MANUAL ON PROCEDURES IN OPERATIONAL HYDROLOGY

VOLUME 1

ESTABLISHMENT OF STREAM GAUGING STATIONS

SECOND EDITION

NORWEGIAN WATER RESOURCES AND ENERGY ADMINISTRATION
HYDROLOGY DEPARTMENT

1997

MANUAL ON PROCEDURES IN OPERATIONAL HYDROLOGY

VOLUME 1

ESTABLISHMENT OF STREAM GAUGING STATIONS

SECOND EDITION

ØSTEN A. TILREM

NORWEGIAN WATER RESOURCES AND ENERGY ADMINISTRATION
HYDROLOGY DEPARTMENT

1997

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

First edition printed in Norway 1979
Second edition revised and updated 1997

ISBN 82-410-0310-2 (Volume 1–5)
ISBN 82-410-0311-0 (Volume 1)
ISBN 82-410-0312-9 (Volume 2)
ISBN 82-410-0313-7 (Volume 3)
ISBN 82-410-0314-5 (Volume 4)
ISBN 82-410-0315-3 (Volume 5)

Printed in Sweden by Motala Grafiska AB, Motala 1997

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

ACKNOWLEDGEMENTS

The author has drawn on many sources for information contained in this Manual and is indebted to these. It is hoped that suitable acknowledgement is made in the form of references to these works. Special credit is due to the United States Geological Survey for permission to reproduce figures and use other material from the Water Supply Paper and the Techniques of Water-Resources Investigations series, and to the World Meteorological Organization (WMO) for permission to reproduce material from the Guide to Hydrological Practices and the Operational Hydrology Report series, and from other reports on hydrology.

Østen A. Tilrem

CHAPTER 1

GENERAL OBJECTIVES AND PROCEDURES IN OPERATIONAL HYDROLOGY

1.1 Evaluation of Water Resources

The purpose of a water resources survey is to determine the source, extent and dependability of a usable water supply.

Water is a basic necessity and as it is found in limited quantities it is important that the available supply be known. An inventory of water supplies proves invaluable in the design and operation of municipal water systems, irrigation projects, water power development, flood control, industrial processes, pollution control, drainage, bridge design and other development projects.

In general, planning of water resources development requires data on precipitation, river stage, river discharge, sediment transport, yield and storage of ground water, as well as other related data such as evapotranspiration and temperature.

The amount of precipitation is a direct indication of water available in an area. Precipitation data have a direct bearing on how to solve problems such as drainage of storm water, control of soil erosion and determination of the quantity of water needed to irrigate crops in addition to that provided by natural precipitation. Also important is indirect computation of surface runoff and flood flow from precipitation data.

Streamflow records provide the basic data for most water resources investigations. The importance of having enough streamflow data for designing water projects can not be stressed enough. The streamflow is the measure both of the quantity of water that can be utilized and of the discharge that should be controlled.

Sediment load plays an important role with respect to silting of reservoirs and irrigation canals, its measurement should not be neglected.

A comprehensive assessment of water resources must also include ground water. In desert regions, nearly all usable water is often found underground. Even in humid regions, the ground water often provides a ready source of pollution-free water.

Furthermore, usable water must meet certain standards of quality depending on its intended use, as for irrigation or for domestic and industrial water supply. Thus, the determination of water quality is also essential.

The occurrence of water as a replenishable resource is dependent on what is known as the water cycle or hydrological cycle. That is, the circulation of water through physical processes from the sea, to the atmosphere, to the land and back to the sea. The potential supply of all water is the precipitation that falls on land and inland water bodies, less evaporation and transpiration. Part of this potential supply sinks into the ground where it recharges the soil moisture and the ground water reservoir. The remaining portion finds its way to streams and lakes. Although the concept of the water cycle is oversimplified, it provides a means of illustrating the most important processes the hydrologist must consider.

Precipitation, and thereby natural flow in streams and rivers, varies widely between geographic locations, from season to season and from year to year. Each of these variations affects the planning and use of water resources.

Future available water resources are estimated on the assumption that the past history of water occurrences will be repeated. In other words, plans for control and use of water assume that precipitation and streamflow conditions which have been observed in the past can be expected to occur, within reasonable limits of similarity, in the future. The method mainly and traditionally used in the evaluation of water resources is statistical analysis of time samples of the hydrological element of interest. A time sample is a record of observations or measurements taken over a finite period of time.

Statistical analysis of time samples provides only qualified statements of the characteristics of the phenomena under investigation. The accuracy and reliability of these estimates are not only limited by the accuracy of the individual observations in the sample, but also by the length of time during which the sample has been collected.

While the assessment of most other natural resources, such as a mineral deposit or the fixation of a topographical feature such as the difference in height between two points on the surface of the earth, can be determined fairly easily and accurately over a short span of time (days, weeks, or months), water resources must be painstakingly observed and gauged over a considerable period of time (years) in order, hopefully, to sample the whole spectrum of variations that may occur.

In fact, it is only when measurements and observations of water occurrences cover many years, i.e. that is, in the order of 25–30 years, that any meaningful information can be extracted from them.

It is obvious that planning and development of water resources can not, in all instances, be delayed for long periods of observation and data accumulation. On the other hand, the hazard of over- or underdevelopment and faulty design is equally evident. In reality, the problem is to determine to which extent recorded data may be interpolated or extrapolated for use as a basis for planning and design. In other words, how big a risk of failure is one justified or willing to take?

In most cases, this is an economic question, which again, in the last instance is often a political question. If failure of a water structure would cause human misery and death by the flooding of downstream populated areas, this additional factor will also have to be considered.

If the estimates, in the final analysis, are found to be too unreliable, then it will be necessary to install additional gauging stations and postpone water supply studies until representative records on available water have been obtained.

1.2 Collection of Streamflow Data

Hydrology, the science of water, is concerned with three broad problems:

a) Measuring and recording, processing and compiling basic hydrologic data.
b) The analysis of these data in order to develop and expand fundamental theories in the discipline.
c) The application of these theories and data to a multitude of practical problems.

Operational hydrology (hydrometry) is concerned mainly with the first of these subjects, which involves:

a) Establishing hydrometric stations for the observation of basic parameters such as streamflow, sediment transport, water quality, groundwater levels, soil water, rainfall, evapotranspiration, and temperature.
b) Operating and maintaining these stations.
c) Processing, compiling and presenting the collected data.

Collection of dependable streamflow data is the foundation on which all hydrology rests. Streamflow is the combined result of all climatological and geographical factors that are operating in a drainage basin. It is the only phase of the hydrological cycle in which the water is confined in well defined channels which permit accurate measurements to be made of the quantities involved.

The basic methods used in stream gauging are universal and have changed little over the last 100 years or so. River stages have to be recorded and discharge measurements have to be made. These two factors and the relationship between them are still the whole story about the collection of streamflow data.

Faster and more automatic methods are being developed, for example by the use of digital stage recorders and micro-electronic computers. These machines do not add anything new however. Accurate and complete data records still depend on the collection of reliable field data and on sound analysis in the office.

Streamflow records are derived from systematic recordings of stream stage and periodic measurements of stream discharge. Derivation of streamflow records is possible in this way because on most streams and rivers locations can be found with a unique relationship between the stage of the stream channel and the discharge in the channel. In order to establish this relationship, it is necessary to carry out simultaneously at a selected gauging site, a sufficient number of measurements of the stage and the corresponding discharge. Knowledge of the stage-discharge relation will provide a means by which simple water-level observations are converted into records of streamflow.

1.2.1 The Stage-Discharge Relation

In order to have a permanent and stable stage-discharge relation, the stream channel at the gauging station must be capable of stabilizing and regulating the flow past the station so that for a given stage the flow past the station will always be the same.

The shape, reliability and stability of the stage-discharge relation is usually controlled by a section or a reach of channel at or downstream from the gauging station, known as the *station control*, the geometry of which eliminates the effects of all other downstream features on the velocity of flow at the station site.

The stage-discharge relation is established by plotting on graph paper measured discharges against their corresponding water level. The smooth curve drawn through the plotted points defines the stage-discharge relation and is termed the *discharge rating curve* for the station.

The discharge rating curve is in many cases not permanent because of changes in the stream channel caused by scour and fill, aquatic vegetation, ice, and debris. Frequent discharge measurements are necessary to define the shifting discharge rating curve under such conditions.

If variable backwater or significantly unsteady flow occurs at a site, the stage-discharge relation can not be defined by stage alone. The discharge under these conditions is a function of both the stage and the slope of the water surface. In such cases, a *stage-fall-discharge* rating is usually developed from measurements of discharge, and observation of the stage at a base gauge and of the fall of the water surface between the base gauge and an auxiliary gauge downstream. If the flow is very unsteady, as in tidal reaches, unsteady-flow equations are used to describe the variation of discharge with time.

Detailed procedures for developing the discharge rating curve are given in Volume 4.

1.2.2 Selection of the Station Site

Before a stream-gauging station is established, a general reconnaissance is made so that the most suitable site may be located. The reconnaissance is greatly facilitated by an examination of geologic, topographic and other maps of the area before the reconnaissance is made. Tentative station sites are often indicated on the maps. Aerial photographs, when available, are specially helpful in this respect.

1.2.3 Observation and Recording of Stage

The stage of a stream is the elevation of the water level above a chosen datum. Records of stream stage are used mainly for the determination of streamflow records. However, records of stream stage are also useful in themselves for the design of river structures and for planning the utilization of flood plains. (Fig. 1).

Records of river stage is generally derived in two ways:

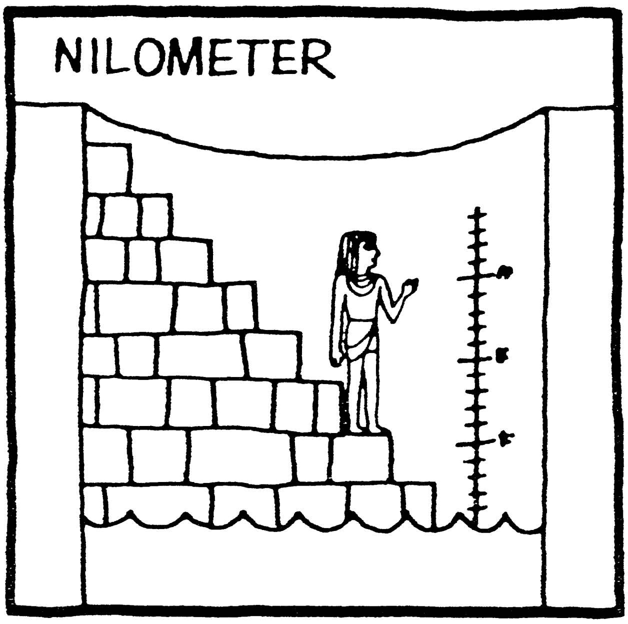


Figure 1. More than 3000 years B.C. the early Egyptian Pharaoh Menes established a system of water level gauges, known as Nilometers, for monitoring the annual floods of the Nile River in order to control and regulate agricultural irrigation. At least 20 stations were located along the Nile for measuring and recording the height of the river and for predicting future high water. Many of the stations were temples with an annex used for hydrologic data gathering. Staircases often led down to the wells for convenience in reading the scale. Statistics on the rise and fall of the Nile were recorded in the temple archives. The Nilometer is believed to be the first measuring device used in hydrology. (Courtesy of Stevens)

a) The elevation or stage of the water level, usually termed the *gauge height* in stream gauging, is read on a staff gauge one or more times a day by an observer and the readings recorded.
b) A continuous record is obtained by installing recording instruments that sense and record the height of the water level in the river channel.

1.2.4 Measurement of Discharge

Measurement of discharge is generally carried out by measuring a cross-sectional area of the stream and the velocity at which the water flows perpendicular to this area. A sufficient number of velocity observations are made to eliminate the effect of variations in velocity through the cross section.

The product of the average velocity and the cross-sectional area gives the discharge. The velocity is measured usually by a *current meter.* Which, perfected by repeated experiments during more than 100 years, is still the most basic and universally accepted instrument for the measurement of stream discharge. The instrument has a rotor which revolves at a speed which is a function of the velocity of flow. By recording the revolutions over a known period of time, the velocity of flow can be computed from the rating of the current meter. Discharge measurements in small shallow streams are made with the current meter attached to a graduated rod as the operator wades the stream. For deep, wide and swift streams, the current meter is suspended on a weighted cable which is lowered from a gauging reel into the water, from a boat, a bridge, or from a cableway. A detailed procedure for the *current meter method* is given in Volume 3.

1.2.5 Calibration of Stream-Gauging Stations

The calibration of stream-gauging stations includes making a sufficient number of discharge measurements in order to define the discharge rating curve and are called the *calibration* or *rating* of the gauging station.

When a new stream-gauging station has been set up, the general practice is initially to carry out a series of discharge measurements well distributed over the range of variation in discharge in order to establish quickly the discharge rating-curve. Usually, there are no difficulties involved in measuring the lower and medium discharges. However, to obtain measurements at the higher stages is often difficult and may take some time. Thus, for many gauging stations, discharge measurements are not available for the high flood stages and the rating curve must therefore be extrapolated beyond the range of available measurements.

At stations where the discharge rating-curve has already been established, gaugings are required regularly to check for any changes that may occur in the rating. At stations where the control is permanent, the initial rating curve may apply throughout the whole period of record for the station and only check gaugings are required.

However, few rivers have absolutely stable channel characteristics. The calibration, therefore, can not be carried out once and for all, but has to be repeated as often as required by the rate of shifts in the station control.

1.2.6 Construction and Operation of Stream-Gauging Stations

The construction of stream-gauging stations involves all the work connected with the installation of gauges, the placing of bench marks from which the gauge datum can be checked, and the building of cableways and measuring bridges from which discharge measurements can be made. It may also involve improvement of the stream channel by building artificial river controls. Artificial controls are structures built in an unstable stream channel in order to stabilize the stage-discharge relation and thereby improve the reliability of the discharge record of the station.

Operation and maintenance of stream-gauging stations begin when the construction and installation work is completed.

There are two important points to be stressed regarding gauging stations:

Firstly. The most important characteristics are those that affect the *stability* of the stage-discharge relation. The degree of stability affects not only the amount of work necessary to establish and maintain the discharge rating curve, and thereby the cost of operating the station, but also and more important, this stability affects the accuracy and reliability of the resulting streamflow records. If the stage-discharge relation is stable, the same rating curve will apply year after year and only occasional discharge measurements are needed in order to verify the curve. Is it unstable, then many measurements will be required in order to define the ever-shifting positions and shape of the rating curve.

Thus, if the rating curve is permanent, the cost of operating the station will be moderate and the accuracy of the records will be high. Is it not permanent, then as a rule, the cost of operation will be high and the accuracy of the data records will be low.

Secondly. Regarding the operation of gauging stations. The important thing is that observational data must be collected *systematically* if they are to have any value. That is, streamflow records must be obtained at gauging stations that are operated continuously and at recognized standards. If not, the data records will neither have the necessary reliability nor contain the necessary information required for meaningful statistical analysis.

1.2.7 Problems and Difficulties in the Collection of Streamflow Data

The theory for obtaining streamflow records, as outlined above, is simple and easy to grasp. However, because of the many variations in conditions governing the flow of water in natural channels, constant attention is essential if reliable results are to be obtained. A few examples follow:

– If the stream channel is not stable but changes due to scour, deposits, or channel vegetation, the rating curve will also change; another set of discharge measurements will then have to be made in order to define a new rating curve.

– At sites where the river stage is influenced by variable backwater from a dam or connecting streams, a single-value stage-discharge relation does not exist. A third variable, the slope of the water surface, must be included. This variable is obtained by an auxiliary gauge downstream from the station site.

– At gauging stations located in reaches where the slope is very flat, the stage-discharge relation is often influenced by the superimposed slope of the rising and falling limb of a passing flood wave. Here again, a third variable, either slope or rate of change in stage, must be introduced.

Other difficulties and problems are associated with climatic factors and geographical location, such as: (a) the humidity and heat in tropical regions that often affect the operation and reliability of recording instruments, (b) accessibility to the gauging site at all seasons of the year, and (c) availability of an observer or caretaker in remote areas.

One problem that merits special attention concerns the heavy load of silt usually carried by streams in tropical and arid regions during floods and high water, and how it affects the recording of the water level. Traditionally, at recording stations the changing water level of the stream is traced on paper by a float and cable-driven tracing stylus, the float being housed in a stilling well set in the river bank and connected to the river by pipes. The crucial thing here is, of course, that the intake pipe and stilling well must be kept open and free from deposits. To solve the silting problem under conditions of heavy sediment load, the stilling well must be provided with facilities for digging or flushing out deposited silt. In some areas, the cleaning operation has to be repeated every day during flood-producing storms.

One can safely say that few other causes have produced more interrupted and lost stage records than failure to keep an open and clear communication between river and stilling well.

Perhaps the greatest single factor that has frequently limited progress in streamflow data collection in the past, is the popular misconception that the collection and processing of streamflow data is easy and that anyone can do this work without prior training and experience in this field. In fact, it takes a long period of specialized experience in both field and office before one can control correctly all the operations employed in streamflow data collection and the processing of reliable streamflow records. The result of operating without training and knowledge of the laid down procedures and standards will invariably show up in poor quality of the processed data records.

1.3 Synthetic Streamflow Records

Formerly, much relevant information contained in the basic hydrological data-records used to be disregarded because of conceptual and computational limitations and difficulties.

With the event of the high speed digital electronic computer and the development of mathematical modelling techniques and time series analysis in recent years, a new era in our ability to analyze and describe hydrological processes was opened up permitting the generation of synthetic streamflow records. These techniques have proved very useful in the evaluation and development of water resources.

It is to be stressed, however, that the new methods of generating data, or any other method in modern analytical hydrology, are methods of extracting information already inherent in the observed basic data record. On no account can computational and mathematical sophistry replace scarcity or lack of basic observed data in hydrology.

In fact, the usefulness of the new analytical methods developed in recent years is limited unless long, undisturbed and continuous series of basic data records of both streamflow and rainfall are available. Minimum length is often considered to be in the order of 30 years.

1.4 International Standards in Stream Gauging

In 1956 the International Organization for Standardization (ISO) set up a Technical Committee known as TC-113, to work out standards on measurement of liquid flow in open channels. The reason being to ensure that new developments in the profession were made universally known, and that water data collected at different places were collected by the same methods and to the same standards so they were comparable and could be used in a larger context. By the end of 1996 TC-113 had produced 54 International ISO-Standards on Liquid Flow Measurements in Open Channels, which today are used world-wide.

The World Meteorological Organization (WMO) which carries the responsibility for hydrology internationally, publishes guides and technical reports on hydrology, including stream gauging, and with minor amendments also selected ISO-Standards in the form of Technical Regulations which are circulated to the WMO member countries.

The WMO System for Technology Transfer in Operational Hydrology (HOMS) is usually in the form of descriptions of hydrological instruments, technical manuals or computer programs. The material has to a large degree been made available for HOMS by the Hydrological Services of member countries of the WMO from the techniques which they themselves use in their normal operations. This ensures that the transferred technologies not only are ready for use but also works reliably.

The reader is further referred to the authoritative works on hydrometry by Herschy [27], [28], [29]; and to Water Supply Paper 2175 on streamgauging by US Geological Survey [16].

Bibliography

Chapter 1: [1], [34].

CHAPTER 2

HYDROMETRIC NETWORKS

2.1 General

A hydrological network is designed and operated to achieve a defined goal in order to meet one or more stated objectives. These objectives would be associated for example with a water-resources assessment, a development plan, a project design or with research purposes. In actual practice, however, most hydrological data collection networks have just evolved casually with time without any design scheme. It seems that the International Hydrological Decade, during the period 1965–75, gave an impetus to the idea of planned and rationally designed hydrological networks.

The World Meteorological Organization (WMO) discusses the design and establishment of hydrological networks in the WMO Guide to Hydrological Practices [2].

2.2 The Minimum Network

In the WMO Guide the design and development of a hydrological network is presented as an evolutionary process in which a minimum network is first established in the early stages of developing the network, and then upgraded gradually until a basic network has been arrived at. The minimum network is defined as "the minimum number of stations that the collective experience of hydrological agencies of many countries indicates to be necessary for initiating planning for economic development of water resources".

The WMO Guide provides tables of recommended minimum densities of observation stations for networks on streamflow, precipitation, evaporation, fluvial sediments, and water quality for six different types of physiographic regions. However, without a thorough understanding of the hydrological setting of the area in which a network is to be established, the chance is small that the resulting network will generate information in an effective manner. Thus, when initiating a data collection network in an area where little or no historical data are available, there is no substitute for the experience and judgement of the professional hydrologist well schooled in his discipline.

Perfect hydrological information does not exist. Because of measurement and sampling errors in time and space, there will always be uncertainty in hydrological data series. Probability theory provides the theorems and the language to deal with this uncertainty and also yields the understanding that is necessary for the appropriate use of statistical tools such as sampling theory, correlation and regression analysis, and stochastic modelling techniques that is commonly used in quantitative network-design approaches.

In the early stages of developing a hydrological network the first step is, as stated above, to establish a minimum network. The minimum network is composed of relatively few stations which are operated indefinitely in order to sample variations in time. Appropriate emphasis is placed on sampling areas with different topography, geology, vegetative cover, and climate. Thus, the minimum network will provide a framework for network expansion in order to meet future needs for specific purposes.

The minimum network should be installed as rapidly as possible by incorporating existing stations as appropriate. In evaluating the location and density of already existing gauging stations, statistical methods are used to determine the degree of independence among these stations. With this criteria, it is possible to eliminate duplicating stations and pinpoint areas needing gauging.

It is emphasized that a minimum network will not be adequate for the formulation of detailed development plans and will not meet the numerous requirements of a developed region for the operation of projects and the management of water resources.

Once the minimum network is operating, work starts to expand it into a *basic network*. The basic network is defined as to provide a level of hydrological information that would preclude any gross mistakes in water-resources decision-making at any location within its region.

2.3 The Basic Network

As the needs for data increase and sampling techniques are improved, the minimum network is gradually expanded into a basic network. As the number of gauging stations grows, it will be necessary from time to time to evaluate and re-evaluate the entire network.

Firstly, the stations are classified according to their purpose and to their hydrological coverage.

Secondly, an assessment is made of the information that will be needed on the basis of present and prospective developments.

Thirdly, the various methods and procedures for operating the network are considered taking into account the climatic, socioeconomic and other applicable constraints, for example use of long or short term stations, and the feasibility of applying sophisticated technology.

The principal classifications of stations that might be derived from such an evaluation would be as follows:

Primary Stations

Permanent stations having essential hydrological significance and collecting complete and high quality data. These stations should be observed continuously and indefinitely as they will furnish the basis for statistical studies. In the present context, these stations are identical to those framework stations of the minimum network that proves to provide significant data of high quality.

Secondary Stations

Where continuous records are collected for a period of a few years only, the data should be of primary station standard. These stations will furnish the basis for interpolating the spatial variability of the hydrological parameters.

Special Stations

Stations established for some special purpose such as research, operational requirements, observing maximum flood stages (crest gauge). The length of operation relates to the purpose for which they were installed.

On the network of the primary stations, there is superimposed a network of secondary stations to be operated for relatively short periods of time–five to ten years–in order to sample geographical variations. The reason for the use of secondary stations is to obtain a maximum amount of useful data at a minimum cost. A secondary station is operated just long enough to establish a stable statistical correlation with one or more of the primary stations, then the observation is discontinued and another secondary station is set up at a new location. In this way, the network of secondary stations is gradually extended to the region, filling in gaps between the primary stations. Then, through regression analyses based on the primary stations and on the concurrent observation at the secondary stations, the secondary station record can be extended almost to the period of the primary station network. It is to be noted, however, that the secondary station records can not be extended fully to the period of the primary station, some information is always lost in such extensions. On the other hand, by also including rainfall records from nearby long-term meteorological stations, the regression may be significantly improved.

