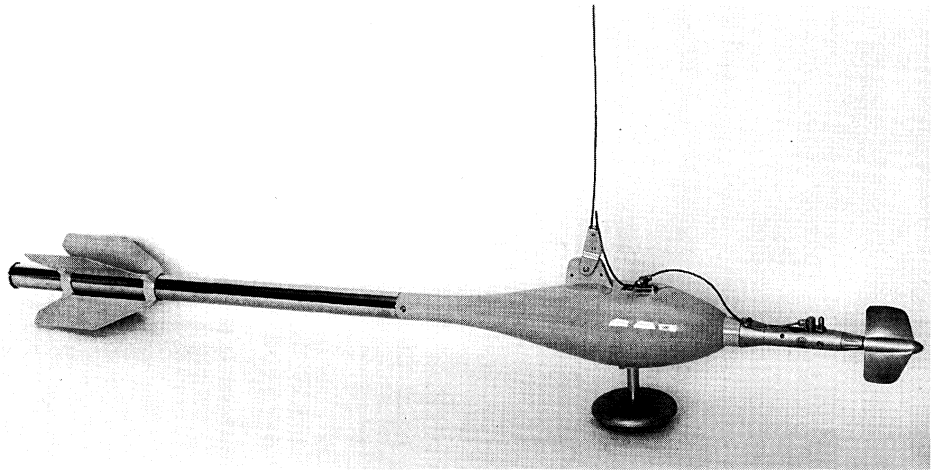

Figure 16. Heavy weight with bottom contact for use with large cableway (courtesy of A. Ott).

Fig. 10 shows a catamaran-type boat-arrangement for current-meter measurements and sediment sampling on large rivers. It is powered by two 18 HP outboard engines.

An engine is normally not required on small streams where the boat can be attached to a cable or a heavy tagline stretched across the river (Fig. 11).

In a boat measurement, the current meter may be suspended on a rod or on a cable using a bridge-board (Section 2.1.8). Specially designed extendable boat-jibs (Fig. 12) or boat-cranes (Fig. 13) are available for boat measurements. By means of a jib, the current meter may be placed and operated so as to be unaffected by any disturbance of the flow that may be caused by the boat itself.

2.1.7 Equipment for Measurement from Cableways

Current-meter measurements can be made from a manned cable car supported by a heavy track cable spanned across the river. The current meter and weight assembly is suspended on a cable from a gauging reel in the cable car (Fig. 14).

A small carriage from which the current meter is suspended can be used instead of a manned cable car. The carriage is controlled by means of a winch stationed on the bank of the river (Fig. 15). Heavy weights are used on large rivers (Fig. 16). For details of cableways, see Volume 1.

2.1.8 Equipment for Measurements from Bridges

The current meter and weight used for measuring from bridges are supported by a handline or by a gauging reel mounted on a crane or bridge board, depending on the size of the current meter assembly. The handline has been described above in Section 2.1.3.5.

2.1.8.1 Bridge Cranes

Hand-operated portable cranes for bridge measurements are commercially available and are designed so that the superstructure can be tilted forward over the bridge rail far enough to enable the current meter and weight to clear the rail (Fig. 17).

2.1.8.2 Bridge Boards

A bridge board is usually made of two planks approximately 2 m long which are joined together. It has a sheave at one end, over which the meter cable passes, and a gauging reel mounted near the other end. The board is placed on the bridge rail during the measurement. (Fig. 18).

2.1.9 Equipment for Measurements from Ice-Cover

Current-meter measurements under ice-cover require some special equipment for cutting holes in

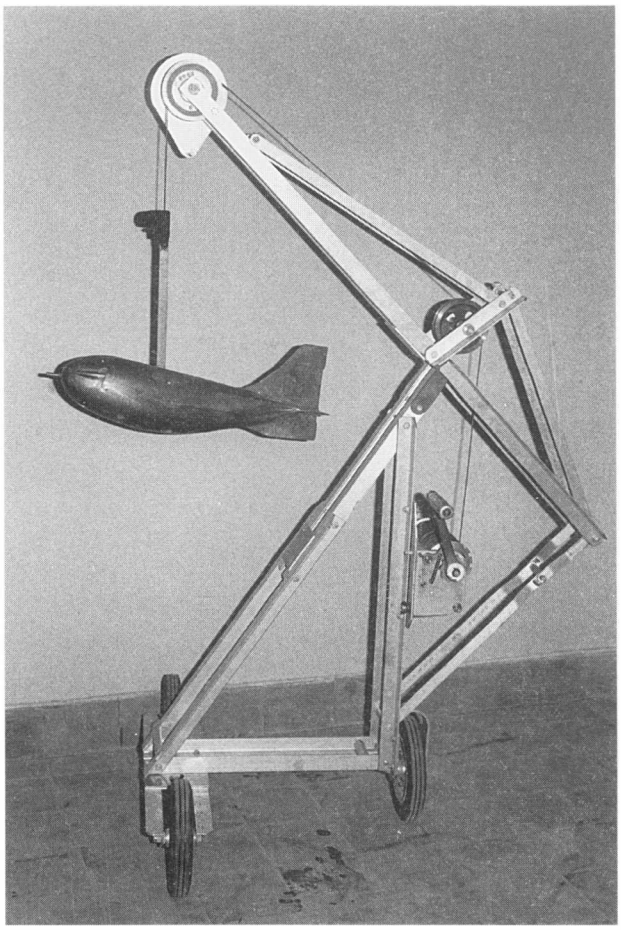

Figure 17. Bridge crane with sediment sampler.

the ice through which to suspend the current meter.

When the ice has a thickness of more than 30 cm, it is most practical to use a *power ice drill* with a cutting knife of 10–15 cm diameter. For thinner ice a light manual *ice auger* is often used. Where it is impractical to use an ice-drill or auger, ice-chisels are used to cut holes. Ice-chisels are normally 25–30 cm long and attached to wooden handles about 120 cm long, it weighs 5–6 kg.

*Ice creeper*s strapped on the soles of boots are used on steep and icy river banks. A life line anchored to the bank is used when examining if the ice is sufficiently thick to be crossed safely.

The current meter is connected to the wading rod by means of a *flap-hinge* by which it is easily raised to the horizontal position after having been suspended into the water through the hole (Fig. 19). When the total depth is greater than 3 to 3.5 m, a handline is normally used. A larger hole through the ice has then to be made for the weight.

2.2 Current Meter Measurement Sites

A prospective location for a gauging station should be examined for the availability of discharge measuring sites for the various stages to be expected. One important aspect of this examination is to be certain that there is a measuring site at low flow where the velocities are in the range where the current meter can measure them accurately. The suitability of cross sections at bridges for accurate discharge measurements at high stages and the suitability of the bridges themselves as measuring structures should also be evaluated. If there are no suitable bridges, a site for a cableway or footbridge must be chosen.

Figure 18. Bridge board.

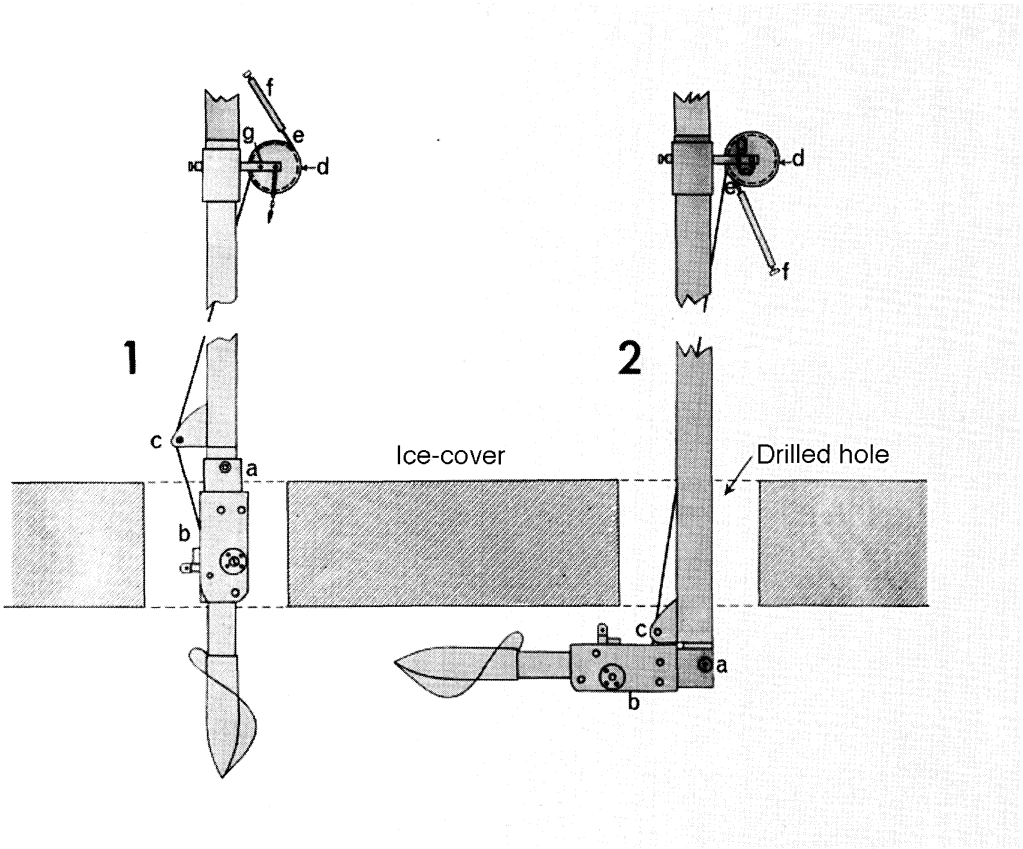

Figure 19. Flap-hinge for connecting current-meter to gauging rod when making current meter measurements from ice-cover.

In the following, some characteristics of a good gauging site are discussed. It is usually not possible to satisfy them all. However, these criteria should be used and the best site available selected.

a) A discharge measurement is generally made in conjunction with a water-level gauge on the stream. The measuring cross section must therefore not be too far from the gauge. There should not be any significant inflow to or outflow from the stream between the measuring cross section and the gauge. If this is unavoidable, corrections are made during the computation of the measurement.

   For measurements made during rising or falling stage, the channel storage in the stream itself may influence the result should there be some distance between the gauge and the measuring cross section. This is especially the case where there are water pools between the two sites. However, if there is no choice, corrections can also be made in this case.

b) The stream at the gauging site should not overflow its banks and should preferably be contained in a single channel. If this is not possible, two straight uniform channels are preferable to one defective channel.

c) The stream channel at the gauging site should be fairly straight and of uniform cross section and slope, as far as possible, in order to avoid abnormal velocity distributions. When the straight length of the channel reach is restricted, the straight reach upstream from the measuring cross section should be at least three times the width of the channel. The straight reach downstream from the measuring cross section should be not less than half of that upstream. The channel bed and banks should be firm and stable.

d) The channel should be free from large rocks, vegetation and any other protruding obstructions which will tend to cause eddies, boils, turbulence, cross currents or backward flow. Sites with converging, and especially with diverging flow, should not be used as it is difficult to allow for the systematic errors that can arise.

e) The depth should not be too shallow. For depths less than about 15 cm there will be difficulties in obtaining good velocity measurements with the use of an ordinary current meter.

f) The velocity should be neither too low nor too high. The most reliable velocity measurements are obtained at velocities between 0.2 and 2.5 m/s.

g) The general direction of flow should be perpendicular to the measuring cross section.
h) The location of cross sections that are used for discharge measurements from ice-cover, should be selected during the open low-water season when channel conditions can be evaluated.

A gauging site such as that described above is not always easy to find in natural streams. However, acceptable results are obtainable even from poor gauging sites if the gauging is done carefully and the hydrologist uses proper judgement and precaution during the measurement. Due to changes in channel conditions, that often occur, all gauging sites should be inspected regularly and restored whenever possible.

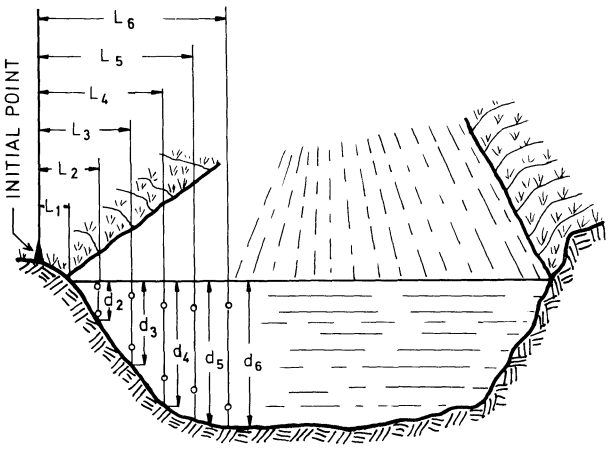

Figure 20. Up-stream view of a stream cross section showing the location of the points of observation in the 0.2/0.8 method.

2.3 Current Meter Measurement Procedures

2.3.1 General

By definition, the discharge of a stream is the product of a stream cross section and the component of the mean flow-velocity normal to that section. The mean flow-velocity is obtained by means of current-meter measurements, taken at a number of points in the cross section. Then by integrating the point-velocities over the cross-sectional area the mean flow velocity is obtained.

A current-meter measurement is explained by reference to Fig. 20 which shows a stream cross section perpendicular to the direction of flow. At a number of verticals in the cross section, the following observations are made: (a) the distance to a reference point on the bank, (b) the depth of the stream, and (c) the mean velocity in the vertical as measured by the current meter.

Discharge measurements performed by current meter are classified in five types according to the way the hydrologist crosses the river channel. The five types of measurement are:

a) By wading,
b) From boat,
c) From cableway,
d) From bridge,
e) From ice cover.

During the measurement the current meter is mounted on a measuring rod, suspended on a weighted cable which is controlled by means of a winch with depth indicator, or by a handline.

Current meter with tail-piece and vane, measuring rod with footplate and direction indicator, counter/timer, stopwatch, 10 metres measuring tape, and a 2 mm tagline 30–50 metres long and wound on a reel are equipment common to most of the measurement types.

2.3.2 Measurement of Width

The distance to the verticals and the width of the stream are measured from a fixed reference point (initial point) on the bank of the stream (fig. 20). The distances are normally determined by use of a tag line stretched across the stream, or read from the length of towing cable played out by the cableway winch.

2.3.3 Spacing of Verticals

The accuracy of a current-meter measurement depends largely on the number of verticals at which the observations of depth and velocities are made. The verticals should be spaced so as to disclose the shape of the streambed and the true mean velocity of the flowing water. Only where the velocity appears to be typically distributed (Fig. 22), and where the profile of the cross section is reasonably regular and smooth, is it desirable to space the verticals at equal intervals throughout the measuring cross section. At two adjacent verticals, neither the depth nor the velocity should differ excessively. The interval between any two verticals should not be more than 1/20 of the total width and the discharge between any two verticals should be in the order of 5–10 % of the total discharge. Normally, the number of verticals required is between

20 and 30. For very small streams, the number of verticals can be reduced if the distance between them becomes less than 30 cm.

2.3.4 *Measurement of Depth*

The depth of the vertical and the position of the current meter in the vertical are measured by the graduated wading rod on which the current meter slides, or by the suspension line or cable on which the current meter and the streamlined weight are suspended. The suspension cable is controlled by a gauging reel or winch with a depth indicator as already discussed.

In order to obtain accurate depths, the sinker weight is equipped with an electric-bottom-contact which gives a signal when the weight touches the streambed. If the weight is not sufficiently heavy to keep the suspension line within 4° of the perpendicular to the water surface, the angle between the suspension cable and the vertical should be measured to the nearest degree with a protractor. The angle should not exceed 30°.

Methods of correcting measured depths for excessive drift of the current-meter assembly in swift water are given in the following section. However, one should not rely on the possibility that corrections can be applied. The accuracy of the measurement is improved if a sufficiently heavy weight could be used to maintain the suspension cable in a nearly vertical position during the measurement.

2.3.4.1 Depth Corrections

When current-meter measurements are made with a cable-suspended current meter in deep, swift water, the current meter and the weight will be carried downstream a certain distance before the weight touches the bottom. This is often the case when measurements are made from a bridge or cableway, which usually are at some vertical distance above the water surface. In such cases, corrections have to be applied in order at determine the correct depth of the water and the depth to which the current meter should be suspended during the observation.

Fig. 21 shows the position assumed by the suspension cable as the weight, just off the bed of the stream, is supported by the line only. It is seen that from the length of line *af*, the distance *ae* and the difference between the lengths of *ef* and *bc*, must be deducted in order to determine the depth *bc*, assuming the streambed *cf* is horizontal. Both these corrections are functions of the vertical angle Θ and are given in Tables 1 and 2 [37].

The values in Table 1 and 2 are based on the assumptions that the drag force on the weight in the comparatively still water near the bottom can be neglected and that the sounding line and weight are designed to offer little resistance to the flow of water. The uncertainty in these assumptions are such that significant errors may be introduced if the vertical angle Θ is more than 30°. If the direction of flow is not normal to the measuring cross section, the corrections as shown in the two tables will be too small.

The same conditions that cause errors in sounding the depth of the stream also cause errors in placing the current meter at the selected depths in the vertical. The correction tables are not strictly applicable to the problem of placing the current meter because of the increased drag force on the current-meter assembly caused by the higher velocities encountered as the current-meter assembly is raised from the streambed. A current meter placed in deep, swift water by the ordinary methods for observation at selected fractions of the depth, will be too high in the water. The use of the correction tables will tend to eliminate this error and although not strictly applicable, its use has become general for this purpose.

The routine procedure for applying depth corrections is as follows (Fig. 21):

a) Measure the vertical distance *ab* from the guide pulley on the gauging reel to the water surface. This will give the vertical distance to be used with the air-line correction table. (Table 1).
b) Place the bottom of the weight at the water surface and set the depth counter on the gauging reel to read zero.
c) Lower the weight to the bed of the stream. Read and record the sounded depth *df* and the vertical angle Θ of the cable when the weight is at the bed of the stream, but entirely supported by the cable.
d) With the aid of Table 1 and 2 compute and record:

   i) The air correction *de* as a percentage of *ab* (Table 1),
   ii) The wet-line depth, *ef* = *df-de*,
   iii) The wet-line correction as a percentage of *ef* (Table 2).
   iv) Add both corrections together and subtract them from the sounded depth *df*. This will give the revised depth *bc*.
   v) Raise the current meter from the sounding

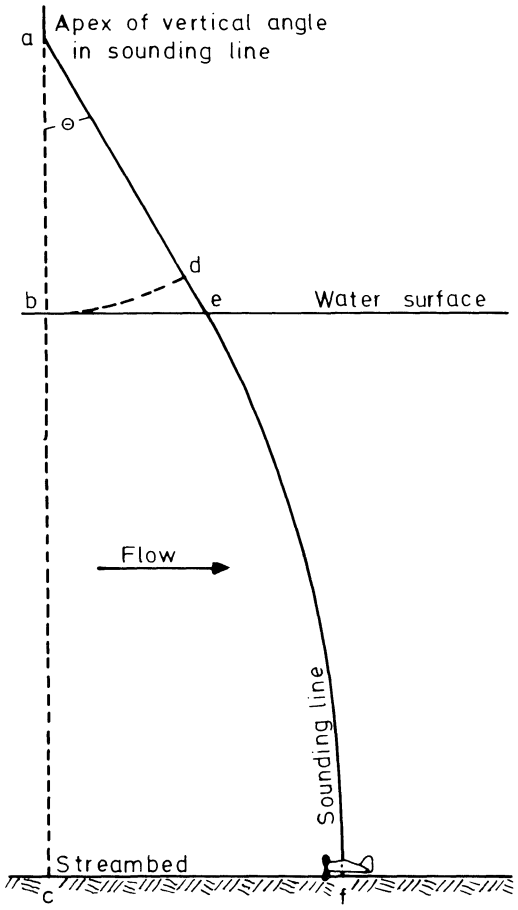

Figure 21. Position of sounding line and current-meter assembly in deep, swift water.

position at the streambed a distance equal to 0.2 of the wet-line depth *ef* minus the distance from the current meter to the bottom of the weight. This places the current meter approximately at the 0.8 depth position.

vi) Raise the current meter to the surface of the water and set the depth counter to read zero. Then lower the current meter until it is at a distance equal to *ae* plus 0.2 of the wet-line depth *ef*. This places the current meter approximately at the 0.2 depth position.

Table 1. Air-line correction [37]

Vertical angle degrees	Correction %	Vertical angle degrees	Correction %
4	0.24	18	5.15
6	0.55	20	6.47
8	0.98	22	7.85
10	1.54	24	9.46
12	2.23	26	11.26
14	3.06	28	13.26
16	4.03	30	15.47

Table 2. Wet-line correction [37]

Vertical angle degrees	Correction %	Vertical angle degrees	Correction %
4	0.06	18	1.64
6	0.16	20	2.04
8	0.32	22	2.48
10	0.50	24	2.96
12	0.72	26	3.50
14	0.98	28	4.08
16	1.28	30	4.72

Another method that is used for correction of the total depth measured, is to survey the bed profile of the measuring cross section at low-water. The bed profile is related to an auxiliary staff-gauge placed in the cross section. In this way, by reading the staff gauge, the correct depth is obtained for any position in the cross section at any stage. Depth corrections for the different points of observation in the vertical are done by multiplying the observed depth by the ratio of true depth of water to the observed depth of water. This method is probably the best for streams with stable beds.

2.3.5 Methods of Measuring Mean Velocity in the Vertical

Methods used for measuring the mean velocity of flow in the verticals are [3]:

a) 0.2 depth method,
b) 0.6 depth method,
c) 0.2 / 0.8 depth method,
d) 0.2 / 0.6 / 0.8 depth method,
e) Five Point method,
f) Six Point method,
g) Vertical Velocity-Curve method,
h) Surface Velocity method.

2.3.5.1 The 0.2 Depth Method

In this method the velocity is observed at 0.2 of the depth below the surface. The observed velocity is multiplied by the factor 0.87 to obtain an estimate of the mean velocity in the vertical.

This method is mainly used during high floods when fast flow and drift of the current meter assembly makes it difficult to obtain velocities deep-

er in the cross section. It is used when measuring from a cableway or a bridge. When the measurement is made from a bridge, the current meter is commonly fixed under a suitable small raft which is controlled by a line from the bridge.

2.3.5.2 The 0.6 Depth Method

The velocity is observed at 0.6 of the depth below the surface. According both to theory and experience the velocity at this point is a fair approximation of the mean velocity in the vertical. The method requires undisturbed velocity distribution in the vertical (Fig. 22).

The 0.6 method is mainly used under the following conditions:

a) When the depth of flow is too small for other methods to be used,
b) When time is short and the gauging has to be quickly finished,
c) When the water level is rapidly changing.

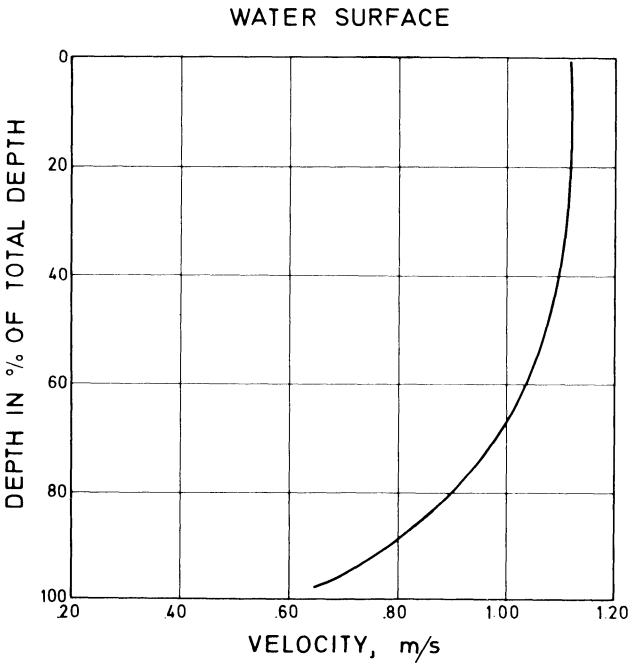

Figure 22. Typical vertical-velocity distribution curve in undisturbed flow.

2.3.5.3 The 0.2 / 0.8 Depth Method

The velocitiy is observed at 0.2 and 0.8 of the depth below the surface. The mean of these two velocities gives a good approximation of the mean velocity in the vertical.

The method is based on many investigations of natural river channels and on hydrodynamical theory.

The method rests on the assumption of undisturbed velocity distribution in the vertical. Where the stream is too shallow so the propeller comes too close to the bottom, or breaks or disturbs the water surface, the 0.6 method is used. Generally, the minimum depth for use of this method is 60 cm.

2.3.5.4 The 0.2 / 0.6 / 0.8 Depth Method

The velocitiy is measured at 0.2, 0.6, and 0.8 of the depth under the surface. This method is a combination of the 0.6 method and the 0.2 / 0.8 method. The mean velocity in the vertical is taken as equal to the mean of the 0.2 and 0.8 velocities, added to the 0.6 velocity, and the result divided by two.

This method is used when the velocity in the vertical is undisturbed, refer Fig. 22, and the depth is greater than 75 cm. In disturbed flow, the five-point or six-point method is used.

2.3.5.5 The Five-Point Method

The velocitiy is observed at the depths 0.2, 0.6, and 0.8 of the depth below the surface, and at one propeller diameter below the water surface and one propeller diameter above the river bed.