Thus, if conditions are favourable, planning and design of water resources projects may proceed safely after a relatively short period of data collection at the project site. Substantial amounts of funds and precious time may thus be saved if 10–15 years of data collection at a specific site, proves sufficient instead of 25–30 or more years, which is often considered the minimum for design of a sizable project.

2.4 Hydrologic Bench Mark Stations

Hydrological bench-mark stations record the evolutional effects caused by natural phenomena alone. Thus, these stations are established at places such as national parks where there is the least risk that man's activities will cause changes in the hydrological regime. The records of bench mark stations are used to adjust the regular stations so that they can be corrected for the influence of man's activities and thereby kept consistent with time. Since long records are the essence of a bench-mark station, consideration should be given to existing primary stations if they meet the other requirements of a bench-mark station. [12].

2.5 Estimation of Statistical Parameters for Annual River Flows

Rodrigues-Iturbe [33] made an analysis of 140 river gauging stations from all over the world with period of observation ranging from 40 to 150 years. A first order Markov process was assumed to be representative for the annual river flows.

The normalized standard errors of the estimates of the mean (μ), the variance (c_v), and the first autocorrelation coefficient (ρ_1) was shown as functions of the sample size for a river which was considered to have average statistical characteristics (i.e. $c_v = 0.324$ and $\rho_1 = 0.175$).

The theoretical analysis was complemented with a study of the variations with sample size of the main statistical parameters of three rivers with large amount of data: the Rhine, the Gøta, and the Broken rivers.

The result showed that on the average between 40 to 60 years of data are desireable to estimate the mean and the variance of annual streamflow series. For the same amount of data the estimation of the mean will be much more precise than the estimation of the variance. If the length of the series is shorter than 40 years, the error might easily run from 2 % to 20 % for the mean and from 15 % to 60 % for the variance.

The estimate of the first autocorrelation coefficient appears to be quite unstable for series of annual streamflow, and errors of 200 % seems to be common when the estimate is based on less than 40 years of data.

Bibliography

Chapter 2: [2], [3], [5], [10], [11], [12].

STREAM-GAUGING STATION CONTROLS

3.1 General

For a full and authoritative discussion on stream-gauging station controls the reader is referred to the classic work of Corbett et al. [17], to the excellent coverage of the subject by Grover and Harrington [34], and to Water Supply Paper 2175 of the US Geological Survey [16].

3.2 The Station Control

The term station control does not only mean a particular cross section of the channel downstream the station, but includes all the elements and features of the stream channel which govern and control the stage-discharge relation at the station site.

The channel characteristics forming the control include the cross-sectional area and shape of the stream channel, the channel sinuosity, the expansions and restrictions of the channel, the stability and roughness of the streambed and banks, and the vegetal cover, all of which collectively constitute the factors determining the channel conveyance.

A control can be either a complete control or a compound control. A complete control governs the stage-discharge relation throughout its entire range by eliminating all other downstream controlling features, while a compound control is composed of several partial controls each governing the stage-discharge relation for a part of the range only.

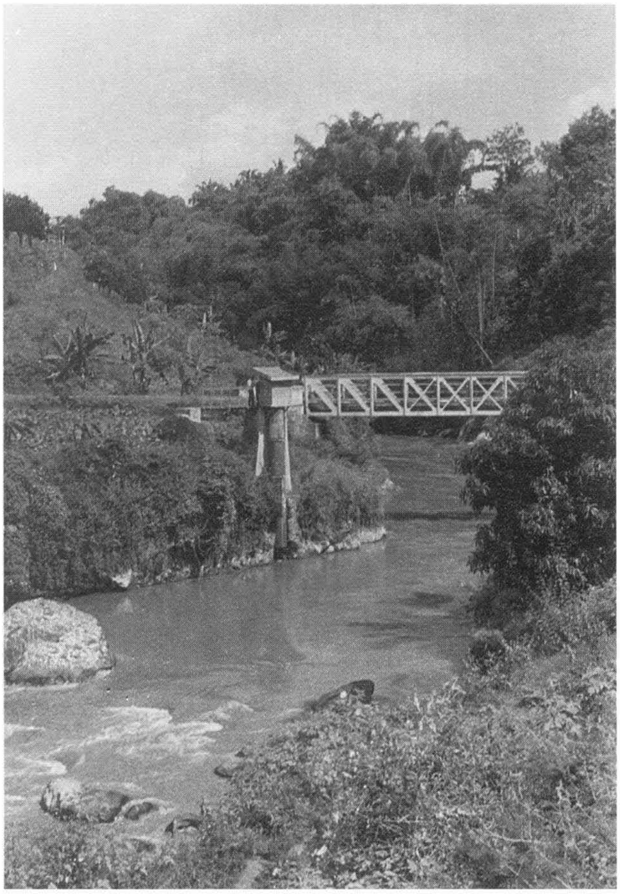


Figure 2. Complete section control with upstream pool (Cimanuk River at Leuwigoong, Java, Indonesia).

Compound controls are common in natural streams. As the stage in a stream rises, the stage at the downstream side of a low-water control may rise faster than that upstream from the control. This may continue until the low-water control is no longer effective, at which time the governing control is transferred to some channel feature downstream from the low-water control, usually a reach of the channel.

If the controlling features are located in a relatively short reach of the channel, the complete, or partial control, is termed a section control. A section control may be made up of a constriction of the stream channel, a rock bar or ledge across the channel forming a kind of natural weir, the crest of a waterfall, or of a reach of rapids that fixes the stage-discharge relation. A section control always has a forebay or pool which may extend from a few to several hundreds of metres upstream from the control itself. The section type of control produces a noticeable fall or break in the longitudinal water surface profile of the stream. The first complete break in the slope at the upper end of the section control indicates the position of the control and the point where the control is most effective in maintaining the stage-discharge relation. (Fig. 2–6).

If the controlling features consist only of frictional resistance, slope, and channel geometry in a relatively long reach, one speaks about a channel

Figure 3. Complete section control with upstream pool, downstream view (Cimanuk River at Leuwigoong, Java, Indonesia)).

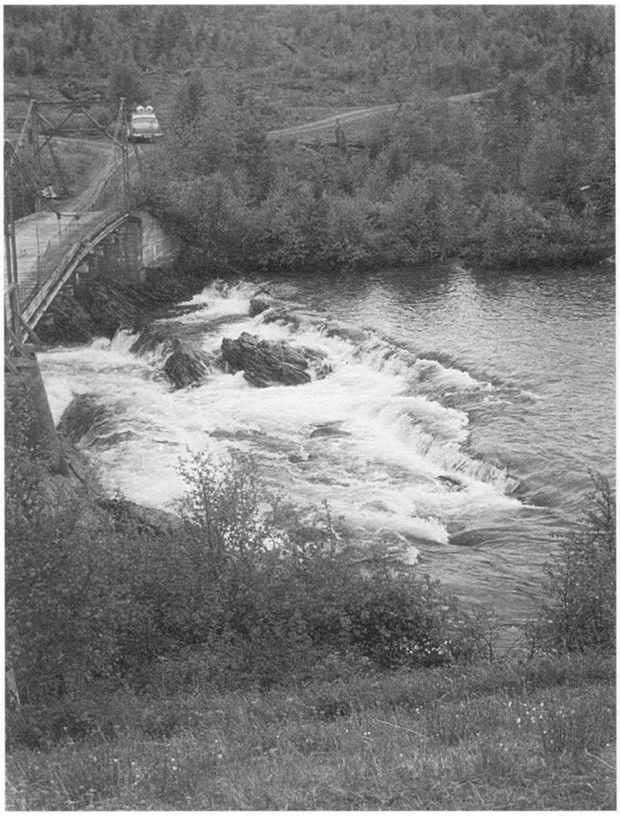


Figure 4. Permanent and complete section control, low-water part of control is sensitive while high-water part is non-sensitive (Torsbjørka River at Mannseter, Norway).

control. The channel type of control does not have any break in the slope of the water surface at the head. At low discharges, a channel control is generally due to the slope of the water surface which is produced by the frictional resistance of the streambed against the flow of water. (Fig. 7 and 8).

Generally, channel controls consist of a long reach of stable bed extending downstream as the stage increases. In general, the distance covered by such a control varies inversely with the slope of the stream and increases as the stage of the stream rises. The tendency for a channel control to extend farther downstream as the stage rises has a marked effect on the stage-discharge relation. As the stage increases, low-water and medium water controlling elements are drowned out and new downstream elements are successively introduced into the station control causing a straightening out of the typical parabola curvature of the discharge rating curve, and at times even causing a reversal of the curvature. In fact, for rivers with very flat slopes the station control may extend so far downstream that backwater complications which do not exist at lower stages are introduced.

If the control on a stream with a large range in stage is not formed by one or more ledges which produce a waterfall or rapids with a considerable drop, it is possible that the features forming the control for low stages may be completely submerged at times of high water. If the low-water control consists principally of a low riffle or other obstruction producing a similar effect, it may be considered as partially submerged as soon as the flow begins to show the effect of additional downstream controlling features. The stage at which the low-water control begins to lose its effectiveness is generally indicated by a change in curvature of

Figure 5. Complete section control with upstream pool (Progo River at Kranggan, Java, Indonesia).

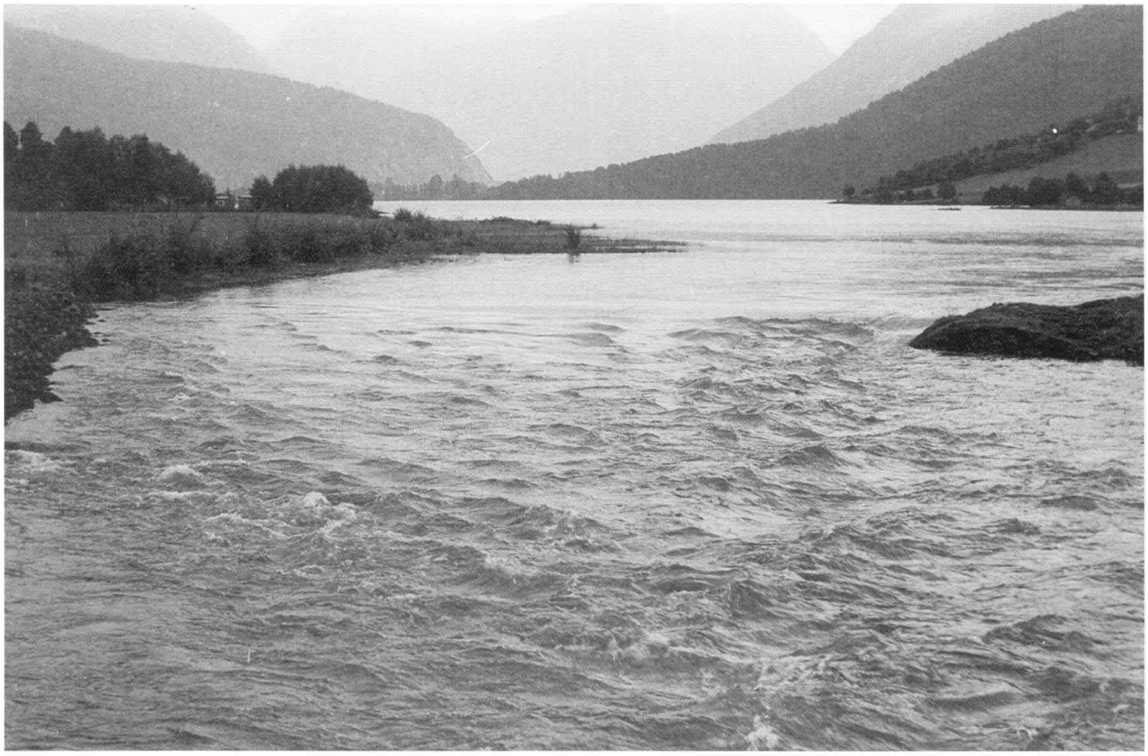


Figure 6. Complete section control at outlet of lake (Stryn River at Strynsvatn, Norway).

the discharge rating curve. On streams with steep slopes and high velocities one and the same reach of channel is often effective in controlling the stage-discharge relation both for the low and the high stages.

Controls, particularly low-discharge controls, should be sensitive, that is, for any change in discharge a rather quick response to the change is reflected by the stage upstream of the control, and for a small change in discharge a relatively

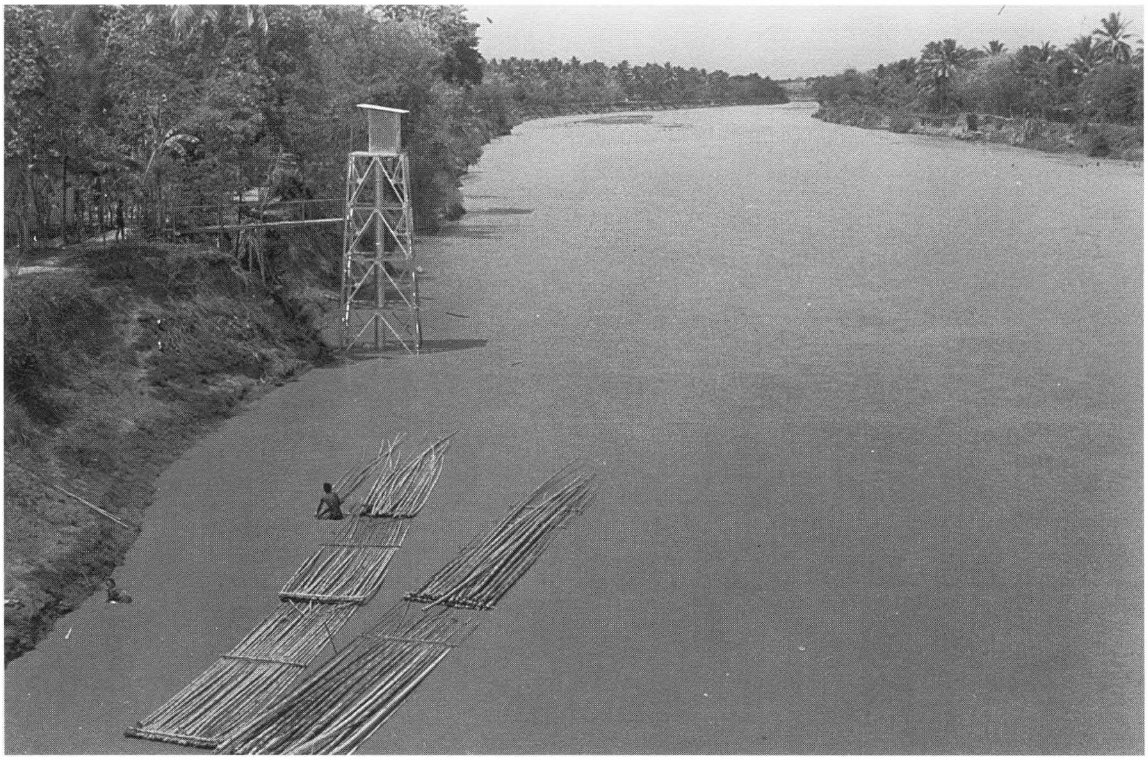


Figure 7. Channel control, moderately stable, probably shifting during and after major floods (Comal River at Comal, Java, Indonesia).

Figure 8. Compound stable control composed of small island, bridge piers and bed resistance; upstream view, river flows probably on solid bedrock, riverbanks composed of sandy soil (Sao Francisco River at Petrolina/Juazeiro, Pernambuco, Brazil. Catchment area about 300.000 km^2).

large change in stage will occur as in a V-notch weir. A nonsensitive control differs from a sensitive control by having a wide flat cross section, but it is possible that a lack of sensitivity is caused by an exceptionally high velocity of approach. A control is considered sensitive if a change in stage of 1 cm does not represent more than about a 5 % change in discharge.

3.2.1 The Low-Water Control

A low-water control usually consists of a natural ledge or riffle across the streambed, or a contraction of the stream channel. Such a control causes a break in the slope of the water surface so that all effects of downstream features are eliminated. A low-water control begins to lose its effect when the water downstream from the control rises to a height above the lowest point on the low-water control. If the water continues to rise, a condition will finally be reached when the low-water control becomes noneffective and it is said to be drowned out.

Although the sensitivity of a station control is important at all stages, it is generally of particular importance at low stages. In many instances, the principal reason for the construction of artificial controls is to improve the sensitivity or steepness of the stage-discharge relation at low flow. In general, a sensitive control tolerates a much greater degree of submergence than a nonsensitive control.

An artificial control is a structure built by man. This may be a low broadcrested dam or a specially-designed measuring weir. A gauging station should always be located above a suitable natural control if available, because artificial controls are expensive to construct and maintain.

3.2.2 The High-Water Control

High-water controls are in general more difficult to recognize than low-water controls, and because of their complex nature require considerably more survey and investigation. High-water controls are usually compound controls and may include such features as a constriction of the channel, one or several bends of the channel, or a series of bars and ledges across the streambed. Sometimes, one of the several controlling features may be more effective than the others and thus becomes the principal element of the control.

It is impossible to determine beforehand accurately the effectiveness of each major channel feature and its part in controlling the stage-discharge relation. However, a knowledge of its existence and position with respect to a gauging station is of great value when analyzing the relation between stage and discharge.

Constrictions of the stream channel downstream from a gauging station are excellent controlling elements and have a marked effect on the stage-discharge relation. Constrictions usually bring about a break in the water-surface slope since they cause the slope to decrease upstream. Bridges usually act as constrictions. A sharp bend in the river has a similar effect in that the slope of the water surface shows a marked break at the bend.

If there are no constrictions or sharp bends, the flow may be considered to be controlled by the frictional resistance of the channel, except in very unstable channel beds where, in fact, there are no controls and the relation between stage and discharge varies more or less continuously.

3.2.3 Permanent Controls

Regardless of how stable and permanent a control may appear, it is always possible that a change may occur in the physical features forming the control. The fact that a change in a generally recognized permanent control may not be readily identified is no assurance that the stage-discharge relation has remained unchanged. The nature of the change may be such as to be overlooked during an ordinary inspection of the controlling features. On the other hand, some of the physical characteristics of a control may appear to have changed, yet the nature of the change may be such as not to include those features which materially affect the stage-discharge relation. Positive assurance that a change has not occurred, is attainable only by comparing the results of discharge measurements with the previously established discharge rating curve.

3.2.4 Shifting Controls

The term shifting control as used in stream gauging, signifies that the stage-discharge relation does not remain permanent but varies or shifts with time. In such cases when the physical features forming the control undergo changes, either abruptly or gradually, the stage-discharge relation will also vary in that the stage corresponding to a given discharge will deviate from the rating curve as defined before the change.

It should be recognized that most natural controls shift with time. However, a shifting control is considered to exist where the stage-discharge relation changes frequently, either gradually or abruptly because of changes in the physical features that form the control. The frequency and magnitude of such shifts are generally dependent upon the climatic, physiographic, geologic, vegetal and soil conditions in the drainage basin.

Usually, shifts in a control are caused by erosion of the stream channel, deposition of sediment, or by channel vegetation.

3.2.5 Erosion

Erosion (scour) of the streambed and banks within the controlling reach of the channel will appear in the discharge rating curve as a shift to the right of the curve indicating an increase in the channel conveyance over that previously existing for a given stage. The more common situation is that the lower part of the rating curve may change as a result of erosion of the low-water control only, while the upper part of the curve may retain its original trace because the high-water elements of the control coming into effect at the high stages maintain the previous stage-discharge relation. On the other hand, the opposite situation may often occur where the low-water control is essentially permanent while the high-water elements of the control are subject to erosion during high floods.

If a radical change has affected the controlling reach in streams with channel control, the variation in the stage-discharge relation may extend over the entire range of stage and discharge. In such cases, some degree of parallelism may exist between the new and the old rating curve.

3.2.6 Deposition

The effect of deposition (fill) on the controlling section and in the controlling reach is opposite to that of erosion and the discharge rating curve representing the new stage-discharge relation will be positioned to the left of the previous curve.

Usually, deposits on a low-water section control will be washed away at high water. Typically, low-water controls subject to erosion and deposition produce a series of rating curves spreading out fanwise at the lower end and converging for stages above the beginning of submergence of the low-water control.

3.2.7 Shifts in the Channel above the Station Control

Shifts and changes in the stream channel above the control may significantly affect the velocity of approach at the gauging site as a result of changes in the slope or the cross-sectional area of the channel. If scouring of the upstream channel takes place, the greater capacity of the forebay upstream from the control results in a lower velocity of approach and thus a decrease in the discharge for a given stage. If deposition occurs, an increase in the velocity of approach and a consequent increase in the discharge for a given stage will result.

3.2.8 Channel Vegetation

Aquatic vegetation in the stream channel will affect both the roughness and the effective cross-sectional area of the channel and thereby also the stage-discharge relation. The vegetation is generally greatest in streams polluted by organic wastes.

Floods may remove part of the effect from aquatic vegetation by flattening it out.

Aquatic growth at and on the control may have greater effects at low water that at high water, and except for the seasonal characteristics, the effects will resemble those due to scour and deposition.

3.2.9 Overflow Stream Channel

Streams with large overflowing areas present many complications in the determination of the stage-discharge relation, particularly during rising and falling stage. The best solution often is to establish separate discharge rating curves for the flow in the main channel and in the overflow area, the total discharge being the sum of these. A control with large overflow areas should be avoided.

3.2.10 Effect of Ice on the Stage-Discharge Relation

Ice affecting the stage-discharge relation produces an increase in the stage above that for normal open water conditions, thus causing backwater effects.

The major stream gauging complications arising from any form of ice, whether surface, frazil or anchor ice, relate to the magnitude of backwater, its variation from day to day and the length of time when the stage-discharge relation is affected. Ice may form gradually with no indication of the time when the stage-discharge relation begins to be affected. On the other hand, there may be a decided rise in stage caused by ice obstructions downstream.

If a continuous stage record is made by an autographic recorder, a steeper slope on the falling side than on the rising side, will indicate that the stage-discharge relation is affected by ice.

The magnitude of backwater caused by ice is determined by measuring the discharge and the corresponding stage. The difference between the measured stage and the stage corresponding to the discharge as defined by the discharge rating-curve for open-water conditions, gives the rise in stage caused by the ice.

3.2.11 The Stage of Zero Flow

The stage of zero flow (also termed the point of zero flow) corresponds to the lowest point on the low-water control and is defined as the stage at which the water ceases to flow over the control. Usually, this stage does not coincide with the zero of the gauge installed above the control. The stage of zero flow is an important item of information and a very helpful aid in developing the discharge rating curve as it is included as a parameter in the discharge equation for the stage-discharge relation.

The position of the point of zero flow is easily determined for artificial controls and in those cases where the control is well defined by a rock ledge over which the water flows.

For other natural controls, particularly channel controls, the determination of the point of zero flow may often be approximate. The stage of zero flow is determined by subtracting the depth of water over the lowest point on the control from the stage indicated by the gauge reading. If the gauge is at some distance from the control, an adjustment is made for the slope. The difficulty in determining the point of zero flow is in finding the lowest point on the control, as not all controls are easily identified. Generally, a cross section is surveyed at the first break in the slope of the water surface, this is usually the location of the upstream lip of the low-water control. For a channel-controlled gauging station the maximum depth directly opposite the gauge will give a reasonable approximation of the depth to be subtracted from the gauge reading in order to obtain the stage of zero flow.

The position of the point of zero flow is best determined at time of low water when streams can be waded. In those cases where the controlling section is difficult to identify it may be identified by surveying a close grid of spot levels, or running a sufficient number of cross sections over the area of the assumed controlling section or reach.

3.2.12 Artificial Controls

An artificial control is a structure built in an unstable stream channel in order to stabilize a channel section to which the stage-discharge relation can be referred. See Section 5.10.

Bibliography

Chapter 3: [15], [16], [17], [34].

CHAPTER 4

SELECTION OF THE STREAM-GAUGING STATION SITE

4.1 General

A stream gauging station is a structure in or close to the stream channel which indicates or records the height of the water surface in the stream. The station may include a structure from which discharge measurements are made and also a stabilized section of the stream channel called an artificial control.

A nonrecording gauging station consists of a staff or some other device graduated in metres and centimetres. The stage of the water surface, usually termed the gauge height, is read by an observer one or more times a day and the readings recorded. Recording gauging stations utilize various types of recording instruments that require shelters and facilities for transmitting the gauge height to the recording instrument.

Either single-gauge or twin-gauge stations may be employed depending on the local conditions. The use of a single-gauge station depends on the assumption that the stage at a section of the channel is a substantially unique function of the discharge. Twin-gauge stations are used if the stage at a location is affected by variable backwater. Twin-gauges are also employed to gauge high flood-discharges at ordinary single-gauge stations.

Gauging stations are further classified as stage stations and discharge stations. Both types provide records of stage. A discharge station also provides a continuous record of discharge by converting the stage record into a record of discharge through the stage-discharge relation.

From the foregoing section it can be concluded that the first and most important step in collecting accurate records of streamflow is the selection of the gauging station site. The selection of a satisfactory gauging site involves far more than the discovery of a place where a gauge may be installed cheaply and securely. It involves the finding of that site which will give the most reliable records of stage and discharge at an acceptable input of manpower and funds.

4.2 General Field Reconnaissance to Locate Gauging Sites

Before a gauging station is established, a general field reconnaissance is made so that the most suitable site may be located. All available topographic and geologic maps of the area drained by the stream should be studied before the reconnaissance is carried out. Aerial photographs when available are especially helpful in this respect. The maps will contain information on the topography and geology of the area, thus indicating possible gauging sites. The location of tributaries, divided channels, overflow areas, steep banks, access roads, bridges and other pertinent facts important for the location of the gauging site may also be found on these maps. As much preliminary investigation as possible should be done while still in the office because this information will prove invaluable during the field reconnaissance.

Each tentative site is given a critical examination in the field. Particular attention is paid to:

a) Accessibility to the site at all seasons of the year.
b) The hydraulic conditions necessary for maintaining a permanent relation between stage and discharge.
c) The availability of a suitable cross section or channel reach where discharge measurements can be made.
d) Favourable conditions for correct placement of the water level gauge.
e) Possibility to instal artificial controls.
f) The availability of a competent local observer or caretaker.

The field reconnaissance report should include sketches and photographs of the physical and hydraulic features at each possible site supplemented by the hydrologist's notes, comments and evaluation of the sites.

A single visit to each proposed site is seldom enough. If possible, all the proposed sites should be visited at various seasons of the year and at various stages of the stream. This is not always possible in practice, but the sites should be visited under as many different conditions as the time allowed for the establishment of the station permits.

Sometimes there is no choice in selecting good sites for gauging stations. For example, all streams in a given area may have unstable beds and banks. In channels on unconsolidated soil, the stage-discharge relation can normally be defined approximately only. Research on sandbed channels has shown that the best gauging site is located at the head of a long uniform reach with comparatively stable banks and on the outer bank downstream from the upstream bend.

Normally, gauging stations should not be located in flood plains because of the possible damage during floods and because the station would be inaccessible at high water, and the station would not produce any meaningful discharge records at this time when the whole area is flooded. In flood plains, stage gauges only are usually required.

The cost of installation and the accuracy and reliability of the records will depend primarily on the stream characteristics at the gauging site. However, these factors may be affected to an extent by a combination of all the items listed above and probably by others as well. Therefore, all factors are carefully considered before a decision is made regarding the location of the station.

4.3 Accessibility

Accessibility depends on the availability of highways, roads and bridges. The nearer a gauging station is to adequate roads that are open all year, the easier the construction and operation of the station will be. The time saved and the convenience of having a gauging station near good roads should be considered in the final selection.

Compared with the channel characteristics necessary to maintain a permanent and sensitive stage-discharge relation, other factors and qualities of a good gauging station are often considered to be of minor importance.

However, these other factors may often prove decisive. For example, a site which is ideal from the hydraulic viewpoint is useless if it can not be regularly attended or if it is impossible or dangerous to approach the station with the necessary equipment to gauge the flow at all seasons of the year and at all stages of the river. (Fig. 9).

Furthermore, the possibility of transporting heavy material and equipment for the construction of the station is of primary importance. Under unfavourable conditions, the problems and cost of

Figure 9. Except for special investigations, a gauging station should always be easily accessible by road or track during all seasons of the year. Crossing water-logged ground between Dodoma and Ilangali on the Kisigo River (Tanzania) during the wet season. Four-wheel drive vehicle and chains on all wheels are required.

transporting heavy material to the proposed site will be decisive with regard to the type of installation to be adopted.

4.4 The Station Control

The control for a gauging station should be the first consideration during a field reconnaissance. The desirable control characteristics are:

a) Stability and consistency.
b) Sensitivity.
c) Freedom from variable backwater.
d) Same amount of water passing gauge and control.

The ideal control should be stable so that there will be no significant shifts in the stage-discharge relation. The possibility of and the necessity for modifying the natural control or building an artificial control should be explored. The control and reach of channel immediately upstream should be examined for evidence of previous major changes which might indicate future changes.

The control for a gauging station site should be sensitive so that a significant change in discharge would be accompanied by a significant change in stage. For a twin-gauge station, the length of the reach between the two gauges should be sufficient to make any inaccuracy in the reading of the gauge heights negligible, relative to the difference in the water levels at the two gauges.

The control should be located so that it is free from variable backwater. There should not be any tributary entering the stream at or below the control. Such tributaries would leave deposits in the stream which would affect the control, and often cause variable backwater because of staggered timing of the flood peaks in the two rivers. The control should be examined to determine what effect ice and aquatic vegetation will have on the stage-discharge relation. There should not be any lake, reservoir or power pool in the reach below the control that would cause variable backwater.

There should not be a tributary entering the stream between the gauge and the control, nor should there be an excessive amount of seepage between the gauge and the control so that the amount of water passing the gauge is less than that passing the control. During high water, there should be no flow bypassing the gauging site in flood channels.

During the reconnaissance, it is necessary to determine what feature will be the control at the various stages expected. At many sites, two, three and sometimes more different features make up the control at the various stages of the stream.

The best and simplest type of a control is formed by a rock ledge at the head of a rapid or at the crest of a waterfall as in Fig. 3 and 4. Firstly, it ensures permanency; secondly, it creates a forebay or pool in which a gauging station is often easily constructed; thirdly, favourable conditions for carrying out discharge measurements may be often found within the reach of such a pool; fourthly, the point of zero flow is easily located in this situation. Whenever practical this type of control should be utilized for stream-gauging stations.

Detailed investigations carried out by an experienced hydrologist are essential to locate and define the channel characteristics which control the stage-discharge relationship. In fact, the hydrologist must have considerable experience in analyzing discharge rating curves, and in studying the relationship between rating curves and the characteristics of their respective controls, before he has gained a basis to anticipate what kind of rating curve that would result from a particular site and thereby judge the general suitability of that site.

Unless an artificial control is available or is to be constructed, the hydrologist must accept the conditions as found. Therefore, sufficient time should be allowed for when making surveys in order to locate new stream gauging sites. Hasty selection of gauging station sites has often meant the difference between an economic and a costly operation. Thus, a careful study of each prospective site must be made in order to find the most favourable location. Unless the control features are conspicuous, it may not be possible to anticipate the permanency or the sensitivity of a possible site. In such cases, it may be better to install temporary gauges at several tentative sites and to observe and compare the gauges for some time before a final choice of the best location is made.

4.5 The Discharge Measurement Site

A prospective gauging station location should be examined for the availability of discharge measuring sites for the various stages expected. One of the aspects of this examination is to be certain that there will be a measuring site at low flow where the velocities will be 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 be evaluated. If there are no suitable bridges, a site for a cableway or footbridge should be selected.

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. Sometimes, different measuring cross sections will be required for the different stages of flow, especially for the low-water measurements.

a) A discharge measurement is generally made in conjunction with a water-level gauge on a 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 must be made.

   For measurements taken during rising or falling stage, the channel storage in the stream channel 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 pools between the two sites.
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 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 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 big protruding obstructions which will create turbulence.

   Where there are tendencies to the formation of eddies, boils, cross currents or backward flow, the site should not be used.

   Especially, sites with diverging flow should be avoided 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 measurements with the use of an ordinary current meter.

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

g) The general direction of flow should be normal to the measuring cross section.

4.6 The Local Observer

Experience has shown that in order to ensure uninterrupted operation of automatic recording stations, the routine attendance of a competent local observer and caretaker is essential, especially under extreme conditions.

If an observer will be needed at a gauging station, the site selected should be near a populated area where people who can serve as an observer are available. Also, the necessity of having a station near adequate roads becomes more acute if an observer is needed.

4.7 Establishment Costs

In most cases, economy is not the controlling factor in the final decision, but it should definitely be given consideration. The two important aspects which should be considered when comparing possible sites are the cost of construction and the cost of operation.

The items to be investigated to determine the approximate cost of construction are:

a) Access road to the site for transport of manpower, material and equipment.
b) Type of soil to be excavated.
c) Need for protection of structure from floods.
d) Need for cableway and artificial control.
e) Type of gauge installation.

To make an accurate estimate of the cost of construction, time must be spent during the field reconnaissance to find high-water marks of past floods and to discuss the height of past floods with local residents. This information will be essential in determining the exact location and height of the gauge and the height and length of the cableway if one is necessary.

Consideration must be given to the type of gauge installation to be used. A decision must be made whether it will be a bank or a bridge installation, and if it is a bridge installation, whether it will be on a pier or on the abutment.

Included in the cost of operation there should be the annual cost of obtaining the field data such as discharge measurements, datum checks, station maintenance, etc.

Once the cost of construction and the cost of operation for each proposed site have been estimated, the economic aspects of the different proposed sites can be compared.

4.8 Preliminary Survey of the Gauging Station Site

The decision concerning the permanent location of a new gauging station is based on the general reconnaissance by an experienced hydrologist, as discussed above, followed by a preliminary survey to establish in detail the physical and hydraulic features of the proposed site. The purpose of the preliminary survey is to check to what extent the desired characteristics of a good gauging site are present and to establish a basis for the design and construction of the station.

The preliminary survey should include: (a) a plan of the site, (b) a longitudinal section of the stream reach, (c) cross sections of the discharge measuring reach, and (d) a detailed plan of the controlling section or reach.

The plan of the station site should indicate:

a) The width ot the river at a stated stage.
b) The edges of the natural banks of the channel and the toe and crest of any floodbank.
c) Any obstructions against the flow of water in the channel.

The longitudinal section of the channel should be drawn extending from below the section control, where this exists, to the upstream limits of the gauging site reach. The longitudinal section should show:

a) The level of the deepest part of the streambed.
b) The level of the lowest point on a section control corresponding to the stage of zero flow.
c) The water-level profile at low and high stages.

The current-meter measurement site should be defined by at least five cross sections. In addition to the measuring cross section, two cross sections below and two above the measuring section should be surveyed, covering a distance equal to one bankfull width of the channel in each direction. The bed in the measuring reach between the five surveyed cross sections should be carefully examined for the presence of rocks and boulders. All cross sections should be taken normal to the general direction of flow and should be extended to an elevation well above the highest expected flood stage. The spacing of levels and soundings must be close enough to reveal any abrupt changes in the contour of the channel.

Where velocities are to be measured by a current meter, exploratory measurements of velocities should be made in the proposed measuring section and in the cross sections immediately upstream and downstream. That is, the vertical velocity-curve method with ten points in the verticals should be used for the current-meter measurements. The measurements should be computed by graphical integration and contours drawn through points of equal velocity. Refer Volume 3, Section 2.3.

Bibliography

Chapter 4: [4], [15], [16], [17], [34]

CHAPTER 5

STREAM-GAUGING STATION STRUCTURES

5.1 General

Four main types of structures are used at gauging stations:

a) Water-level gauge and bench mark. The gauge is usually a nonrecording vertical staff gauge or an inclined staff gauge.
b) Water-level recorder. The water-level recorder is traditionally a float-actuated recorder housed on top of a stilling well, and with communication to the river through water pipes.
c) A structure for taking current-meter measurements, usually a cableway or a footbridge.
d) An artificial control such as a weir or a flume.

The first item is required at all gauging stations. The second item is needed if the stage is to be continuously recorded. The two last items may or may not be needed depending on the gauging conditions at existing bridges and the natural control conditions at the site.

Highway bridges used in making streamflow measurements must be utilized as they are found. The only problem they present is whether or not they will be practicable for making discharge measurements. The advantage of using existing bridges is the saving in construction and maintenance costs that is associated with cableways, but this advantage is often outweighed by poor measuring conditions at bridges, and the safety hazard caused by traffic conditions. A bridge that is used regularly for discharge measurements is marked at suitable intervals on the handrail or on some similar feature of the bridge for convenient spacing of the measuring verticals.

No standard design for footbridges is recommended because each footbridge installation represents its own particular problem. The type of footbridge used will depend on the span, availability of material, stability of the banks, accessibility to the site, type of equipment to be used and funds available. Footbridges are designed so that they give the hydrologist room to move about and to operate the current-meter equipment comfortably.

The construction of the facilities at gauging stations must be planned carefully to be certain that the resulting structures are correctly located, safe to use, and economical to operate and maintain.

5.2 The Staff Gauge

The staff gauge is the type of gauge ordinarily used at nonrecording gauging stations. At recording stations the staff gauge is used as both an outside reference gauge and an inside water level gauge in the stilling well after which the recording instrument is set. These two gauges should give identical readings.

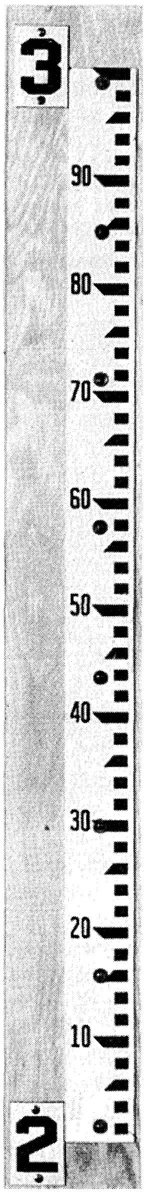


Figure 10. Staff gauge scale-section 1 m long and graduated in cm, made of porcelain enameled iron plate (courtesy of Stevens).

The staff gauge may be either a vertical or an inclined gauge following the contour of the bank of the stream. The vertical staff gauge usually consists of standard porcelain-enamelled iron plate sections (Fig. 10). The sections are supplied in lengths of 0.50 and 1.00 metre and are graduated in cm. The sections are usually screwed on to a board which is fastened to a vertical support. Slotted holes in the plates are provided for final adjustment in setting the gauge.

The gauge is placed in the forebay just upstream of a section control (Fig. 4 and 5). It should be sited in such a way that it will be naturally protected against the force of the current and against flood water. However, it must not be placed too close to the control so it measures the stage of the rapidly curving water surface immediately upstream from the control. Thus, the gauge and the intake orifice to a water-level recorder must never be located on

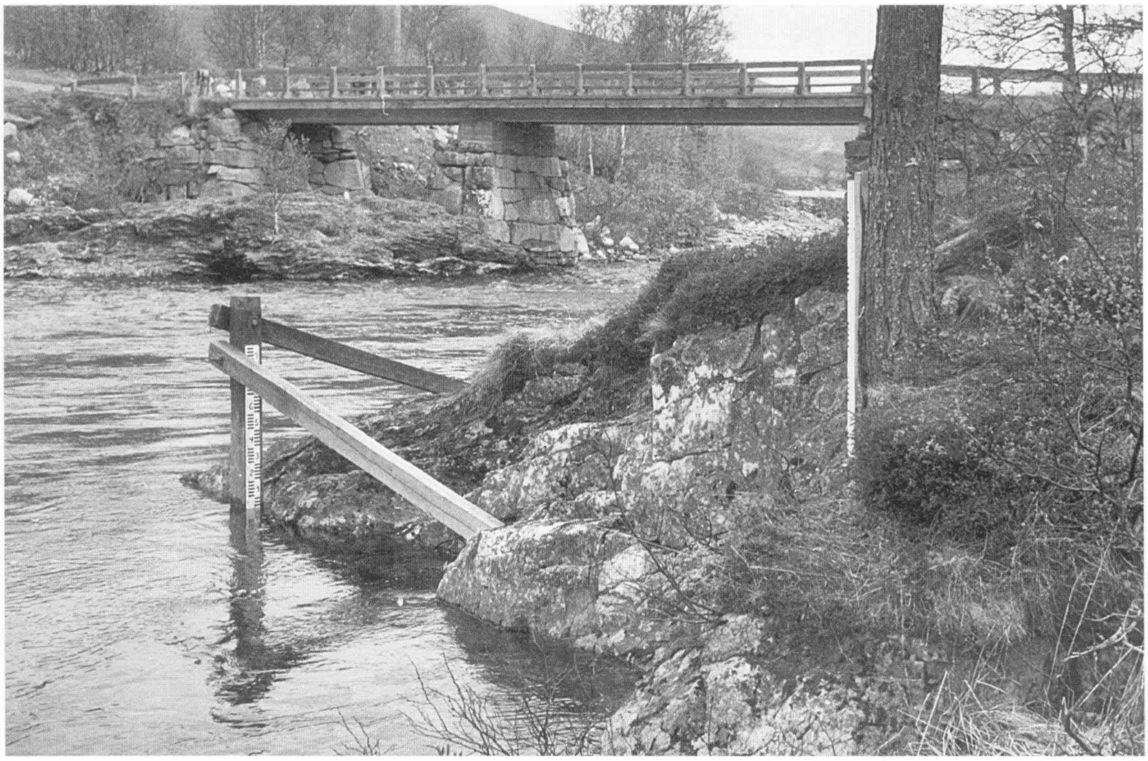


Figure 11. Staff gauge (Bua River at Lillebudal, Norway).

the crest of the control or in a place where the water surface has a considerable slope or fall.

Preferably, the gauge should be placed in a small bay at the side of the stream so that a direct reading of the water level may be made and where it is protected against floods and ice (Fig 11). If this is impractical because of excessive turbulence, wind effect or inaccessibility, the observations may be maid in a suitable stilling well in which the wave action is reduced but the water level still is representative. To ensure this, intakes to stilling wells must be properly designed and located.

Wave action disturbing the reading of staff gauges is often overcome by attaching a transparent plastic tube with a narrow bottom-intake alongside the gauge scale. Water level fluctuations in the tube will be damped and the correct water level can be read on the scale.

The gauge should not be placed where the water is disturbed by turbulence or where there is danger of damage by drift. Bridge abutments and piers are generally unsuitable locations. Wherever the gauge is situated, it must be readily and conveniently accessible so that the observer can make readings as near as possible at eye-level. Where necessary, the construction of a flight of steps to give convenient access is recommended.

A suitable backing for a vertical staff gauge is provided by a board fixed to a wall having a vertical face parallel to the direction of flow. Gauges may also be fixed to piles, either driven firmly into the river bank or set in concrete in order to avoid sinking, tilting or being washed away. In either case, the anchorage should extend below the ground surface to a level free of any disturbing effects. Where the range of water level variations exceeds the length of a single vertical gauge section, additional sections are installed in line normal to the direction of flow (Fig. 12).

An inclined gauge usually consists of heavy timber securely attached to a permanent foundation. The graduations are marked directly on the timber or are carried on manufactured plates that are screwed on to the timber. Except where use is made of manufactured gauge plates, an inclined gauge is calibrated in situ by accurate levelling from the station bench mark. An inclined gauge is installed so that it follows the contour of the bank. The profile of the bank may be such that a gauge of a single slope can be installed, often however, it may be necessary to construct the gauge in several sections, each with a different slope. The readings are then adjusted for the slope during the preprocessing of the data at the office. It is often convenient to construct a flight of steps alongside the inclined gauge to facilitate taking readings. The accuracy of readings of an inclined gauge may be improved if a small portable stilling tube made of transparent material is used when reading it.

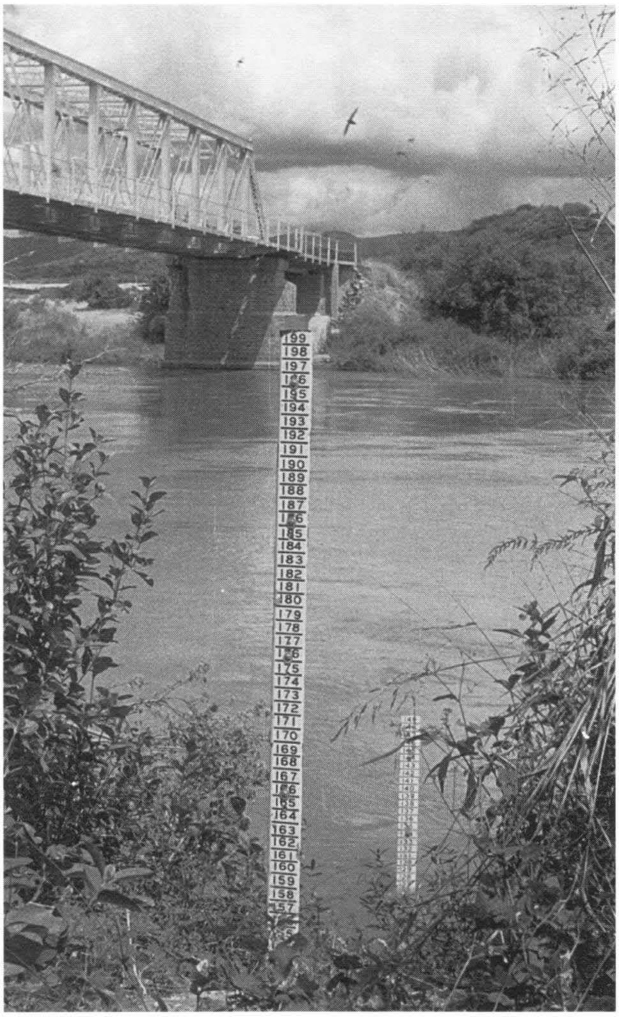


Figure 12. Staff gauge-sections installed in line upstream of Mtera Bridge on the great Ruaha, Tanzania.

5.3 The Gauge Datum

The datum of the gauge may be a recognized datum such as mean sea level, or an arbitrary local datum selected for the convenience of using gauge readings of low numbers. It is desirable to avoid negative values for gauge-height readings. Therefore, the gauge zero is set below the level of zero flow, in the case of a section control, and below the lowest stage anticipated in the case of channel controls. It is recommended that one should always start the lowest gauge section at 1.00 metre instead of 0.00 metre so that minus readings are avoided if a an extreme low year should occur in the future.

A permanent datum must be maintained so that only one datum is used for the stage record throughout the life of the station. However, a staff gauge is not a stable construction and is often exposed to destruction, especially during high floods. In order to be able to reset gauges at their correct datum, a permanent bench mark is required. A bench mark must always be entirely detached from the gauges and their supports and secured against destruction.

5.4 The Station Bench Mark

The station bench mark must be set in a position offering maximum security against disturbances. It should be securely fixed in a concrete block that extends below the ground surface to a level free from disturbance, or drilled into solid rock, if possible. It should be connected to the Geodetic Survey Net by levelling. To facilitate accurate levelling between the station bench mark and the gauge zero, the bench mark should be located in such a position that the transfer of the level may be carried out by levelling with equally balanced foresights and backsights. The level is transferred to the gauge zero by a closed levelling circuit, starting and finishing on the bench mark. The misclosure of the two levelling runs should not exceed 4 mm. The mean of the two runs is taken as the difference in level between the bench mark and the gauge zero.