The mean velocity in the verticals is determined by Eqn. (2.3), or by graphical integration.

$$\bar{v} = 0.1(v_{surface}+3v_{0.2}+3v_{0.6}+2v_{0.8}+v_{bed}) \quad (2.3)$$

The procedure of the integration method is as follows, refer Section (2.4.3):

Firstly, draw up the depth-velocity curve for each vertical on graph paper by plotting the velocity observations against their corresponding depths, draw a smooth curve through the points.

Secondly, measure the area contained by the depth-velocity curve, its vertical, and the water surface by means of a planimeter, or simply by counting it up by use of a draftman's dividers. This area represents the mean velocity in the vertical.

This method is used in disturbed flow that causes atypical velocity distribution in the verticals.

2.3.5.6 The Six-Point Method

The velocity is observed at the depths 0.2, 0.4, 0.6, 0.8 of the total depth, and at one propeller diameter below the water surface and one propeller diameter above the river bed.

The mean velocity in the verticals is determined by a graphical integration, or from the equation:

$$\bar{v} = 0.1(v_{surface}+2v_{0.2}+2v_{0.4}+2v_{0.6}+ 2v_{0.8}+2v_{bed}) \quad (2.4)$$

This method is used when the velocity distribution in the measuring section is very irregular.

2.3.5.7 The Vertical Velocity-Curve Method

In this method the velocity is observed at 10 points regularly distributed between the water surface and the riverbed in each vertical, as follows:

One propeller diameter below the water surface,
0.2 of the depth
0.3 ”
0.4 ”
0.5 ”
0.6 ”
0.7 ”
0.8 ”
0.9 ”
One propeller diameter above the river bed.

This method with 10 observation points in each vertical is too time-consuming for general use. It is mainly used for control of other methods that have less points, and for an exact determination of the velocity-distribution in the verticals and/or in the measuring cross section.

The computation of the measurement is done by graphical integration, see Section 2.3.5.5 and 2.4.3

2.3.5.8 The Surface Velocity Method

If an optical current meter is available (refer Volume 1), the surface velocity method is used in preference to the 0.2 method. In a natural channel a surface velocity coefficient of 0.85–0.86 is used to compute the mean velocity on the basis of equation (8.1) in Volume 1.

2.3.5.9 Typical Vertical Velocity Curves

Intensive investigations of vertical velocity curves have shown that the following equation can be used to calculate average velocities of the vertical velocity curve [3]

$$v_d = ((D-d)^{1/c})/a \quad (2.5)$$

where v_d is the velocity at depth d, D is the total depth, and c is a constant varying from 5 for coarse beds to 7 for smooth beds, generally taken as 6.

2.3.5.10 Velocity Corrections

The *angle of the curr*ent, as applied to stream gauging, is the difference between the normal to the measuring cross section and the horizontal angle made by the current with the measuring cross section. To eliminate errors introduced by such angles, it is necessary to obtain the horizontal component of the velocity normal to the cross section.

The method by which this angle is corrected depends on the type of current meter used. A vertical-shaft cup-type current meter, if supported on a rod, will measure the full velocity in the direction in which the water is flowing and not in the direction represented by the horizontal axis of the current meter. The horizontal-shaft propeller-type current meter, when supported on a rod, will in oblique flow measure the velocity component normal to the measuring section when held rigidly at right angles to the section, as discussed in Section 2.1.1.2.

If oblique current is unavoidable at one or more of the measuring verticals, the velocity-component normal to the measuring cross section must be obtained. The velocity in the direction of the current is then measured and the angle of deflection is read by a protractor. If no protractor is at hand, the angle can be measured by holding the note sheet parallel with the cross section, and with a ruler lined up with the direction of the current, drawing a line whose angle with the normal is later measured with a protractor.

The measured velocity, when multiplied by the cosine of the angle of the current, will give the velocity-component normal to the measuring cross section. For small angles, the correction will be negligible. When the angle is no more than 8 degrees, the correction is less than 1 % and may be ignored.

Propeller-type current meters with a component propeller will accurately measure the velocity

component normal to the measuring cross section in oblique flow and there will be no need for corrections, provided the current meter is held rigidly at right angles to the cross section.

The horizontal axis of either type of current meter suspended from a cable will take the mean direction of the current.

2.3.6 *Current Meter Measurements*

When the width of the measuring cross section has been measured and the positions of the verticals in the cross section have been determined, the appropriate equipment for the current-meter measurement is assembled and the measurement notes are prepared in order to record the observations. See Appendix A for examples of these forms and instructions for filling them in. For each current-meter measurement the following information is recorded:

a) Name of the stream.
b) Name and ID number of the gauging station.
c) Date.
d) Time and gauge height at the start and end of the measurement.
e) Type and serial number of the current meter and of the rotor.
f) Spin time of the rotor before and after the measurement.
g) Type of measurement (wading, cableway, bridge or boat) and method of supporting the current meter (rod or cable suspension).
h) Method of velocity measurement (the 0.6 depth method, the 0.2/0.8 depth method, etc).
i) Name of the hydrologist.
j) Other pertinent information regarding the accuracy of the discharge measurement and conditions which might affect the stage-discharge relation.

Once the equipment and the measurement notes have been prepared, the measurement is started. Record from which bank, right bank (RB) or left bank (LB), the measurement is started and the distance from the initial point on the bank to the edge of the water. Measure and record the depth at the water edge, in natural streams this depth is normally zero.

Move to the first vertical. After the depth of the vertical has been measured and recorded, determine the method for the velocity observation, refer Section 2.3.5. Record the depth of observation (position of the current meter). After the current meter is placed at the correct depth, allow it to become adjusted to the current before starting the observation. The time required for such adjustments is normally a few seconds. If the velocity of flow is low or the current meter is suspended on a cable, a longer adjustment period is needed.

After the current meter has become adjusted to the current, start the counter/timer and record the number of revolutions made by the rotor during a period of normally 60 seconds. If actual counting is done, start the stop watch at the end of a signal (buzz) and stop it at the end of a signal.

If the velocity is to be observed at more than one point in the vertical, determine the current meter setting for the additional observations, time the revolutions and record the data. Move to each of the verticals and repeat the procedure: Record the distance from initial point, the depth, depth of the current meter position, revolutions and time interval, until the entire cross section has been traversed.

When the measurement has been completed in this way, record the time, the gauge height and at which bank of the stream the measurement ends.

The spin time of the rotor at the end of the measurement is checked and recorded.

During the course of a discharge measurement made when the stream stage is changing, record the time and the gauge height periodically, usually at intervals of 30 minutes. This is important, because if there is any appreciable change in stage during the measurement, these data are needed in order to determine a weighted mean gauge-height for the measurement, refer Section 2.4.4.

When the first measuring traverse has been completed, a second measurement is made when crossing the stream back. The second measurement is made independently of the first. The verticals for the second measurement are placed approximately midway between the verticals of the first measurement. The average value of the two measurements is taken as the true discharge. Should the difference exceed 4 %, a third measurement is made and the average of the two closest are used.

2.3.6.1 Measurement by Wading

Current-meter measurements by wading are preferred if the conditions permit. Wading measurements offer an advantage over measurements from bridges and cableways in that it is usually possible to select the best of several available cross sections. (Fig. 23).

In this type of current-meter measurement, the hydrologist uses either high boots or chest waders

Figure 23. Wading measurement with current meter suspended on wading rod (Kisigo River, Tanzania).

when crossing the river and doing the observations. The first step is to check the measuring cross section and remove any stones and debris that could affect the accuracy of the depth and velocity observations. All this work should be done before the measurement is started and nothing must be shifted or removed from the streambed while the measurement is being made. Selection of the measuring cross section for wading measurements is important, because the effects of minor irregularities in the stream channel at the lower stages, in which wading measurements are normally carried out, are relatively much greater than at the higher stages.

A tag line or tape is spanned across the measuring cross section at right angles to the general direction of the flow. If the same measuring cross section is used always, the cross section should be defined by clearly visible markers, one on each bank, for holding the tag line and for easy identification. While placing the tag line, the hydrologist should obtain a general idea of the proper spacing of the measuring verticals by observing the width of the cross section and the geometry of the streambed. The first velocity observation is taken close to the bank.

With the current meter supported on a graduated wading rod, the velocity observations are taken at the appropriate distances along the tag line keeping the rod in a vertical position. The hydrologist should stand in a position that affects the flow of water passing the current meter as little as possible. This position is usually obtained by standing a little downstream of the tag line, facing the bank with the water flowing against the side of the leg and holding the rod at the tag line at arm's length.

When gauging streams with shifting bed, the hydrologist's feet can affect soundings and velocities. Generally, the current meter should be placed ahead of and upstream from one's feet.

The limiting factors for wading measurements are determined by both depth and velocity and may be expressed in terms of the product of these two quantities. In general, it may be stated that even with good footing, this product should not exceed 1, thus

$$d \times \bar{v} < 1$$

where d is the depth at the vertical and is the mean velocity in the vertical.

For example, if the mean velocity is about 1 m/s, measurements may ordinarily be made by wading in depths of up to 1 metre. For the lower velocities, the depth at which wading measurements can be made will be determined by the stature of the hydrologist.

When the conditions for making current-meter measurements at the gauging site are unfavourable at low-water, then modify the measuring cross section, if possible, to improve the conditions. It is often possible to build small dikes in order to cut off dead water and shallow flows, or to improve the cross section by removing rocks and debris within the section and from the reach immediately upstream from it. After modifying the cross sec-

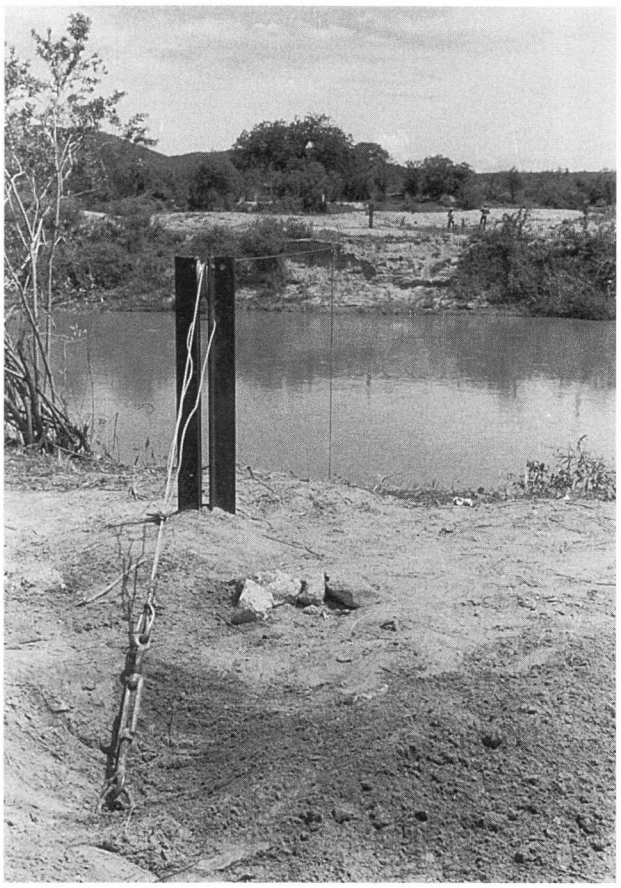

Figure 24. Permanent cable for supporting light boat during current-meter measurement. Posts are made of two angle-irons bolted together and concreted into the ground, anchorages consists of concrete blocks buried in the ground (The Great Ruaha upstream of Mtera Bridge, Tanzania).

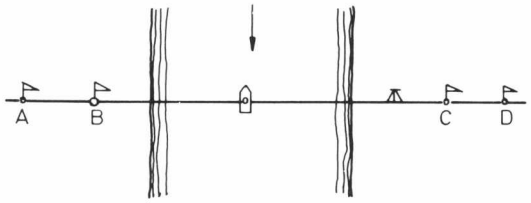

Figure 25. Fixing position of boat by transit during discharge measurement.

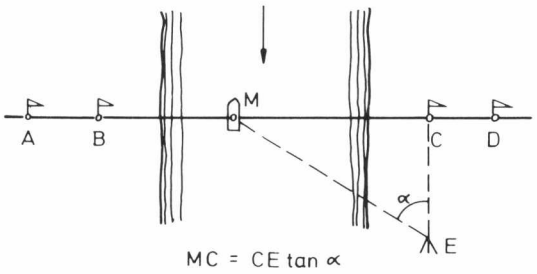

Figure 26. Fixing position of boat by transit from E during current meter measurement, Angular method.

tion, the flow must be allowed to stabilize before starting the current-meter measurement.

For measurement of flow too small to be measured by a current meter, a volumetric method, or a small portable Parshall flume or V-plate weir is often used.

2.3.6.2 Measurement from Boat

Discharge measurements taken from a boat is a common way of measuring discharges when the stream is too deep to wade. One limiting factor in the use of boats is high velocity of the water, as personal safety must be considered.

A heavy tag line is spanned across the river at the measuring section. The tag line serves the dual purpose of holding the boat in position during the measurement, and of measuring the width of the river and positioning the measuring verticals.

The tag line is wound on a reel which is operated from the stern of the boat as the boat is propelled across the river. On the bank, the slack of the cable is taken up by means of a block and tackle attached to the reel and to a tree or an anchored support on the bank.

If there is boat traffic on the river, one man must be stationed on the bank to lower and raise the tag line to allow the traffic to pass. Streamers should be fixed on the tag line so that it may be seen by boat pilots.

A permanent supporting cable spanned across the river will often prove advantageous. This method is less laborious and safer for the personnel performing the measurement, especially at high water conditions. A permanent cable must be constructed well above the highest flood stage to be expected (Fig. 24).

If there is a continuous flow of traffic on the river, or if the river is too wide to be spanned by a wire, the boat can be kept in the measuring cross section by anchoring it up in line with flags positioned on the river banks. The distance from the bank to the boat can be read directly by means of a transit on line on the shore and a stadia rod held vertically in the boat (Fig. 25). The transit may also be placed in a line at right angles to the cross section some known distance from it, and by measuring the angle the boat makes with this line the position may be calculated by triangulation (Fig. 26).

Figure 27. Large cableway for manned operation (Karun river near Ahwas, Iran).

Figure 28. Current-meter measurement being made from manned cableway (courtesy of S. Roen). Dez River at Tang-e-Panj, Iran.

Figure 29. Cableway with current-meter carriage operated by gauging-winch stationed on river bank (Malagarasi River at Mbelagule, Tanzania).

2.3.6.3 Measurement from Cableway

Current-meter measurements are often made from a permanent heavy track cable spanned across the river where a good measuring cross section has been located (Fig. 27). The current meter is suspended from a manned cable car running on the track cable and with capacity to carry the hydrologist and his equipment (Fig. 28).

The current meter may also be suspended from a small carriage which is operated from the bank by a gauging winch (Fig. 29). Because the cableway is installed permanently, the measuring cross section can not be changed, but it should be checked and if necessary cleared during the dry season months.

2.3.6.4 Manned Cableway

Regarding cableways generally, see Volume 1, Section 5.9.

The manned cable car is provided with a support for the gauging reel, a guide pulley for the suspension cable, and a protractor for reading the vertical angle (Fig. 30). The gauging procedure is as follows:

a) The water's edge is identified in relation to a permanent initial point on the bank by means of a tag line or by use of painted marks on the track cable.
b) The current meter and the weight are lowered at the first vertical until the bottom of the weight touches the water surface. The depth counter is set to zero.
c) The current-meter assembly is lowered until the weight touches the streambed. The length of cable played out is read and the sounded depth is recorded.
d) If necessary, the air-line and the wet-line corrections are computed and the revised depth recorded, refer Section 2.3.4.1.
e) Next, the velocities are measured at the selected depths in the vertical.
f) If there is floating drift in the stream channel, the current meter should be raised occasionally for control and cleaning. This is always done if there is a sudden drop in the velocity as indicated by the revolution counter. The channel upstream from the gauging section should be watched closely for any driftwood or material which could damage the current meter.

It is advisable to carry a pair of cutter pliers when gauging from a cable car. If the current-meter as-

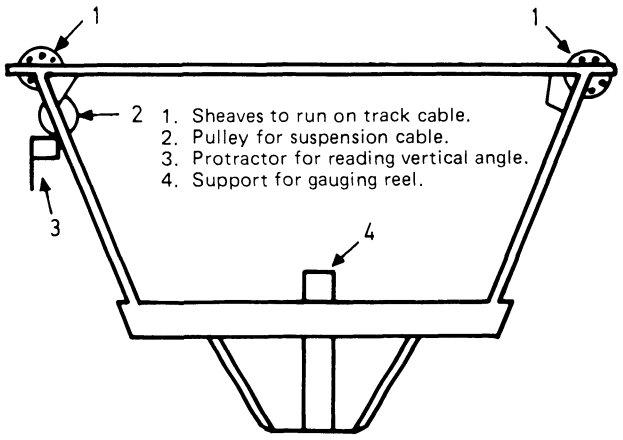

Figure 30. Two-man cable car for manned cableway.

sembly becomes caught on large floating objects and it is impossible to release it, cut the current-meter suspension cable to ensure personal safety. In some cases, it may be possible to pull the cable car to the river bank and release the drift.

One problem encountered when observing velocities from the cable car is that moving the car from one vertical to the next, makes the car oscillate for a time after coming to a stop. Needless to say, one must wait until the oscillations have subsided before starting the measurement.

2.3.6.5 Cableways with Instrument Carriage

The gauging procedure with an instrument carriage is the same as that for the cable car with the exception that only the current meter and the weight are travelling on the track cable. The hydrologist stays on the bank and operates the gauging winch. The winch is provided with both distance and depth counters for placing the current meter at the desired positions. The electric-impulses from the current meter are returned through the core conductor of the suspension cable.

2.3.6.6 Measurement from Bridge

Highway or railway bridges may often be utilized for current-meter measurements. However, measurements from bridges are normally less accurate than other types of measurements. Contracted sections, piers and other obstructions affect the distribution of the velocity and it is therefore necessary to use a larger number of verticals as well as more observation points in each vertical, especially close to the bridge piers. There are two types of bridge measurements, either by rod or line suspension.

2.3.6.7 Rod Suspension from Bridge

Foot bridges may sometimes be used for gauging small streams. Although the procedure for low velocities may be the same as for a wading measurement, at higher velocities it is often advisable to measure the depth in the following manner:

a) For each vertical, a point is established on the bridge gangway or on the rail.
b) With this point as an index, the distance to the water surface is measured by lowering the suspension rod until the base plate touches the water.
c) The rod is then lowered to the bottom of the stream and the rod reading is again noted at the index point. The difference in the readings is the depth of water at the vertical.

Measuring the depth in this manner tends to eliminate errors that may be caused by the piling up of water on the upstream face of the rod.

The natural flow of water is not disturbed when measuring from a foot bridge, as may be the case when measuring from a boat.

2.3.6.8 Cable Suspension from Bridge

From higher bridges and at greater depths, the current meter and weight have to be suspended on a cable. The cable is controlled by a gauging reel mounted on a bridge crane (Fig. 31) or on a bridge board (Fig. 32). A handline may be used with the smaller weights. The gauging procedure is essentially the same as that for measurements from a cable car.

No set rule can be given for selecting the upstream or downstream side of a bridge for discharge measurements. The advantages of using the upstream side of the bridge are:

a) The hydraulic conditions at the upstream side of the bridge are normally more favourable.
b) Approaching drifts can be seen and avoided more easily.
c) The streambed at the upstream side of the bridge is not likely to be scoured as badly as the downstream side.

The advantages of using the downstream side of the bridge are:

a) Vertical angles are easily measured on the downstream side as the suspension cable will move away from the bridge.

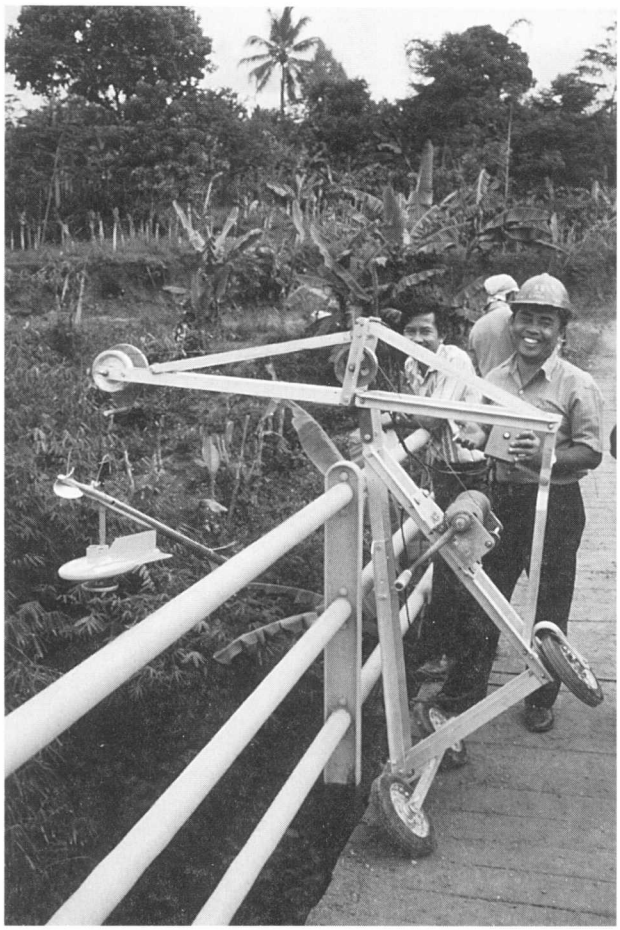

Figure 31. Current-meter measurement from bridge using bridge-crane (Cirnameh River at Nanjung, Java, Indonesia).

Figure 32. Current-meter measurement from bridge using bridge-board (Cimanuk River at Leuwingoong, Java, Indonesia).

b) The streamlines may be straightened out when passing through a bridge opening with piers.

Whether to use the upstream or the downstream side of a bridge for a current-meter measurement is decided individually for each bridge after considering the factors mentioned above and the conditions at the bridge such as location of the walkway and traffic hazards.

2.3.6.9 Measurement from Ice-Cover

Current meter measurements on ice-covered rivers require warm clothing and shoes, and carefulness.

Making hole in the ice for the measuring verticals is best done using a power drill when the ice is thick. For ice less than about 30 cm thick a hand auger and an ice-chisel are often the most practical tools.

Holes are made first over the deepest part of the river, after which the holes towards the banks are made. This in order to easily locate where the river is frozen solid to the bottom, thereby saving oneself for unnecessary work and the drilling equipment from hitting stones at the bottom damaging the cutting edge.

At low temperatures (less than -10°C), the holes should be made one at a time and the velocity observations in each vertical completed before the next hole is opened.

The current-meter is connected to the suspension rod by means of a flap-hinge (Fig. 19) and suspended through the hole while the meter is hanging with propeller down, after which the meter is raised and placed at the measuring position. During the observations the rod is rested against the edge of the hole.

To prevent the current meter from icing up, it must be kept inside the car during transport and in a temperate room outside working hours. During measurements, the meter should be kept in the water, except when moving it (quickly) from one hole to the next. (Refer Section 3.11)

2.4 Computation of Current Meter Measurements

Current meter measurements are computed either arithmetically or graphically. Choosing between these two methods depends upon the accuracy required, the nature of the stream, and the working conditions and training of the hydrologist. The arithmetical method is rapid and is particularly useful when computations must be carried out in the field. The graphical method is more laborious but increases the accuracy of the computation and gives a more comprehensive insight into the flow pattern at the gauging site.

2.4.1 Arithmetical Mid-Section Method

The method consists essentially of: (a) dividing the total area of the cross section into partial sections and determining the area and the mean velocity of each partial section separately, (b) computing the discharge in each partial section as the product of the velocity and the area, and (c) summing up the partial discharges to obtain the total discharge.

The mid-section method is explained in detail by reference to Fig. 33, which shows a cross section of a stream channel. The discharge passing through a partial section is computed as

$$q_4 = v_4\left(\frac{(L_4-L_3)+(L_5-L_4)}{2}\right)d_4 = v_4\left(\frac{L_5-L_3}{2}\right)d_4 \quad (2.6)$$

q_4 = discharge through partial section 4,
v_4 = mean velocity in vertical 4,
L_3, L_4, L_5 = distance from initial point to verticals 3, 4 and 5,
d_4 = depth of water at vertical 4.

The area which is defined by this formula is that shown by the x-line around vertical No. 4 in Fig. 33.

The equation for partial section 1 at the beginning of the cross section is

$$q_1 = v_1\left(\frac{L_2-L_1}{2}\right)d_1 \quad (2.7)$$

For the case shown in Fig 33, q_1 would be zero because the depth and therefore the velocity at vertical No. 1 is zero. However, when the cross section boundary is vertical at the edge of the water, the depth is not zero and the velocity at the edge of the water may or may not be zero. In such cases, it is usually necessary to estimate the velocity at the end vertical as some percentage of the preceding or subsequent vertical, because it is often impossible to measure the velocity accurately, as the current meter will be affected by the closeness to the boundary and there is also the possibility of damage to the current meter. In most cases, however, the flow through the end sections may be neglected if care is taken to space the verticals so that this flow is very small in comparison with the total flow.

The summation of the discharges for all the partial sections is the total discharge of the stream. The computation procedure for the mid-section method is illustrated in Appendix B.

2.4.2 Arithmetical Mean-Section Method

The mean-section method differs from the mid-section method in the computation procedure. Partial discharges are computed for the section between successive verticals. The velocities and depths at successive verticals are each averaged, the discharge being the product of the two averages and the distance between the verticals.