The level of the bench mark relative to the gauge zero is referred to as the reduced level of the bench mark. Bench marks may consist of specially made brass bolts or ordinary steel bolts, 10 cm long and about 15 mm in diameter. (Fig. 13).

If the station is equipped with a water-level recorder, it is practical to establish an auxiliary control mark on the instrument shelf. It is then easy to check the inside gauge if it is at the correct level, or check the inside water level by an electric-tape gauge if no inside reference gauge has been installed (Section 7.1.3).

5.5 The Water-Level Recorder

5.5.1 The Autographic Water-Level Recorder

The traditional autographic (analogue) water-level recorder, still widely used, consists of a float attached to a counter-weight by means of a stainless steel wire or tape (Fig. 14 and 15). The tape is graduated in metres and centimetres and passed over a float pulley, the shaft of which drives a writing stylus. The rise and fall of the water level is traced on a paper chart with respect to time, while the chart is being rotated on a drum or being conveyed from a strip-chart roll at even speed by a spring-wound or weight-driven type clock. The

Figure 13. Bench mark brass bolts.

Figure 14. OTT Type X Autographic water-level recorder with counter-weighted float and clock drive (courtesy of A. OTT).

clock may also be powered electrically by batteries or from the mains.

The float is placed in a stilling well that is connected to the stream by intake pipes. The stilling well protects the float-system against floods and ice, and eliminates, or at least reduces the effect of surface waves and short period surges in the natural channel thus providing an accurate representation of the water level in the stream.

Stilling wells, though usually placed in the bank of the stream, may be placed directly in the stream and attached to a bridge, abutments, or specially designed steel towers.

The advantage of the autographic recorder is that it presents an analogue hydrograph of the stage where errors in the recordings may often be easily detected by visual inspection. Today, the graphic charts are converted to digital form by use of a digitizing table, saving the hydrometric engineers from much of the time-consuming chores of former days.

By attaching an external optical shaft-angle encoder to the drum-shaft of the autographic recorder (Fig. 16), the graphic presentation of the stage may be converted to electrical signals and recorded by use of modern micro-electronic recorders (Section 7.4.3) in which the data are stored on solid-state internally memory or on takeaway memory packs. If the data are required in real-time for operational use, they are transmitted to base by telemetry.

5.6 The Recorder House

The recorder instrument is housed in a weatherproof and securely-locked house on top of the stilling well (Fig. 17) . The house should be of such dimensions to permit the entry of the observer and give him protection from the weather when changing the chart and servicing the instrument. The recorder instrument is mounted on a rigid shelf or table firmly fixed to the foundations of the house.

A recorder house with inside dimensions 120 cm by 120 cm with ceiling height 210 cm above the floor is about the ideal size (Fig. 18 and 19). "Look-in" shelters may be used in special cases where short-time streamflow records are of interest and therefore provisional arrangements are satisfactory (Fig. 20 and 21). The house is usually

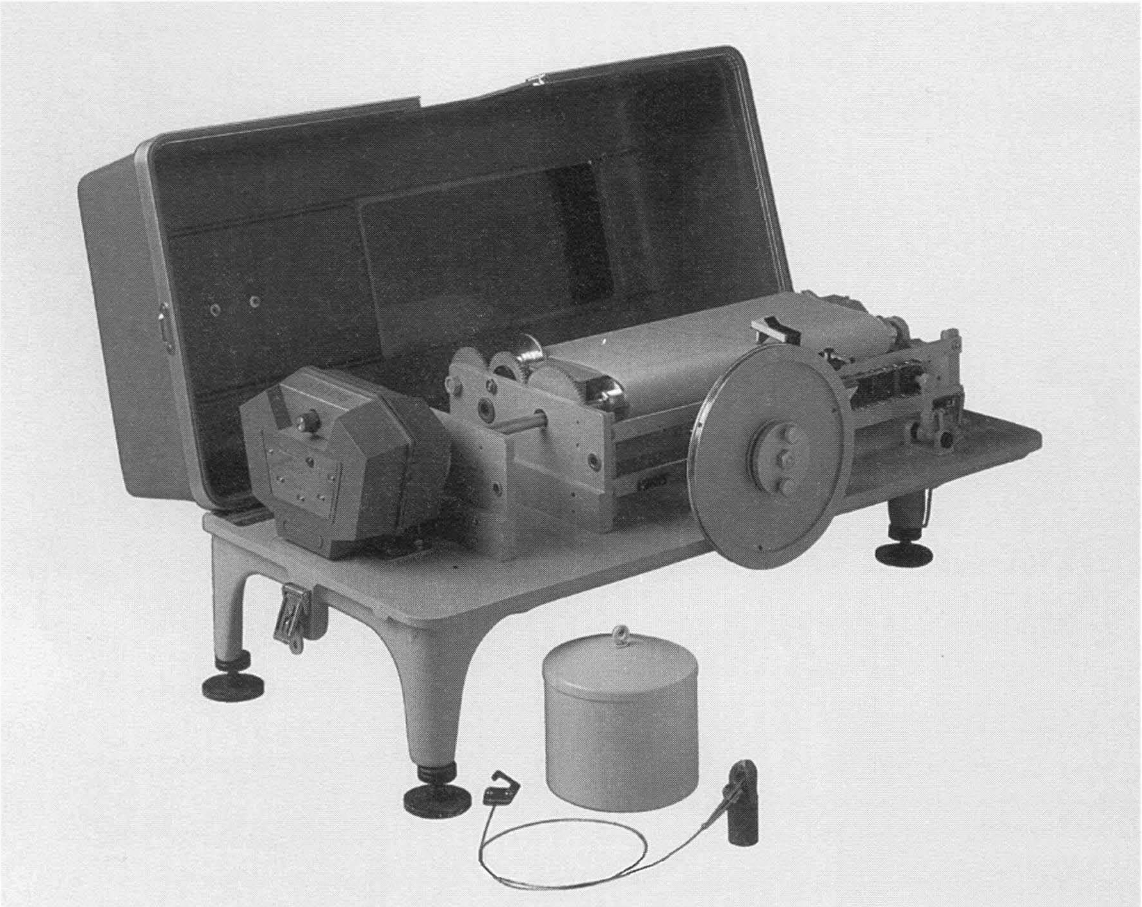
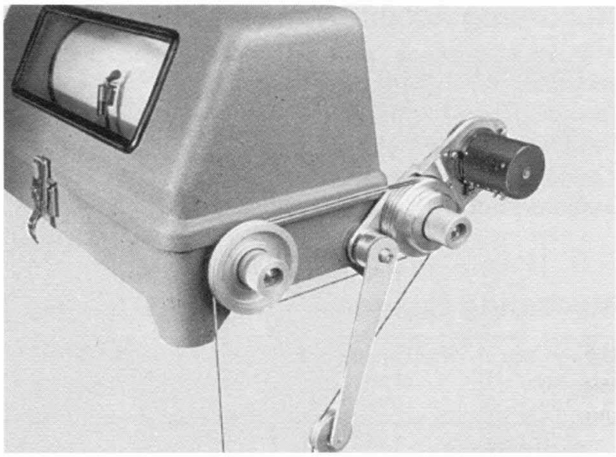


Figure 15. STEVENS TYPE A-71 Autographic water-level recorder with counter-weighted float and a Quartz Multispeed Timer (QMT) run on batteries. Options for data logging and telemetry (courtesy of Stevens).



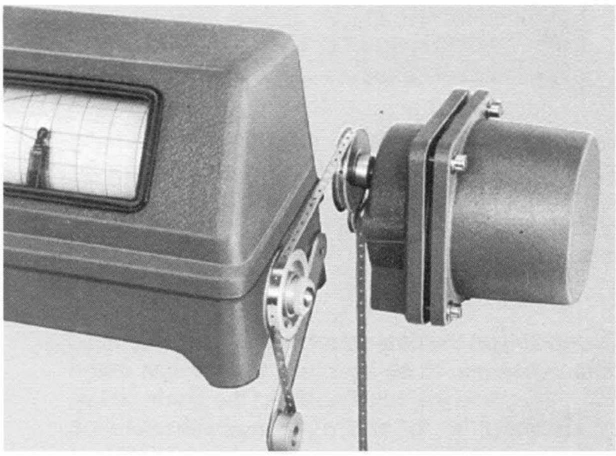


Figure 16. Remote Transmitters to be attached to the OTT Type X Autographic Water-Level Recorder for logging and teletransmission of water-level data. Left: Potentiometer for converting measured data into analog resistance values. Right: Shaft Encoder for converting measured data into digital binary coded output signals (courtesy of A. OTT).

made of wood, concrete, concrete block, corrugated metal pipe or prefabricated steel, and varies widely in shape and other details depending on local customs and conditions. In humid climates, shelters should be well ventilated and have a closefitting floor to prevent entry of water vapour from the well. Screening and other barriers are used over vent holes and other open places in the well or shelter to prevent the entry of insects, rodents and reptiles.

Different types of recorder house and stilling well are illustrated in Fig.18 to 24.

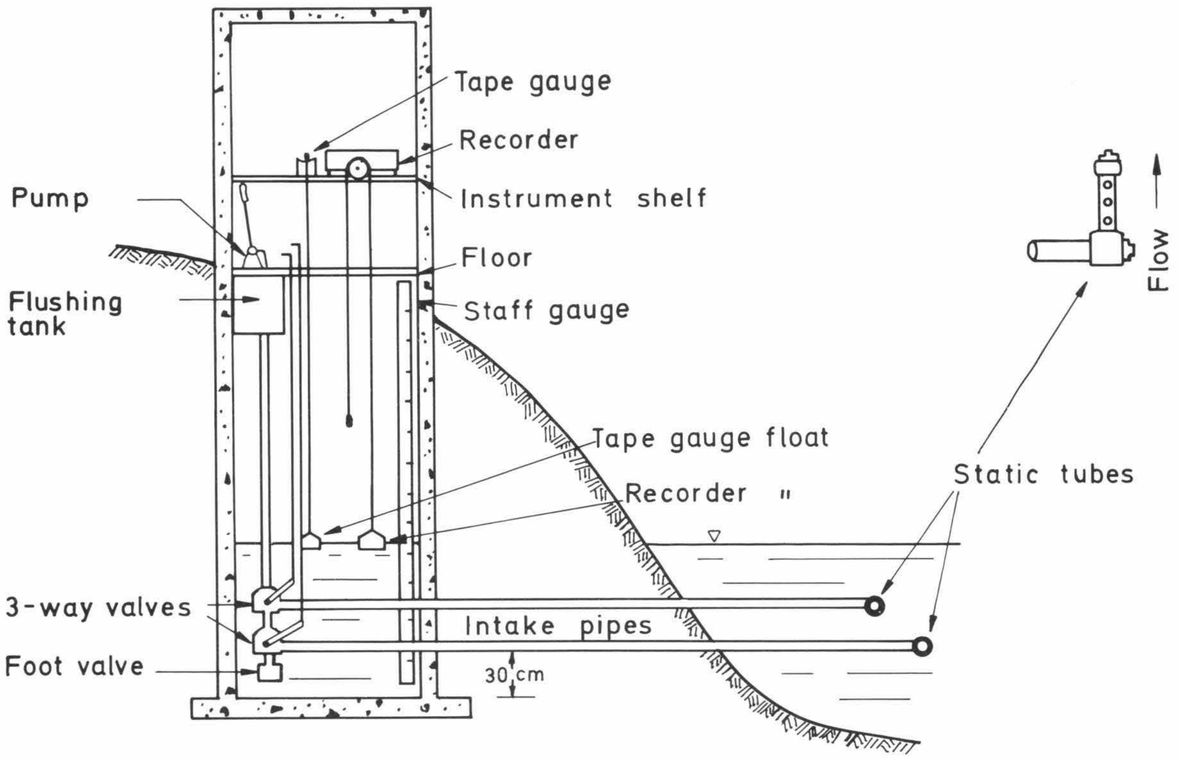


Figure 17. Standard design of autographic water-level recorder set in river bank. Section of house, stilling well and intakes (courtesy of US Geological Survey).

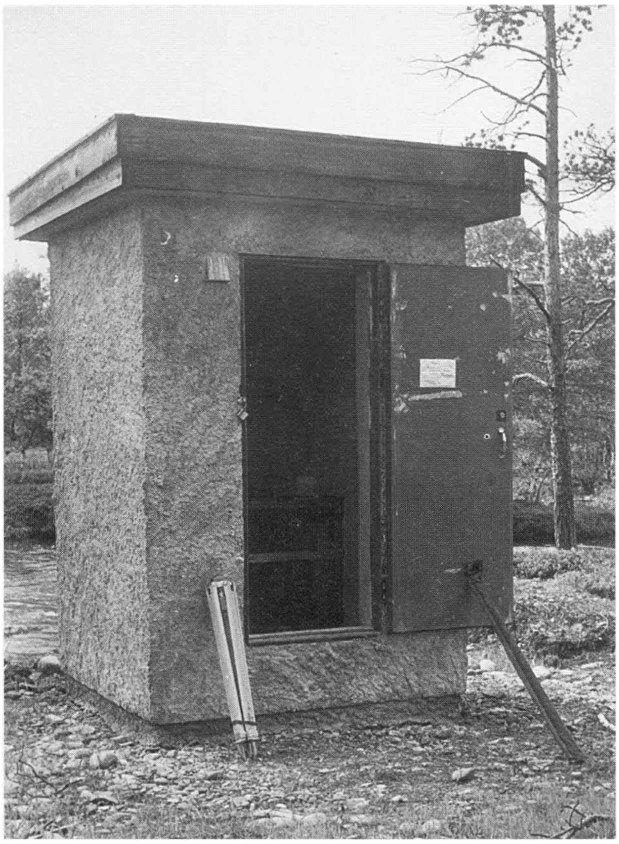


Figure 18. House for water-level recorder. Stilling well set in river bank, house made of plastered porous concrete blocks (Rinna River at Rinna Dam, Norway).

Figure 19. Hydrometric station. Stilling well made of heavy concrete tube, house made of plastered brick, bank-protection made of masonry, staircase leads down to the water for convenience in reading the scale. (Cimanuk River at Djatibarang, Java, Indonesia).

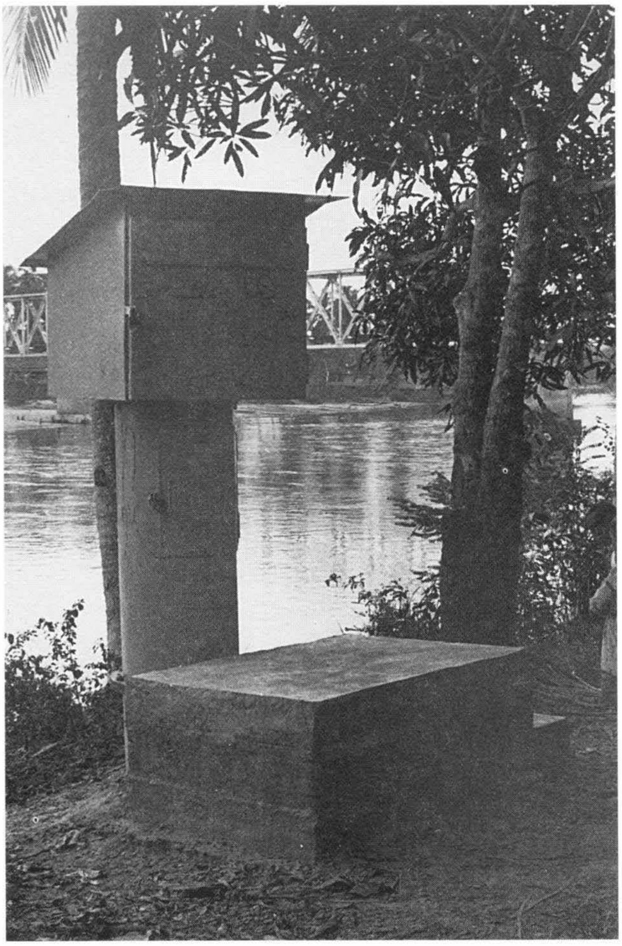


Figure 20. Recorder house. Stilling well made of steel tube and set in river bank, "look-in" type instrument shelter made of steel plates, door in wall of stilling well to facilitate cleaning out sediment deposits (Tributary to Musi River, Sumatra, Indonesia).

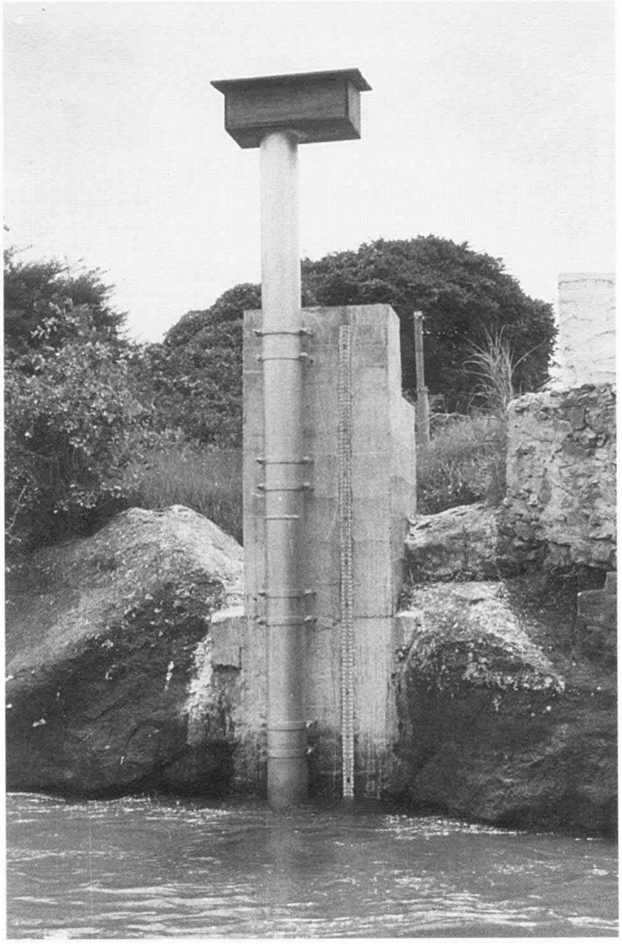


Figure 21. Hydrometric station. Stilling well made of steel tube and supported by concrete pier, wooden "look-in" type instrument shelter, crest-stage gauge a little to the right of concrete pier (Little Ruaha at Ihimbu, Tanzania).

5.7 The Stilling Well and Intakes

The functional requirements of the stilling well are:

a) To protect the float system against damage by floods and ice.
b) To provide within the well an accurate representation of the water level in the stream.
c) To reduce oscillations and fluctuations of the water surface caused by wind and turbulence.

Stilling wells are constructed of masonry, reinforced concrete, concrete pipe, steel pipe and galvanized corrugated metal pipe. Stilling wells are usually placed in the bank of the stream. Sometimes, however, they are placed in the stream and attached to bridge piers, abutments or specially designed supports. The stilling well should be deep enough for its bottom to be at least 50 cm below the minimum stage anticipated and high enough for its top to be above the level of the 50-year flood. The inside of the well should be large enough to permit the operation of all the equipment to be installed. In no case should the diameter of the well be less than twice the diameter of the float of the recording instrument.

Normally, the dimensions of the stilling well should be large enough to provide ample space for the hydrologist to enter it and clean it or to make repairs. A concrete tube 120 cm in diameter or a well with inside dimensions of 120 cm by 120 cm is a suitable size. The smallest inside dimensions permitting entry and some space for cleaning out deposited mud are about 70 cm by 100 cm.

Narrow steel tube wells may have doors to facilitate cleaning and repairing. (Fig. 20).

The stilling well should have a bottom and when placed in the bank of the stream it should be watertight so that ground water can not seep into it.

Water from the stream enters and leaves the stilling well through one or several intakes so that the water in the well is at the same elevation as the water in the stream. If the stilling well is placed in

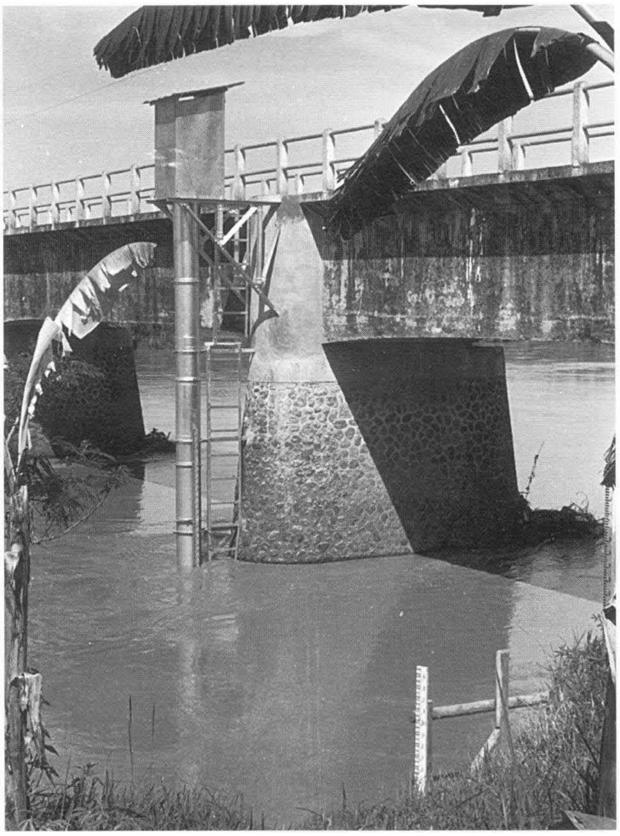


Figure 22. Hydrometric station. Stilling well made of steel tube and attached to downstream side of bridge pier, house made of sheet iron (Cimanuk River at Mandjot, Java, Indonesia).

Figure 23. Hydrometric station. Stilling well made of steel tube and supported by specially designed masonry pier, bank-protection by laid stones (Seraju River at Banjumas, Java, Indonesia).

Figure 24. Hydrometric station. Stilling well made of steel tube, house made of sheet iron, supported by specially designed steel tower made of angle-iron whose corner members are driven several metres into the riverbed (Comal River at Comal, Java, Indonesia).

the stream, the intake consists of holes made in the side wall or bottom of the well, and if the stilling well is placed in the bank, the intake consists of one or more pipes connecting the stilling well and the stream. The lowest intake hole or intake pipe should be at an elevation of at least 20 cm below the lowest expected stage at the site and at least 30 cm above at the bottom of the stilling well so that if silt builds up at the bottom of the well it will not plug the intake. In temperate climates the intake should be below the frost line. Stilling wells should be provided with ventilation vents in order to reduce or prevent excessive dampness inside the well.

The intakes for wells placed in the bank of the stream are usually made of galvanized steel pipes. The most common size used is 5 cm diameter pipe, but in some places up to 10 cm diameter pipe is used. After the size and location of the well have been decided, the size and number of intakes are determined. Two or more pipe intakes are generally installed at vertical intervals of about 30 cm. During high water, the lower intake pipes may be covered by sand at the stream end or clogged, but the higher ones will function freely.

The ratio of the area of the stilling well (A_w) to the area of the intake pipe (A_p) should not be too large on a flashy stream if the lag between the elevation of the water surface in the river and the well is to be held to a minimum. The following relationship may be used to determine the lag for an intake pipe for a given rate of change of stage [25]:

$$\Delta h = (0.01)/g \cdot L/D \cdot (A_w/A_p)^2 \cdot (dh/dt)^2 \qquad (5.1)$$

where

Δh = lag (m),
g = acceleration of gravity (9.81 m/s^2),
L = length of intake pipe (m),
D = diameter of intake pipe (m^2),
A_w = area of stilling well (m^2),
A_p = area of intake pipe (m^2),
dh/dt = rate of change of stage (m/s).

A good average value of A_w/A_p is 1000, but suspended silt in the stream water often sets a lower limit of 5 cm diameter on the size of the intake pipe.

Intake pipes are laid at 90° to the direction of flow and at a slight slope (1:100) to prevent air-pockets from forming inside the pipe and blocking the communication between river and well. A valve may be fitted at the well end of the intake pipe in order to control lag and surge in the well.

If the velocity past the end of the intake is high, drawdown of the water level in the stilling well will occur. In order to eliminate this drawdown, static tubes are placed on the stream end of the intake pipes. The static tube (Fig. 25) consists of a short length of pipe attached to a 90° elbow on the end of the intake pipe and extending downstream in the same horizontal plane as the intake. The end of the tube is capped and water enters and leaves through holes drilled in its sidewall.

A well gauge is normally installed inside the stilling well to provide a check if there is a free flow of water between the stream and the well. The datum of the inside gauge is the same as of the outside reference gauge. For convenience, a permanent reference point inside the recorder house is often provided for easy periodic check surveys. This reference point is referred to the datum of the station bench mark.

A reading of the gauge height on an outside gauge should be made each time the gauging station is visited. Intakes can become plugged, floats can leak and several other things can happen which can cause the recorded gauge height to differ from the stream gauge height. Normally, a comparison of the outside and inside gauge readings will reveal the problem and proper mainte-

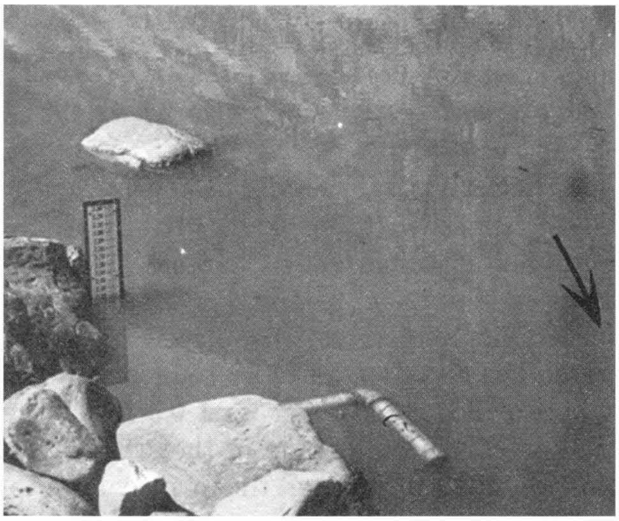


Figure 25. Static tube for pipe-intakes (courtesy of US Geological Survey).

nance can be carried out, corrections can be made and loss of records can be prevented.

Stations installed on streams carrying a significant amount of suspended sediment, must be provided with the means of cleaning the well and the intake pipes. The following means are in general use:

a) Flushing devices whereby water under considerable head 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 through the intakes by the operation of valves. Water may also be raised from the stream by use of a length of hose connected to the pump or carried in buckets if a pump is not installed. (Fig. 17).
b) Pumping water through the intake pipes.
c) Building up a head of water and stirring up deposited sediments in the well with a stationary hand-pump or a small enginedriven portable pump to force an obstruction out of the intakes.
d) An endless loop of a bronze-chain of diameter 8–10 mm is passed through the intake pipe and back up the river bank to the well. Pulling the chain through the pipe, can speed up the pipe cleaning process where there is a water level difference to induce a flow in the pipe.
e) Handcleaning of well and intake pipes by use of shovel and bucket, and flexible steel rods.
f) 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. (Appendix A).

Where the distance between stream and stilling well is not too large, 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. Flushfitting pipes are more likely to reduce well drawdown effects due to high velocities. Static tubes are not recommended owing to difficulty in desilting them.

To reduce and eliminate the silting problem of stilling wells, the vertically hung tube-well has proved practical (Fig. 26, 27, 28). This is a 40 cm diameter steel tube provided with a hopper bottom that will, in general, keep itself clear of silt. Fig. 26 shows a hopper bottom of a 40 cm diameter steel tube well with a 25–50 mm inlet hole at the point of the hopper. If such a well is placed in flowing water, the increased velocity under the point of the hopper prevents the inlet from being choked from the outside, and the steep slope of the bottom (45°) combined with small oscillations and fluctuations of the water surface will not permit the deposition of silt inside the well.

Sometimes not even the hopper bottom can keep the well clear of silt. In these cases, a selfseating cone with an inlet hole at the apex must be provided where the cone closes a larger hole in the hopper bottom. In order to remove the accumulated silt, the cone is pulled up by means of a chain (brass or bronze) and churned up and down until the silt has been worked through the large hole. When clear, the cone is reset in its place (Fig. 27). Instead of a cone, a light weight may be provided as illustrated in Fig. 28. With this arrangement, the chain is worked up and down through the intake hole and the accumulated silt cleared away.

The drawdown inside the stilling tube can be kept to a minimum by drilling a few small intake holes of diameter 8 mm in the sidewall of the tube at various levels and at an angle of 30°–45° with the direction of flow. In general, for a stilling tube mounted on a pier or wall, the angle should be 38°–40° as indicated in Fig. 26. However, the self-cleaning effect of the hopper bottom will be reduced when the sidewall of the well is punctured and it is no longer watertight.

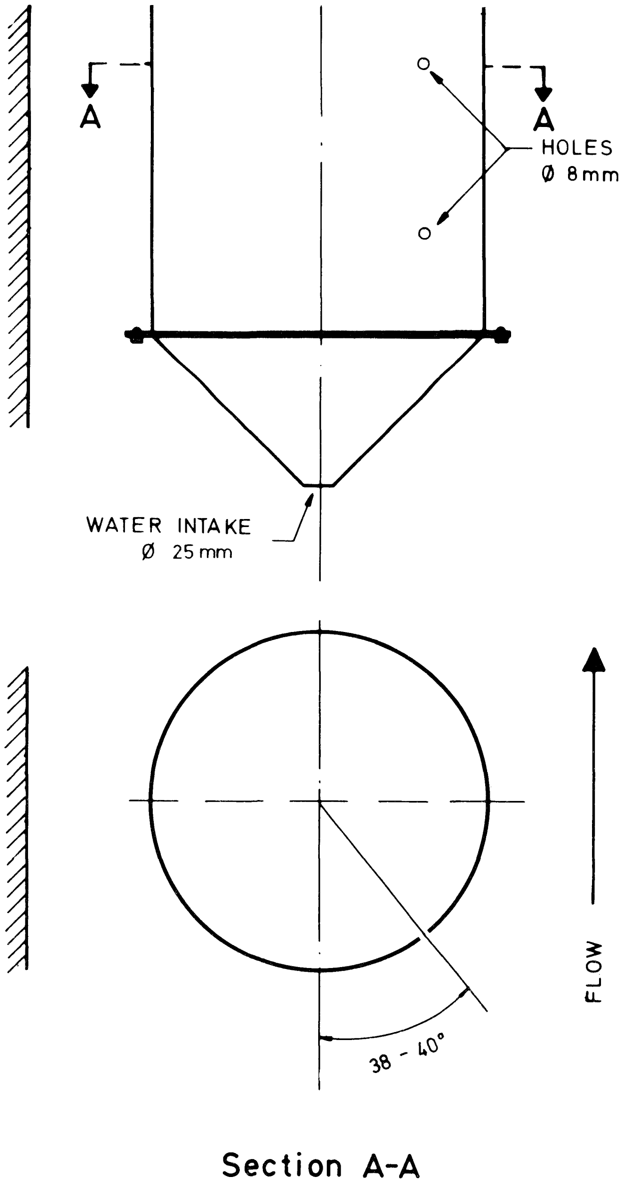


Figure 26. Hopper bottom for tube stilling well.

5.7.1 Draw-Down and Super-Elevation

Unless the stream end of the intake is protected from the dynamic effects of the water flowing past it, there may be a draw-down or a building up of the height of water in the well (super-elevation) as compared with the height of water in the river channel at the end of the pipe. These differences in height have been observed to reach as much as 30 cm, and they vary not only for different stages but they may also vary for the same stage of the river. Stilling wells attached to bridge piers or abutments are generally provided with small openings whereby the water is admitted directly into the wells without the use of intake pipes. Under these circumstances the dynamic effects of the

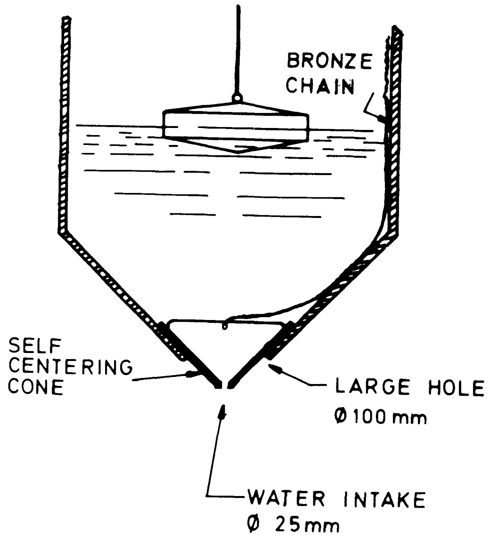


Figure 27. Section of hopper bottom for tube stilling well with cone and chain for cleaning out sediment deposits.

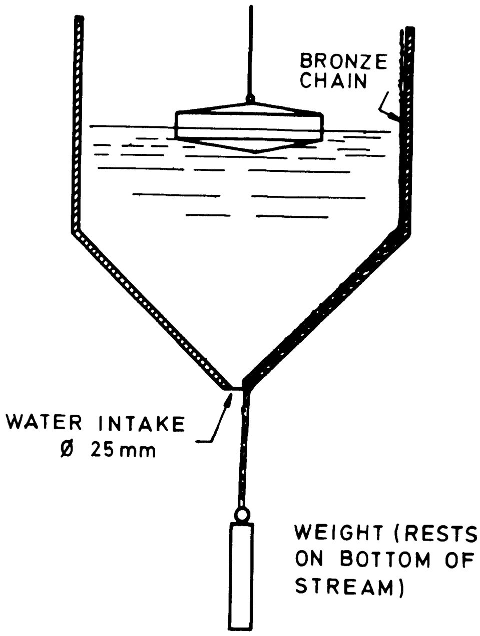


Figure 28. Section of hopper bottom for tube stilling well with weight and chain for cleaning out sediment deposits.

water may be even more pronounced than those experienced where the connection is made through pipes.

5.7.2 Static Tubes

The static tube appears to be the most satisfactory device for eliminating draw-down at pipe-intakes to stilling wells.

The static-tube may be made in various designs and in a size corresponding to the size of the intake pipe with which it is to be used. A typical design of the static tube showing dimensions and arrangements of openings is illustrated in Appendix B. The total area of the holes should be about 20–25 % greater than the cross-section area of the pipe so that deposits of mud and silt may be effectively removed by flushing the intake. A suitable arrangement of openings to provide the required area for the 50 mm and 75 mm intake pipes may be obtained by using five rings of holes with four holes in each ring, the rings being 25 mm apart and the holes staggered in alternate rings. For the 100 mm pipe, six rings with six holes in each are suggested (Appendix B).

Generally, the minimum length of the static tube should be about four times the diameter of the intake pipe. The static tube may be connected to the intake pipe by means of a 90° elbow or by a standard tee. The other end of the tube may be threaded for a standard pipe-coupling and closed by means of a standard plug. If preferred, a cap may be used instead of the coupling and plug.

Although the hydraulic performance of the static tube as described is the same either it points upstream or downstream, the latter is preferred because it is then less likely to collect submerged drift and debris.

5.8 Selection of Stage Gauge Equipment

Often, the funds available for the establishment of new gauging stations limit the choice of the equipment to the nonrecording type of gauge. Nonrecording gauges are cheap to install and supply reliable data if the observer is dependable and the river stage does not change rapidly. Nonrecording gauges on flashy streams often provide inaccurate records because two or three observations per day are not enough to properly define flood hydrographs.

The main advantage of nonrecording gauges is that frequent visits by well trained observers ensure that any unusual conditions regarding the station will be noticed at once and steps to remedy disturbances or damages can be taken without delay.

The choice of a particular type of nonrecording gauge depends on the local conditions. A vertically mounted staff gauge is the most practical and most commonly used. At some sites, an inclined staff gauge or a wire-weight gauge may be better. In any case, the gauge must be placed so that the observer can make accurate readings and the readings must be the true and representative water level at the site.

Nonrecording gauges are always used as auxiliary gauges where water-level recorders are installed in order to serve the following purposes:

a) They serve as a reference gauge to indicate the water surface elevation in the river.
b) They serve as a reference gauge to indicate the water surface elevation in the stilling well. Gauge readings on the stream are compared with reference readings in the well to determine whether stream stage are being obtained in the well.
c) When the intakes are silted up or there is equipment failure, the outside reference gauge can be observed daily or more often by a local observer in order to continue the record of stage during the malfunction.

Selection of either the drum-type or the continuous strip-chart water-level recorder depends on the time scale expansion needed at the particular site and how often the recorder can be visited by a well trained observer. If change in stage occurs slowly with time, a drum-type recorder that will operate for 30 days may be adequate, while a day-operating recorder may be needed for the recording of periodical fluctuations with short periods, such as seiches. Generally, at stations where a local observer is available, weekly drum-type recorders are practicable. Continuous strip-chart recorders are required at sites where local observers are not available. Most of the drum-type recorders are more simple and easier to operate and maintain than the continuous strip-chart recorder. The latter should be serviced and maintained by well trained inspectors only. Refer Chapter 7.

5.9 Cableways

Cableways are normally used when making discharge measurements by current meter and the depth of flow is too deep for wading, when wading in a swift current is considered dangerous, or when the measuring section is too wide to string a tag line or tape across it.

There are two basic types of cableways:

a) Those with an instrument carriage controlled from the bank by means of a winch, either manually or electrically operated (Fig. 29, 30 and 31).

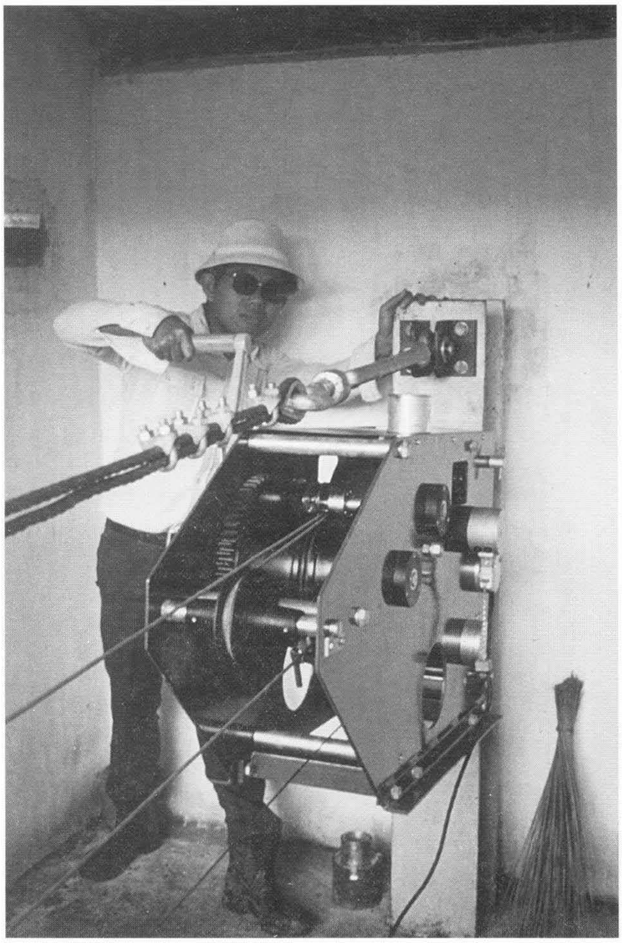


Figure 29. Cableway with double-drum winch. (Solo River at Wonogiri, Java, Indonesia).

b) Those with a manned personnel carriage, commonly known as a cable car, in which the operator travels across the stream to make the necessary observations (Fig. 32). For guidance in the design of manned cableways for current-meter measurements the reader is referred to references [19] and [50].

5.9.1 Cableway with Instrument Carriage

A cableway system with instrument carriage consists normally of the following components:

a) Supporting towers,
b) Main (track) cable,
c) Anchorages,
d) Staylines (backstay and sidestay),
e) Towing cable,
f) Instrument suspension cable,
g) Instrument carriage (Trolley),

Figure 30. Cableway with suspended current-meter assembly from track cable (Solo River at Wonogiri, Java, Indonesia).

h) Either a double-drum winch (Appendix C), a single-drum winch (Appendix D), or two separate winches (Appendix E) in order to operate the current meter.

5.9.1.1 The Supporting Towers

The supporting towers are constructed one on each bank of the channel. The towers support the main cable at a sufficient height as the suspended equipment travels on the cable between the towers. The tower on the operating bank has pulleys for guiding the suspension cable and the towing cable, and may also have means for securing the winch. The main cable should pass freely over a saddle on top of the tower at the operating bank with negligible bending movement on the tower. The tower on the opposite bank has a saddle on its top for the main cable and a pulley for the towing cable. The saddle of the two towers should be at the same level. Instead of a tower, the support on the opposite bank may often consist of a sidehill anchorage where the bank is steep.

Safe and convenient access should be available throughout the year so that the hydrologist can inspect the installations on both banks.

Towers are designed to take all loads which are to be supported in addition to their own weight, wind load included. The pressure on towers due to wind load may vary from 1000 to 2000 kg/m^2 for towers not exceeding 30 m in height.

The foundations of the towers normally extend from below the frost line to at least 1 m above the general flood level.

The height of the towers should allow the bottom of the equipment, suspended from the centre of the main cable span, to be not less than 1 metre above the highest flood level.The cableway must not interfere with navigation on the channel. Aircraft warning signs may be provided according to local regulations.

Various types of constructions are used as supporting towers. For long spans, high towers are used. Steel and timber A-frames are often used as supports when the span is not too large and the height of the support is less than 12 m. An H-beam used as a steel-post support has been found very satisfactory. This type of support has been used for spans up to 200 m and for heights up to 8 m.

If trees are used, either for support or anchorage, wooden blocks should be placed between the cable and the bark of the tree to protect the tree from injury that might cause failure of the support or anchorage. The use of trees as cableway supports should be avoided, except as a temporary expedient until more permanent structures can be built.

5.9.1.2 The Main (Track) Cable

The main or track cable runs over the saddles on top of the supporting towers and its two ends are fixed to the anchorages. The instrument carriage travels on this cable.

For comparatively short spans, wire rope may be used. For large spans, particularly where a manned carriage is to be supported, special high-strength cables such as "tramway track" are necessary.

The horizontal component of the tension in a cable suspended between supports of equal heights is given by the formula, refer [50]:

$$H = (wS^2 / 8D) + (PS / 4D) \qquad (5.2)$$

where

H = horizontal component of the tension in the cable (kg),
w = load per running metre of cable (kg/m),
S = horizontal span (m),
D = loaded sag at mid-span (m),
P = concentrated moving load (kg).

The actual tension in the cable is given by the formula, refer [50]:

$$T = H\,(1 + 16D^2 / S^2)^{1/2} \qquad (5.3)$$

The loaded sag at mid-span of the cable shall not exceed 2 % of the span.

Design loads to be used for an unmanned cableway with 15 mm track cable, as for example the OTT SK3 cableway [20]:

a) Track cable suitable for cableway with instrument trolley: galvanized wire rope (6 x 19 + 1 FC, Filler), diameter 15 mm. Breaking load: 12,000 kg.
b) Suspension cable with insulated two-conductor core: diameter 2.5 mm, breaking load 450 kg, diameter 3.8 mm, breaking load 580 kg.
c) Load per running metre of cable (weight of cable + wind) for 15 mm cable: 1.0 kg/m.
d) Concentrated moving load (weight of current-meter assembly + carriage + pressure head) with:
   25 kg suspended equipment: P = 65 kg,
   50 kg suspended equipment: P = 100 kg,
   100 kg suspended equipment: P = 170 kg.

The mid-span loaded sag of the above 15 mm track cable suspended between supports of equal height is given by the following equation [20]:

$$D = S \cdot (0{,}5 \cdot S \cdot w + P) / 4T_{in} \qquad (5.4)$$

where

D = loaded sag at mid-span (m),
S = horizontal span (m),
w = load per running metre of cable (kg/m),
P = concentrated moving load (kg),
T_{in} = intended tension in track cable (kg).

It is recommended that a stop is placed near the far end of the track cable at a known distance to allow for verification of the horizontal measurement given by the distance indicator of the winch.

5.9.1.3 The Anchorages

The anchorages are fixtures to which the track cable and staylines are attached. The anchorages are to take up the maximum load for which the cableway is designed and it is set in direct line with the track cable and is so placed that it can be easily inspected. Load to anchor is taken as twice the working load.

Anchorages are usually constructed of mass concrete whereby the weight of the concrete and the soil resistance to movement are the principal factors in the security of the anchorage. In places where the river banks contain solid rock, anchorbolts or rods properly set in the rock are used.

When a rigid connection is made to an anchorage by means of an anchorbolt, the anchorbolt is set in a direct line with the connecting stayline so that there will be no bending moment in the anchorbolt.

5.9.1.4 The Staylines

Staylines (back-stay and side-stay) are cables attached to the top of each supporting tower and to the anchorages to counteract the load of the track cable and to ensure stability for the supporting towers. The staylines should be of corrosionresistant steel and of sufficient strength to maintain the tower in a vertical position under all loading conditions. It is necessary to provide means for adjusting the tension in the staylines (turnbuckles).

5.9.1.5 The Towing Cable

With a double-drum winch the towing cable is usually laid one turn around the towing drum and has both ends fixed to the instrument carriage making it an endless circuit, refer Fig. 29 and Appendix C.

With the portable single-drum winch the towing cable also passes over a sheave on the operating side of the river. This sheave is connected to a crank-chain drive on the winch, refer Appendix D. The towing cable must have means of adjusting the tension in the cable, usually a turnbuckle is employed. The towing cable should be corrosion-resistant and as light and flexible as possible.

5.9.1.6 The Suspension Cable

The suspension cable is wound on the second drum on the double-drum winch or on a single-

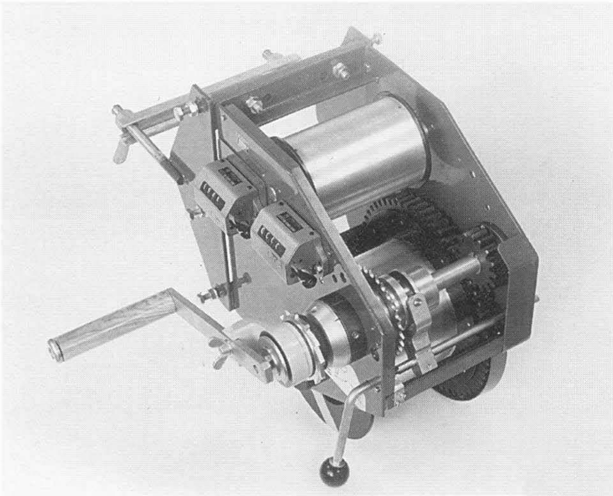


Figure 31. Portable single-drum winch (courtesy A. OTT).

drum winch. It then passes over the sheave on top of the tower at the operating bank and over the pulley on the instrument carriage. The measuring instrument is attached to the end of the suspension cable. The suspension cable has an insulated double inner core which serves as an electrical conductor for the current meter.

The tension in the suspension cable is given by the weight of the current-meter assembly plus the drag force of the current when the assembly is submerged to where the water velocity is at its maximum.