The method is explained in detail by reference to Fig. 34. The discharge passing through a partial section is computed as

$$q_{3-4} = \left(\frac{v_3+v_4}{2}\right)\left(\frac{d_3+d_4}{2}\right)(L_4-L_3) \quad (2.8)$$

where

q_{3-4} = discharge through partial section 3–4,
v_3, v_4 = mean velocity in verticals 3 and 4,
d_3, d_4 = mean depth of verticals 3 and 4,
L_3, L_4 = distance from initial point to verticals 3 and 4.

The computation procedure for the mean-section method is shown in Appendix C.

The mid-section method is simpler to compute and is a slightly more accurate procedure than the mean-section method.

2.4.3 The Graphical Integration Method

The procedure for the graphical integration method is as follows (Fig. 35):

Firstly, draw up the graphical integration curve for each vertical on graph paper by plotting the velocity observations against their corresponding

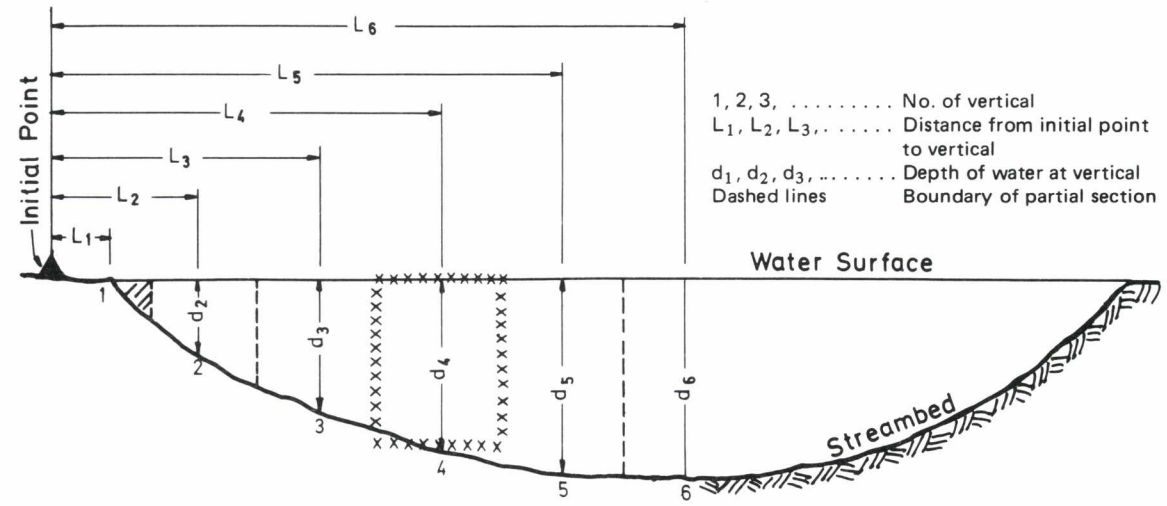

Figure 33. The mid-section method of computing current-meter measurements.

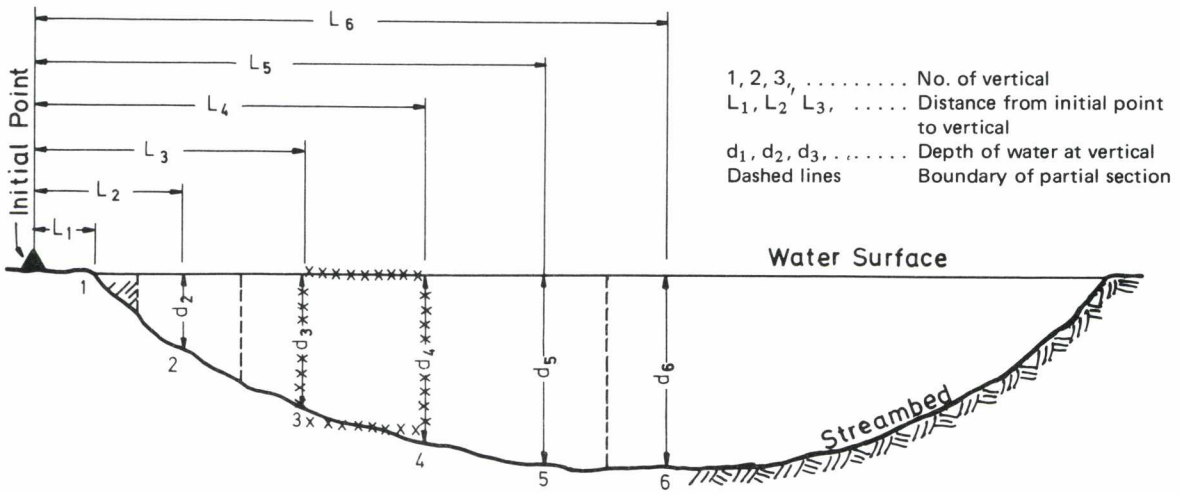

Figure 34. The mean-section method of computing current-meter measurements.

depths and vertical, and draw a smooth curve through the points.

Secondly, measure the area contained by the depth-velocity curve, its vertical, and the water surface by means of a planimeter, or simply by counting it up by use of a draftman's dividers.

Thirdly, plot the areas obtained in step two over the water-surface line of the measuring cross section and draw a smooth curve through the points. The area enclosed between this curve and the water surface line represents the discharge through the cross section.

The above computation procedure is mainly used when the velocity has been observed at multiple points in the vertical due to irregular vertical-velocity distribution.

2.4.4 Mean Gauge Height During Current Meter Measurements

The mean gauge height corresponding to the measured discharge is one of the two coordinates used in plotting the discharge rating curve. An accurate determination of the gauge height is therefore as important as an accurate measurement of the discharge. The correct gauge height for a measurement will be that which is observed at the same time as the gravity centre of the flow is gauged.

When gauging discharge during constant or nearly constant stream stage, there is no difficulty in deciding the gauge height that corresponds with the measured discharge. If the change in gauge height is less than 3 cm during the measurement, the arithmetical mean of the gauge height at the start and end of the measurement can normally be taken as the mean gauge height.

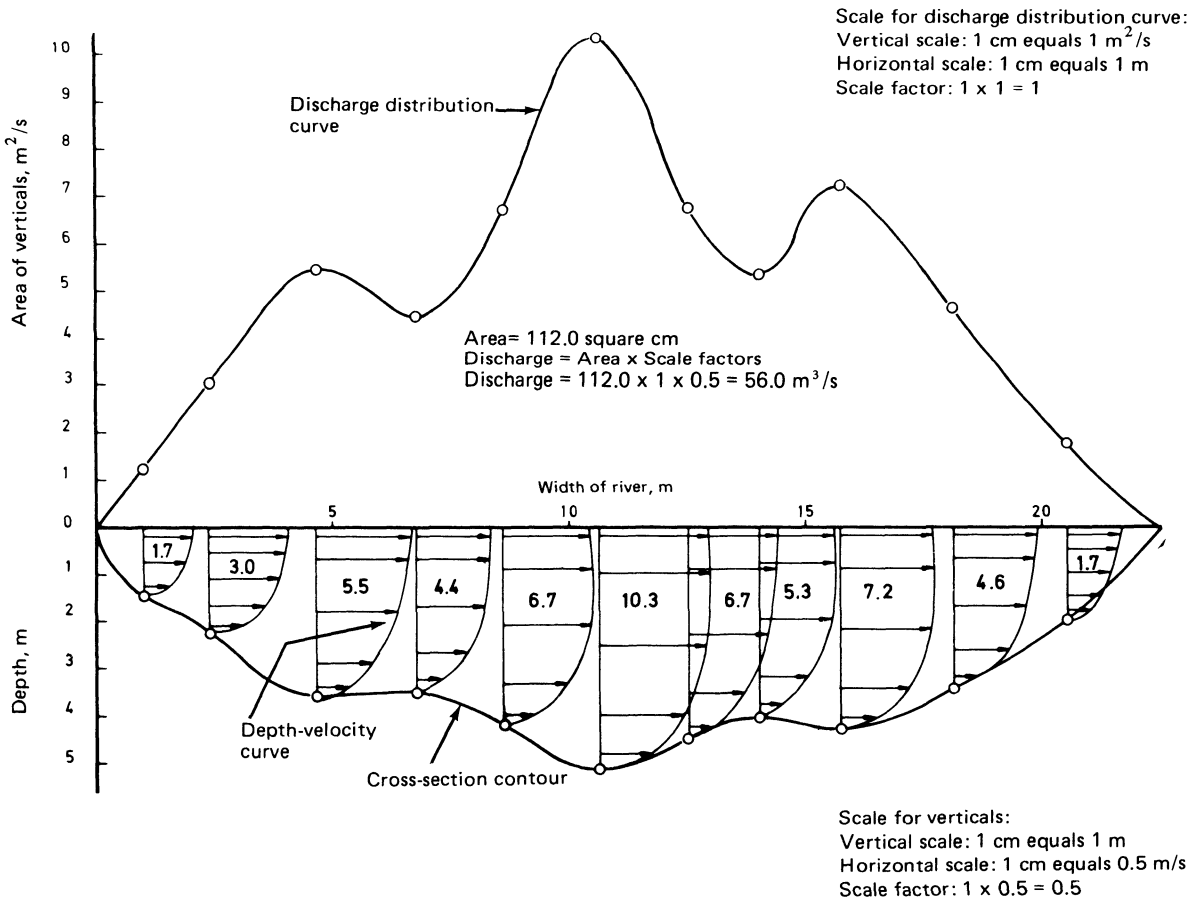

Figure 35. The graphical integration method (Harlacher's method) of computing current-meter measurements.

Discharge measurements at time of high water must usually be made during a rising or falling stage when a considerable change in the gauge height may occur. The correct gauge height is obtained by computing a weighted mean gauge height, which for a nonrecording gauge requires additional observations of stage between the start and end of the measurement. These readings are made at regular intervals, say every 20 or 30 minutes. The assistance of a gauge reader is necessary for obtaining the readings. The mean gauge heights during the set time intervals and the corresponding measured partial discharges are used to compute the mean gauge height of the measurement. The formula used is

$$H = \frac{q_1 h_1 + q_2 h_2 + q_3 h_3 + ... + q_n h_n}{Q} \qquad (2.9)$$

where

H = weighted mean gauge height,
$q_1, q_2, ...$ = discharge measured during time interval 1, 2,...,
$h_1, h_2, ...$ = mean gauge height during time interval 1, 2,...,
Q = total discharge measured.

Fig. 36 shows the computation of a weighted mean gauge height using the given formula. The graph is a reproduction of the gauge height graph during the discharge measurement.

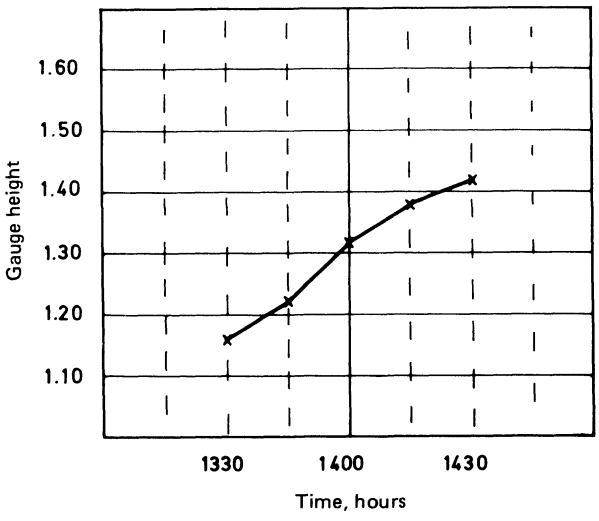

Figure 36. Computation of a weighted mean gauge height.

As stated above, an accurate gauge height for the discharge measurement is as important as the accuracy of the discharge measurement itself. In this respect, it is to be emphasized that a fixed and permanent gauge datum must be maintained. The datum of the gauge must be carefully checked by level relative to a permanent bench mark at periodic intervals, at least once a year and especially after the floods.

It is recommended that a check level of the gauge datum should be regarded as an integrated part of the discharge measurement. It should always be run and the water-level gauge reset as required *before* the discharge measurement is carried out.

2.5 Factors Affecting the Accuracy of Current Meter Measurements

For accurate and reliable measurements of discharge by current meter, especially in natural stream channels, a knowledge of many factors is essential, in addition to the specific procedure to be followed in making the discharge measurement. The wide variety in the character of streams and rivers with respect to climatic conditions, both seasonal and regional, and in the behaviour of the measuring equipment when used under various circumstances, gives rise to many problems which may affect the procedure of the work.

2.5.1 Use and Care of the Equipment

Accuracy in stream gauging can only be expected when the equipment is properly calibrated, assembled, adjusted and kept in good condition. In particular, the current meter, the stop watch, and the revolution/time indicator must receive care and protection both when in use and when being transported as they are the most sensitive items of the gauging equipment.

The current meter receives necessarily a certain amount of hard usage that may result in damage, such as a chipped rotor, damaged bearings or a bent shaft. Any one of which may cause the current meter to under-register. Observation of velocities taken at sections with irregular and uncertain profiles and the presence of floating drift probably present the greatest hazard to the current-meter equipment. Floating drift can usually be seen in time to allow removal of the equipment from the water. Sometimes however, a measurement is so valuable that considerable rough usage of the equipment is justified. After such usage the current meter should be thoroughly checked.

Damage to the gauging equipment during transportation is generally due to careless packing or negligence in protection. Cases are provided for use in transporting the current meters and the weights. The stop watch should be carried in a protective case or on a string around the neck when in use. Revolution counters and combined revolution/time indicators should be packed carefully to avoid accidental short circuits which may discharge the battery. The hydrologist who takes pride in the care and protection of his gauging equipment will find himself amply repaid for the extra time and effort that may be spent to maintain it in the best possible condition.

2.5.2 The Measuring Cross Section

Regardless of the method employed, the accuracy of current-meter measurements will depend to a large degree on the characteristics of the gauging site. If those characteristics are ideal or even favourable, an inexperienced operator should obtain satisfactory results without much difficulty. On the other hand, if these conditions are adverse, it may demand the ingenuity of the most skilful and experienced hydrologist to make satisfactory discharge measurements.

2.5.3 Spacing of the Verticals

Where the profile of the cross section is irregular, velocities are also irregular and additional verticals are required to obtain an accurate measurement. The verticals should be spaced so as to disclose the real shape of the bed profile and thus the true mean velocity of the flowing water.

2.5.4 Measurement of Depth and Width

Because the discharge is computed as the product of area and velocity, any incorrect readings of the depth of water and the width of the channel will produce a corresponding error in the measured discharge.

2.5.5 Oblique Flow

The current meter measurement will not give a correct result if the current is not at right angles to the measuring cross section. Oblique flow occurs

normally where the channel is diverging or converging, such as at the inlet and outlet of pools. At such places, oblique flow occurs both in the horizontal and vertical plane. For small angles the error is negligible. If a serious error is suspected, another measuring cross section should be selected.

2.5.6 *Turbulent Flow*

Current meters are rated in laminar (streamline) flow by being pulled through still water. Therefore, any turbulent flow at the gauging site will cause inaccuracies. However, unless these disturbances of the flow are pronounced, the errors will be small and negligible. If there is excessive turbulence, the gauging site should be improved or moved to a better location.

In general, a vertical-shaft cup-type current meter tends to over-register in excessive turbulence and a horizontal-shaft propeller-type current meter tends to under-register under those conditions.

2.5.7 *Vibration of Suspension Rod*

During measurements with the current meter mounted on a suspension rod where the distance between the streambed and the upper anchor point of the rod is large and the flow velocity is high, as for instance when gauging from a bridge, the rod may easily start vibrating sideways. This effect will seriously affect the velocity observation. To stop the vibration: fix a line (sidestay) to the rod at the water surface and with one end to each side, keep it tight, and the vibration will stop.

2.5.8 *Insufficient Weight*

To prevent large vertical angles while gauging with a line-suspended current meter from a cableway or bridge, and in order to keep the current meter steady, a sufficiently heavy weight should always be used.

2.5.9 *Low Temperatures*

The propeller-type current meter has a horizontal shaft with ball-bearings enclosed in an oil chamber. At low temperatures the oil becomes more viscous so the propeller does not rotate as freely as at higher temperatures. This effect may cause significant under-registration by the current meter when used in cold water. (Refer Section 3.11)

2.5.10 *Wind*

Wind may affect the accuracy of a current-meter measurement by causing vertical movements of the current meter or agitating the water surface and affecting the 0.2 depth velocity in shallow water. (Refer Section 3.10)

2.5.11 *Vertical and Horizontal Motion of the Current Meter*

A current meter suspended on a line is not held rigidly in position and so may occasionally have vertical and horizontal movements. Insufficient weight, wind, wave action or a poor gauging site will generally increase these movements. The hydrologist should try to keep the movements to a minimum.

2.5.12 *Drift and Aquatic Vegetation in the Stream Channel*

Large drift such as logs or tree branches may necessitate hurry in making observations in order to avoid damage or loss of the current meter. This may cause errors in the observations of both depths and velocities.

Fine drift may collect around the shaft or pivot of the current meter which will cause it to under-register.

The presence of aquatic growth in the measuring cross section may not only interfere with the operation of the current meter, but may also seriously affect the distribution of the velocity, particularly near the bed of the stream. If the current meter is used under such conditions, it should be inspected frequently and given spin tests to check its performance. (Refer Section 3.5)

2.5.13 *Bedload*

When gauging streams carrying heavy bedload of sand and the current meter is held in the bedload zone, sand grains may become caught between the propeller shaft and the screw socket which attaches the propeller assembly to the meter body. Thus interfering with, or even stopping, the run of the propeller. Under these conditions the function of the current meter must be checked at short intervals by means of the spin test. (Refer Section 3.8)

2.5.14 *Effects of Piers, Pilings and Eddies*

As a rule, these conditions should be avoided. They do not generally occur and the hydrologist has to make his own decision on the spot as to which way the gauging should be carried out.

2.6 Accuracy of Current Meter Measurements

From Section 2.5 it can be concluded that a current-meter measurement at a given site is subject to three principal sources of error: (a) personal, (b) instrumental, and (c) methodic.

2.6.1 *Personal Error (The Human Factor)*

Personal errors are those made by the hydrologist when reading the instruments, counting the revolutions and in making biased observations by consistently reading too high or too low. Some of the factors contributing to such errors are weather conditions, the hydrologist's attitude, and inadequate training. These errors can not be controlled, but they may be minimised by training and by instilling a pride of accomplishment. Personal errors are difficult to evaluate, but in general, they are considered to be small.

2.6.2 *Instrumental Error*

The kind of instruments used, the accuracy of their calibration and their condition affect the discharge measurement. Instruments used in making discharge measurements include the current meter, the timer, the depth indicator and the width indicator.

The current-meter error is caused by defects in the current meter and by turbulent flow. Turbulent water affects the revolution-velocity rating of the current meter which is based on towing it through still water. The instrument-error due to rating the current meter in still water and operating it in turbulent flow is difficult to evaluate. A comparison of the results of velocity measurements made by the PRICE cup-type current meter and the OTT propeller-type current meter agreed within one per cent. Because the propeller-type current meter tends to under-register and the cup-type current meter tends to over-register in turbulent flow, these comparisons indicate that the effect of turbulence, normally, is small.

The errors introduced by the other instruments used are believed to be even smaller than those introduced by the current meter. Most investigators agree that the combined instrumental errors are not greater than one per cent.

2.6.3 *Methodic Error*

The methodic error is made up of three components:

1. The error due to the restricted observation time at each individual observation point, the *velocity-pulsation error.*
2. The error due to the restricted number of observation points in each vertical, the *velocity-depth error.*
3. The error due to the restricted number of verticals in the measuring cross section, the *velocity-width error.*

2.6.4 *Velocity-Pulsation Error*

The velocity-pulsation error is due to the character of the flow. The true mean velocity will be approached closer the longer the time interval of the velocity observation is made. Investigations indicate that a time interval of 40–70 seconds is sufficient for most natural streams.

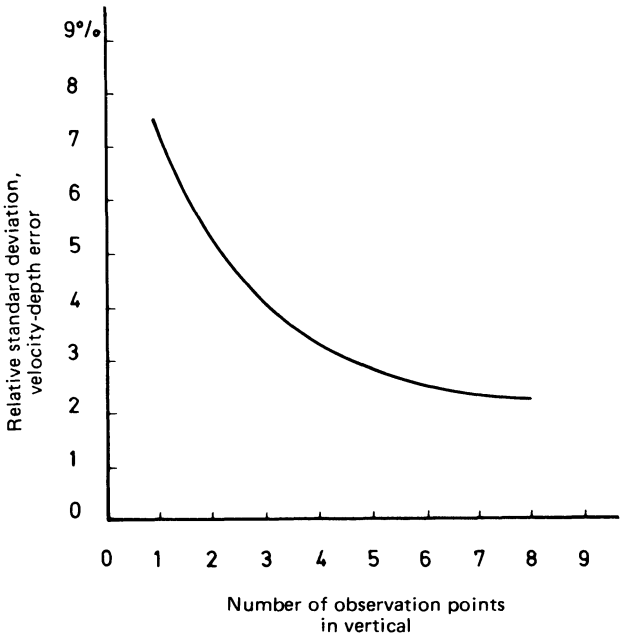

Figure 37. The velocity-depth error as a function of the number of observation points in the vertical [23].

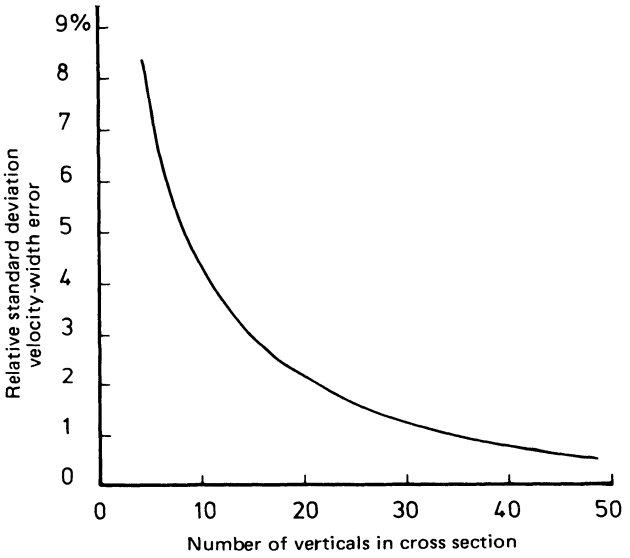

Figure 38. The velocity-width error as a function of the number of verticals in the measuring cross section [23].

Errors caused by pulsating flow can be reduced considerably by use of a light-weight rotor blade made of for instance plastic material.

2.6.5 Velocity-Depth Error

In order to closely approach the mean velocity in the measuring vertical, observations at many points in the vertical should be made. However, as long as the flow is regular, or nearly so, the number of points in the vertical is of less importance than the number of verticals in the measuring cross section (Fig. 37).

2.6.6 Velocity-Width Error

The number of verticals in the measuring cross section has a large influence on the final error of the current-meter measurement (Fig. 38). This is quite natural since most streams have a relatively small depth-width ratio which promotes an irregular velocity distribution across the stream.

Bibliography

Chapter 2: [3], [7], [9], [11], [12], [13], [14], [15], [16], [18], [20], [23], [33], [36].

CHAPTER 3

LEVEL AND DISCHARGE MEASUREMENTS UNDER DIFFICULT CONDITIONS

3.1 General

This chapter provides a general discussion on the measurement of river discharge under difficult conditions. It is based on WMO operational Hydrology Report No. 24, the report has an extensive list of references, [21].

3.2 Unstable Stream Channel

Obviously, in order to establish and maintain a stage-discharge relation at a gauging site, the first and most important step is to choose an accessible location on the river where a genuine stage-discharge relationship exists and where the recording instruments and gauging equipment will function safely. Thus, the selection of a proper gauging-station site is the first and most important operation in avoiding and overcoming difficult conditions.

However, the selection of gauging sites is also dictated by the needs of water management, hydraulic engineering, or by the requirements of the hydrological network. In the first case, there is little or no freedom of choice in selecting gauging sites and frequently records must be obtained under highly adverse conditions. On the other hand, hydrological network requirements allow more choice in the selection of good sites for gauging stations, although in some cases gauging conditions can be poor throughout an entire region. For example, all the streams in a given region may have unstable beds and banks, resulting in continually changing stage-discharge relations.

3.2.1 Cases

— Stream channels passing through alluvium are characterized by soft and erodible beds and banks.

— The stream channel is subject to scour and deposition.

— A stream will carry a heavy load of suspended sediment, often to its full carrying capacity.

— During the low-flow season when the flow of water does not cover the whole width of a flat riverbed, the flow will tend to meander, or the low-flow channel will shift position from one low season to the next.

3.2.2 Problems

— The soft and erodible banks of alluvial streams often make it difficult to place staff gauges securely and to maintain a stable gauge datum.

— The construction and establishment of staff gauges and water-level recorders may upset the balance of the ground and thus cause erosion, undercutting of the channel bank and destruction of the gauging station.

— The staff gauge and the intake of water-level recorders may be left dry in the low-water season owing to shifting and meandering of the low-water channel.

— The intakes and stilling wells of water-level recorders are frequently silted-up with fine sediment. Small stilling wells (less than 90 x 60 cm) of sheet metal or sheet tubes sunk into the stream bank are generally unsatisfactory because of the difficulty in desilting them.

— The gas-outlet of gas-purge water-level recorders may be clogged with sediment.

— It is often difficult to obtain correct depth-soundings when making current-meter measurements because the sounding (gauging) rod or weight sinks into the soft streambed.

— The bearings and rotor of the propeller-type current meter are often adversely affected by high sediment concentrations. Especially at locations near the bottom of streams carrying a heavy bed-

load, sand particles may become lodged between the propeller nut and the worm sleeve, thus preventing the propeller from rotating.

— Signals emitted by echo-sounders are often blocked in streams with a high sediment concentration.

— Signals from acoustic flow-meters will scatter too much when the sediment concentration is too high.

— Chemical and fluorescent tracers (except of NaCl) tend to become adsorbed onto sediment particles. Dilution methods of measuring discharge by these tracers are therefore not suitable in streams with a high sediment concentration.

— Increased viscosity of the water due to low temperatures increases the mobility of sand particles and consequently also the scouring and bed-load carrying capacity of the stream. The reverse occurs at high temperatures.

— In alluvial sand-bed streams, the stage-discharge relation usually varies (shifts) with time, both gradually and abruptly, owing to scouring and silting in the stream channel and because of moving sand dunes and bars. The shifts are especially evident during and after floods.

— Changes in the stage-discharge relation at permanent section controls may occur owing to changes in the streambed (stilling pool or forebay) upstream of the control. Scour of bed material upstream of the section control will reduce the velocity of approach and result in an increased stage for a given discharge. The reverse will occur when material is deposited.

3.2.3 Solutions

3.2.3.1 Relocation of Gauging Stations

If feasible, as soon as the first site is found unsuitable, the gauging station should be relocated on another site which is not subject to shifting and displacement of the stream channel.

3.2.3.2 Stabilization of Banks and Stream Bed

If possible, unstable banks should be protected. Such protection should extend upstream and downstream from a measuring section for a distance equal to at least one quarter of the bank-full width of the channel in each direction.

In the case of float-gauging, the whole of the measuring reach should be protected.

Instability of the streambed may be corrected or reduced by means of structures built across the bed. For small streams the structure may be made of concrete. For larger streams gabions are often used. These are large baskets of thick wire-netting, each with a capacity of about 3 m^3 and filled with stones. The gabions are sunk in the river bed and anchored in line across the bed by iron bars. The top of the bars must finish flush with the streambed. The gauging station is sited immediately upstream of the protective works and is calibrated by current-meter measurements from a cableway placed at the stabilized cross section, from a nearby bridge or by wading. [19].

On smaller streams and canals where a sufficient fall is available, the control section may be stabilized by a weir or a flume. An attempt should be made to ensure that the structure is self-cleaning, removing sand and silt, drifting leaves, etc.

By these means the lower part of the stage-discharge relation is usually stabilized. However, the permanency of the upper part will depend on whether the downstream high stage control is stable or not. The high-water stage-discharge relation is checked regularly for permanency by current-meter measurements.

3.2.3.3 Prevention of silting of intakes and stilling well

Refer Volume 1 where it is discussed how silting of intakes and stilling wells can be prevented and reduced by attention to proper hydraulic design criteria commonly used for hydrometric stations.

a) Silting problems associated with float-actuated water-level recorders are usually prevented by the use of a steel tube-well of about 40 cm in diameter, mounted on a vertical rock wall or on a specially constructed pier. The tube-well is provided with a self-cleaning, cone-shaped hopper bottom with an inlet at the apex. In principle, when such a well is placed in flowing water, the flow will accelerate past the inlet. In addition, the steep slope of the hopper bottom, together with water-level oscillations due to waves and surges, will prevent the deposition of silt inside the well. (See Volume 1).
b) Sediment traps can be useful in preventing silting. These consist of a large box-like structure located between the stream-end intake and the

stilling well. Inside it, baffles are fitted to promote settling before the suspended sediment reaches the stilling well. The trap is made to open for easy access and removal of the deposited material.

Where the distance between stream and stilling well is not too large, the following type of sediment trap is recommended.

Instead of intake pipes, communication to the stilling well may be provided by a duct of rectangular cross section. The duct has a covered opening for inspection and easy cleaning of its interior. The wall facing the river has two or more perforations at different levels holding short tubes set flush with the outer side of the wall. Flush-fitting pipes are more likely to reduce well drawdown effects due to high velocities. Static tubes are not recommended owing to difficulty in desilting them. (See Volume 1).

c) Silting in the stilling well can be reduced by minimizing the size of the inlet pipe, but care must be taken not to introduce lag effects. (See Volume 1).

3.2.3.4 Desilting Methods

a) Gauging stations which are subject to silting and clogging should be provided with flushing devices whereby a considerable head of water can be applied to the well-end of the intake pipes. Ordinarily, the water is raised from the well to an elevated tank by use of a hand pump. The water is then released via pipes through the intakes by the operation of valves. Water may also be pumped from the stream through a length of hose or carried in buckets if a pump is not installed. (See Volume 1).
b) Stilling wells without flushing systems can be cleaned manually with shovel and bucket and flexible steel rods, or with a head of water in the well from a stationary hand pump or a small engine-driven portable pump to stir up deposited silt and force the water-sediment mixture out of the intakes. (See Volume 1).
c) Where long pipes are necessary to reach low flows, it is useful to thread an endless loop of a small diameter bronze chain through the lowest inlet pipe and a higher one. Pulling the cable through the pipe during low flow can speed up the pipe-cleaning process where there is a water-level difference to induce a flow in the pipe.
d) Gas-pressure recorders have been used with success in sediment-laden streams, including both the gas-purge (bubbler) system and the enclosed pressure-bulb system. These recorders are easy and cheaper to install than the conventional float-operated type. If the gas outlet of a gas-purge recorder does become clogged, it may be cleaned by releasing enough pressurized gas to force out the sediment. However, one should be aware that if the sediment is cemented in place, a violent blowout of mercury from the instrument will result. [23].

3.2.3.5 Soundings

Where the streambed is soft, the sounding rod should be equipped with an extra-large footplate. Sounding weights should be equipped with an electric-bottom contact.
Echo-sounders may be used where the sediment concentration is not too high.

3.2.3.6 Discharge Measurements

The cup-type current meter is more suitable for use in sediment-laden streams because the pivot bearing which supports the vertical shaft is less affected by sediment than the bearings of propeller-type current meters.

3.2.3.7 Shifting Stage-Discharge Relation

a) At gauging stations subject to abrupt changes in the stage-discharge relation, the discharge rating is checked regularly by discharge measurements, especially during and after the high-water season. If the check measurements show a trend which deviates significantly from the original rating, a new discharge rating is prepared. See Volume 4.
b) Frequent discharge measurements are made at gauging stations on typical alluvial and moving streams. By applying the Stout method, daily discharges are estimated by interpolation between the measurements. The frequency of measurement depends on the importance of obtaining a discharge record at the site, on the desired accuracy and on the season of the year, and may vary from once a month to once or twice a week, or even once a day at important locations. The discharge is measured by means of a current meter from a cableway or boat, or by the moving-boat method. On smaller streams the electromagnetic method may be used. (See Volume 4).

c) The shift-correction method may be used instead of the Stout method. This method is based on fewer measurements, but supplemented by a knowledge of shifting control behaviour. The method is described in reference [3].

3.2.3.8 Intercomparison between Gauging Stations

Where there are several gauging stations on a stream, the discharge data from all the stations may be compared in order to trace possible changes in the station controls and the time at which they occurred.

3.2.3.9 Change of Variables

In alluvial streams with shifting beds and banks, the stage-discharge relation is indeterminate. By changing the variables, a hydraulic relationship may be obtained, i.e. the effect of the change in bed elevation is eliminated by replacing stage by mean depth (or hydraulic radius) and the effect of varying width is eliminated by using mean velocity instead of discharge. By establishing the relationship of mean depth against mean velocity, the discharge can be computed and then applied to the depth-velocity relation. (See Volume 4).

3.3 Flash Floods

3.3.1 Cases

— By definition, flash floods are localized and short-lived, with sharp-peaked hydrographs and with flood waters suddenly appearing and disappearing in headwater streams. They rise and fall almost equally rapidly. The essential difference between a flash flood and a broad, regional flood is the speed with which it occurs, that is, the short duration between the causative event and the flood. [4].

— Flash floods may be considered under three categories:

a) Those which are caused by intense localized rainfall on natural catchments not substantially modified by man.
b) Those which result from heavy rainfall on catchments which have been altered by man so as to reduce the stability of the catchment itself or to have changed the runoff, storage or hydraulic characteristics of the catchment.
c) Those which are caused by the sudden release of impounded water from the failure of a dam or other man-made or natural barrier, e.g. outburst floods from landslide barriers, ice dams or glacier-dammed lakes.

— Most flash floods result from: (a) intense localized rainfall produced by heavy thunderstorm activity, (b) cyclonic storms or (c) marked low pressure areas.

Flash floods may be disastrous on small and medium-sized streams but have little significance on large rivers. Although they may occur anywhere, some regions are more subject to them than others. Mountainous areas are particularly flood-prone, owing to orographic effects, steep slopes and limited valley storage. Many arid and semi-arid regions are also susceptible to flash flooding, especially those with high relief, a large percentage of superficial bed rock, sparse vegetation and shallow soils.

3.3.2 Problems

— On float-actuated recorders, the float-string may jump off the float-pulley during rapid flood rises and records will be lost.

— Internal inertia of an autographic water-level recorder does not permit accurate monitoring of the rapid rise of the flash-flood wave.

— Because of the high velocity of the flash-flood wave, drawdown will occur in the recorder stilling well, followed by intake lag.

— When stage changes rapidly during a current meter discharge measurement, the computed discharge figure loses much of its reliability and there is uncertainty as to the appropriate gauge height to apply to the discharge figure.

— Stream discharge is usually measured by a current meter. However, during flash floods the peak may be so sharp that there will not be time to make conventional current-meter measurements.

— The difficulty in predicting the place and time of occurrence of intense thunderstorms and heavy local rainfall, and the short time of concentration and storm duration seriously limit the possibility of being on site to gauge flash floods when they arrive at the gauging station.

— Owing to economic constraints and practical difficulties, it may not be possible to collect flash-flood data on every stream in a region.

— Pulsating flow sometimes occurs during flash floods in arid or semi-arid areas. In pulsating flow the longitudinal profile is marked by a series of abrupt translator waves which move rapidly downstream. Translator or roll waves develop in steep channels of super-critical slope.

3.3.3 Solutions

3.3.3.1 Maintenance and Service of Recording Instruments

Operational failures of recording instruments are prevented by regular maintenance.

3.3.3.2 Adaptation of Standard Designs to meet Adverse Conditions

Special features may have to be incorporated into the standard design of gauging stations to ensure that they will function under adverse conditions. Standard designs should not be used indiscriminately in problem cases. Regarding drawdown in recorder wells and lag in intake pipes, a check computation with local input data and requirements should be carried out in the design/construction phase to ensure that the intakes and stilling well meet local conditions.

3.3.3.3 Flood-Crest Gauges

In order to ensure that the flood crest is obtained in the case of failure of the recorder, a simple device known as a flood-crest gauge should be installed at the gauging station. Refer Volume 1.

3.3.3.4 Advance Warning

To ensure that the hydrologist is prepared to gauge flash floods, he needs advance warning of impending flood events. Such warnings may be given by the observer at the gauging station, or supplied by the regular weather-forecast service.

3.3.3.5 Optimized Current-Meter Measurement

When gauging flash floods by current meter, shortened and optimized procedures should be followed, as described in the WMO Manual on Stream Gauging [3].

3.3.3.6 Indirect Discharge Measurements

Where the current-meter method is impractical, indirect methods may be used to gauge floods. These methods make use of energy and continuity equations and require post-flood surveys of the physical and hydraulic characteristics of the channel reach. Three types of indirect methods have been developed and are readily available for use: a) the *slope-area* method, b) the *contracted-opening* method, and c) the *culvert method*. The methods are described in reference [3].

3.3.3.7 The Velocity-Index Method

If a continuously recorded velocity index, at a point or in a transverse line, can be related to stage and mean velocity in the cross section, the product of cross-sectional area and mean velocity gives the discharge at any time. The calibration of the velocity relation, that is, the relation of recorded index velocity to mean velocity, and to stage, requires discharge measurements for the determination of mean velocity. The discharge measurements also furnish the values of the cross-sectional area to be used in the stage-area relation. Instrumentation for providing four types of indexes are available. These are [3]:

a) Standard current meter,
b) Deflection meter,
c) Acoustic point-velocity meter,
d) Electromagnetic point-velocity meter.

3.3.3.8 River-Model Analysis

The technique of hydraulic river-model analysis carried out in a laboratory has been successfully applied for the high water extrapolation of discharge rating curves.

Based on accurate field data, a model is built of the gauging station controlling features. Some field measurements of low and medium discharges are also required in order to adjust the model to conform to the prototype. By observing the model

when its discharge is increased, the rating curve for the prototype can be determined for the high flood stages. Refer Volume 4.

3.3.3.9 Dilution Methods

Dilution methods may provide the only effective means of gauging flow under extreme flood conditions. Radioactive isotopes are preferable as tracers when high discharges are considered. These tracers are detectable in large dilutions and the small quantity of tracer required allows for flexibility with regard to injection techniques.

3.3.3.10 Float-Measurements

When no other means are available for measuring high discharges, simple floats may be utilized to measure surface velocities. The cross-sectional areas must be measured after the flood has subsided. [3].

3.3.3.11 Regionalization

To gauge every small stream in an area is economically impractical and physically impossible. Consequently, efforts should be directed towards the generalization or regionalization of streamflow characteristics within an area. In this way, data obtained at gauged sites are used to estimate streamflow characteristics at ungauged sites.

3.3.3.12 Pulsating Flow (Roll Waves)

The method of determining the discharge of pulsating flow requires computation of the discharge in the overriding waves and computation of the discharge in the shallow, overrun part of the flow. The sum of the two discharges is the total discharge at the time of observation. [3].

3.3.3.13 Plan of Operation

For successful data collection, especially floodflow data, it is not enough for every individual member of the field personnel to be familiar with the particular gauging techniques and procedures, and to be proficient in his special task. Each regional office of a hydrological service should maintain an effective plan of operation aimed at obtaining the maximum return from the available input of resources, i.e. personnel, transport and gauging equipment. [30].

3.4 Inability to Define Stage-Discharge Relation

The ordinary (single-valued) discharge rating curve used in stream gauging rests on the basic assumption of approximate steady flow with a constant energy slope with respect to time at any given stage. So, when the type of flow departs significantly from the steady flow state, the simple stage-discharge relation is no longer sufficient to define the discharge. Another parameter has to be included, namely the slope. Refer Volume 4.

3.4.1 Cases

— Variable backwater caused by varying stage at a downstream confluence.

— Variable backwater caused by the manipulation of gates at a downstream regulation dam.

— Variable backwater due to aquatic vegetation in the stream channel (Section 3.5).

— Variable backwater due to ice in the stream channel (Section 3.11)

— Highly unsteady flow due to the passage of a flood wave, causes a looping effect in the stage-discharge relation. The problem is often complicated by the accumulation and subsequent release of overbank storage. The looping effect may be large on lowland rivers with a flat slope. The effect on steep headwater streams is never of any practical significance. Refer volume 4.

— Unsteady flow due to tidal effects. (Section 3.9).

— Unsteady flow combined with variable backwater. This situation may often occur at or near river confluences where one of the rivers rises while the other remains low.

— Shifts in channel geometry (scour and fill) and/or changes in flow conditions (aquatic vegetation), combined with unsteady flow and variable backwater. (Section 3.2).

— Changes in channel geometry due to hydraulic engineering works and dredging. These operations destabilize the stream regime causing unforeseen scour and fill in a stream reach. When equilibrium is restored, the stream reach becomes stable, but this may take years.

3.4.2 Problem

The general problem is that the ordinary approach, using the single-valued stage-discharge rating for the computation of discharge records, is not applicable. The discharge rating under condition of variable backwater and for highly unsteady flow can not be defined by stage alone. Other methods must be used to define the discharge rating.

3.4.3 Solutions

3.4.3.1 Variable Backwater

A stage-slope-discharge relation is developed which is based on observed stages at each end of a channel reach and the concurrent discharges measured by current meter. The method is described in several books and manuals. [3], [11].

3.4.3.2 Looped Discharge Rating

For gauging stations sited on stream reaches with looping effects, the discharge rating must be developed by the application of adjustment factors which relate steady flow to unsteady flow. [3], [11].

3.4.3.3 Unsteady Flow and Backwater Combined

Where the discharge rating for a gauging station equipped for measurement of the surface slope, is affected by a combination of variable backwater and unsteady flow, the rating should be determined as if it were affected by variable backwater alone. But if the backwater as well as the discharge varies during the period of the measurement, the problem becomes too complex for any form of general solution to be stated. [11].

Generally, for regulated reaches and for reaches affected by variable backwater, the appropriate solution is the use of the ultrasonic method of continuous measurement of mean velocity at the measuring cross section.

3.4.3.4 Shifts and Aquatic Vegetation

Shifts in the channel (scour or fill) and/or alterations in the flow condition (aquatic vegetation) will cause changes in the stage-slope-discharge rating just as they cause changes in the simple stage-discharge relation.

The appropriate solution to the problem for small streams (up to approximately 30 m) is the application of the electromagnetic method of continuous measurement of the discharge. For larger streams, shift-corrections will have to be applied to the stage-slope-discharge relation. Refer Section 3.5.3.1.

3.5 River Channel Affected by Aquatic Growth and Weeds

Where the climate is favourable to aquatic growth and weeds in the stream channel, this is a common cause of instability in the stage-discharge relation in small and medium-sized rivers.

3.5.1 Cases

— In temperate climates the occurrence of aquatic vegetation such as growth and weeds is seasonal and recurrent. The plants start to grow in late spring or early summer, reach maturity in midsummer, and diminish rapidly in the autumn after the first sub-freezing temperatures. In tropical and sub-tropical climates, aquatic growth is less seasonal and may appear the whole year round.

— Aquatic vegetation is generally greatest in polluted streams carrying organic waste. In some chemically polluted streams, the vegetation may thrive during periods of high discharge when the chemicals are diluted but may die off at times of lower discharge when the pollution is more concentrated.

— Weeds are flattened and sometimes uprooted and carried away by floods and high water.

3.5.2 Problems

— Weeds in stream channels affect the stage-discharge relation of the stream by increasing the roughness factor and decreasing the cross-sectional area of the channel, and so causes backwater as progressively higher stages are needed to obtain the greater channel depths required for the passage

of a given discharge. These effects will terminate abruptly if the vegetation is washed away by a stream rise or flood. Except for their seasonal characteristics, the effects of aquatic vegetation in many respects resemble the variable backwater pattern produced by shifting controls.

— Artificial control structures such as weirs may be seriously affected by aquatic vegetation, especially in streams polluted by organic waste: (a) aquatic reeds growing in the weir pool will slow the velocity of approach, (b) long strands of weed trailing over the weir crest may substantially alter the flow pattern over the crest, and (c) moss or algal growth may attach itself to the weir crest and so increase the head on the weir for a given discharge.

— It may be difficult or even impossible to find a stretch of stream for a gauging site where there will not be backwater caused by weeds.

— There appears to be no effective and practicable means of preventing aquatic growth and weeds as chemicals added to the water for this purpose would probably have toxic effects on fish and other animal life and, furthermore, it would probably have only a short-term effect on the vegetation.

— The presence of reeds and weeds in the measuring section may interfere with the operation of the current meter by fouling the rotor.

— Aquatic vegetation may obstruct the acoustic methods of measuring discharge.

3.5.3 Solutions

3.5.3.1 Shifting Control Corrections

Shifting control corrections (adjustments) to the stage-discharge rating can be used for computing discharge records during periods of variable backwater caused by aquatic vegetation. The method requires that several discharge measurements be performed during the period of backwater. The method is explained in reference [3].

When the shift-correction method is used to compute the discharge record of gauging stations affected by aquatic vegetation, the discharge is measured at intervals by current meter during the growing season. For this purpose, a measuring reach equal to one stream width is cleared and maintained throughout the growing season. Frequent manual clearing appears to be the most practical method. The weeds and reeds growing in the streambed and banks may be cut by a special machine attached to a mechanical chain saw or by means of an ordinary scythe. The provision of an artificial gravel blanket across the streambed may also be useful in preventing vegetation. Applicable to small streams only. Refer Section 3.4.3.4.

In the discharge measurement notes, a short description of the actual state of the vegetal growth should always be given.

3.5.3.2 Family of Stage-Discharge Curves

In streams with a profuse growth of weeds and reeds the appropriate method of computing the discharge may be to develop a family of stage-discharge curves for different periods and conditions of weed growth.

3.5.3.3 Electromagnetic Method

Experience indicates that the electromagnetic method of measuring discharge is highly suitable for measuring flow in stream channels affected by aquatic vegetation.

3.5.3.4 Anti-Growth Measures

Several measures have been tried to prevent aquatic growth on measuring structures. These measures include: (a) anti-fouling compounds added to the building materials, (b) surface coating on the structures and (c) alternative building materials. In most cases these methods have failed and regular and frequent manual cleaning of flumes and weirs by brushing and scraping has to be performed.

3.6 Bank Overflow—Flood Plain

3.6.1 Cases

— In time of flood, large rivers may more or less regularly overflow their banks and inundate large areas of their lower, flat reaches.

— Plains higher up in the middle/upper reaches of sizeable rivers may also be inundated owing to a valley constriction at the downstream end of the plain which may critically reduce the discharge capacity of the river.

3.6.2 Problems

— It may be difficult to define a measuring cross section owing to the presence of several more or less clearly defined flood channels, backflow and oblique flow.

— It may be difficult to cross the flood plain when performing the measurement. The flood plains of large rivers may be up to several kilometres wide, and may be covered with dense vegetation.

— Owing to dense undergrowth such as grass and reeds, the velocity of water may be very low and stagnant water may be present.

3.6.3 Solutions

3.6.3.1 Clearance of a Discharge Measuring Section Across the Flood Plain

The measuring flow section should be perpendicular to the flow. Some trees are left as signs and for the temporary establishment of cableways over the largest flood channels and bypasses. Only the main channel and the largest flood channels are measured by current meter from cableways or boats by the ordinary procedures. The rest of the measuring section is divided into sub-sections and the flow in each individual section is estimated with the help of point measurements of depths and velocities.

The exact siting of marks, signs and separate gauging sections is based on a reconnaissance survey made just after the passage of a flood wave when flood marks are still easily visible. This is important for defining the direction of flow in the different gauging sections, which often does not coincide with the direction of the main flow.

3.6.3.2 Width Constriction of the Flood Plain

Constrictions of flood plains may occur naturally but are usually man-made. Highway and railway bridges are the most common. These structures are frequently used to obtain discharges from water-surface profiles based on high-water marks recovered after a flood. The peak discharge of a flood can be estimated from the constriction and flood plain geometry, flood plain roughness and the difference in water-surface elevation upstream and downstream from the constriction.

3.7 Large Interchange Between Surface Water and Groundwater

3.7.1 Cases

— The water which flows naturally in surface streams at low and medium stages is derived principally from groundwater.

— The streams may contribute to groundwater in some reaches and in some periods of the year, and receive groundwater in other reaches and in other periods of the year.

— In typical limestone terrains with high permeability, the stream runoff is low and short-lived, while the groundwater flow and discharge from springs are correspondingly high.

3.7.2 Problem

In open-channel gauging, the end product is the discharge passing in the stream without recognition of the component received from groundwater storage, or that part being contributed ("lost") by the stream as groundwater recharge. Where the total discharge contains a major groundwater component, measurement of the groundwater discharge can be as important as that of the stream discharge.

3.7.3 Solution

3.7.3.1 Water-Balance Analysis

The water balance in various sections of the stream channel is calculated to obtain stream-gain (baseflow) from the groundwater storage and stream-loss (recharge) to the groundwater storage. Thus, an analysis may be made of the interchange process between surface water and groundwater. Errors in the runoff calculations for the individual gauging stations may also be revealed in this way. The method used is an analysis of the stream recession hydrographs.

3.8 Arid Conditions

Generally, regions with a mean annual temperature of more than 18° C and an annual rainfall of up to 150–200 mm are known as arid regions. Semiarid regions are those with an upper rainfall limit of 500–600 mm. Regions with a mean annual

temperature of less than 18° C are considered arid when the rainfall is less than 100 mm per year, and semi-arid when the annual rainfall is less than 300 mm.

3.8.1 Cases

— In arid regions, surface runoff is characterized by extreme variability from one year to the next. Appreciable runoff may occur in some areas as short, isolated flow periods separated by longer periods of low or zero flow. Sustained flow is rare and occurs only in channels whose origin lies outside the arid region or in channels fed by groundwater.

— Flood flows may occur over a short season of, say, two months. They are produced by intense, localized convective storms and appear typically as short, torrential flash floods.

— The flood water usually diminishes during its passage downstream by infiltration into the channel bed and overbank spill. In fact, transmission losses represent the single most important recharge mechanism for alluvial aquifers in arid regions.

— The lack of vegetation may lead to considerable erosion and the flash floods especially may carry a very heavy sediment load.

— Under extreme arid conditions the main part of the yearly runoff may take place in a few weeks or even days, while virtually no flow occurs during the remainder of the year.

3.8.2 Problems

In arid climates, it is the extreme irregularity of runoff together with the high sediment load of the streams which creates the main problems:

— There may be a not-exist of stable natural controls due to high mobility of alluvial channels and periodic changes in the stream reach upstream of a permanent section control.

— The scour of gauging cross section may occur during current-meter measurements.

— A very high load of debris and sediment obstruct current-meter measurements and water-level recorders.