The suspension cable is made of corrosionresistant material and reverse laid to prevent spinning and rotation The cable is of sufficient strength to suspend the current meter and sounding weight. A breaking strength of five times the maximum weight of the current-meter assembly is a sufficient and suitable safety margin to allow for the loading effect of drag and live load during the performance of a measurement. Its elongation when loaded should not exceed 0.5 %. The cable should have the minimum diameter consistent with the strength requirement so as to offer minimum resistance to the force of the flow. The cable must be smooth and flexible so that it can take turns without any permanent bends and twists. The cable is equipped with a suitable connector for attachment of the measuring equipment.

5.9.1.7 The Instrument Carriage (Trolley)

Two track pulleys are usually fixed at the top and one suspension pulley at the bottom of the instrument carriage. The carriage runs on the track cable when pulled from either side. For spans larger than about 100 m, a guide pulley is normally provided to prevent too large a sag in the suspension cable, refer Appendix C.

5.9.1.8 The Gauging Winches

In the double-drum winch (Fig. 29) the suspension cable is wound on one of the drums and the endless towing cable is passed around the other drum. Horizontal and vertical travel of the measuring equipment attached to the suspension cable are controlled by a lever which couples either, the suspension cable only, or both drums simultaneously. Each drum has a counter to indicate the released length of cable, one for measuring the horizontal distance travelled by the carriage and the other to indicate to which depth the suspended instrument has been lowered. Refer Appendix C.

A portable single-drum winch is often used (Fig. 31). In the single-drum winch, the suspension cable is wound on the drum. The travel of the trolley is managed by a lever coupling the crank by a chain-drive to the endless circuit controlling the movement of the trolley. Refer Appendix D.

Two separate winches may be used, one for the horizontal and the other for the vertical movements. Refer Appendix E.

5.9.1.9 Safety Factors

As a rule, the components of the instrument-carriage cableway system are designed to provide a minimum safety factor of 2 at maximum load. The maximum load to be considered shall be the breaking load of the suspension cable. Thus, the suspension cable shall break before the track cable, towers and anchorages if the current-meter assembly is caught on floating drift.

5.9.2 Manned Cableways

The manned cableway system, refer Appendix F, consists of:

a) Supporting towers,
b) Track cable,
c) Anchorages,
d) Staylines,
e) Personnel carriage (cable car).

Item (a), (b), (c) and (d) are similar to those described for cableways with instrument carriage.

5.9.2.1 The Personnel Carriage

The carriage, also called cable car, from which the hydrologist makes the gauging observations (Fig. 32) travels on the track cable by means of two track pulleys. The cable car is often driven manually by a cable-car puller (Appendix H). The cable car may be designed for operation from a sitting position or a standing position. One-man or two-man cable cars are used (Appendix G). The cable car must be of adequate design and strength to ensure the hydrologist's safety and provide reasonable comfort during the measurement. The cable car is provided with a brake to secure it in all required positions. It has means of support for the gauging reel and is equipped with a protractor for measuring the angle of the downstream drift of the measuring equipment.

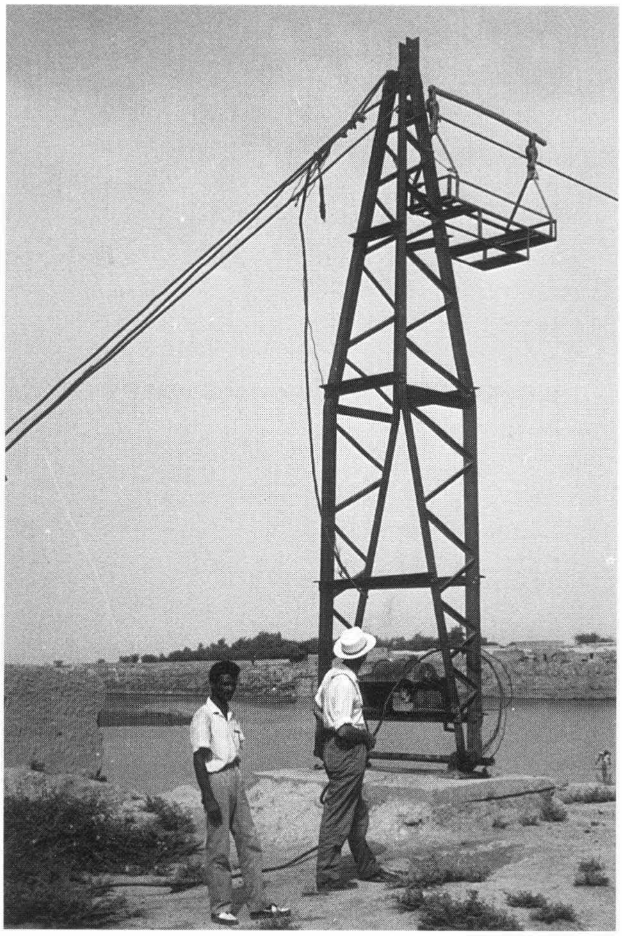


Figure 32. Side-tower and cable car for manned cable-way (Karun River near Ahwas, Iran).

5.9.2.2 Design and Safety Considerations for Manned Cableways

Important considerations in the design of cableways are the clear span between the supports, the weight of the track cable and the concentrated load, the loaded and unloaded sag, the effect of changes in temperature and the heights of the supports required for the necessary clearance above extreme high water. An authoritative design guide for cableways used in stream gauging by the US Geological Survey is given in reference [19], also see [50].

The design of the track cable consists of the determination of the necessary length, the correlation of sag and allowable stress for any loading that may occur when the cableway is in use including an allowance for the effect of changes in temperature, and the selection of the size and kind of wire rope and track cable that will meet the requirements most satisfactorily.The loads to be considered in the design are:

a) The deadload weight per running metre of cable, which is the limiting load for long spans.
b) The concentrated load carried by the cable car.
c) Loads caused by wind and ice.

The concentrated load that is carried by the cable car consists of the weight of the car, the equipment and the hydrologist, the sum of which is generally taken as 230 kg. Also, the additional pull that may be exerted by the suspension cable in case the suspended equipment should become fouled in drifts, etc., must be considered. The suspension cable must break before the track cable, towers or anchorages.

The breaking strength of the suspension cables in general use with the gauging reels may vary from 150 to commonly 450 kg. Thus, a concentrated load of 680 kg applied at the point of maximum sag is commonly used in the design of the track cable, except in those instances where it is known beforehand that a heavier suspension cable will be used or additional heavy equipment will be carried on the cable car.

Also, wind load is considered in the design of towers, and the staylines. The possible effect of ice covering should be investigated if the structure is located in a region subject to freezing temperatures. A wind pressure of 40 kg per square metre on projected area of cables and 100–200 kg per square metre of the tower is commonly used, for towers less than 30 m in height.

Two different types of cable are used for the track cable: wire rope or tramway track cable. Generally, the smallest diameter used for the track cable is 20 mm regardless of type.

The wire rope that is used for track cable in cableways consists of several individual strands, usually six, each of which is composed of a number of wires. The number ot wires in a strand is generally 7, 19 or 37. A strand of 7 wires may be used in cableways for stream gauging, but a 19-wire strand is often preferred because of its greater flexibility and somewhat greater strength. However, the smaller size of the wires in a 19-wire strand compared with a 7-wire strand makes the 19-wire strand more vulnerable to abrasion and corrosion. Normally, wire ropes with hemp core are used.

A wire rope has the advantage of flexibility and is adapted to the use of thimble-and-clip connections to the turnbuckles and anchorages. For these reasons and because of its general availability and ease of employment, hempcore wire rope is generally used in cableways of short and medium span. The thimble-and-clip connections are the greatest sources of weakness in this type of construction.

Tramway track cable, because of its greater smoothness of operation, greater strength and reliability, higher modulus of elasticity and less sag, is generally preferred for longer spans. However, the stiffness and lack of flexibility of tramway track cable, compared with wire rope, necessitates the use of socket connections. The ends of the tramway track cable are untwisted and set in the socket by use of molten zinc (lead must never be used!).

In the design of cableway structures, different safety factors are generally used for the component parts. The parts of the structure for which individual designs are necessary are (a) the track cable, (b) the supports, (c) the anchorages, (d) the footings for the supports, (e) the anchorage connections, and (f) the staylines.

With proper design and construction, the uncertainties affecting concrete anchorages and footings can be so reduced that a relatively small factor of safety is adequate. It is therefore customary to design anchorages and footings for twice the working loads that may be anticipated. For very favourable conditions where allowable bearing pressures and frictional resistances of the soil are known, the ratio of the design load to the working load may be taken as 1.5, otherwise 2.0.

A-frames and towers that are constructed of galvanized lightweight structural members are designed for twice the expected working loads, the allowable tensile stress used in the design does not exceed 1100 kg/cm^2. The l/r ratio for columns and struts should not exceed 120 for main compression members and 200 for bracing and other secondary members.

According to the practice of the US Geological Survey, the following maximum allowable tensions are recommended for the track cable: one fifth the breaking strength of galvanized improved plowsteel wire rope and one fourth the breaking strength of galvanized tramway track cable.

Anchorage connections include the sockets, eyebars, turnbuckles, rods and pins that transmit the tension from the track cable to the fixed anchorage. Experience has shown that these connections are the places of greatest weakness in the structure. Therefore it is recommended that sockets, eyebars and bolts, turnbuckles and anchorage rods are designed for a working load at least 20 % greater than the allowable working load of the main cable to which the connection is made. No welding is permitted on any parts of eyebars, turnbuckles or anchorage rods. The specifications should require that each individual part that goes into the finished product, such as an eyebar or a turnbuckle, be forged in one piece. The required minimum breaking strength of the finished eyebar or anchorage rod is specified by the purchaser.

The connections between the wire rope and the turnbuckles and between the turnbuckles and the anchorages are generally made by means of thimbles and clips. The number of clips for each wire rope end should be at least five for the 20 mm diameter rope with a minimum spacing of 120 mm between the clips, and six clips for the 25 mm diameter rope with a minimum spacing of 160 mm. It is important that the "live" or long rope rests upon the broad bearing surface of the base of the clip with the U-bolt bearing against the "dead" or short end of the rope. [19]

5.9.3 Maintenance of Cableways

All steel cables must be regularly inspected and lubricated by grease. All other connections and structural components made of steel are protected against corrosion by painting. Anchorages should be regularly inspected and repaired when necessary. The tension in the track cable is controlled by the size of the unloaded sag. Thus, the unloaded sag is checked routinely and adjusted as necessary by means of the turnbuckles. Particularly, when great changes in temperature occur, the tension in the track cable must be checked and adjustments made.

5.9.3.1 Unreeling and Uncoiling Steel Cable

When unreeling and uncoiling wire rope, it is essential that the reel or coil rotates as the wire rope unwinds. Attempts to unwind wire rope from a reel or coil which is held stationary will result in kinking the rope and ruining it beyond repair.

5.10 Artificial Station Controls

At gauging stations where the natural controlling features do not provide the stability and sensitivity required of the station control, artificial controls can be used. Artificial controls are structures built in the stream channel to stabilize and constrict the channel at a section. (Fig. 33 and 34)

However, a change in the hydraulic conditions which results from such a constriction must be expected to produce a change in the streambed. The artificial control will increase the depth of water upstream of the structure and thereby reducing the velocity of approach causing the sensitivity to improve. If the stream does not carry any appreciable amount of sediment, the streambed may become stabilized under the new conditions and the artificial control will function satisfactorily. On the other hand, if the stream carries a heavy load of sediment, there may be continually deposition and erosion in the channel reach upstream from the artificial control, so that for the same stage the slope of the water surface and the velocity of approach may vary from time to time resulting in a shifting stage-discharge relation. For streams carrying bedload, the pool created above the structure will rather quickly fill up permanently with gravel, and the velocity of approach will be little affected, thus the structure will serve to raise the water level upstream the structure only.

It is important to realize that practical experience is essential before the design of artificial controls should be attempted. As a general rule, particular attention should be paid to the following points:

a) Sructural stability.
b) Discharge capacity of the structure at all stages.
c) Prevention of seepage under and around the structure.
d) Avoidance of turbulence.
e) Sensitivity of the stage-discharge relation.
f) Likelihood of keeping the crest clear of debris and bed material.

The purpose of the artificial control and the reasons for its use at a particular location must be kept in mind when deciding whether or not to build one. For streams with an unstable and shifting bed, the control should be designed primarily to stabilize the streambed in its existing shape as far as possible, and for this purpose the structure would raise the surface of the water the minimum practicable height above its previous elevation. On another stream, it may be desirable to raise the water level by means of a structure to eliminate the effects of other variable features downstream. For larger streams, it is generally desirable not to introduce any radical change in the hydraulic conditions. In small streams such a change may be, in most cases, less important.

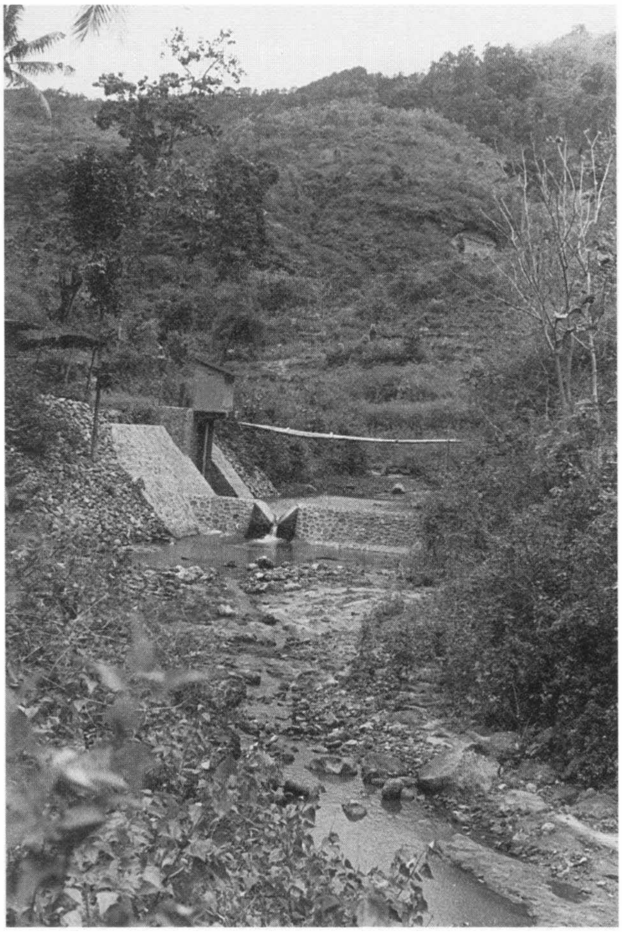


Figure 33. Hydrometric station with artificial control on small stream, steep gradient, calibrated in situ (Tributary to upper Solo River, Java, Indonesia).

Artificial controls built in natural streams are usually broad-crested weirs that conform to the general shape and height of the streambed. The broad-crested weir can be rectangular, trapezoidal or triangular in cross section. The profile in the flow direction can be either a rectangle, with or without rounded edges, or a triangle. The broad-crested weir is simple in configuration and easy to build. It has a structural stability which sharp-crested weirs lack and permits a higher downstream water level without submergence effects than do the thin-plate weirs. On the other hand, it

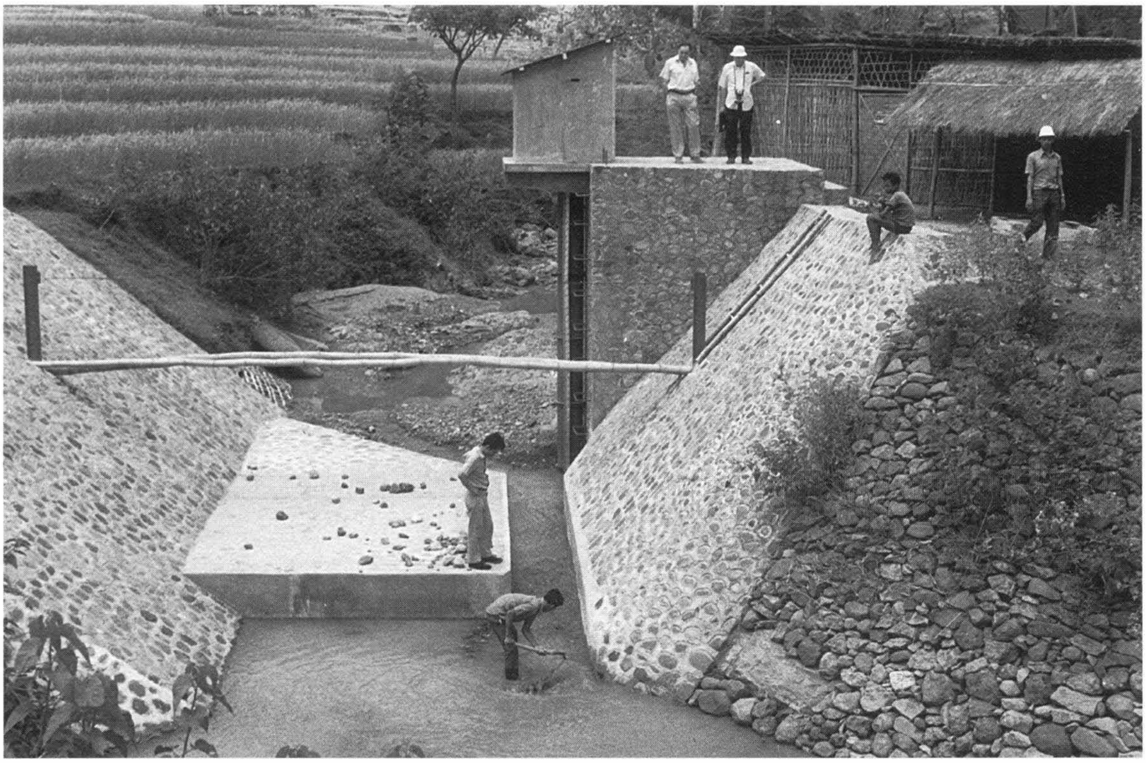


Figure 34. Hydrometric station with artificial control, steep gradient, calibrated in situ (Tributary to upper Solo River, Java, Indonesia).

also possesses the main disadvantage of the sharp-crested weirs, namely, trapping of debris and sediments, and sensitivity of the calibration to wear and abrasion of edge and crest. [6].

A special type of the broad-crested weir which has become popular in recent years is the triangular-profile weir. This weir is constructed with a horizontal crest, known as the Crump weir [30] or with the crest sloping gently from the sides down towards the mid-point, known as the Flat V-weir [51]. The triangular-profile weir can accommodate a wide variation in flow and is little affected by debris and sediment-laden water. The ability of this weir also to operate in the drowned flow range allows the crest to be constructed comparatively low, thereby reducing the cost of the structure and the danger of upstream flooding. The triangular-profile flat V-weir has a better sensitivity than the Crump weir and is also less affected by ice.

Artificial controls installed in canals and ditches are sharp-crested weirs and critical-depth meters, known as flumes. Where there is sufficient available fall in a canal and the quantity of water to be measured is not too large, the sharp-crested weir is the most serviceable and economical type of control. V-notch weirs are used for small discharges and the rectangular and trapezoidal weirs are used for larger discharges.

Where there is little available fall, high transport of sediments, much floating debris, or the discharge is too large for a weir, critical-depth meters known as flumes are used. One type of critical-depth meter is the Parshall flume [61] or some variation of this flume. Debris and silt tend to be swept through critical-depth meters by the increased velocity which results from the constriction.

Bibliography

Chapter 5: [2], [3], [4], [6], [15], [16], [19], [29], [30], [44], [45], [46], [49], [50], [51], [55], [57], [61], [62].

CHAPTER 6

DEFINITIVE SURVEY AND DESCRIPTION OF GAUGING STATION

6.1 General

After the gauging station has been constructed, a final detailed survey is made of all the station features, including all structural installations. Of particular importance is the elevation of the station bench mark, the zero of the reference gauge, the invert of intakes for stilling wells and the point of zero flow.

6.2 Plan of Station

The plan should give the location and details of the station features as follows:

a) The instrument shelter or house.
b) Staff gauges and other nonrecording gauges.
c) Intake pipes and static tubes.
d) Station bench mark and any auxiliary bench mark or datum marks within the instrument house for checking and setting the recorder.
e) The control.
f) The depth and length of the forebay above the control.
g) The position of the cableway.
h) The channel conditions below the main features of the control.
i) For artificial controls, a separate plan to scale of the structure is required.

6.3 Longitudinal Profile and Cross Sections

The following sections drawn to scale are required:

a) A longitudinal section of the stream reach at the station showing the bed profile, including the lowest point on the control (point of zero flow), the staff gauge, intakes for stilling well, and the current-meter measuring section.
b) Cross sections extended up each bank in case of a section control, including one section through the point of zero flow.
c) A cross section through the staff gauge extended up each bank.
d) The current-meter measurement site should be defined by at least five cross sections. In addition to the measuring cross section, two cross sections below and two above the measuring section should be surveyed, covering a distance equal to one bank-full width of the channel in each direction. The bed in the measuring reach between the five surveyed cross sections should be carefully examined for the presence of rocks and boulders. All cross sections should be taken normally to the general direction of flow and should be extended to an elevation well above the highest expected flood stage. The spacing, levels and soundings must be close enough to reveal any abrupt changes in the contour of the channel.
e) A cross section of the forebay approximately 3 m above an artificial control. In the calibration of weirs, it is desirable to know the flow approach condition, as any cross section variation produces changes in the velocity of approach and, therefore, the characteristics of the weir. This cross section should be checked every year.
f) Copy of all initial survey information for the station should be kept in the recorder house for easy and quick reference.

6.4 Description of Gauging Station

When the survey of the gauging station has been completed, a Station Description is prepared.

The following information is included in the station description:

a) Name of the stream and name of the nearest town or special geographical feature located nearby.
b) The station number allocated according to the numbering system used for the region.
c) The date when the construction of the station

was accomplished and the date on which observations were started.

d) The geographical location of the station in coordinates of longitude and latitude. The elevation of the station if available. A barometric observation of the elevation is satisfactory, otherwise a contoured map of scale 1:50 000 may be used if available.
e) The catchment area draining to the station in km^2. The boundary should be drawn on the best map available and measured by a planimeter. This work is done at the Regional Office.
f) A short description of the geographical characteristics of the catchment, such as mountains, hills, swamps, vegetation, slope and shape of catchment.
g) The total range in stage covered by the staff gauge.
h) Short statements covering on which bank (LB or RB) the station is located, the distance from the staff gauges to any conspicuous feature near the site, such as a bridge, houses, rocks, a large tree, etc.
i) A short description of the riverbed forming the control, such as whether the riverbed and banks consist completely or partly of rocks, boulders, gravel or sand. If it is narrow or wide, if there are traces of erosion, if the banks are covered with vegetation such as trees, scrub, etc., and if there is vegetation in the riverbed itself. Give a statement as to the stability of the control, if it is permanent for all stages or only partly so, or if it is a shifting control.
j) The type, make and serial number of the recording instrument are noted. Give the height ratio or reduction scale of the chart as 1:5, 1:10 or 1:20. State the recording interval in number of days as 8, 16 or 32 days, or if it is a strip-chart recorder. If an electronic logger is installed, state which type of logger and water level sensor.
k) *The reduced level of the bench mark* (R.L.B.M.) means the elevation of the bench mark above the zero of the staff gauge. If possible, the station bench mark is connected to the National Geodetic Survey Net.