— High flood-discharges may carry so much sediment that the flow behaves as heavy sand-water or mud mixtures rather than normal water. Under these circumstances, flow conditions are radically changed and slope-area computations based on standard equation and constants can not be used.

— There may be difficulty in obtaining good-quality and continuous water-level records because of waves and a high sediment load.

— Extreme surges may develop in streams which are eroding and changing their cross section.

— There is a common occurrence in the wet season of flash floods with a rapid rise in discharge and high velocities shortly after the onset of storms.

— The range of flow is often very great, from zero in the dry period to very high during major floods.

— Access to gauging stations is difficult during the wet periods.

3.8.3 Solutions

There has been a significant advance, in recent years, towards the automation of data-collection systems using electronic sensing and logging methods and data transmission by radio. These developments are aimed at producing more accurate recording and computer-compatible records. In many cases the systems are used for flood-warning purposes to ensure that occurrences of flood-producing rainfall, or of upstream flooding, are communicated to operation centres or flood-control dams for operational forecasting. In other cases, for instance with densely instrumented representative or experimental basins, sophisticated sensing, transmission and central recording systems may be essential to the purpose of studies which would otherwise suffer from inaccuracies in the timing of events. Water-level recorders are now being installed which automatically transmit data through satellite repeaters.

None of these systems reduces the need for regular field trips by experienced hydrologists. Field trips are more important in arid zones than elsewhere and should be made whenever necessary to ensure the efficient recording of infrequent flood events as they occur.

3.8.3.1 Siting of Gauging Stations

To obtain reliable runoff data, gauging stations are located where the stage-discharge relation is relatively stable. However elementary and obvious as this may be, there are many instances of gauging stations being sited where there is no prospect of control stability nor the likelihood of producing data by continuous current-meter measurements. It is infinitely preferable to establish gauging stations at points where controls exist or can be constructed economically, even if such sites are not readily accessible or are less relevant to the problem at hand, than to do so where the data may be meaningless or dangerously misleading. With well-trained and well-equipped field teams, it may be possible to rate a naturally stable control over a single high-water period, even at sites of difficult access.

Bridges and culverts may provide a partial or complete control. One should bear in mind, however, that the cross-sectional area of flow under a bridge is variable for a given discharge if the bed is not stabilized. Also, the streambed downstream from the bridge shifts as much as elsewhere in alluvial channels.

3.8.3.2 Stabilization of the Stream Bed

Frequently, stable natural controls can not be found at all in a particular area, which necessitates the construction of artificial controls. (Refer Section 3.2.3.2).

For small streams, pre-calibrated measuring structures constructed of concrete and with a sloping approach apron may be used, as for instance the *Crump weir* or the *Flat V-weir.* This type of weirs will clear itself of silt in the approach area. [3].

3.8.3.3 Recess Staff Gauge

In arid zones, flood water carries large quantities of detritus including branches and whole trees which frequently damage the staff gauges. It is therefore desirable and often necessary to recess staff gauges on to the bank in order to avoid damage to the gauge and also to obtain quiescent conditions for accurate stage readings.

3.8.3.4 Stilling Well

For the design and desilting of stilling wells, see Section 3.2.

Regarding the desilting of stilling wells, it should be borne in mind that frequent desilting operations render float-operated recorder mechanisms vulnerable to damage by inexperienced or careless operators.

3.8.3.5 Recording Instruments

Two basic types of gas-pressure recording instruments have been used with success under arid conditions. These are the gas-purge (bubbler) recorder and the enclosed pressure-bulb recorder.

The former is claimed to be the more accurate, although requiring a higher degree of skill and effort in operation and maintenance. Refer Volume 1, Chapter 7.

Stilling wells on streams in arid regions are frequently dry for long periods of time. Sometimes no staff gauge to check the position of the recorder-pen can be safely or easily installed. If the float-cable or tape is not graduated, an index mark should be provided on the float-cable and a reference point specified on the instrument shelf. With some instruments the float-tape is graduated numerically and an index point is provided. The tape reading, adjusted by a positive or negative constant, then gives the stage reading represented by the float-elevation.

Flat floats have the advantages that they are both sensitive and follow the water level to a lower level as silting of the stilling well advances, than long narrow ones. Also, they are less likely to become embedded in the silt as it settles on the bottom of the well as the water level recedes.

The clearness and precision of the pen-trace produced by the instruments is variable and depends not only on the instrument-design but on such factors as (a) bubble rate, length of tubing and design of air outlet, in the case of a gas-purge instrument, and (b) length of tubing, moisture content of air in the tubing and quality of sealing, in the case of the pressure-bulb instrument.

The pen-trace response of the gas-purge recorders to water-level fluctuations may be made more sensitive by increasing the bubble rate and by enlarging the gas outlet diameter by adding a piece of piping to form a vertical and well-shaped outlet point.

In arid zones the dusty conditions make instrument-maintenance difficult. It is only by high maintenance standards and use of reliable and

sturdy instrumentation that reliable stage records can be obtained. Instruments must be checked meticulously during field visits. This, of course, applies to all instruments, but the scarcity of runoff events could mean that water-level recorder failure for one month may result in loss of record of the greater part of the runoff for an entire year.

3.8.3.6 Gauging Structures

In arid regions it is generally preferable to install cableways for current-meter measurements. It is seldom practicable to carry out measurements from boats owing to the high velocities which often occur.

Bridges and culverts may also be utilized for carrying out discharge measurements by current meter, using cranes and gauging reels. Truck-mounted gauging equipment may be appropriate in some situations.

If practicable, footbridges are installed on small streams. Very accurate current-meter measurements can be obtained from footbridges using rod suspension.

3.8.3.7 Discharge Measurements

Procedures for discharge measurements in arid regions are basically the same as those applicable elsewhere, although they may require adaptation to specific conditions.

For current-meter procedures applicable under conditions of shifting control and flash floods see Section 3.6 and 3.9. Detailed procedures for current-meter measurements and computation of discharge are given in Volume 4.

Bridges and culverts may be used in the contracted-opening method of measuring flow. The computation of flow is based on continuity and energy equations and is possible because of the abrupt drop which occurs in the water level at the contracted section.

A channel reach for gauging flood flows by the *slope-area* method is frequently required where high-water current-meter measurements can not be carried out. A suitable reach should be surveyed and high-water staff gauges installed at the upstream and downstream ends of the reach. Flood-crest gauges should be included with the staff gauges in order to obtain the surface slope in the reach at peak stage. See Chapter 5.

Sometimes measurements cannot be performed by current meter owing to a high content of debris and sediment or to drift on the water surface. Under these conditions the surface velocity may be measured by use of the Optical current meter (refer Volume 1), or by timing floats and drift over a measured channel reach. The float reach can advantageously be combined with the slope-area reach.

Discharge measurements by dilution methods may be applied successfully in arid conditions. The main difficulty with these techniques is the requirement for well-organized, trained and equipped teams, the success of whose operations is governed by their team work and mutual dependence to a much greater degree than that of current meter teams. The need for skill in site selection and for co-ordination of effort at the injection and sampling sites, which may be remote from each other, is usually difficult to fulfil. Whereas current meter work can be successful with only one proficient team member, dilution gauging cannot.

Storage reservoirs are potentially valuable gauging structures capable of producing good-quality runoff data with little effort in comparison with that required for the effective operation of conventional runoff stations. The change in reservoir storage is estimated from water-level records and the stage-storage relationship established by survey. Rainfall on the reservoir surface is included in the storage-change term of the water-budget equation and may usually be ignored. Evaporation must be estimated.

3.8.3.8 Measurement of Changes in Stream Bed Level during Floods

Data on variation in the stream cross-sectional area during flood flows in alluvial channels are obtained by scour indicators. Devices commonly used are:

a) Chains buried vertically in the channel bed and anchored by means of heavy concrete blocks below the expected scour depth; in theory, the depth of scour is the depth to that part of the chain subsequently found to be lying horizontally.
b) Tiles or other expendable material are buried at specified vertical intervals, the depth of scour is assumed to be the depth between the top tile and the tile located subsequently.

3.9 River Channel and Estuary Affected by Tides

Tidal action is caused by the gravitational attraction of the Moon and the Sun, of which the force of the Moon is the predominant factor, being about twice that of the Sun. The fundamental tide is of semidiurnal type with two nearly equal cycles in each lunar day of 24 hours and 50 minutes, with an essential sinusoidal pattern. The tides with the greatest range in each lunar month, the spring tides, occur at the time of the full and new Moon, depending on the relative declinations of the Sun and the Moon. The tides with the least range, neap tides, occur at half Moon, midway between full and new Moon. A number of other factors are involved in the forces producing the tides, making them highly complex.

Any sizeable body of water is subject to wind set-ups (sometimes called wind tides) which may be of considerable magnitude, with no regular period but associated with wind velocity and direction. The greatest wind set-ups are those associated with hurricanes. The steady, high winds of a hurricane tend to raise the water level along the sea shore and, during the period of maximum wind velocity, they can cause destructively high stages.

The size of the tidal range is particularly important in low-lying country where the channels and drainage may be considerably affected by tidal backwater.

A distinction is made between tide and current, in that tide is the vertical change in surface elevation of a body of water, while current is the horizontal movement of water caused by the tidal action.

3.9.1 Cases

— A stream channel directly connected to a tidal body of water is usually affected by tidal variations for some distance above its outlet. The length of the reach affected depends upon the elevation of the bottom of the channel, the amount of freshwater discharge, and the friction-producing elements in the channel.

— The effect of tidal variations is not simultaneous throughout the length of a tidal reach of a stream, and the result is a wave which travels upstream. Because the vertical motion of the water affected by the wave is a result of continuous and alternate storage and release of water in the channel, it follows that a tidal impulse can travel upstream against the flow of water in a channel. Therefore, a tidal wave moving upstream does not necessarily indicate actual upstream movement of the water.

— The tidal wave will produce unsteady flow conditions as it moves up a waterway. As long as the acceleration head is moderate, the flow pattern will belong to the gradually varied unsteady-flow type. However, in regions of the world where the tidal range is very large and the gradient of the waterway is low, a tidal bore moving rapidly upstream may result. A tidal bore (or surge) refers to a moving hydraulic jump which possesses a sharp and steep advancing front (i.e. rapidly varied unsteady flow).

— The tidal range decreases as the wave moves upstream and it disappears at some point inland. The rate of decrease would be uniform in a uniform canal, but it varies in a natural stream channel because of changes in the channel section and channel alignment. For a given channel, the limit of the tidal backwater varies with the amount of freshwater discharge in the stream because the discharge has a damping effect: the greater the discharge, the shorter the reach affected by the tide.

— Close to the sea at outlets of tidal streams, the time of slack water (i.e. zero current) is almost the same as the time of high and low tide. But this does not hold true in the upper reaches, here tide and current become progressively more out of phase as the tidal wave moves upstream. Furthermore, the tidal wave in the lower reaches of the stream usually has the same shape as in the outlet bay, but a change in symmetry occurs as the wave progresses upstream. The freshwater discharge and channel friction oppose the upstream propagation of the wave, and they tend to shorten the duration of the rise and to lengthen the duration of the fall, although the period of the wave remains the same. This is the characteristic river-type tide which is common in the upper tidal reaches of coastal streams.

3.9.2 Problems

Because of the periodical ingress and regress of the tide in estuaries and tidal river reaches, a number of possible difficulties may occur, as listed below:

— There is a continuous change in stage with time.

— There is a continuous change in flow velocity, i.e. a steady flow condition is never attained.

— In tide-affected rivers the high and low tides (stage) do not occur at the same time as the maximum and minimum current (discharge), i.e. tide and current are out of phase, the extremes of current occurring before the extremes of tide.

— The distribution of velocity changes with time, both in width and depth.

— Generally, in estuaries and downstream reaches of tidal channels, there is a periodic reversal of the current, the velocity attaining zero magnitude during the transition. In the upstream reaches the tide will not cause a change in the direction of the current, but will manifest itself in a form of pulsating current.

— The change in direction of the current does not occur simultaneously throughout the width and depth of the lower tidal reaches.

— The occurrence of high tide and low tide will not generally take place at the same time as the change in the direction of current, and will not occur at the same time along the tide-affected channel.

— There may be great and rapid variations in the width and conveyance of the different cross-sections due to successive covering and uncovering of the banks and shoals by the tide.

— There may be density currents (i.e. stratified flow caused by a salt-water wedge), even with the upper strata flowing in one direction and the lower strata flowing in the opposite direction.

— There may be large-scale turbulence and seiches, e.g. fluctuations with periods of more than 30 seconds and amplitudes of up to 50 % of the mean velocity have been measured.

— There may be wind set-ups aggravating and complicating the regular tide pattern.

3.9.3 Solutions

Discharge ratings can be obtained for tide-affected streams as discussed below.

3.9.3.1 Direct Measurements

a) The moving-boat method. The moving-boat technique is similar to the conventional current-meter measurement in that both use the velocity-area approach in determining discharge. It is a method suitable for tide-affected rivers where the unsteady flow conditions require that measurements be made as rapidly as possible. The method is especially suitable for large rivers. It is not practical in channel reaches with density currents and stratified flow.
b) The acoustic methods, for larger rivers. It can not be used when there are density currents with stratified flow, i.e. in estuaries and the lower reaches of tide-affected streams.
c) The electromagnetic method, for streams up to about 100 m wide. It can be used in stratified and reverse flow and gives a continuous record of the discharge.

3.9.3.2 Empirical Methods

There are four empirical methods (i.e. mathematically derived from measured relationships) for rating tidal reaches, all of which have their shortcomings in given situations:

a) Method of cubature. The method of cubature is based on the law of conservation of mass: outflow equals the sum of inflow and change in storage. It consists of using the rate of rise and fall of the water surface to determine the rate of gain or loss of channel storage in a reach. The discharge at the downstream end of a reach is calculated from a known inflow and known gain or loss in channel storage during the time required for the surface to rise and fall.

   The method of cubature has certain limitations, of which the greatest is that errors in calculation of base or upstream flows are included in the flows computed for stations downstream, and that the accuracy of the calculations must be expected to be in the order of ± 10 %.
b) Method of stage-slope-discharge rating. Stage-slope-discharge relations have been used successfully for rating tide-affected streams where acceleration head is a minor factor. Acceleration head is often a minor factor where the slope reach is located at the upper end of a tidal channel near the limit of the tidal backwater, and it is generally at or near such locations that the method can be used.
c) Tide-correction method. The tide-correction

method assumes that a direct proportionality exists between the cyclic range in stage observed at any two points within a tidal reach. Based on that assumption, a relation of mean discharge for a tidal cycle to mean stage for a tidal cycle is developed for the base-gauge site. In calibrating this relation, the mean discharge for a tidal cycle, obtained by averaging several individual measurements made 1 to 2 hours apart throughout the cycle, is plotted against adjusted mean stage at the base gauge. The adjustment applied to the mean stage at the base gauge, is determined from the difference at the secondary gauge between observed mean stage and the stage which is presumed to exist under conditions of least tidal fluctuation. That difference (D) is multiplied by the ratio of the stage range at the base gauge to the stage range at the secondary gauge; the product is the stage adjustment required at the base gauge. In practice, the secondary stage observations are frequently made at a nearby ocean inlet. Mean sea-level is assumed to represent the condition of least tidal fluctuation and, therefore, if all gauges have their datums set to mean sea-level, D is always equal to the mean stage for a tidal cycle at the secondary gauge. Essentially, the tide correction method attempts to approximate the stage which would occur with a particular steady-flow discharge under a fixed backwater condition.

The tide-correction method of rating a tide-affected stream may be used where reverse flows occur during a part of each tidal cycle, because the mean discharge for the cycle is the value used in the computation.

d) Coaxial rating-curve method. The coaxial method of graphical correlation to determine discharge in a tidal reach was developed to fill the need for a simple method of making reasonably accurate "on-the-spot" determination of streamflow. A method of this kind is required, for example, in the operation of a sewage plant discharging its effluent into a tide-affected stream. The method that was developed fills this need in that readings from a pair of stage gauges can be used to determine momentary discharge directly from a set of rating curves.

3.9.3.3 Velocity-area Method

In this method, the velocity is measured during the entire flood-ebb cycle. The time interval between measurements at the various verticals is kept to a minimum. Measurements are usually made at several points, in order to be able to take into account the different directions of flow at the verticals. At the same time, the water level is measured continuously, and thus the depth at the verticals also. Then, all measurements are reduced to the same time for which the discharge is calculated. However, this method is labour consuming, it requires a large number of observers, boats and equipment. The method is particularly difficult if the amplitude of the tide is large, if there are large changes in the width of the river channel during the period of the tide and if there are significant changes in the mean direction of flow during a tidal cycle. However, the method shows the distribution of velocities, the stratification of the tidal current, etc.

The velocity measurements may also be carried out by the moving-boat method or using a network of current meters.

3.9.3.4 Unsteady Flow Mathematical Modelling Method

This method is based on the complex mathematics of the differential equations of unsteady flow, involving the principles of conservation of mass and the conservation of energy.

The basic assumptions made are: (a) gradual variation in unsteady flow, (b) homogeneous and one-dimensional flow, and (c) prismatic channel geometry. On these assumptions a system of unsteady-flow equations can readily be set up to describe the tidal flow. Initial and boundary conditions are determined by field measurements. The actual computation of discharge is performed by digital computers.

From the basic assumptions it follows that the use of the method is limited to those portions of tidal reaches which are affected by the propagation of long, low-amplitude, translator waves and are beyond the range of influence of appreciable salinity intrusion which might result in the stratification of flow by density currents.

3.10 River Channel Affected by Wind

When wind is blowing over a water surface, ordinary oscillating waves occur. The waves are caused by friction between the air and the water surface and, having arisen, they are also exposed to direct wind pressure as well as the effect of air eddies formed leeward of the wave crest. The combined forces to which the water surface is thus subjected are called the wind force.

3.10.1 Cases

— In lakes, the wind force generates surface currents driving the water against the leeward shore. This gives the water surface a rising slope which causes return currents in the deeper water. The increase in stage at the leeward shore, added to the decrease in stage at the windward shore, is called the wind effect. The wind effect is also referred to as the wind set-up.

— The wind effect should not be confused with seiches, which are the free oscillation of the whole mass of water in a lake and the resultant rhythmic motion of the water surface.

— In rivers, the wind force will increase or decrease the velocity of the water depending on whether the wind is blowing with or against the flow. The water surface is thereby lowered or raised, as the case may be. The difference in stage from the normal stage of calm weather is called the wind effect.

3.10.2 Problems

— The wind effect may have considerable influence on the outflow from lakes. In the St. Lawrence River, for instance, the variation in river flow caused by wind effects on Lake St. Francis has been observed to reach 1 000 m^3/s. According to documents in the Geneva city archives, wind drove the water back from the outlet of Lake Leman in 1495 and 1695, part of the lake bottom was exposed and no water entered the River Rhone [27].

— Regarding flow in rivers, the wind force will increase or decrease the velocity of flow as the wind blows in a downstream or upstream direction. The water level is thereby lowered or raised, decreasing or increasing the cross-sectional area required for discharging a given flow, the discharge being independent of the wind. Under these conditions, the discharge rating curve is no longer valid if there is an appreciable distance between the station control and the stage gauge or recorder.

Regarding outflow from lakes, two cases are considered:

a) The wind blowing over the lake does not significantly affect the river at the outlet of the lake.

b) The wind blowing over the lake also blows up or down the river causing a change in the velocity of flow.

In case a) the discharge from the lake depends on the water level in the lake at the outlet only and the discharge rating curve remains unaffected.

In case b) the discharge depends not only on the water level in the lake, but also on the wind effect on the river at and downstream from the outlet of the lake.

— When making discharge measurements from boats, the wind-caused waves may induce vertical motion in a cable-suspended current meter, or the wind may cause an oscillatory horizontal movement of the boat against the tag line. Either movement may affect the operation of the current meter.

— When making current-meter measurements from manual cableways, the cable car may be set in a swaying motion by even a light breeze, precluding any measurement from being taken. This problem often occurs with cableways with long spans.

— In general, wind may affect the accuracy of a current-meter measurement by causing abnormal variation in velocity, by agitating the water surface, by obscuring the angle of current and by affecting the uppermost velocity reading in the observation verticals.

3.10.3 Solutions

3.10.3.1 Correct Location of Gauging Station

Gauges on lakes and reservoirs should be located near the outlet, but upstream of the zone where the velocity causes a drawdown in the water level.

Gauges on lakes and reservoirs should be located so as to reduce the fetch of strong and/or prevailing winds which may cause damage or misleading data (fetch, that is, the distance which the wind blows over a water surface).

When siting regular stream-gauging stations, sites with serious wind effects should be avoided.

3.10.3.2 Orientation of Gauging Sites on Rivers

The orientation of the stream reach where the gauging station and discharge-measuring site is located should be such that the direction of flow

is as closely as possible normal to that of the prevailing wind.

In rivers, the gauge and recorder should be located close to the station control, but outside the range of the velocity drawdown curve. This is particularly important where the depth of water upstream of the control is small, where the reach above the control is exposed to the prevailing wind and where the low-stage head at the station control is small.

3.10.3.3 Gauge and Control Separated by a Distance

When the gauge or recorder is unavoidably separated by some distance from the station control, discharge measurements for calibration should not be made if an appreciable wind is blowing up or down the river.

3.10.3.4 Conditions for Discharge Measurements

In general, discharge measurements for calibration purposes should not be performed under conditions in which the wind effect will impair the quality and accuracy of the measurement. The measurement should be postponed until conditions are calmer. In most cases this will not present a serious problem. However, in hot desert regions the problem may become a real obstacle regarding current-meter measurements from manned cableways. As stated in Section 10.2, the cable car of a manned cableway may easily be set and maintained in a pendulum-like motion by even a slight breeze. In a hot desert region, a light breeze often starts to move down the river valleys quite early in the day (say at 10–11 a.m.). In order to finish his current-meter measurement in time, the hydrologist therefore should start the day at sunrise.

3.10.3.5 Special Cases

Sometimes a gauging station may have to be established on a site subject to wind effects. In this case, the wind set-up may be computed and the observations corrected.

In other cases, it is the rise in water level at the leeward side of a lake that is of interest, rather than the total wind set-up. This value may also be computed on the basis of fetch, depth of water and wind velocity.

3.11 River Channel Affected by Ice

In temperate and cold climatic regions ice will form on lakes and rivers during the winter season. In streams where the current is of moderate strength, a complete ice cover will eventually be formed. This cover will ordinarily be in flotation but not in motion.

Frazil ice (slush) is an accumulation of fine, elongated needles and thin sheets of ice which form on the surface of turbulent water, as at riffles.

Anchor ice consists of masses of spongy ice or slush adhering to rocks on the streambed. Anchor ice is released and floats to the surface when the streambed is warmed by short-wave radiation from the sun.

3.11.1 Cases

— A cover of surface ice in contact with the water will, in effect, change the flow of a stream from open channel flow to closed conduit flow, thereby reducing the conveyance of the stream. The recorded stage will therefore increase for a given discharge, that is, backwater occurs. The backwater effect may be aggravated by the accumulation of frazil ice and/or anchor ice under the surface ice.

— In early winter, frazil ice may cause temporary backwater in shallow stream reaches or at section controls. Anchor ice, which has formed on the bed of the stream at or near controlling sections and reaches, may have similar effects, usually of short duration.

— In regions with a stable winter regime, there are commonly two discharge minima during the winter. The first occurs in early winter. A sudden drop in temperature is accompanied by a sharp decrease in discharge resulting from: (a) the reduced discharge capacity of the river under ice cover, (b) the loss of some of the flowing water to ice formation, and (c) the temporary reduction of inflow of groundwater due to freezing of the ground. The drop in discharge will be of short duration (one or a few days). It is then usually followed by a quick recovery up to the normal recession. The second minimum, which occurs at the end of the winter, is caused by the exhaustion of the available groundwater reservoir.

— Small streams are usually less subject to backwater from surface ice than large streams. A small stream may acquire an ice cover when the water

level is at a fairly high stage. With continued freezing temperatures the stage of the stream will decrease. However, the ice cover will often remain in place, supported by arch action and by large stones in the streambed, allowing the diminished flow to pass beneath the ice.

— Surface ice may cause siphonic action when it forms on a section control. When siphoning occurs, it causes rapid fluctuations of stage: the gauge pool is rapidly drained low, then, when air enters the system, the pool fills up and the siphoning starts all over again.

— In an unstable winter regime with alternating periods of thawing and freezing, the inflow of snowmelt water causes increased flow during the thaws. Rainfall during thaw periods often intensifies snow-melting and may lead to a sharp increase in discharge, especially when the ground is frozen and prevents infiltration. Periods of alternate freezing and thawing often result in the formation of several layers of solid ice with water flowing between the layers. One or more break-ups of the ice cover may occur during the winter, causing ice-jams of the broken floating ice.

3.11.2 Problems

— Stage recorders do not function because of failure of the recording instrument due to low temperatures, or because of ice formation in the stilling well and intake pipes.

— Outside staff gauges cannot be read because of ice cover on the stream.

— Current-meter equipment and current-meter measurement procedures for open water conditions have to be adapted to ice conditions.

— It is difficult to locate and evaluate good current-meter measurement sections.

— Ice lodged in stream channels affects the normal open water stage-discharge relation of a stream, varying with the quantity and nature of the ice, fluctuations in air temperature and discharge, and by causing backwater effects. Thus, backwater effects due to ice preclude the direct use of the open-water discharge rating.