   Describe the construction of the station bench mark as bolt drilled into rock or large boulder, or cemented into heavy concrete block. Indicate its position and give its accurate distance in relation to the staff gauge or other station features. Any auxiliary bench mark is described in a similar way.
l) State whether the purpose of the station is general investigation or to procure data for special purposes.
m) Obtain information from local people as to the duration of high water, low water, and of zero flow.
n) Give distance in km from the Regional office to the station and state which type of transport is to be used during dry and wet season. State hours or days spent on the trip to the station.
o) Give name of local observer and his pay per month. Also state number of readings per day.
p) Give information on the manner of collecting returns from the observer, whether by the Regional office, by mail, or by other means.
q) A sketch of the station site is required. Show the position of the gauges, the recorder, the bench marks, the cableway and other installations. The distance between each item should be based on measured distance and entered on the sheet together with sketches of any conspicuous feature or structure in the vicinity.
r) Photographs giving a pictorial record of the stream reach at the station site should be included.

CHAPTER 7

ALTERNATIVE EQUIPMENT AND METHODS FOR MEASURING STAGE

7.1 Non recording Stage Gauges

In addition to the ordinary staff gauge, there are four other types of nonrecording stage gauges that may be used at gauging stations. These are [25]:

a) The Wire-weight gauge,
b) The Float-tape gauge,
c) The Electric-tape gauge,
d) The Crest-stage gauge.

7.1.1 The Wire-Weight Gauge

The typical *wire-weight gauge* (Fig. 35) consists of a drum wound with a single layer of cable, a bronze weight attached to the end of the cable, a graduated disc and a counter, all housed in a cast-aluminium box. The disc is graduated and is connected permanently to the counter and to the shaft of the drum. The cable is guided to its position on the drum by a threading sheave. The reel is equipped with a pawl and ratchet for holding the weight at any desired elevation. The gauge is set so that when the bottom of the weight is at the water surface, the gauge height is indicated by the combined readings of the counter and the graduated disc.

The wire-weight gauge is used as an outside reference gauge where other outside gauges are difficult to maintain. The wire-weight gauge is mounted normally on a bridge parapet, on a dock or on other structures over the water. [25].

7.1.2 The Float-Tape Gauge

The *float-tape gauge* (Fig. 36) is used mainly as an inside stilling well reference gauge for water-level recorders and consists of a float attached to a counterweight by means of a stainless steel tape. The tape is graduated in metres and centimetres

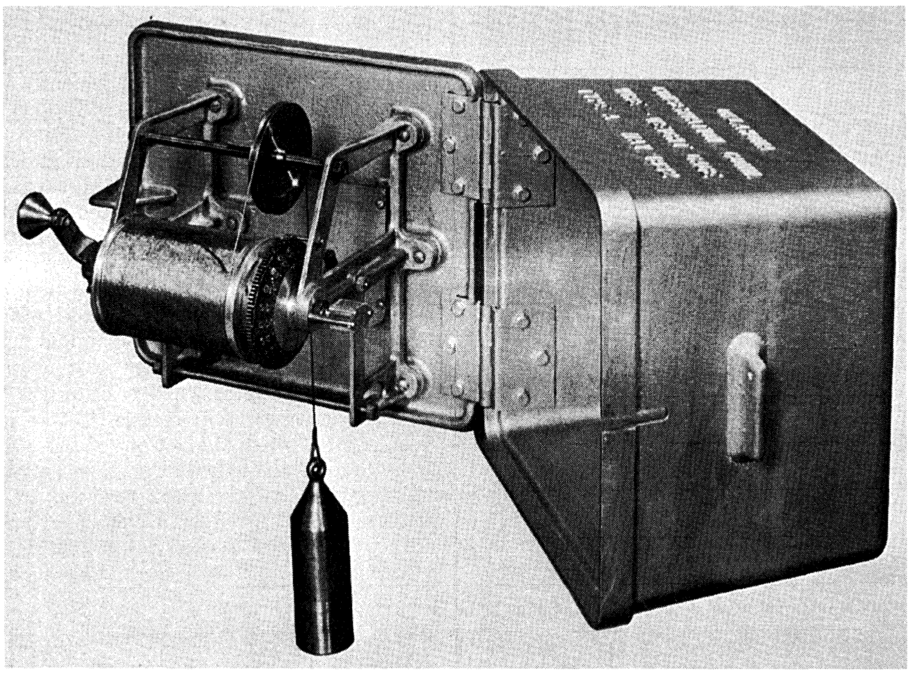


Figure 35. Type A wire-weight gauge (courtesy of US Geological Survey).

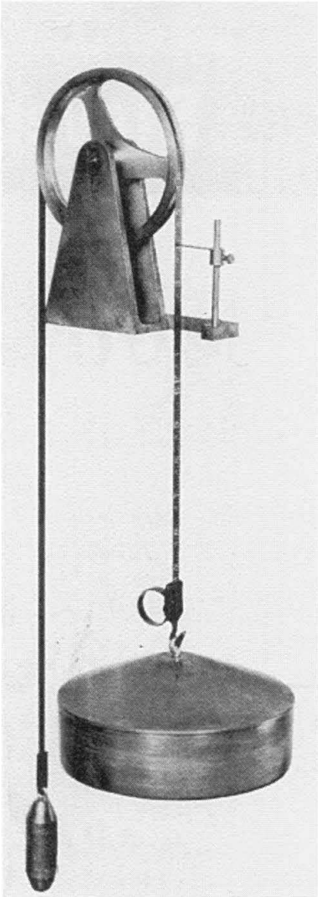


Figure 36. Float-tape gauge (courtesy of Stevens).

and passes over a pulley. The float pulley consists of a wheel about 150 mm in diameter and is grooved on the circumference to accommodate the tape and it is mounted in a standard. An arm extends from the standard and carries an adjustable index. The tape is connected to the float by means of a clamp that also may be used for making adjustments to the tape reading if the adjustments necessary are too large to be accommodated by the adjustable index. A 250 mm copper float and a 0.9 kg lead counterweight are normally used. [25].

7.1.3 The Electric-Tape Gauge

The *electric-tape gauge* (Fig. 37), like the float-tape gauge, is used mostly as an inside reference gauge for water-level recorders. It offers two advantages over the float-tape gauge as it can be used in a stilling well which is to small to accommodate two floats, and the possibility of errors caused by a leaky or damaged float is eliminated. The gauge consists of a graduated tape with an inlaid two-conductor electric circuit, fastened to which is a cylindrical weight, a reel for the tape, a 4.5 V dry-cell battery and an electric indicating device. These parts are supported by a bracket. With the

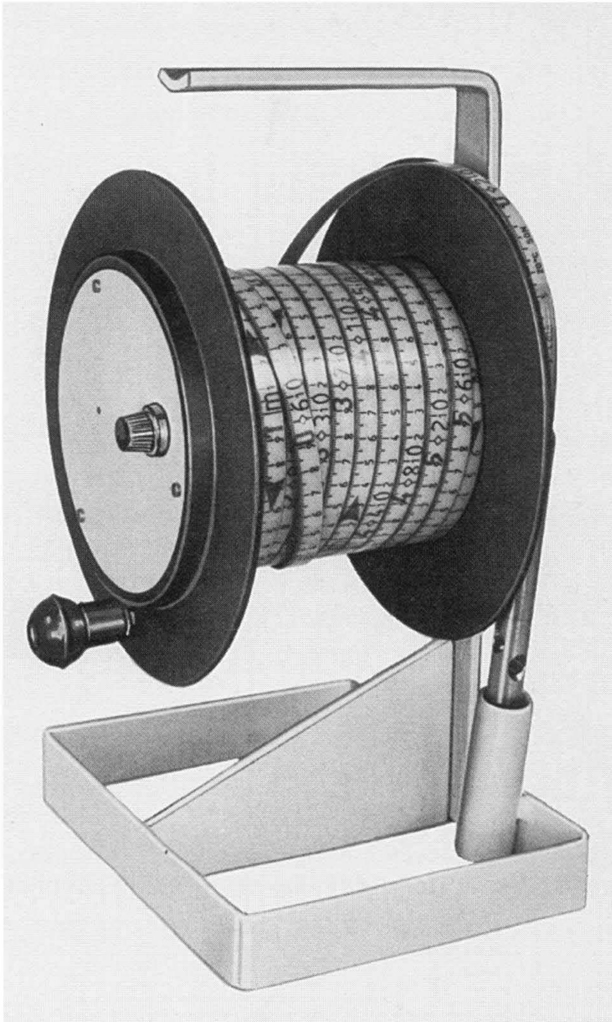


Figure 37. Electric-tape gauge (courtesy of A. OTT).

gauge set to correct datum, the weight is lowered until it makes contact with the water surface which completes the electric circuit and causes either a bulb to light up or a buzzer to sound. With the weight held in position of contact, the tape is read at the index provided on the reel mounting or by a counter. With a hand-held electric-tape the tape is read against a datum index-mark.

If oil is floating on the water surface as a protection against ice, the gauge will give the water level of the interface. [25].

7.1.4 The Crest-Stage Gauge

The *crest-stage gauge* (Fig. 38) is a device for obtaining the elevation of flood peaks. It is a simple, economic, and reliable gauge that is easily installed. The gauge consists of a 50 mm diameter galvanized pipe 1.5–2.0 metres long containing a graduated wooden staff held in a fixed position and referred to a gauge datum. The bottom cap has

Figure 38. Crest-stage gauge (Note: Intake is covered with fine sand, pipe should be lifted a little).

several small intake holes so as to keep the draw-down or super-elevation inside the pipe to a minimum. The top cap contains a small vent hole. A perforated tin cup attached to the lower end of the staff contains granulated cork. As the water rises inside the pipe, the cork floats on its surface. When the water reaches its peak and starts to recede, the cork adheres to the wooden staff and thereby retaining the highest stage of the flood, refer Appendix I.

The crest-stage gauge was designed by the US Geological Survey. The bottom cap was provided with six intake holes located so as to keep the non-hydrostatic drawdown, or super-elevation, inside the pipe to a minimum This arrangement of intake holes proved to be effective with velocities up to 3 m/s, and at angles up to 30 degrees with the direction of flow. [25].

7.2 Pressure Sensors

There are a variety of pressure sensors used in hydrometry. They fall into two main categories, namely the hydrostatic pressure to be measured acts either against gravity (e.g. a manometer) or against the known elastic property of some material (e.g. silicon oil).

Pressure sensors can be used when the density of the water remains constant.

The general advantages of pressure sensors are: (a) stilling wells and intakes are not required, (b) the recorder can be located at some distance from the point of measurement, (c) it is non-sensitive to fluvial sediments at concentrations normally encountered, and (d) it is easy to install and the installation cost is low.

The disadvantages are: (a) in general, they exhibit a non-linear response to both pressure and temperature which requires that they be calibrated not only over the pressure range but also over the expected temperature range, (b) pressure sensing is instantaneous, thus to eliminate undesired surface disturbances in the output, readings must be averaged over time which can be performed by the sensor if the sensor incorporates a microprocessor, or it must be done by the data logger interfaced with the sensor, and (c) it requires a relatively high level of technical skill to properly maintain the sensor. [7], [25].

7.2.1 The Gas-Purge (Bubbler) Gauge

The bubbler gauge is a pressure sensing device where the hydrostatic pressure to be recorded is transmitted to the sensor element through the use of a gas-purge system, refer Appendix J.

The bubble gauge works on the following principle. When an inert gas (or dry air) is bubbled slowly through a small-calibre tube and discharges freely from an orifice located at a fixed elevation in the water, the pressure at the orifice, and anywhere in the tube-system, is a function of the depth of water over the orifice.

The measurement output can be transferred to recording devices in a number of ways. By use of a *servo-manometer* or by a *servo-beam-balance* system the pressure is converted to shaft rotation and transferred to an *autographic* recorder, or more often to a *digital tape-punch* recorder. By adding a *shaft encoder*, the shaft output can be converted to electric signals which are transmitted to electronic data loggers through appropriate interfaces. Again, by the use of a pressure transducer connected directly to the gas-tube system, the pressure can be converted to electric signals and transmitted to an electronic recorder.

Proper placement of the gas-orifice in the stream is essential to avoid draw-down and thereby incorrect measurement of the stage. The orifice must not be placed in turbulent flow or in swift currents, but close to the bank where the velocity is low, preferably in a small bay where the water is still and with negligible velocity head. The orifice must be oriented parallel to the flow should there be any movement in the water.

If the orifice becomes covered by mud or sand, the recorded stage will be greater than that actually in the channel. [25].

7.2.2 *The Pressure-Bulb Sensor*

The pressure-bulb sensor (also known as a *pressure transducer* or a *depth transmitter*) is in general terms a device which converts hydrostatic water pressure and hence water level into electric signals which can be recorded at, or remotely from the point of measurement by electronic recorders.

The pressure-bulb sensor (Fig. 39) has two main components: (a) a metallic cylinder with one end closed and the other sealed with a pressure-sensing diaphragm, and (b) the transducer that converts the pressure output of the diaphragm into an electrical signal. To compensate for the influence of varying atmospheric pressure, the inner side of the diaphragm is vented by means of a thin plastic tube incorporated within the cable transmitting the electrical signals to the recorder.

In early designs of the pressure bulb a closed gas-system was used to transmit the pressure from the diaphragm to the pressure sensing element. The major disadvantage of this closed gas-system is that eventually some gas will escape from the system, after which the internal gas pressure no longer represents the true pressure of the water column to be measured. This will occur as a slow drift of the recorded values away from the calibration. Newer design of pressure probes uses no longer gas as a transmitting medium, but some elastic material with known properties (e.g. silicon oil). Thus, the main disadvantage of using pressure-bulb sensors seems to have been solved.

The proper placement of the sensor in the stream is as essential as for the orifice of the gas-purge gauge. Again it is stressed that the inlet hole of the transducer always must be oriented parallel to flowing water.

The electric output signals from the transducer may be influenced by electromagnetic fields generated during thunder storms, especially when there is some distance between the transducer and the recorder.

The measurement error is in the order of ± 0.3 to 0.8 % of the range of measurements.

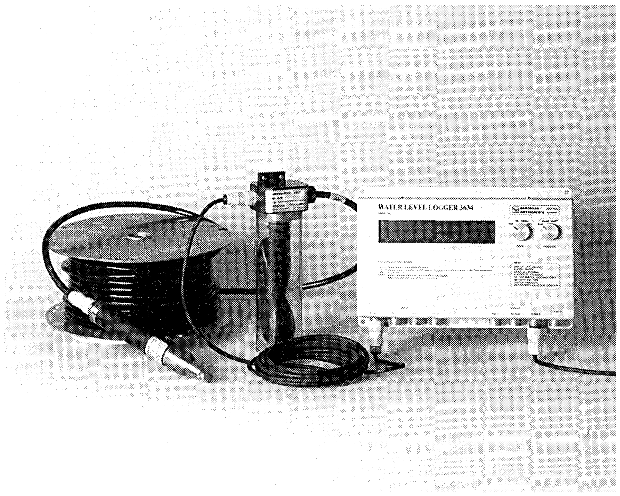


Figure 39. Pressure-bulb sensor interfaced with data-logger, including compensation unit for varying atmospheric pressure (courtesy of AANDERAA INSTRUMENTS).

7.3 The Acoustic Distance Water Level Sensor

This distance measuring sensor measure the distance from the sensor head to the air/water interface when downward looking, and the water/air, or the water/ice, interface when it is upward looking. Thus, the acoustic distance sensor is used both in a top-down mode and in a bottom-up mode. The sensor operates by a signal bouncing off the interface of two media of different densities and measuring the time taken for the signal to make the round trip. Thus, the device measures the time-of-flight of very high speed pulses over very short distances. This is accomplished by use of microprocessors and extremely high speed counters. The sensors are interfaced with data loggers.

The advantage of distance measuring sensors when used in the top-down position, is that they can be used in flashy mountain streams or debris laden streams which would destroy other types of stage measuring installations. The drawback is that these instruments are relatively costly. [7], [27].

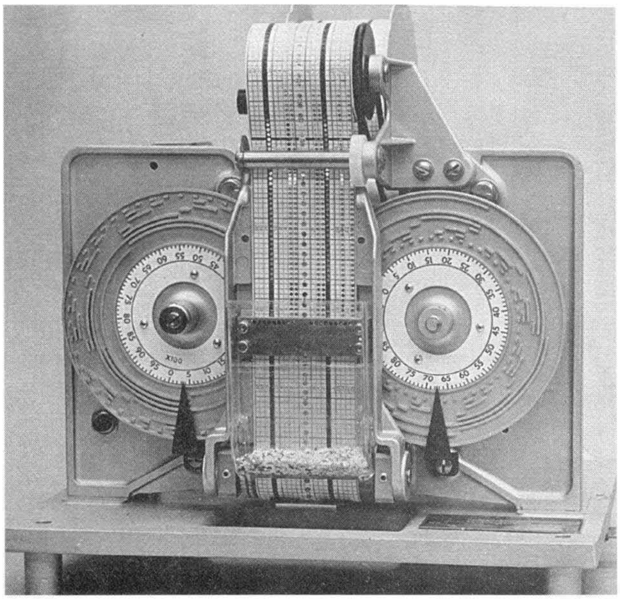


Figure 40. Digital tape-punch recorder (courtesy of US Geological Survey).

7.4 Water-Level Recorders

7.4.1 The Autographic Water-Level Recorder

The autographic water-level recorder is described in Section 5.5.

7.4.2 The Digital Tape-Punch Recorder

The digital tape-punch recorder is a battery-operated slow-speed paper-tape punching device (Fig. 40). The shaft rotation is converted by the instrument into a coded punch-tape record consisting of four-digit numbers that represents the stage at preselected time intervals. The code is simple enough to be read directly from the tape for checking purposes. The recorder may miss absolute flood peaks, therefore, flashy streams require short time intervals, while larger rivers allow longer time intervals. The digital punching recorder is used with rotating shaft sensors. Usually, it is used with the gas-purge sensor where the servomanometer converts the gas pressure to a shaft rotation. [16], [25].

7.4.3 The Electronic Recorder

During the last 10 years the "intelligent logger" suitable for field application has come into operational use in hydrometry (Fig. 41 and 42) The recorder has a low power consumption, is reliable, and of relatively low cost. It may be powered by batteries or by the mains. These loggers are fully electronic micro-computers recording on solid-

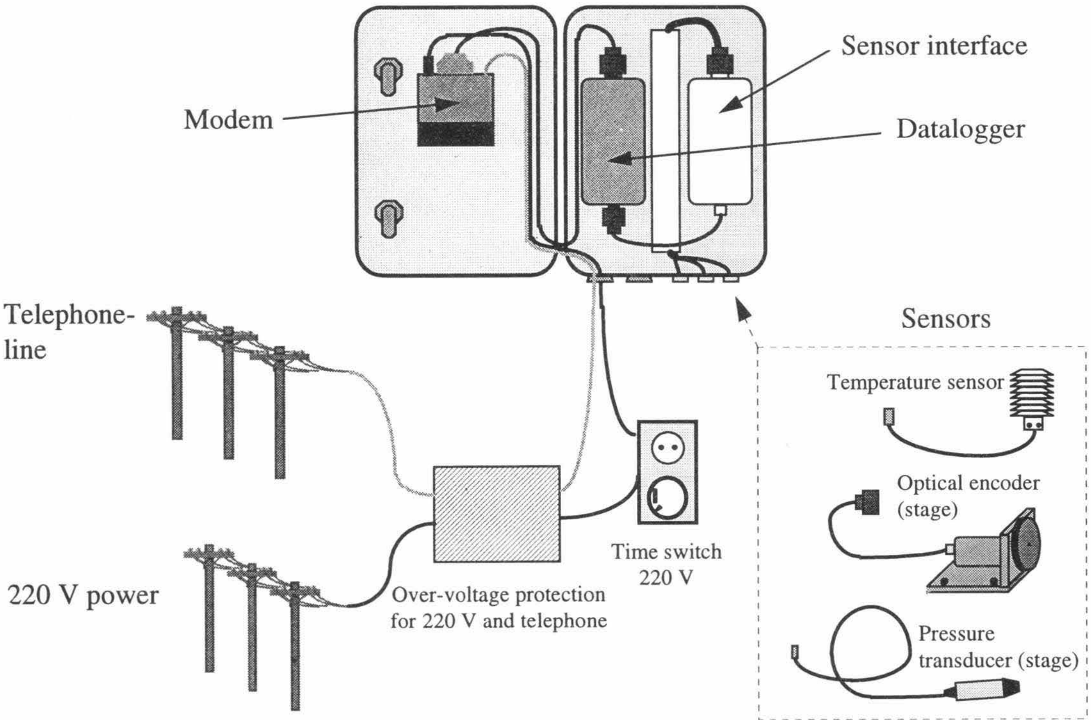


Figure 41. Digital multichannel data-logger that can be interfaced with different sensors. System developed so that the standard modules can be easily replaced, or modules added in order to increase memory capacity, number of input channels, etc. Teletransmission of data. Fully interactive for system-interrogation, fault-finding and reprogramming from base. Power supplied from the mains (220 V), or from batteries/solar-cells. (NVE, Hydrology Department).

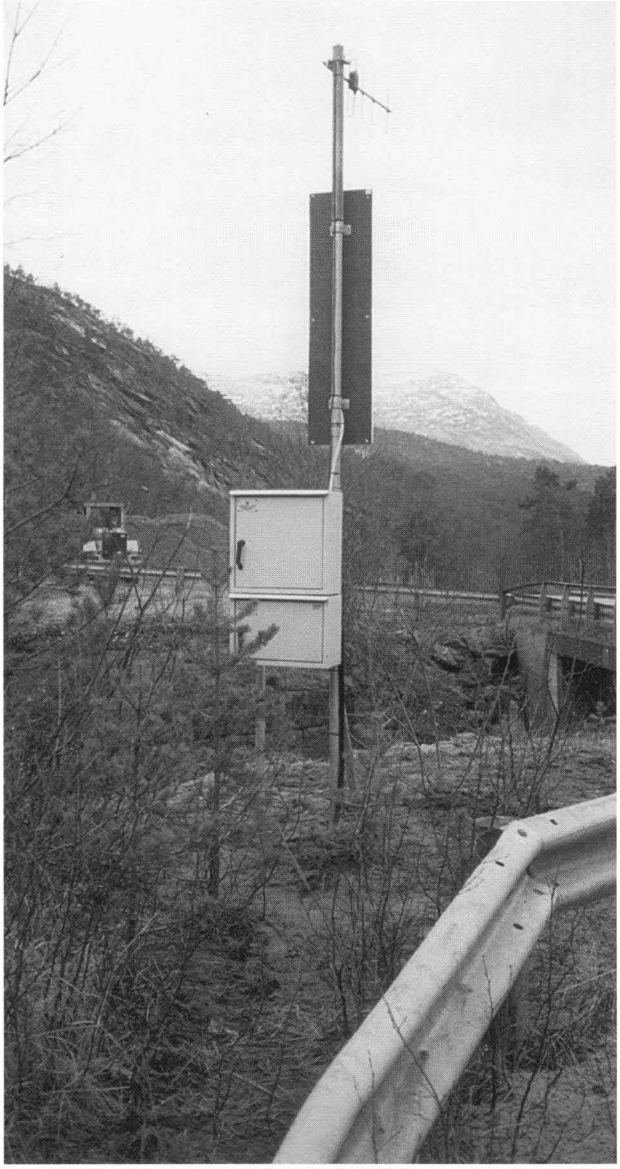


Figure 42. Photo shows the same data-logger as in Fig. 41 installed in the field. The logger is powered by solar-cell and batteries, mobiltelephone is used for teletransmission of data. (NVE, Hydrology Department).

state memory either in the form of exchangeable cassettes (EPROM packs), or on internal memory. The logger has display where the sensed parameter-values can be read from memory for easy check, resetting, and reprogramming. It also gives the state of the system, such as the battery voltage, internal clock time, etc. It can be either of a single or multi-channel type for the recording of additional parameters, such as rainfall and temperature. The recorder can be easily linked up with telemetering systems for transmission of data to the Regional Office, in real time, at fixed intervals, and at pre-set treshhold values.