3.11.3 Solutions

3.11.3.1 In Temperate Climates—Siting of the Gauging Stations so that Variable Backwater Effects are Eliminated or Reduced.

This may include:

a) Siting the gauging station near the outlet of a lake or large pool. Because of the comparatively high temperatures which exist in the outflow from such water bodies during the winter season, ice will seldom, if ever, form at the outlet.
b) Siting the gauging station below: (a) an industrial plant, (b) immediately downstream from a dam with outlet gates.
c) Installing an artificial control. Artificial controls are less likely to be affected by the formation of ice than natural controls are.

In cold climates the above solutions are not feasible because all water bodies will freeze over during the winter season.

3.11.3.2 In Cold Climates—Installation of Gauging Stations so that they may be kept reasonably free of Ice

This may include:

a) For a nonrecording gauge, the daily clearing of ice from that part of the staff gauge which extends into the river, or the cutting of a hole through the ice under a chain or wire-weight gauge, so that the water beneath will rise to its static level and readings of stage may be made.
b) For a float-actuated water-stage recorder, the construction of the stilling well at such a distance from the bank of the river, and at such a depth that the surface of the water in the well will be below the frost line.

   The intake pipe should be placed at as low an elevation as the streambed will permit, so that the pipe may be protected by the greatest possible depth of earth cover, and that it may be well below the zone of ice formation in the stream.

   In the design of stage recorders, provision should be made for the use of insulating materials in the walls and ceiling of the house and stilling well, and around the intake pipes.

3.11.3.3 Prevention of Formation of Ice in Autographic Recorders and at other Gauges

This may include:

a) Installing a temporary floor within the stilling well just below the frost line. The temporary floor is set in early winter.
b) Installing two intake pipes, the lower of which is positioned below the bottom of the ice sheet and the upper above the ice sheet. In this way the lower pipe will function during the freezing period and, should the lower intake become frozen, the upper intake will become operative during the snow-melt flood while the lower intake thaws.
c) Installing a bottomless cylinder, partly filled with a nonvolatile petroleum distillate, vertically in the stilling well to accommodate the float.
d) Installing heating devices in the recorder house, stilling well and intake pipe. These may include electric-heaters and lamps, electric-immersion coils or an electric-heating cable placed inside or wrapped around the intake pipe, kerosene and gas burners, and lamps. The quantity of heat provided must be the minimum required Overheating will result in the production of excessive water vapour which will condense as rime-frost inside the recorder house and well.
e) Where feasible, heating of structures such as notches, weirs and flumes during the freezing period to ensure that the stage-discharge relation is applicable during the winter. This may be accomplished by suspending an array of electric or propane radiant heaters above the structure, or by enclosing the entire structure in a wooden cover during winter time, leaving openings for the free inflow and outflow of water only. The space enclosed in this manner may then be heated. A heating cable embedded in the crest of weirs has also proved useful when electric power is available.
f) Wrapping a heating cable around the gauge scale and backing board in order to prevent the formation of ice around staff gauges.
g) Between readings of nonrecording gauges, covering the hole through the ice with insulating mats to prevent or reduce the thickness of new ice.

3.11.3.4 Determination of the Magnitude of Backwater caused by Ice and Computation of Discharge during Periods of Backwater

Current-meter measurements should be carried out as frequently as feasible when the stream is under ice cover, particularly during freezing and break-up periods when the flow is highly variable. In mid-winter, the frequency of measurement will depend on climate, accessibility, size of stream, winter runoff characteristics and required accuracy of the discharge record. In very cold climates where ice cover persists and winter discharge shows a smooth recession, fewer winter measurements are needed than in climates which promote the alternative freezing and thawing of river ice.

By means of the measured discharges, the backwater effect at the time of the discharge measurement is determined. Thus, based on the measured backwater effect, the daily mean discharges in the time intervals between measurements are interpolated, making use of other relevant information such as: (a) ice notes by the observer and visit reports by a hydrologist, (b) weather notes by the observer, (c) temperature records by the observer and/or a nearby meteorological station, and (d) comparisons and consistency checks with other comparable stations, particularly with stations which are unaffected by ice. A number of methods for computing the discharges between measurements are described in the literature, as in [3]:

- Backwater method,
- Interpolated discharge method,
- Adjusted discharge method,
- Effective-stage method, also known as the Shifting-control method, or the Stout method,
- Recession-curve method,
- Correction-factor method, also known as the discharge-ratio method,
- Hydrographic and climatic comparison method.

3.11.3.5 Special Procedures and Equipment used for Measurement of Discharge under Ice Cover

This may include:

a) Selecting possible locations in the cross-section, to be used for measurements from ice cover, during the open water season when channel conditions can be evaluated;
b) If there are several layers of ice cover, determining the discharges flowing between the layers of ice separately. In each flow, sound-

ings and velocity measurements are made independently.

c) Where water flows above the ice, measuring separately the discharge under the ice and above it. The upper current is often measured by wading.
d) Cutting holes through the ice cover with an ice chisel, ice auger, ice power drill, or a chain saw.
e) Using ordinary propeller-type current meters, or vane current meters, for measurements under the ice cover. Cup-type current meters are not suitable as the cups tend to fill with slush.
f) Once the measurement has started, keeping the current meter in the water as much as possible to avoid exposure to the cold air.
g) In extremely cold weather, using a heated water tank to keep the current meter from freezing while moving it from one ice hole to the next.
h) Taking into account that, when holes are cut in the ice, the backwater effect will usually press the water up into the hole. In order to determine the effective depth of the stream, ice measuring sticks are used to measure the distance from the water surface to the bottom of the ice. This is done with a graduated bar with an L-shaped projection at the lower end. An ordinary sounding rod with a footplate may be used for the same purpose.
i) Using a special weight assembly for line sounding under the ice cover because a regular sounding weight will not fit through the hole cut by the ice drill. The weight and current meter are placed in a framework which will fit through the drilled hole.
j) Connecting a propeller-type current meter which is suspended from a rod to a special tool whereby the meter is turned to a vertical position when being passed through the ice hole, after which it is turned to a horizontal position.
k) When time is available, determining velocity curves from velocity observations at every tenth of the effective depth, in at least two verticals, to determine which coefficients, if any, are necessary to convert the average velocity obtained by standard open-water methods of observation to an average velocity in a vertical under the ice cover.
l) If there is no surface flow in the channel in winter and the channel is covered with snow, prepare the gauging site for the spring measurements just before the onset of floods. For this purpose, a ditch in the snow 0.5 to 1 m wide and not less than 10 m long, is dug across the channel in the lowest part of it. Subsequently, this ditch will be enlarged by the water flowing across it.
m) If there is a discontinuous ice cover, only part of the current being covered with ice, carrying out measurements in the free sections as in an open channel, and in the covered part as in a continuous frozen section. If direct measurements of velocity cannot be made by current meter in the open part, the float method should be used. For this purpose, either specially made floats or ice floes floating in the area may be used.
n) Using an ice chisel when first crossing an ice-covered stream to determine whether the ice is strong enough to support the hydrologist. If a solid blow with the chisel blade does not penetrate the ice, it is safe to walk on, providing the ice is in contact with the water.
m) When the safety of the ice is in doubt, using a life line when first crossing and probing the ice cover.

3.12 Steep Mountain Streams

3.12.1 Cases

— Supercritical flow with pulsation, high turbulence and highly fluctuating water surface,

— Entrainment of air in the water current,

— Little water in winter.

3.12.2 Problems

— For installation of recorders, there is normally found small shallow pools only which do not offer protection against freezing of the recorder intake pipes in winter.

— Artificial pool for water-level recorders and forebay for weirs are rapidly filled from upstream with gravel and rocks making the control ineffective.

— Measurement of flow velocity by current meter gives questionable results because of excessive turbulence and entrainment of air in the water.

— Propeller of current meter is easily damaged by heavy bedload transport.

3.12.3 Solutions

3.12.3.1 Construction of Artificial Control with Upstream and Downstream Apron

In case of insufficient dam height to create sufficient water cover to prevent freezing of the intake pipe, a higher structure is built with a sloping upstream apron of 5:1. Such weirs are effective in streams carrying bedload as the load will easily be passed over the crest of the control.

3.12.3.2 Construction of Standard Crump Weir or Flat V-weir

On larger mountain streams it is recommended to construct standard Crump weirs or Flat V-weirs. These weirs are highly effective in passing suspended and rolling material over the crest in streams carrying much bed material.

These standard weirs are calibrated in situ by means of discharge measurements because of the highly irregular flow conditions.

3.12.3.3 Construction of Upstream Check-dam

Construction of check dams retaining the bedload that otherwise would be deposited in the pool above artificial controls is not recommended. Experience has shown that weirs with sloping aprons are greatly to prefer to check-dams because their greater effectiveness and lower cost of maintenance.

3.12.3.4 Construction of Critical-depth Flume

Construction of a critical-depth flume with side constrictions only and with the throat slope similar to the approach channel slope. Thus the bedload will be swept through and no deposition will take place.

The flume is calibrated in situ by discharge measurements.

3.12.3.5 Discharge Measurements by Dilution Method

Discharge measurements in mountain streams are normally carried out by the Dilution method. In the turbulent and well-mixed water this method normally yields excellent results.

Bibliography

Chapter 3: [1], [3], [4], [5], [7], [8], [11], [18], [19], [22], [21], [29], [30], [35].

CHAPTER 4

THE RELATIVE SALT DILUTION METHOD

4.1 General

The application of chemical tracers in gauging streamflow has been known for 70 years. Early techniques consisted of injecting a chemical substance of known concentration into the stream water at a constant rate and then determining the steady state concentration of the tracer at a location sufficiently far downstream where a homogeneous mixture of the tracer and the stream water was assured. The degree of dilution of the tracer permits the stream discharge to be calculated from the equation

$$qc = (Q + q)\,C \qquad (4.1)$$

where

- q = rate of injection of tracer,
- c = concentration of tracer,
- Q = stream discharge,
- C = steady state concentration of tracer at sampling site.

As Q is much greater than q, Eqn. (4.1) reduces to

$$Q = M/C \qquad (4.2)$$

where M is amount of tracer injected into the stream per unit of time: M = q c.

Originally the concentration of the chemical substance used as tracer was determined by titration, and this, together with the complicated procedure of maintaining a constant injection, limited the field applicability of the *tracer dilution method.*

The method was developed further by making use of an ionizing substance as tracer and the corresponding change in the electrolytic conductivity of the stream water to determine the dilution of the tracer. In addition, instead of a constant-rate injection a sudden bulk injection was introduced. Thus, the improved technique consisted of the sudden bulk injection of a known amount of salt in solution followed by the determination of the time-concentration graph at the downstream sampling site. The stream discharge was then obtained from the amount of salt injected and the area under the time-concentration graph.

Aastad and Søgnen in their *Relative Salt Dilution* method (1928, 1954) refined and simplified the method by introducing relative concentration and developing a practical procedure for field application. [25], [26].

4.2 Theory

S litres of a salt solution are released into a stream carrying an unknown discharge of Q litres per second (l/s). The volume of S is assumed negligible compared to the discharge Q. At a downstream observation site where the salt solution is homogeneously mixed with the stream water, the flow will consist of a very dilute salt solution. The salt concentration will rise from zero (or the background level), reach a peak value and then fall back to zero as the solution wave passes the site (Fig. 39). Each instant, the stream water at the observation site will contain different quantities of the injected salt solution, that is

$$S = s_1 + s_2 + \ldots + s_i + \ldots + s_n$$

where

- S = amount of salt solution injected (litres),
- s_i = amount of salt solution passing the observation site at the i-th instant (litres),
- n = time required for the passage of the salt solution wave (seconds).

Assume that the concentration of the salt solution in the stream water each instant is $c_1, c_2, \ldots c_n$. Thus,

$$s_1 = Qc_1,\ s_2 = Qc_2,\ \ldots\ldots,\ s_n = Qc_n$$

Further,

$$S = s_1 + s_2 + \ldots + s_i + \ldots s_n$$
$$S = Qc_1 + Qc_2 + \ldots + Qc_i + \ldots + Qc_n$$
$$S = Q(c_1 + c_2 + \ldots + c_i + \ldots + c_n)$$

$$S = Q \sum_{0}^{n} c_i \, dt$$

$$S = QA$$

or,

$$Q = S/A \qquad (4.3)$$

where

Q = water discharge of the stream,
S = volume of injected salt solution,
A = area under the time-concentration graph.

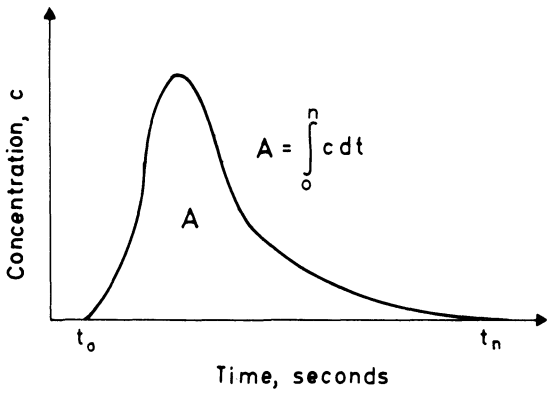

Figure 39. Time-concentration graph resulting from a sudden injection of tracer. Good mixing conditions. Long-tailed graphs indicate poor mixing conditions.

From Equation (4.3) it can be seen that the determination of the stream discharge is theoretically independent of:

a) distance between the injection site and the observation site,
b) duration of the injection,
c) velocity of the flow,
d) size and shape of the cross section.

However, there are two critical conditions which must be fulfilled:

a) The injected salt solution must be homogeneously mixed with stream water when passing the downstream observation site.
b) The whole of the salt solution must pass the observation site.

4.3 The Measuring Procedure

4.3.1 The Measuring Reach

The measuring reach should not have any deadwater zones or eddies where the salt solution may be trapped and slowly leak back into the flow, thus greatly increasing the measuring time. To reduce the measuring time, the distance between the injection site and the observation site should not be unnecessarily long. However, it is essential that the mixture of salt solution and stream water is complete over the whole cross section at the observation site. This is easier obtained in relatively deep and narrow channels. The mixing is further promoted by high turbulence and disturbances such as narrows, rapids and falls. An uneven bottom with rocks and boulders is better than an even sand-bed channel. [42].

In general, rapid mixing occurs where the flow of water is discontinuous. Such discontinuities are found at waterfalls and rapids, at large hydraulic jumps, and at contractions followed by rapid expansion of the stream channel. These conditions must apply across the whole of the stream channel so that all the flow is affected.

Although mixing is promoted by turbulence and disturbances in the stream channel, lateral mixing in streams where no discontinuity occurs requires a great distance, much longer than one would expect. Under such conditions, the following empirical formula has been proposed

$$L = b \, Q^{1/3} \qquad (4.4)$$

where

L = distance between injection site and observation site (m),
b = 50 for mid-stream injection,
b = 200 for injection at one bank,
Q = stream discharge (m^3/s).

4.3.2 Preparation of the Salt Solution

Any readily soluble salt may be used to make up the salt solution. However, the cheapest and most convenient to use is common salt (NaCl), preferably fine-grained table salt which dissolves rapidly in water.

The amount of salt (NaCl) required per 1 m^3/s of stream discharge depends on the mixing length. A long reach requires more than a short reach for the same discharge. The *background conductivity* (i.e. the natural conductivity measured when no salt solution is present) of natural water also affects the minimum amount of salt that can be used. As a rule of thumb, 0.2 kg of salt per 1 m^3/s of discharge is considered sufficient

Figure 40. Battery-powered conductivity meter for field use.

for natural water with low background conductivity. Under good conditions however, discharges of up to 140 m^3/s have been measured by the use of not more than 12 kg of salt (i.e. 86 grams of salt per 1 m^3/s of discharge).

The solubility of NaCl at 15°C is 3.6 kg to 10 litres of water. However, under field conditions not more than 2.5 kg are used to 10 litres of water.

A conductivity meter suitable for field use is shown in Fig. 40.

It is not necessary to know exactly the concentration of the salt solution. However, the *volume* of the salt solution must be exactly known. Since it is important that only salt in solution be added to the stream water, the solution should be prepared in a separate container and then decanted into a calibrated injection tank with a needle gauge. This is the *primary solution.*

It is most convenient to standardise the volume of the solution used and to vary the concentration according to the magnitude of the flow. For small streams, a volume of 20–50 litres of primary solution is suitable. For larger streams, a volume of 100 litres may be necessary.

A small sample of about 100 millilitres is retained in a clean bottle for the purpose of developing the conductivity-concentration relation, see Section 4.3.4. The procedure in drawing off this sample is as follows: When decanting the primary solution into the calibrated injection tank, the injection tank is filled to about half a litre above the index mark. The small sample is then drawn off after which the excess solution in the injection tank is removed. Before the small sample is drawn off, the contents of the tank must be stirred thoroughly.

Table 3. Observation of the Solution Wave in the Stream

Time seconds	Conductivity scale units	Time seconds	Conductivity scale units
0	102	100	161
10	102	105	153
15	105	110	146
20	110	115	140
25	117	120	136
30	129	130	129
35	146	140	123
40	170	150	118
45	191	160	113
50	210	170	110
55	225	180	107
60	230	190	105
65	228	200	103
70	223	215	103
75	215	230	102.5
80	201	245	102.5
85	191	260	102.5
90	180	275	102.5
95	170	300	102.5

4.3.3 Observation of the Salt Solution Wave

The primary solution is injected into the river, preferably as close as possible to the centre of flow in order to reduce the mixing length. It is not necessary that the injection is instantaneous, an injection time of up to 2–3 minutes is quite tolerable.

The passage of the solution wave at the downstream observation site is recorded by means of an electrode placed in the main flow and connected to the conductivity meter. Readings are taken every 5 seconds during the passage of the main part of the wave. When recording the tail of the wave, longer intervals are used. (Table 3).

Table 3 shows that readings 1 and 2 give the background conductivity of the stream water. The solution wave arrives at the sampling site shortly before 15 seconds, when the reading is 105 scale units on the conductivity meter.

In the *relative salt dilution method*, it is of no consequence whether or not the conductivity meter is correctly calibrated. All that is required is a set of conductivity readings which are compared with a *conductivity-concentration* relationship which is developed by use of the same instrument. The reading of the background conductivity measured in the stream may be adjusted by manipulating the gap between the electrode plates until a setting is obtained that will give a favourable range of readings when the solution wave passes the observation site. For this purpose, an adjustable electrode is necessary. (Fig. 41).

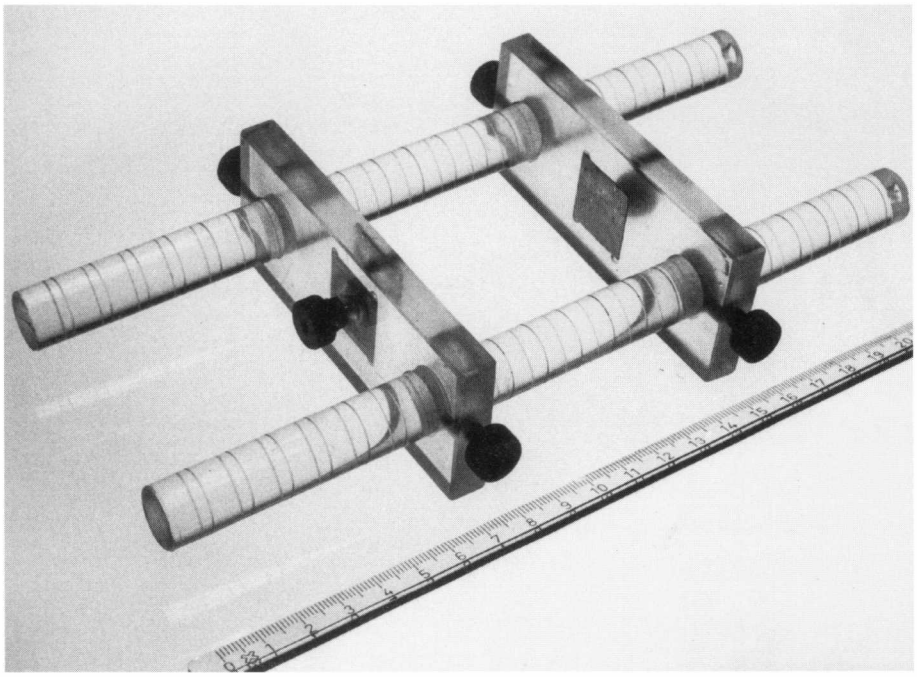

Figure 41. Adjustable electrode about 25 cm long. Frame made of resin plastic, electrode plates made of platinum or silver.

The temperature of the stream water must be recorded both before and after the measurement.

In relatively steep and cascading streams, an alternative arrangement is to divert some of the stream water into a wooden trough in which the electrode is placed. In this way, disturbances in the recordings due to air bubbles passing between the electrode plates are avoided. The diverted flow would be about 2–5 l/s. (Fig. 42).

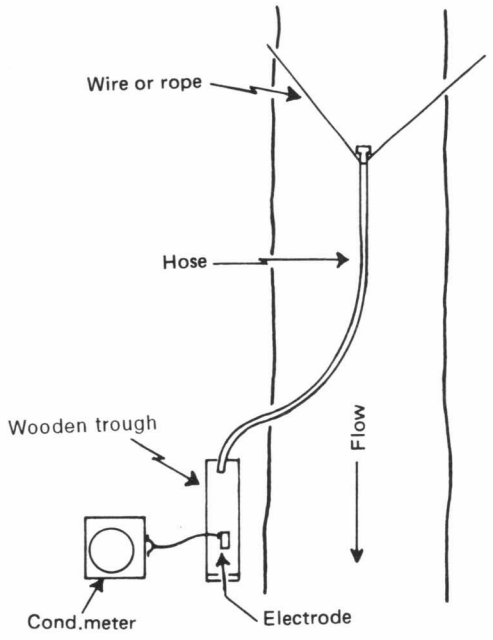

Figure 42. Sketch of measuring site. Air bubbles in the water will disturb the readings. Sampling in the presence of air bubbles is achieved by means of a hose placed in the stream passing water through a wooden trough.

4.3.4 The Calibration Curve

In order to convert the conductivity recordings of the solution wave into concentration values, a *concentration-conductivity* relationship (calibration curve) is developed. In actual practice, the calibration curve is developed before the measurement of the solution wave is carried out. The accuracy of the relative dilution method depends largely on a careful development of the calibration curve. The calibration procedure is as follows, see flow chart Fig. 43:

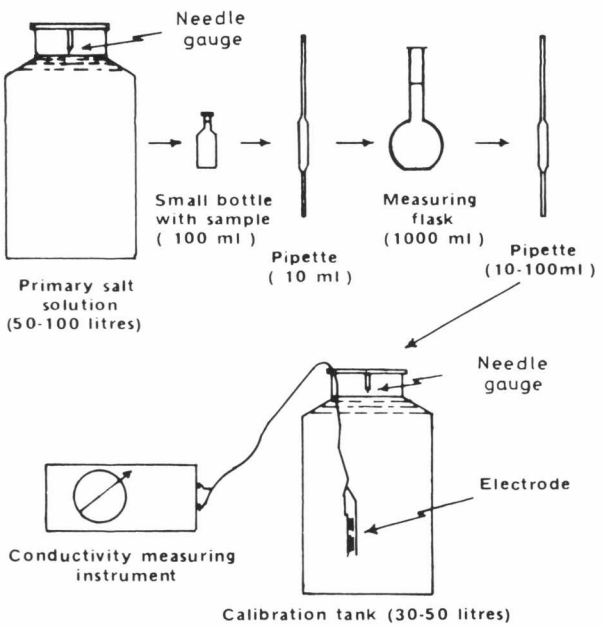

Figure 43. Flow-diagram illustrating the calibration procedure.

a) Measure 10 ml of the primary solution that was retained in the small bottle into a 1000 ml flask by a pipette rinsed in the primary solution. Fill up the flask to the index mark with stream water and mix well. By arbitrarily selecting the concentration of the primary solution equal to one, the solution in the 1000 ml flask will have a concentration equal to

$$\frac{10}{1000} \times 1 = 0.01$$

This is the *secondary solution,* that is, the primary solution diluted 100 times.

b) Measure exactly 20 litres of stream water into a wide-necked tank and place it in the stream in order to keep the temperature of the content constant during the calibration process.

c) Place the electrode in the stream and record the conductivity of the water. This is the natural background conductivity of the stream water. The temperature of the water is recorded.

If the background conductivity of the stream water is relatively high, then adjust the electrode until a low scale-reading is obtained. The final reading of the background conductivity is recorded.

d) Place the electrode in the wide-necked tank and stir the water in the tank until the needle of the conductivity meter has come to rest. A reading is taken and recorded. The temperature in the tank is also recorded.

It would be expected that the conductivity reading taken in the tank would give the same value as the reading taken of the water in the stream. However, it is normally found that the readings in the tank is 5–15 % higher than readings taken simultaneously in the stream, because the restricted volume of the tank affects the resistance of open electrodes. However, this is of no consequence as corrections are applied.

The difference in background readings may be eliminated by use of confined electrodes. A confined electrode is an electrode mounted in an insulating casing.

e) Withdraw exactly 10 ml of the secondary solution by a pipette and empty it into the 20 litres tank, thus obtaining a solution of relative concentration

$$\frac{10 \times 0.01}{20{,}010} = 5.0 \times 10^{-6}$$

The solution is stirred thoroughly and a conductivity reading recorded when the needle has come to rest.

Table 4. Developing the Calibration Curve

Secondary solution added to tank cumulative ml	Relative concentration	Conductivity, scale units	
		Readings	Adjusted readings
0	0.0	112	102
10	5.0×10^{-6}	136	124
20	10.0×10^{-6}	162	148
30	15.0×10^{-6}	185	169
40	20.0×10^{-6}	209	191
50	24.9×10^{-6}	232	212
60	30.0×10^{-6}	258	236
70	34.9×10^{-6}	281	257

f) Add consecutively 10 ml, 10 ml,...., 25 ml into the tank in the same way as in Step e). Record the results as shown in Table 4, columns 1, 2, and 3. In order to minimize inaccuracies, it is advisable to use 10 ml and 25 ml pipettes filled to capacity.

g) The calibration curve is constructed by plotting the relative concentration values (ordinate axis) against the corresponding conductivity values (abscissa axis) as shown in Fig. 44. The calibration curve should be linear, although in practice, a small curvature may be tolerated at the lower end of the curve. However, if the plot is not substantially linear, the procedure is repeated. Before the calibration curve can be finally plotted, however, two corrections are made as follows.

Firstly, since the conductivity readings made with the electrode in the stream will be converted to concentration values by means of the calibration curve, the calibration curve must start from the same base value as the background reading of the stream water.

The calibration is proportionally adjusted by multiplying every conductivity reading by the ratio

$$\frac{\text{stream background conductivity}}{\text{tank background conductivity}}$$

Secondly, if there was an appreciable temperature change in the tank during the calibration process, the readings must be adjusted. This problem is normally avoided by keeping the calibration tank submerged up to the neck in the stream during the calibration (Fig. 43).

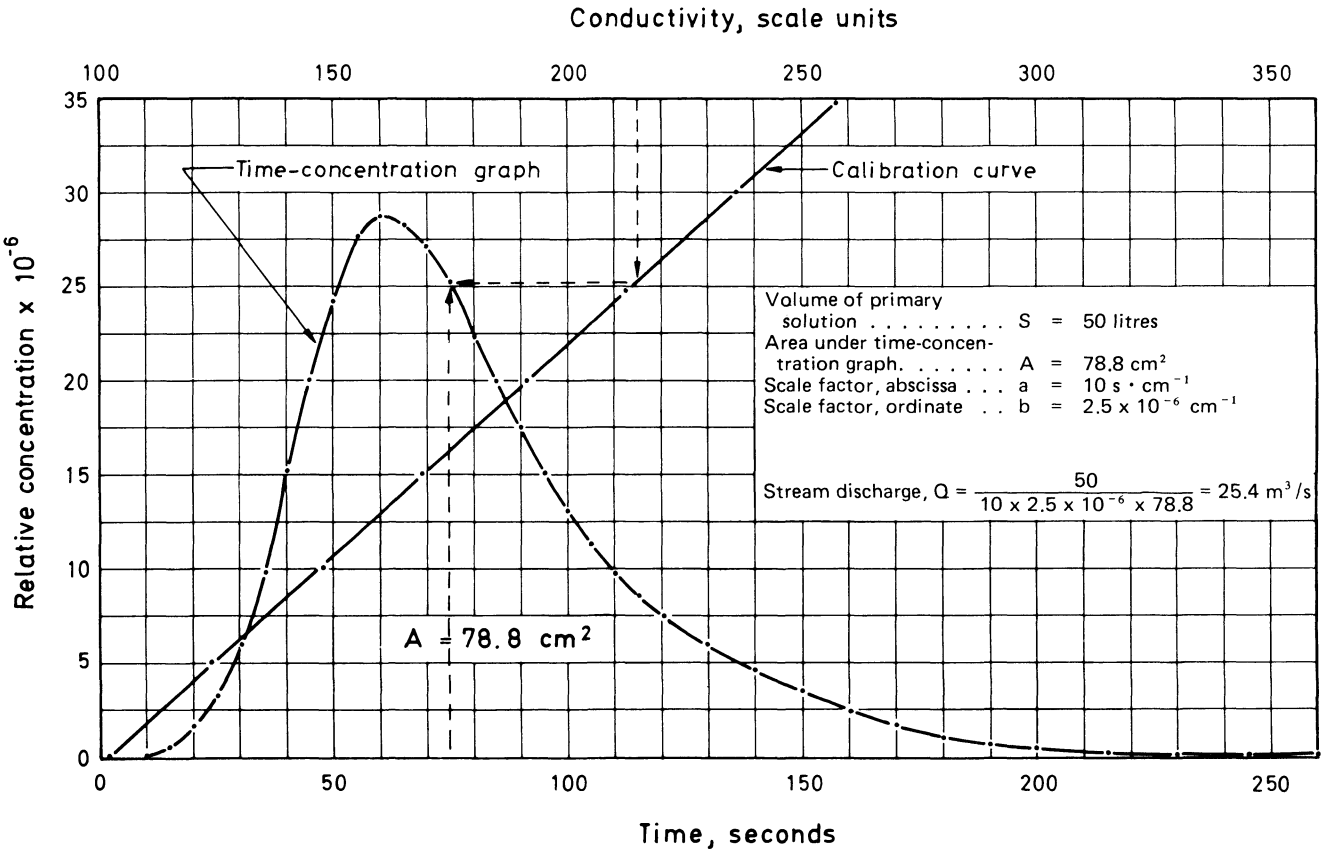

Figure 44. Computation of a relative salt dilution discharge measurement.

The first calibration reading, without added salt solution, gives the background conductivity in the tank, which is 112 scale units. The background conductivity in the stream water is recorded as 102 scale units in Table 4.1:

$$\text{Adjustment factor} = \frac{\text{stream background conductivity}}{\text{tank background conductivity}}$$
$$= 102/112$$
$$= 0.915$$

That is, in order to adjust the conductivity recordings in the tank (Table 4, column 3), the readings have to be multiplied by 0.915.

The temperature in the tank is measured to 21.2°C both at start and end of the calibration. That is, no adjustment of the readings due to change of temperature during the calibration is needed.

4.4 Calculation of the Discharge

The conductivity readings in Table 3 are converted to relative concentration values by means of the calibration curve and plotted against the corresponding time readings on graph paper. A graph is drawn through the plotted points and the area under the resulting time-concentration graph is determined by planimeter or simply counted up by means of a draftsman's dividers. (Fig. 44).

The discharge is calculated as

$$Q = \frac{S}{a \times b \times A} \qquad (4.5)$$

where

Q = stream discharge (l/s),
S = volume of primary solution (l),
a = scale factor for abscissa axis,
b = scale factor for ordinate axis,
A = area under the time-concentration graph (cm^2).

The calibration curve and the time-concentration graph are constructed on the same graph sheet. The procedure for plotting the time-concentration graph is as follows, see Table 3 reading at 75 seconds, and Fig. 44. Draw a vertical line through a conductivity reading on the conductivity axis to the calibration curve. Where this line meets the calibration curve, extend a horizontal line until it intersects a vertical line drawn through the corre-

sponding time reading on the time axis. The point of intersection is a point on the time-concentration graph. Repeat the procedure for all the corresponding time and conductivity readings and draw a graph through the resulting points.

4.5 Sources of Errors

— The importance of complete mixing of the primary solution with the streamflow is essential.

— Change in the temperature of an electrolyte causes variation in the electrolytic conductivity. Therefore, care must be taken to keep the calibration tank at a constant temperature during the calibration process. It is of no consequence should the temperature in the tank not be exactly equal to the temperature in the stream because the readings are adjusted (Section 4.3.4). The important thing is that the water temperature should be constant in the tank during the calibration process, and in the stream during the observation of the solution wave. If temperature variations should occur, corrections can be made by constructing a temperature correction graph. The error caused by changes in temperature during a measurement is more serious in cold water than in warm tropical water because the change in conductivity is greatest at lower temperatures.

– The careful and correct use of the pipettes is of utmost importance.

— Polarization at the electrode plates may occur. To avoid this effect, the electrode plates are made of pure silver or platinum.

— Air bubbles in the water may have a disturbing effect if they pass between the electrode plates. This is avoided by placing the electrode in a wooden trough into which a constant flow of water is led by a hose (Fig. 42).

— The electrode must be kept in the same position in the tank during the calibration procedure and the stirring should always be done in the same manner.

— If all the measurement procedures are carried out accurately and carefully, and if the physical characteristics of the measuring reach are fully satisfactory, the relative dilution method have at least the same degree of accuracy as the current meter method under good conditions.

Table 5. List of Equipment for the Relative Salt Dilution Method (Manual version)

a) Conductivity meter. For rivers with high background conductivity, a multiple range instrument is recommended. Linear scale is preferable to logarithmic scale.
b) Adjustable electrode with silver or platinum faces mounted on a suitable plastic frame, Fig. 41. Commercial conductivity cells may be adapted to this purpose.
c) Insulated two-conductor low inductance cable of sufficient length.
d) Frame with weight for anchoring the electrode in the stream.
e) Stopwatch.
f) Calibration tank, 20–50 litres capacity, made of aluminium, with a wide neck for easy access of the electrode, and equipped with a needle gauge.
g) Two water tanks of 50–100 litres capacity, calibrated and equipped with a needle gauge, for preparing the primary solution.
h) Glass or plastic bottle of about 100 ml capacity with a tight stopper, for storing the calibration sample of primary solution.
i) 1000 ml flask with long narrow neck, calibrated with index mark.
j) Pipettes of 10, 25, 50 and 100 ml capacity.
k) Thin paper tissue, absorbent, for drying and cleaning equipment.
l) Thermometer subdivided to 0.1°C, mounted in a housing.
m) Mixing dowels for use in preparing the primary solution and for the calibration, separate dowel to be used for each tank.
n) Graph paper.

All glassware should be in duplicate.

4.6 Computerized Calibration, Sampling and Computation

The calibration, sampling and computation phase of the method can easily be computerized by use of commercially available micro-electronic components, as for example:

a) Multiscale conductivity meter with scale 0–200 μS/cm interval for low and 0–2000 μS/cm for high background conductivity, with automatic temperature compensation.
b) Suitable confined conductivity sensor.
c) Datalogger, splashproof:
   – Memory 40–50 KB,

  - Logging-interval to choice: 1 and 2 sec,
  - Display,
  - Indicator for low battery,
  - Date and time to be set at start of measurement.

d) Portable PC.

e) Main Software:
  - Communication program for transferring data from logger to PC,
  - Calibration program,
  - Computation program for computing the discharge,
  - Graphics programs.

Bibliography

Chapter 4: [1], [2], [3], [5], [11], [15], [18], [19], [22], [24], [25], [31], [41], [42].

CHAPTER 5

MEASUREMENT OF PEAK DISCHARGE BY THE SLOPE-AREA METHOD

5.1 General

The slope-area method is the most commonly used technique of indirect discharge determination in streams and rivers. In this method, steady state flow in a uniform channel reach is computed on the basis of uniform flow equations involving channel characteristics, water-surface profiles and a roughness or retardation coefficient.

The slope-area method may be used to determine the discharge at any water stage. However, its real value lies in the means it affords to determine the magnitude of peak flows. The method is especially helpful in the extension of rating curves when current-meter measurements are difficult to obtain for the high flood stages.

5.2 Uniform flow equations

5.2.1 The Manning Equation

When the channel characteristics are known, the steady flow in a uniform channel reach can be calculated by either the Chezy or the Manning uniform flow equations, of which the latter is the more popular.

The Manning equation was developed for conditions of steady flow in uniform channels, that is, channels whose cross section, slope, and boundary roughness do not change along its length, and in which the water-surface slope and energy gradient are parallel to the streambed. Under these conditions, the drop in the water-surface profile represents head loss caused by bed and bank roughness only and is known as the friction slope (S_f).

The use of the Manning equation requires an estimate of three basic factors: (a) the area of the average cross section in a longitudinal reach of channel of known length, (b) the slope of the water surface in the reach, and (c) the character of the channel bed so that a suitable roughness factor may be estimated.

The flow velocity in a channel reach where the flow is not significantly different from steady and uniform flow, using Manning's equation, is

$$v = (1/n)\, R^{2/3} S_f^{1/2} \qquad (5.1)$$

where

- v = steady velocity in the reach (m/s),
- R = hydraulic radius of the cross section, equal to area of cross section divided by wetted perimeter: R = A/P (m),
- n = Manning's coefficient of roughness, mean value in the reach,
- S_f = friction slope of the reach.

5.2.1.1 The Friction Slope

Referring to Fig. 45, the energy equation for a reach of a natural channel between cross-section 1 and cross-section 2 is

$$z_1+h_1+h_{v1} = z_2+h_2+h_{v2}+h_f \qquad (5.2)$$

Further,

$$h_f = (z_1-z_2)+(h_1-h_2)+(h_{v1}-h_{v2}) \qquad (5.3)$$

where

- z_1, z_2 = elevation of the streambed at the cross sections,
- h_1, h_2 = water depth at the sections,
- h_v = velocity head at the sections,
- h_f = head loss, that is, energy loss due to boundary friction in the reach, equal to the drop in the water-surface profile in a uniform channel.

Assuming uniform channel with $h_1 = h_2$ and $h_{v1} = h_{v2}$, (5.3) reduces to

$$h_f = z_1-z_2 \qquad (5.4)$$

Dividing on both sides by L, the length of the reach, obtains:

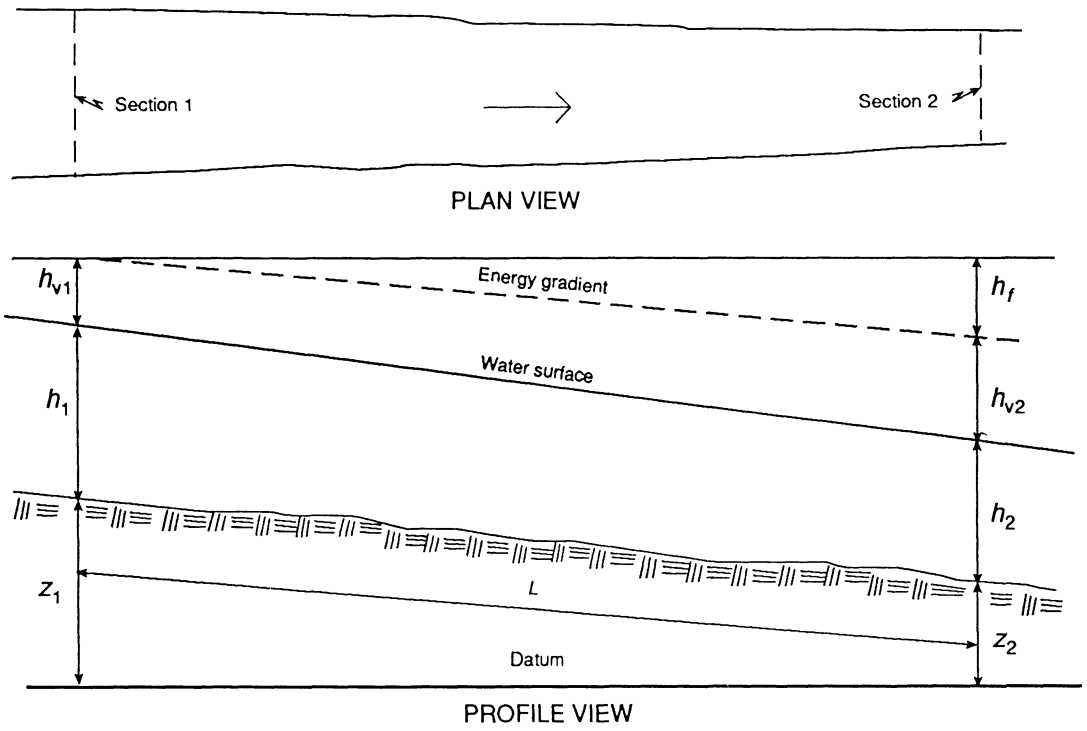

Figure 45. PLAN and PROFILE view of a channel reach.

$$h_f/L = (z_1-z_2)/L \quad (5.5)$$

which shows that at steady flow in a uniform channel the friction slope equals the slope of the water surface.

When the angle of inclination of the streambed is small (i.e. <10°), it can be shown that the friction slope (S_f) and the slope of the water surface both will equal the bed slope (S_o) at steady flow in a uniform channel [27].

When using Manning's equation, the reach should not be significantly nonuniform. If no truly uniform channel reach can be found, the reach should be converging rather than diverging in order to minimize the energy loss due to large-scale eddies, etc.

5.2.1.2 Values of the Manning Coefficient

Often a reasonable value of the roughness coefficient can be extrapolated from discharge measurements taken by more accurate methods at lower stages, as for example by the current meter method. These values may be used provided there are no significant changes in the channel characteristics at the higher stages. Needless to say, the accuracy of such extrapolated coefficients decreases as the difference between the stage of the highest current meter measurement and the extrapolated stage increases.

In the absence of measured data, the values given in Table 6 may be used as a guide. Reference [10] gives a good introduction to roughness estimation of natural channel beds.

5.2.1.3 The Conveyance Factor

Conveyance is a measure of the carrying capacity of a stream channel and it has the dimension m^3/s. The conveyance factor in a cross section is expressed as

$$K = (1/n)\, AR^{2/3} \quad (5.6)$$

where A is the cross sectional area and R is the hydraulic radius which equals the area of the cross section divided by the wetted perimeter (P) of the section.

The mean conveyance in a reach is calculated as the *geometric mean* of the conveyance of the individual cross sections. This procedure is based on the assumption that the conveyance varies uniformly between sections. Thus, the mean conveyance in a channel reach is calculated as

$$K_{reach} = (K_1K_2K_3 \ldots K_m)^{1/2} \quad (5.7)$$

where m is the number of cross sections.

5.3 Calculation of the Discharge

There are three ways of calculating the discharge when using the slope-area method, depending on whether the requirements of steady flow and uniform channel are fully, partly or poorly met.

5.3.1 Truly Uniform Channel

When the condition of uniform channel on which the Manning's equation was developed is fully met, the discharge is calculated by multiplying the velocity given by the Manning's equation by the cross-sectional area of the channel, as follows.

$$Q = (1/n)AR^{2/3} S_f^{1/2} \quad (5.8)$$

where

Q = discharge (m^3/s),
A = cross-sectional area (m^2),
R = hydraulic radius, equal to A/P, where P is the wetted perimeter (m),
S_f = friction slope,
n = Manning's roughness coefficient.

5.3.2 Channel not Truly Uniform

When the channel is not truly uniform, which is invariably the case in natural channels, the use of average values for the area A, the wetted parameter P, and the hydraulic radius R of the cross sections, will not yield correct results. In such cases, it is common practice to use the geometric mean conveyance factor K (see above) in order to calculate the discharge. Thus, the Manning's discharge equation in terms of the geometric mean conveyance in a channel reach is equal to the product of the conveyance and square root of the friction slope, and is written as

$$Q = K_{reach} S_f^{1/2} \quad (5.9)$$

5.3.3 Significantly Non-Uniform Channel

In case the channel reach is significantly nonuniform, the discharge in the reach is calculated by an iterative procedure. An illustrative example of the procedure to be followed is given in reference [18].

5.4 Characteristics of the Channel

5.4.1 Length of a Channel Reach

The *length* of the channel between the end cross-sections is measured along the ground. The projection on the horizontal of this measured length is not used.

5.4.2 Wetted Perimeter of a Cross Section

The *wetted perimeter* of a cross section is known as P and it equals the length of the boundary between the water and the channel bed.

5.4.3 Hydraulic Radius of a Cross Section

The *hydraulic radius* is the cross-sectional area of a stream divided by its wetted perimeter.

$$R = A/P \quad (5.10)$$

where

R = the hydraulic radius of the section (m),
A = cross-sectional area of the section (m^2),
P = wetted perimeter of the section (m).

5.5 Selection of the Channel Reach for Slope-Area Measurements

The selection of a suitable channel reach is the most critical factor in the application of the Manning's equation. Ideal reaches are difficult to find, and as a rule, it is a matter of selecting the best reach available.

The channel reach should be essentially uniform and the flow should be confined within a simple trapezoidal channel. It is desirable that the channel be uniform also for some distance above the measuring reach.

5.5.1 Minimum Length and Slope of the Reach

It is advisable to select a reach as long as practicable, and in large rivers reaches of 300 m or more are desirable having at least 30 cm difference in hight of the water surface between the upstream and downstream gauges. Generally, a useful rule is to estimate the reach required as being four times the channel width 75 times the mean depth in the channel. [18].

Table 6. Values of the Manning Roughness Coefficient

Type of bed material	Size of bed material mm	Manning's Coefficient (n)
Firm earth		0.025–0.032
Sand	1–4	0.026–0.035
Gravel	4–8	0.019–0.020
Gravel	8–20	0.020–0.022
Gravel	20–60	0.022–0.027
Pebbles	60–110	0.027–0.030
Cobbles	110–250	0.030–0.032

5.5.2 The Cross Sections

Cross sections represent samples of the geometry of the measuring reach. Thus, the accuracy of the discharge measurements will to an extent depend on the number of cross-sections used. A minimum of three sections is recommended. One at each end of the reach and one in the middle of the reach. The position of each cross section must be normal to the general direction of the flow, and they are referred to a common datum.

5.5.3 Reference Gauges

When the channel is straight, comparatively narrow, and the slope of the water surface essentially uniform, a reference gauge at each end of the reach is normally sufficient. The gauges are supplemented by crest-stage gauges which are installed at each end of the reach, one on each side of the river. The peak flood-stage at each end is obtained by averaging the two crest stages.

5.6 Field Survey of the Channel Reach

The data required for applying the slope-area method are obtained by a field survey. The survey includes a plan view and a profile view of the reach, cross sections, an estimate of the roughness coefficient of the bed from tables and/or experience, and if possible also samples of the bed material in order to make experimental determinations of the roughness characteristic.

In sand-bed channels an error may be introduced due to unobserved and temporary changes in the channel bed during floods. Thus, the cross sections should be check-surveyed just after the flood peak has passed. If however, the measuring reach is stable, it will be sufficient to check the cross sections after the flood has subsided.

Various instruments have been used for making the field survey, but experience has shown that an engineer's transit is best suited for the job. It is recommended that a transit be used to make a *transit-stadia* survey. This method combines vertical and horizontal survey in one operation, it is accurate, simple and fast.

5.7 Accuracy of the Slope-Area Method

The accuracy of the measurement depends on the correct determination of the slope and of the coefficient of roughness. The coefficient of roughness is likely to change with varying stages of flow. If no experimental determination has been made, considerable experience is necessary in choosing the correct value of the roughness coefficient.

An error will also be introduced if the areas of the cross sections of the measuring reach are not approximately equal. The uncertainty of a single slope-area measurement may be taken as 10–20%. [18].

5.8 Simplified Slope-Area Method

The US Geological Survey has proposed a simple logarithmic model for calculation of discharge in uniform channels. The model is based on analyses of data from rivers in the United States and it is based on the form:

$$Q = aA^bS^c \tag{5.11}$$

where A is the mean cross-sectional area, S is the water surface slope, and a, b and c are constants.

Assuming that the slope may replace n and that the hydraulic radius is related to the cross-sectional area, the simplified discharge equation is

$$\log Q = 0.191 + 1.33 \log \bar{A} + 0.05 \log S - 0.056 (\log S)^2 \tag{5.12}$$

where Q is in m^3/s and $\bar{A}$ is in m^2.

The method seems to give good results in channels with uniform flow and no significant difference in velocity head between the upstream and downstream cross-sections. [18].

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Appendix A

CURRENT METER MEASUREMENT NOTES

CURRENT METER MEASUREMENT NOTES

To systematize the recording and computation of current-meter measurements, data are recorded on standard forms of which Plate 1 and 2 are illustrative examples. Page 1 of the form contains headings showing necessary data that are recorded before a measurement is started. Page 2 has self-explanatory columns that are filled in during the measurement and no measurement should be considered complete until all information indicated by the column headings has been obtained and entered in the space provided.

All measured data are entered directly on the form after their observation and not recorded elsewhere to be transferred at a later date. Those headings that do not apply to the particular measurement should be deleted so as to leave no doubt that the heading may have been overlooked. The substitution of initials for names and the abbreviations of names of places should be avoided.

Computation of the discharge is done after the measurement has been completed, but before leaving the site.

Data are recorded in the following order beginning at the left side of page 2, refer Section 2.3 Current Meter Measurement Procedures:

1. *Distance from Initial Point*
   Distance from initial point to the vertical as read off from a tag line stretched across the stream.
2. *Sounded Depth*
   Depth with no corrections applied.
3. *Angle*
   Vertical angle of the suspension cable as measured by a protractor.
4. *Revised Depth*
   Values obtained by subtracting air-line and wet-line corrections from column 2.
5. *Unrevised Depth of Observation*
   Use this column when unable to compute corrections during the measurement.
6. *Revised Depth of Observation*
   Position of the current meter below the water surface, that is, 0.2, 0.6, 0.8, etc. of the revised depth.
7. *Revolutions*
   Number of revolutions of the rotor of the current meter during an observation interval.
8. *Time*
   Time interval over which the revolutions of the rotor are observed.
9. *Velocity at Point*
   Velocity at point of observation in a vertical obtained from the rating table of the current meter. To be filled in after the measurement has been completed, but before leaving the site.
10. & 11. *Multiplier*
    Used for multiple-point method only.
12. *Mean Velocity in the Vertical*
    a) for 0.6 method, mean velocity in vertical is equal to value in column 9.
    b) for 0.2/0.8 method, the average of the two velocities in column 9 is taken as mean velocity in vertical.
    c) for multiple-point method, mean velocity is computed by arithmetic integration using column 10 & 11, or by graphic integration after plotting up the depth-velocity curve for the vertical.
13. *Mean Velocity in Section*
    The average of the mean velocity in two adjacent verticals; the velocity near the water's edge is estimated as a percentage of the mean velocity in the first vertical measured. In most cases it might approach zero, in which case the mean velocity in the section is half only of the mean velocity in the first vertical.
14. *Area of Section*
    Product of mean depth of a section and width of the section.
15. *Discharge in Section*
    Product of mean velocity of a section and area of the section, i.e. (column 13) x (column 14).
16. *Discharge accumulated*
    For successive accumulation of the values in column 15.
17. *Remarks.*

INSTRUCTIONS

1. Hydrographers must fill out and complete these measurement notes in full, have them checked, and forwarded to Ubungo through R.H.O. within two weeks of carrying out the gaugings.
2. The current rating curve for the gauging station should be available and where possible the gaugings are to be calculated and checked against this curve in the field.
3. Where the gauging deviates more than 4 per cent from the current rating curve, a check gauging is required as soon as possible.
4. The most Probable sources of error are:—
   (a) poor gauging stretch;
   (b) changed control;
   (c) changed staff gauges.

   If check gaugings still plot more than 4 per cent out, then the above points should be investigated and the action being taken should be noted under remarks.

NOTES:

DISCHARGE MEASUREMENT NOTES

Gauging Stn. No. .....

Gauging No. .....

Date .....

.....River at.....

Observer ... ...

Mean gauge height... ... .

Discharge in m^3/sec. ... .

Area in m^2 ... ...

Mean vel. in m/sec. ... .

Width in metres ... ...

Time	Recorder	Staff Gauge

Meter type and No..... Pivot or propellor No.....

Date meter rated.....Spin test before.....after.....

Weights used and means of measurement.....Position.....

of gauging section..... above m below gauge.....

Chart removed from.....to.....

Condition of (1) control.....(2) intake pipe.....

.....(3) gauge staves.....

Wind and weather conditions.....

Per cent deviation from current rating curve.....No. of sheets.....

Remarks .....

.....

.....

.....

Plotted by ____ Date ____ Entered by ____ Date ____

PLATE 1

Distance from initial point	Sounded depth	Angle	Revised depth	Unrevised depth of obs.	Revised depth of obs.	Revs.	Time	Velocity					Area of section	Discharge in section	Discharge accum.	Remarks
								Vel. at point	Multiplier		Mean vel. in vert.	Mean vel. in section				
Totals																

Computed..... *Date*..... *Checked by*..... *Date*.....

PLATE 2

Appendix B

THE MID-SECTION METHOD OF COMPUTING CURRENT METER MEASUREMENTS

INSTRUCTIONS

1. Hydrographers must fill out and complete these measurement notes in full, have them checked, and forwarded to Ubungo through R.H.O. within two weeks of carrying out the gaugings.
2. The current rating curve for the gauging station should be available and where possible the gaugings are to be calculated and checked against this curve in the field.
3. Where the gauging deviates more than 4 per cent from the current rating curve, a check gauging is required as soon as possible.
4. The most Probable sources of error are:—
   (a) poor gauging stretch;
   (b) changed control;
   (c) changed staff gauges.

   If check gaugings still plot more than 4 per cent out, then the above points should be investigated and the action being taken should be noted under remarks.

NOTES:

Current-meter measurement computed by the mid-section method.

DISCHARGE MEASUREMENT NOTES

Gauging Stn. No. 10

Gauging No. 23

MALAGARASI River at MBELAGULE

Date 24.7.76

Time	Recorder	Staff Gauge
0810		1.47
1045		1.47

Observer ... ... T. S. ALLIY

Mean gauge height 1.47

Discharge in $m^3/sec.$ ... 50.2

Area in m^2 ... ... 460.4

Mean vel. in m/sec. ... 0.109

Width in metres 102.0

Meter type and No. A. OTT 7675 Pivot or propellor No. 1

Date meter rated ... Spin test before 93 sec. after 85 sec.

Weights used and means of measurement 25 kg, cableway Position .2/.8, .6

of gauging section ... m above/below gauge ...

Chart removed from ... to ...

Condition of (1) control clean (2) intake pipe cleaned

(3) gauge staves intact

Wind and weather conditions calm and sunny

Per cent deviation from current rating curve ... No. of sheets 3

Remarks ...

Plotted by ... Date ... Entered by ... Date ...

GAUGING STATION.... MBELAGULE ..... No..10..... ..... SHEET No..1.of..3.....

DATE..... 24.7.76 ..... MEAN GAUGE HEIGHT..... 1.47 .....

Distance from initial point	Sounded depth	Angle	Revised depth	Unrevised depth of obs	Revised depth of obs.	Revs.	Time	Velocity: Vel. at point	Velocity: Multiplier	Velocity: Mean vel. in vert.	Velocity: Mean vel. in section	Area of section	Discharge in section	Discharge accum.	Remarks
0.00	0.00		Water's edge,		R B	at 08.10 hrs.									
6.00	3.08	0	-	-	0.62	10	81	.037		.038	.038	18.48	0.702	0.702	
					2.46	10	75	.040							
12.00	4.28	0	-	-	0.86	40	70	.151		.137	.137	25.68	3.518	4.220	
					3.42	30	65	.123							
18.00	4.66	0	-	-	0.93	50	75	.176		.150	.150	27.96	4.194	8.414	0840 hrs
					3.73	30	64	.125							
24.00	5.54	0	-	-	1.11	30	61	.131		.123	.123	33.24	4.089	12.503	
					4.43	30	70	.115							
30.00	5.30	0	-	-	1.06	30	60	.133		.130	.130	31.80	4.134	16.637	
					4.24	30	63	.127							
Totals															

Computed..... *Date*..... *Checked by*..... *Date*.....

GAUGING STATION MBELAGULE No. 10 SHEET No. 2 of 3

DATE 24.7.76 MEAN GAUGE HEIGHT 1.47

Distance from initial point	Sounded depth	Angle	Revised depth	Unrevised depth of obs.	Revised depth of obs.	Revs.	Time	Velocity: Vel. at point	Velocity: Multiplier	Velocity: Mean vel. in vert.	Velocity: Mean vel. in section	Area of section	Discharge in section	Discharge accum.	Remarks
36.00	5.26	0	-	-	1.05	30	55	.145		.142	.142	31.56	4.482	21.119	
					4.21	30	57	.140							
42.00	5.25	0	-	-	1.05	30	60	.133		.131	.131	31.50	4.126	25.245	0910 hrs
					4.20	30	62	.129							
48.00	5.38	0	-	-	1.08	30	62	.129		.127	.127	32.28	4.100	29.345	
					4.30	30	64	.125							
54.00	5.38	0	-	-	1.08	30	61	.131		.130	.130	32.28	4.196	33.541	
					4.30	30	62	.129							
60.00	5.52	0	-	-	1.10	20	53	.102		.096	.096	33.12	3.180	36.721	0940 hrs
					4.42	20	60	.090							
66.00	5.18	0	-	-	1.04	20	52	.104		.101	.101	31.08	3.139	39.860	
					4.14	20	55	.098							
Totals															

Computed ..... *Date* ..... *Checked by* ..... *Date* .....

GAUGING STATION....MBELAGULE..... **No.**..10..... ..... **SHEET No.**....3.of.3.....

DATE..24.7.76..... **MEAN GAUGE HEIGHT**.....1.47.....

Distance from initial point	Sounded depth	Angle	Revised depth	Unrevised depth of obs.	Revised depth of obs.	Revs.	Time	Velocity: Vel. at point	Velocity: Multiplier	Velocity: Mean vel. in vert.	Velocity: Mean vel. in section	Area of section	Discharge in section	Discharge accum.	Remarks
72.00	5.10	0	-	-	1.02	20	52	.104		.095	.095	30.60	2.907	42.767	
					4.08	20	63	.086							
78.00	4.92	0	-	-	0.98	20	53	.086		.090	.090	29.52	2.657	45.424	
					3.94	20	58	.093							
84.00	4.90	0	-	-	0.98	20	56	.097		.093	.093	29.40	2.734	48.158	1010 hrs
					3.92	20	61	.089							
90.00	4.62	0	-	-	0.92	10	55	.052		.053	.053	27.72	1.469	49.627	
					3.70	10	52	.054							
96.00	2.37	0	-	-	0.47	10	58	.043		.041	.041	14.22	0.383	50.210	
					1.90	10	76	.039							
102.00	0.00	Water's edge, L.B. at 1045 hrs.													
												460.44			
Totals															

Computed..... *Date*..... *Checked by*..... *Date*.....

Appendix C

THE MEAN-SECTION METHOD OF COMPUTING CURRENT METER MEASUREMENTS

INSTRUCTIONS

1. Hydrographers must fill out and complete these measurement notes in full, have them checked, and forwarded to Ubungo through R.H.O. within two weeks of carrying out the gaugings.
2. The current rating curve for the gauging station should be available and where possible the gaugings are to be calculated and checked against this curve in the field.
3. Where the gauging deviates more than 4 per cent from the current rating curve, a check gauging is required as soon as possible.
4. The most Probable sources of error are:—
   (a) poor gauging stretch;
   (b) changed control;
   (c) changed staff gauges.

   If check gaugings still plot more than 4 per cent out, then the above points should be investigated and the action being taken should be noted under remarks.

NOTES:

Current-meter measurement computed by
the mean-section method.

DISCHARGE MEASUREMENT NOTES

MALAGARASI River at MBELAGULE

Gauging Stn. No. 10
Gauging No. 23
Date 24.7.76

Time	Recorder	Staff Gauge
0810		1.47
1045		1.47

Observer ... ... T. S. Alliy
Mean gauge height 1.47
Discharge in m³/sec. ... 49.5
Area in m² 460.3
Mean vel. in m/sec. ... 0.108
Width in metres 102.0

Meter type and No. A.OTT 7675 Pivot or propellor No. 1
Date meter rated ... Spin test before 93 sec. after 85 sec.
Weights used and means of measurement 25 kg.s cableway Position .2/.8, .6
of gauging section ... above/below gauge ... m
Chart removed from ... to ...
Condition of (1) control clean (2) intake pipe cleaned
(3) gauge staves intact
Wind and weather conditions calm and sunny
Per cent deviation from current rating curve ... No. of sheets 3
Remarks ...

Plotted by ... Date ... Entered by ... Date ...

GAUGING STATION.... MBELACULE..... No..10..... SHEET No..1..of..3.....

DATE..... 24.7.76 MEAN GAUGE HEIGHT.....1.47.....

Distance from initial point	Sounded depth	Angle	Revised depth	Unrevised depth of obs	Revised depth of obs.	Revs.	Time	Velocity: Vel. at point	Velocity: Multiplier	Velocity: Mean vel. in vert.	Velocity: Mean vel. in section	Area of section	Discharge in section	Discharge accum.	Remarks
0.00	0.00		Water's edge,		R B	at 08.10 hrs.									
6.00	3.08	0	-	-	0.62	10	81	.037		.038	.038	18.48	0.702	0.702	
					2.46	10	75	.040							
12.00	4.28	0	-	-	0.86	40	70	.151		.137	.137	25.68	3.518	4.220	
					3.42	30	65	.123							
18.00	4.66	0	-	-	0.93	50	75	.176		.150	.150	27.96	4.194	8.414	0840 hrs
					3.73	30	64	.125							
24.00	5.54	0	-	-	1.11	30	61	.131		.123	.123	33.24	4.089	12.503	
					4.43	30	70	.115							
30.00	5.30	0	-	-	1.06	30	60	.133		.130	.130	31.80	4.134	16.637	
					4.24	30	63	.127							
Totals															

Computed..... *Date*..... *Checked by*..... *Date*.....

GAUGING STATION....MBELAGULE..... **No.**10..... ..... **SHEET No.**..2.of.3.....

DATE..24.7.76..... **MEAN GAUGE HEIGHT**..1.47.....

Distance from initial point	Sounded depth	Angle	Revised depth	Unrevised depth of obs.	Revised depth of obs.	Revs.	Time	Velocity					Area of section	Discharge in section	Discharge accum.	Remarks
								Vel. at point	Multiplier		Mean vel. in vert.	Mean vel. in section				
36.00	5.26	0	-	-	1.05	30	55	.145								
					4.21	30	57	.140			.142					
												.136	31.53	4.288	22.742	
42.00	5.25	0	-	-	1.05	30	60	.133								
					4.20	30	62	.129			.131					
												.129	31.89	4.114	26.856	
48.00	5.38	0	-	-	1.08	30	62	.129								
					4.30	30	64	.125			.127					
												.128	32.28	4.132	30.988	
54.00	5.38	0	-	-	1.08	30	61	.131								
					4.30	30	64	.125			.130					
												.113	32.70	3.695	34.683	
60.00	5.52	0	-	-	1.10	20	53	.102								
					4.42	20	60	.090			.096					
												.098	32.10	3.146	37.829	
66.00	5.18	0	-	-	11.04	20	52	.104								
					4.14	20	55	.098			.101					
Totals												.098	30.84	3.022	40.851	

Computed..... *Date*..... *Checked by*..... *Date*.....

GAUGING STATION....MBELAGUILE..... No.10..... SHEET No..3.of..3.....

DATE..24.7.76..... MEAN GAUGE HEIGHT....1.47.....

Distance from initial point	Sounded depth	Angle	Revised depth	Unrevised depth of obs.	Revised depth of obs.	Revs.	Time	Velocity: Vel. at point	Velocity: Multiplier	Velocity: Mean vel. in vert.	Velocity: Mean vel. in section	Area of section	Discharge in section	Discharge accum.	Remarks
72.00	5.10	0	-	-	1.02	20	52	.104							
					4.08	20	63	.086		.095					
											.092	30.06	2.766	43.617	
78.00	4.92	0	-	-	0.98	20	53	.086							
					3.94	20	58	.093		.090					
											.092	29.46	2.710	46.327	
84.00	4.90	0	-	-	0.98	20	56	.097							
					3.92	20	61	.089		.093					
											.073	28.56	2.085	48.412	
90.00	4.62	0	-	-	0.92	10	55	.052							
					3.70	10	52	.054		.053					
											.047	20.97	0.986	49.398	
96.00	2.37	0	-	-	0.47	10	68	.043							
					1.90	10	76	.039		.041					
											.020	7.11	0.142	49.540	
102.00	0.00	Water's edge, L.B. at 1045 hrs.													
												460.34			
Totals															

Computed..... *Date*..... *Checked by*..... *Date*.....

Appendix D

RATING OF CURRENT METERS

RATING OF CURRENT METERS

The reader is referred to the WMO Technical Regulations, Volume III, Annex 1, Section I: *Calibration of current meters in straight open tanks.* [2].

Practical Hints

When rating current meters, the following precautions should be observed:

a) The towing velocity should not coincide with the velocity of propagation in the rating tank.

The *Epper Effect* is a complex phenomenon influenced by the geometry of the rating tank and the size of the current meter and its means of suspension. Simply stated, the effect is a slowing down of the current-meter rotor causing an under-registration of the current meter when the rotor rotates within the wave produced as the current meter is towed through the tank. Ratings within the range of the wave show a greater velocity for a given towing velocity than would be indicated by interpolating the normal ratings for higher and lower velocities. The wave produced by towing the current meter moves with a certain velocity, the *velocity of propagation*, independent of the towing velocity. The dependence of this critical velocity v_c on the depth of the water in the tank is given by the equation

$$v_c = (gd)^{1/2} \qquad \text{(D.1)}$$

where

v_c = velocity of propagation (m/s),
g = acceleration due to gravity (m/s^2),
d = depth of water (m).

The Epper Effect may cause a significant error in the rating of the current meter within a narrow band in the velocity range from 0.5 v_c to 1.5 v_c. The magnitude of the Epper Effect depends on the size of the current meter and suspension equipment relative to the cross-sectional area of the tank. It may be negligible when a very small current meter is rated.

b) Before the current meter is immersed in the water, it is checked for cleanliness, lubrication and for its mechanical and electric functioning.

c) The current meter is towed along the centre line of the rating tank.

d) The current meter is placed at such a depth below the water surface that the surface influence is negligible. For a propeller-type current meter, a depth twice the diameter of the propeller is generally sufficient. A cup-type current meter is immersed to a depth of at least one and a half times the height of the rotor, or 30 cm, whichever is greater.

e) Care must be taken to ensure that vibrations of the carriage (especially noticeable at lower speeds) and vibrations of the rod (especially noticeable at higher speeds) are low enough not to influence the speed of revolution of the current meter rotor.

f) The minimum response velocity is determined by gradually increasing the carriage velocity from zero until the rotor revolves at a constant speed.

g) Measurements are carried out at a sufficient member of towing velocities in order to ensure that the rating of the current meter is defined accurately. The intervals between the towing velocities should be closer at the lower end of the range. The total number of rating points is generally about:

10–12 for ratings up to 2 m/s
12–16 for ratings up to 5 m/s
16–20 for ratings up to 8 m/s

h) The water in the tank should come to rest after each run. The time needed for the water to still, depends on the dimensions of the tank, the use of baffles, the previous test velocity, and the size and shape of the current meter and suspension equipment.

The following mean values may be given for guidance:

Velocity m/s	Stilling time min
0.5	10
2	15
5	25
8	30

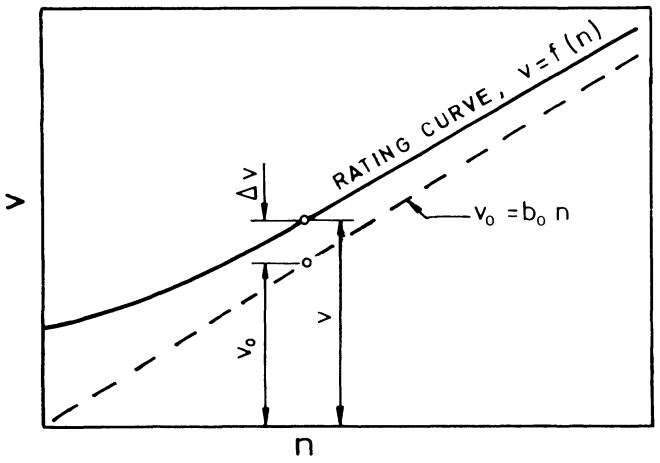

Figure D.1. Schematic graph of current-meter rating curve and assumed asymptote.

Computation of the Rating Equations

From the distance travelled, the time and the number of propeller revolutions, the velocity in metres per second (v) is computed for each run in the rating tank. An expanded method of plotting the data is used in order to magnify the normal scatter of the data points and to facilitate estimation of the rating curve. In the expanded method, an assumed asymptote to the actual rating curve v = f(n) is drawn through origo (Fig. D. 1). The equation of the assumed asymptote is $v_0 = b_0 n$, where b_0 is equal to the pitch of the propeller.

The pitch is the distance in metres the current meter must travel in the rating tank in order for the propeller to make one revolution.

The expanded rating curve is drawn to show the difference Δv between the observed velocity v and the velocity determined by the assumed asymptote v_0 that is shown in Fig. D.1. This difference is written $\Delta v = (v - v_0)$. Substituting $b_0 n$ for v_0, gives $\Delta v = (v - b_0 n)$ as the ordinate for the expanded rating curve shown in Fig. D.2. Typical observed data and calculation of runs in a rating tank for a propeller-type current meter are shown in Table D.1.

After the data are plotted on graph paper, the next step is to draw the expanded rating curve through the plotted points (Fig. D.2). In most cases, the rating curve is estimated by two straight line segments. Coordinates are selected from the

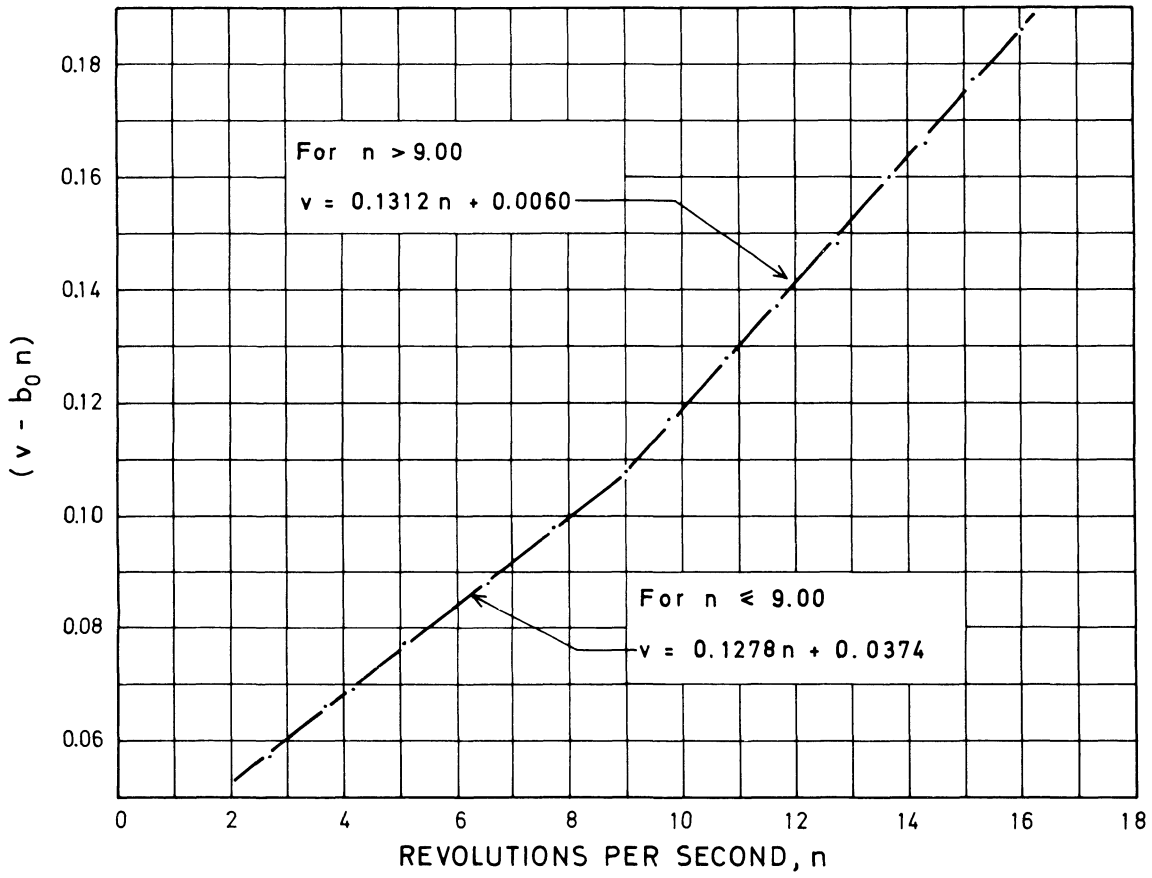

Figure D.2. Plot of expanded current-meter rating curve, from Table D.1.

Table D.1. Observed and calculated data of a current-meter rating

Run	Distance m	Time s	Rev.	Rev. per second (n)	Metres per second (v)	$v_o = b_o n$	$\Delta v = (v - b_o n)$
1	21.244	56.15	150	2.671	0.378	0.321	0.057
2	27.581	54.63	200	3.661	0.505	0.439	0.066
3	34.196	60.63	250	4.123	0.564	0.495	0.069
4	40.535	50.02	300	5.083	0.687	0.610	0.077
5	46.735	53.63	350	6.526	0.871	0.783	0.088
6	46.439	45.64	350	7.669	1.018	0.920	0.098
7	46.205	38.95	350	8.986	1.186	1.078	0.108
8	46.186	35.89	350	9.752	1.287	1.170	0.117
9	46.141	32.43	350	10.792	1.423	1.295	0.128
10	46.116	30.00	350	11.667	1.537	1.400	0.137
11	46.086	27.46	350	12.746	1.678	1.530	0.148
12	46.086	25.68	350	13.629	1.795	1.635	0.160
13	46.071	24.50	350	14.286	1.880	1.714	0.166
14	46.067	23.06	350	15.178	1.998	1.821	0.177
15	46.061	21.80	350	16.055	2.113	1.927	0.186

Table D.2. Calculations to Determine the Current-Meter Rating Equations

1	2	3	4	5	6	7	8	9	10	11
$(v-0.12n)_2$	$(v-0.12n)_1$	n_2	n_1	Col. 1–2	Col. 3–4	k = col. 5 / col. 6	kn_1	b=col 2– col. 8	0.12 + k	v=(0.12+k)n+b
0.170	0.060	17.000	2.900	0.110	14.100	0.0078	0.0226	0.0374	0.1278	v=0.1278n+0.0374
0.185	0.090	15.950	7.500	0.095	8.450	0.0112	0.0840	0.0060	0.1312	v=0.1312n+0.060

Intersection of the two segments at n = 9.00

For $n \leq 9.00$ | For $n \geq 9.00$

$v = 0.1278\ n + 0.0374$ | $v = 0.1312\ n + 0.0060$

straight line segments (or extension of these) for computation of the rating equations.

The form of the rating equation is based on the equation for a straight line

$$y = kx + b \qquad \text{(D.2)}$$

Substituting $(v - b_0 n)$ for y, and n for x, the equation becomes

$$v - b_0 n = kn + b$$

Solving for v, the equation is simplified to form

$$v = (b_0 + k)n + b \qquad \text{(D.3)}$$

where

v = velocity (m/s),
b_0 = pitch of propeller (m),
k = slope of the plotted line,
n = revolutions per second,
b = intercept on y-axis.

An example of the computations to determine the rating equations is shown in Table D.2.

Bibliography

Appendix D: [2], [28], [38].

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