Bibliography

Chapter 7: [3], [25], [27], [47], [56].

ALTERNATIVE METHODS FOR MEASUREMENT OF DISCHARGE

8.1 General

The most direct and common method of measuring river and stream discharges is probably the velocity-area method by use of the mechanical current meter as outlined in Section 1.2.4. Now, since virtually all stream gauging methods employ the velocity times the area concept (except the dilution method which is an absolute method), it could be reasoned that strictly all methods are velocity-area methods. Nevertheless, the velocity-area method and the current-meter method are often considered to be synonymous methods.

8.2 The Current Meter Method

Discharge measurement by the mechanical current meter is described in detail in Volume 3.

8.3 The Optical Current Meter

The optical current meter uses optical methods to determine surface velocities of streams.

A series of mirrors is carried on the periphery of a drum that can be rotated at precisely controlled speeds. Light coming from the water surface is reflected by the mirrors into a lens system and an eyepiece. By adjusting the rate of rotation of the mirror-carrying drum, while viewing the reflected images in the eyepiece, the sweep of the field of the mirrors along the water surface can be speeded or slowed until it matches the speed of water. When the rotational speed is proper, the images become steady and appear as if the surface of the water was being viewed while moving along exactly in pace with it. By reading the rate of rotation of the drum and knowing the distance from the drum to the water surface, the velocity of the water surface can be determined.

The velocity measurement is made from any bridge, walkway, or other structure that will support the meter and the operator. The surface velocity is computed from the equation:

$$v_{surface} = kRd \tag{8.1}$$

where k is a constant for the meter, R is the meter readout, and d is the distance between the instrument and the water surface.

The computed velocity is corrected by an appropriate coefficient. Test data from conventional current-meter measurements indicate that the application of a coefficient of 0.85 for natural channels will keep errors within ± 5% of the real value. The meter measures the velocity vector normal to the cross section only, thus there is no need to apply horizontal angle corrections.

The meter is designed to measure the surface velocity in open channels without immersing any equipment in the water. Because it measures only surface velocities, the optical meter is not considered to be a substitute for conventional equipment in those situations where good and acceptable measurements can be made by standard techniques.

It is a device used in situations under which standard current-meter techniques can not be used, including high flood velocities, flow carrying a very high sediment load, and in the presence of floating debris during flood periods that makes it hazardous to immerse equipment in the stream.

The meter has the advantage of not having any parts immersed in the flowing water, it has the disadvantage of measuring surface velocities only, rather than the average or integrated velocity. [4], [16].

8.4 The Salt-Velocity Method

In the salt-velocity method, a salt solution is injected suddenly into the stream at such a place and in such a manner that it becomes evenly distributed across the stream very rapidly. The time of travel of the salt pulse between two downstream sections where the salt dilution is completely mixed with the stream water, is measured by means of electrodes which detect the increased conductivity associated with the passage of the salt solution wave.

The discharge can be determined provided that the mean cross section between the two downstream detection sections is accurately known. The method is best suited for use in artificial canals witch have an even and regular bedprofil. [34].

The method has a potential for better than 1 % accuracy when properly used.

8.5 The Slope-Area Method

Peak floods are often determined by use of the slope-area method. In this method the flood flow velocity is measured indirectly by means of energy equations. These equations relate the velocity of flow to the longitudinal slope of the water surface and to the geometry and roughness of the riverbed in the measuring reach. Usually, when determining flood peaks, a field survey is made after the flood has passed in order to survey the elevation of high-water marks and the geometry of the cross-sectional area of the measuring reach. The product of the computed velocity of flow and the mean cross-sectional area gives the discharge.

The Slope-Area Method as used for indirect measurement of peak floods is described in Volume 3.

8.6 Dilution Gauging

The measurement of stream discharge by the dilution method has been known for more than 70 years [36]. The method depends on the determination of the degree of dilution of a tracer solution added to the flowing water. The method consists of injecting a tracer solution at some point on a stream channel and to sample the water further downstream where turbulence has mixed the tracer solution uniformly over the cross section. The degree of dilution of the initial tracer solution in the stream water at the sampling cross section permits computation of the stream discharge.

The tracer may be of three types: (a) a chemical, (b) a fluorescent dye, or (c) a radioactive substance. The accuracy of the method depends critically on complete mixing of the injected tracer with the stream water before the sampling cross section is reached, and on no adsorption of the tracer on streambed material. The dilution method is used for gauging streams with excessive turbulence which are difficult to gauge by use of the conventional current meter method. Thus, the method supplements the current meter method and does not replace it.

Detailed procedures for a modified version of the method, the *Relative Salt Dilution Method*, are given in Volume 3.

8.7 The Moving-Boat Method

The moving-boat method was developed by the United States Geological Survey for the gauging of large rivers as reported by Smoot [22]. Subsequently, The Inland Waters Directorate, Water Resources Branch of Canada introduced an automated version of the method by use of microprocessors [23]. An excellent discussion on the moving-boat method can be found in reference [28].

The moving-boat method is an advanced current-meter technique particularly suited to the accurate and rapid gauging of larger rivers, that is, rivers more than 150 m wide and at least 2 m deep. This is especially true at remote sites where no facilities exist, or during floods when measurements with conventional methods are difficult and involve costly and tedious procedures. It has the advantage of speed, high mobility, and relatively low cost. However, the method is not suitable in tidal reaches.

As with conventional current-meter measurements, the moving-boat method requires information on the location of the observation points (verticals), the depth of the stream at each point, and the mean velocity of flow perpendicular to the cross section at each point. As the current meter is mounted usually one metre (0.9–1.2 m) below the waters surface, a coefficient is required to adjust the measured velocity to the mean velocity in the vertical. The coefficient is obtained by determining the velocity-profile in several verticals by conventional current meter and calculate a mean value for the whole cross section. In large rivers, this coefficient is usually uniform across the section and has generally a value between 0.90 and 0.92.

A measurement is made by traversing the river with a boat along a pre-selected path normal to the flow. Equipment required are, Fig. 43:

a) Component current meter with tail fin (vane) mounted on current meter rod.
b) Magnetic direction compass mounted on current meter rod.

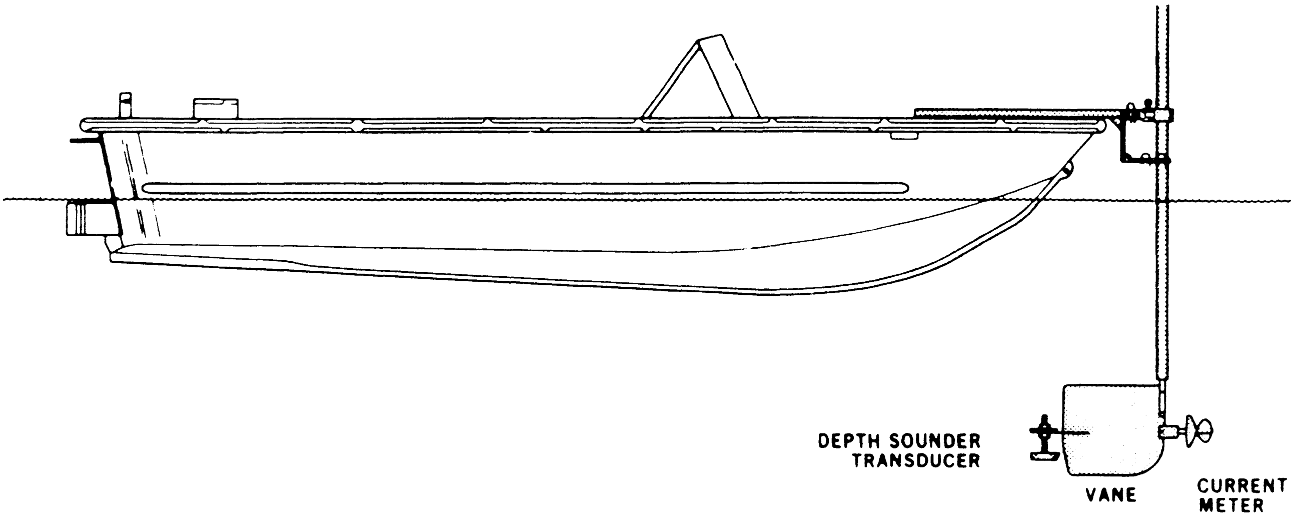


Figure 43. Sketch of typical boat with current-meter assembly for moving boat measurement of discharge, including component current meter with tail fin, sonic depth sounder, and magnetic direction compass. (Courtesy of Inland Water Directorate, Canada).

c) Acoustic sounder, high frequency with digital readout, sensor fixed to boat or to current meter tail fin.
d) Processor to control and compute the data.
e) Suitable easily manæuvrable motor-boat with mounting fixtures for the equipment. Generally, the requirements are for shallow draft and high manæuvrability, also at low speed.

During a traverse of the river the acoustic sounder records the bottom profile, while the continuously operating current meter records the combined boat and stream velocity. The angle indicator attached to the vane assembly indicates the angle between the current meter and the course of the boat. All sensor outputs connect with the electronic processor where they are processed and the river discharge parameters and discharge computed, stored in memory and printed out in real-time.

Normally, data are recorded at 30–40 points in the cross section during a run. About six traverses in each direction are usually made and the results averaged to give the river discharge. During a traverse the boat is moving crab-like across the river along a cross section and held on course by sighting on a pair clearly visible markers mounted on each bank in line with the traversing path (Fig. 44).

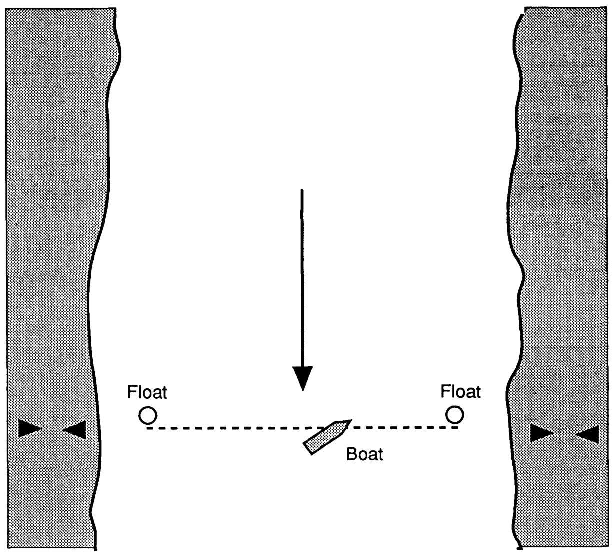


Figure 44. Moving-boat measurement of river discharge. Sketch of measuring site with sighting-markers on the river banks and traversing-line marked with floats.

Bibliography

Chapter 8: [2], [3], [4], [16], [21], [22], [23], [27], [28], [32], [32], [34], [35], [39], [41], [43], [44], [48], [52], [56], [57], [60].

CHAPTER 9

ADVANCED TECHNOLOGY

9.1 General

Determination of discharge by the mechanical current meter, the dilution method, and by means of hydraulic structures have their limitations and are thus not applicable in all instances. Three relatively new methods of flow measurements in open channels are:

a) The Electromagnetic Flowmeter,
b) The Acoustic Flowmeter,
c) The Acoustic Doppler Flowmeter.

9.2 The Electromagnetic Flowmeter

The method is based on electromagnetic induction. That is, when an electrical conductor, in this case water, flows through a magnetic field set up by an electromagnetic coil, an electric current will be induced in the conductor. Fig. 45.

The electromagnetic flowmeter records continuously the velocity of flow at a fixed cross section of the stream. The method utilizes a magnetic field generated by passing an alternating current through a horizontal coil buried in the channel bed. Voltage probes are placed at the banks to record the induced potential in the stream water which is proportional to the mean velocity of the flow through the cross section. The electromagnetic output is related to discharge by calibration using the current meter or the dilution method.

The accuracy of the method depends on the signal processing equipment measuring the small potentials at the voltage probes, it is possible to detect a signal of 10^{-9} volts which represents a velocity of about 1 mm/s.

The flowmeter requires that the streambed at the site be insulated to isolate the magnetic field from the varying conductivity of the bed and bank materials. Thus, the installation cost is highly dependent of the river width and therefore, the decision to instal an electromagnetic flowmeter will depend on a cost/benefit analysis. Usually, the analysis will limit the applicability to rivers up to 30–40 m wide.

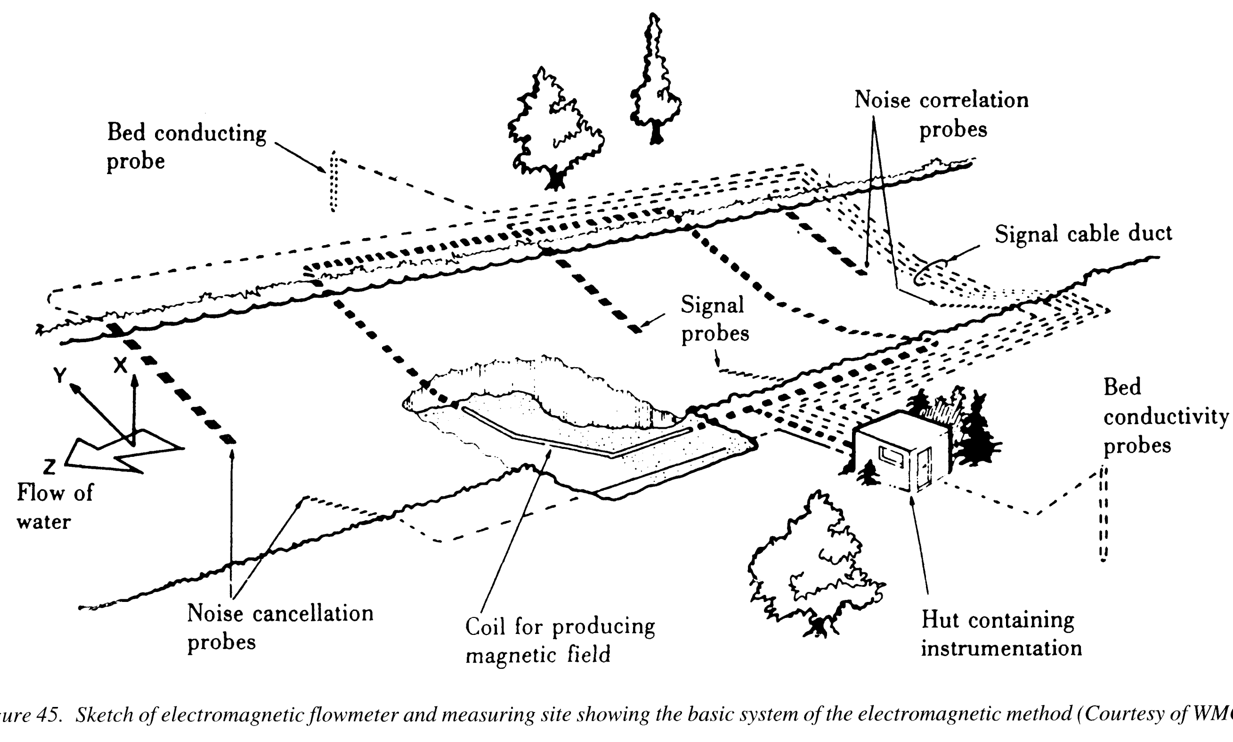


Figure 45. Sketch of electromagnetic flowmeter and measuring site showing the basic system of the electromagnetic method (Courtesy of WMO).

Figure 46. Electromagnetic current meter NAUTILUS C 2000 (courtesy of A. OTT).

The electromagnetic flowmeter is generally not influenced by high sediment concetration, reverse flow, excessive channel vegetation, varying density due to impurities or temperatures, or skew flow.

The method can be influenced by electrical noise.

There is also available a portable point velocity probe which is used in the same manner as the mechanical current meter (Fig. 46). The point velocity probe can be used in situations not suitable to the mechanical current meter such as very low velocities, channel vegetation, and frazil ice. However, the probe is not as rugged as the mechanical current meter and should not be used in heavy debris-laden flow, such as streams carrying significant amounts of bedload. It can not be repaired in the field. [28].

9.3 The Acoustic Flowmeter

The acoustic velocity meter operates on the principle that an acoustic signal transmitted through water moves faster with the flow than against the flow.

Two acoustic transducers are installed diagonally on opposite sides of the river at an angle of 30°–60° between the direction of flow and the diagonal path between them, and at equal depths of water. The transducers can both transmit and receive acoustic pulses.

The velocity of flow is measured by determination of the time of travel of acoustic pulses between the two transducers. The difference in time of travel of the pulses crossing the river in the downstream direction and those crossing the river in the upstream direction is directly related to the mean velocity of flow in the section at the same depth as the transducers.

When the variation of stage in the channel is small, a single pair of transducers will suffice. For larger variations, transducers may be required at several depths.

The site for installation should be chosen in a channel reach which is straight for several channel widths both in the upstream and downstream direction in order to ensure that the direction of flow can be determined accurately. If it is not possible to determine accurately the direction of flow, it may be necessary to use two acoustic paths crossed at 90° to each other in order to resolve this problem.

For single-paired transducers in fixed positions, the site must be calibrated by current meter in order to obtain the mean velocity at different stages in the cross section versus the velocity measured by the acoustic meter. Acoustic velocity meters designed with multi-paired transducers, or sliding transducers that can be placed at different depths, are self-calibrating. The discharge is determined by the velocity-area principle.

By incorporating a water-level recorder and a table of stages versus cross-sectional areas into the electronic processor, the discharge is determined by the velocity-area concept and a direct output of the discharge is obtained.

Figure 47. The Acoustic Doppler Current Profiler (ADCP) mounted for use (Courtesy of G. Gautun).

As it has a relatively high installation cost, the method is most useful for continuous measurement of velocity on a permanent or semi-permanent basis.

The method is suitable for rivers up to 400–500 m wide, the river should have a stable channel and the measuring reach should be straight and uniform and free from channel vegetation. The water should be reasonably free of suspended sediment and entrained air, and there should not be temperature or salinity gradients.

Wide and shallow rivers are not suitable as the sound pulses are reflected by the water/air and the water/bed interfaces and will disturb the measurement.

The flowmeter works well under conditions of variable backwater and reversed flow. The output is continuous and in real-time values.

9.4 The Acoustic Doppler Flowmeter

The Acoustic Doppler Flowmeter is a recent development which seems to be a breakthrough in stream gauging, especially for the measurement of high floods in sizeable rivers. The equipment can be stationary, moored at the bottom or at the surface for continuous flow measurements, or mounted on a boat as in the conventional moving-boat method. Fig. 47.

The method is based on the Doppler effect. A phenonemon characterized by a shift in the apparent frequency of an acoustic signal as a result of the relative motion between the source of the signal and the receiver of the signal. Here the source and the receiver both are ultrasonic transducers built into a single probe. Particles carried in the moving water, such as suspended sediments, reflect the sound emitted by the transmitter back to the receiver where the signals are converted to water velocities and water depths allowing the river discharge through the measuring section to be computed instantly by the velocity-area principle. The output is in real-time and compatible with electronic data handling, hardware, and software. The flowmeter is known under brand names, e.g. the Acoustic Doppler Current Profiler (ADCP). Fig. 47.

The advantages of the Acoustic Doppler Flowmeter are:

a) The velocity distribution in the whole cross section is fully defined.
b) The boat need not be kept on an absolutely straight course across the river as small irregularities will not effect the measurement.
c) Suitable for discharge measurements in wide and deep rivers.
d) The discharge output is in real-time.

The disadvantages are:

a) As with all acoustic systems, the measurement is affected by excessive temperature and salinity gradients, air entrainment in the water, high sediment concentration and excessive channel vegetation.
b) The measurement is affected by signal inter-

ference at the channel/water and the water/air interfaces as the acoustic path requires approximately 0.5 metre clearance above the bottom of the river and 90–100 cm below the water surface, however, the system is still under development and the boundary effect is being reduced.

c) The purchasing cost of the equipment is comparatively high.
d) Highly skilled operators are required.

The Acoustic Doppler method is receiving increasing attention as a potential solution to flow measurement problems where conventional approaches are unsuitable. However, the method is not as yet supported by the WMO Guide to Hydrological Practices or by the ISO Standard series on liquid flow in open channels. [7].

Bibliography

Chapter 9: [2], [4], [7], [14], [27], [28].

CHAPTER 10

AUTOMATIC TRANSMISSION, PROCESSING AND STORAGE OF HYDROMETRIC DATA

10.1 Data Transmission

According to the WMO Technical Regulations [3], a National Hydrologic Service should ensure that hydrological data transmission facilities meet both national needs and international requirements agreed upon on the basis of bilateral or multilateral agreement.

The data transmission system should include [3]:

a) Communication facilities to transmit, relay and collect data from a hydrological observing system and to distribute processed data to users.
b) The transmission plan should include provision for sensorinterfacing, communication equipment, data formatting, operating personnel and operating procedures.
c) The operating plan should be reviewed and revised as needed.
d) According to needs, a data communication link between the Hydrological Service and the National Meteorological Centre should be established.

The International Organization for Standardisation (ISO) has issued Standards for Hydrometric Data Transmission Systems to which the reader is referred.

Part 1 of the Standard specifies the general requirements for hydrometric telemetry. It defines characteristics of the system required to transmit field data to a receiving station and the minimum processing for subsequent use [53].

Part 2 of the Standard outlines a method for specifying hydrometric telemetry systems and identifies factors which influence the design and operation of such systems. It also covers the specification of system requirements, installation, commissioning, acceptance testing and documentation [54].

The reader is referred to [32] where data transmission systems are described and recommendations based on operational experience are given.

10.2 Processing, Storage and Retrieval of Data

The collected hydrological data are processed and stored in a database that is easily available for the users. The emphasis is on reliable data, centrally filed, permanently preserved and readily available for hydrologic analysis and for instant use in forecasting models as real time inputs. The reader is referred to [32] where data processing, data storage and data retrieval systems are covered.

10.2.1 Database HYDRA II

The flow chart in Fig. 48 of the Hydra II Database gives the system of processing data from the raw state to quality controlled data, missing data are generated and filled in if possible. The Hydra II was developed by the Hydrology Departrment at the Norwegian Water Resources and Energy Admimistration. It is an integrated system with flexible data structures and with standardized treatment of data where the presentation and analysis is done using common software.

The Hydra II is a Computer based system for:

- collecting
- storing
- quality controlling
- processing
- presenting
- analysing

hydrological and meteorological data.

The system carries information on:

- Stage and discharge time series
- Drainage basin characteristics
- Discharge rating-curves
- Gauging equipment
- Gauging-station observers
- Operational rules for the regulation of rivers and reservoirs.
- Groundwater levels
- Depth of frozen soil
- Soil moisture content
- Meteorological time series
- Water temperature series
- Snow data.

The common menu system has programs available in the following groups:

- Presentation of data
- Statistics
- Data quality control
- Models.

Presentation of data includes:

- Tables
- Graphics.

The time resolution is from 1 per minute to daily and annual values depending on the initial time resolution of the data.

Statistics includes:

- Seasonal moments and percentiles
- Flow duration curves
- Storage-yield analysis
- Regression analysis
- Classification
- Time series analysis (trends, seasonality, correlation studies, distribution)
- Flood frequency analysis (simple site and regional).

Data quality control is mandatory in use when data is processed:

- Visualisation
- Test for unreasonable values and jumps
- Manual correction
- Comparison with other series
- Reduction of water level for backwater due to ice
- Check of water balance
- Homogeneity tests
- Double-mass analysis
- Methods based on time series analysis
- Jump tests
- Corrected values are flagged.

Models:

ROUTING	– routing of inflow through lakes and reservoirs
PQRUT	– event-based precipitation-runoff model for floods
HBV	– conceptual precipitation-runoff model for floods
GVB	– gridded water balance model (under development).

Bibliography

Chapter 10: [27], [32], [53], [54].

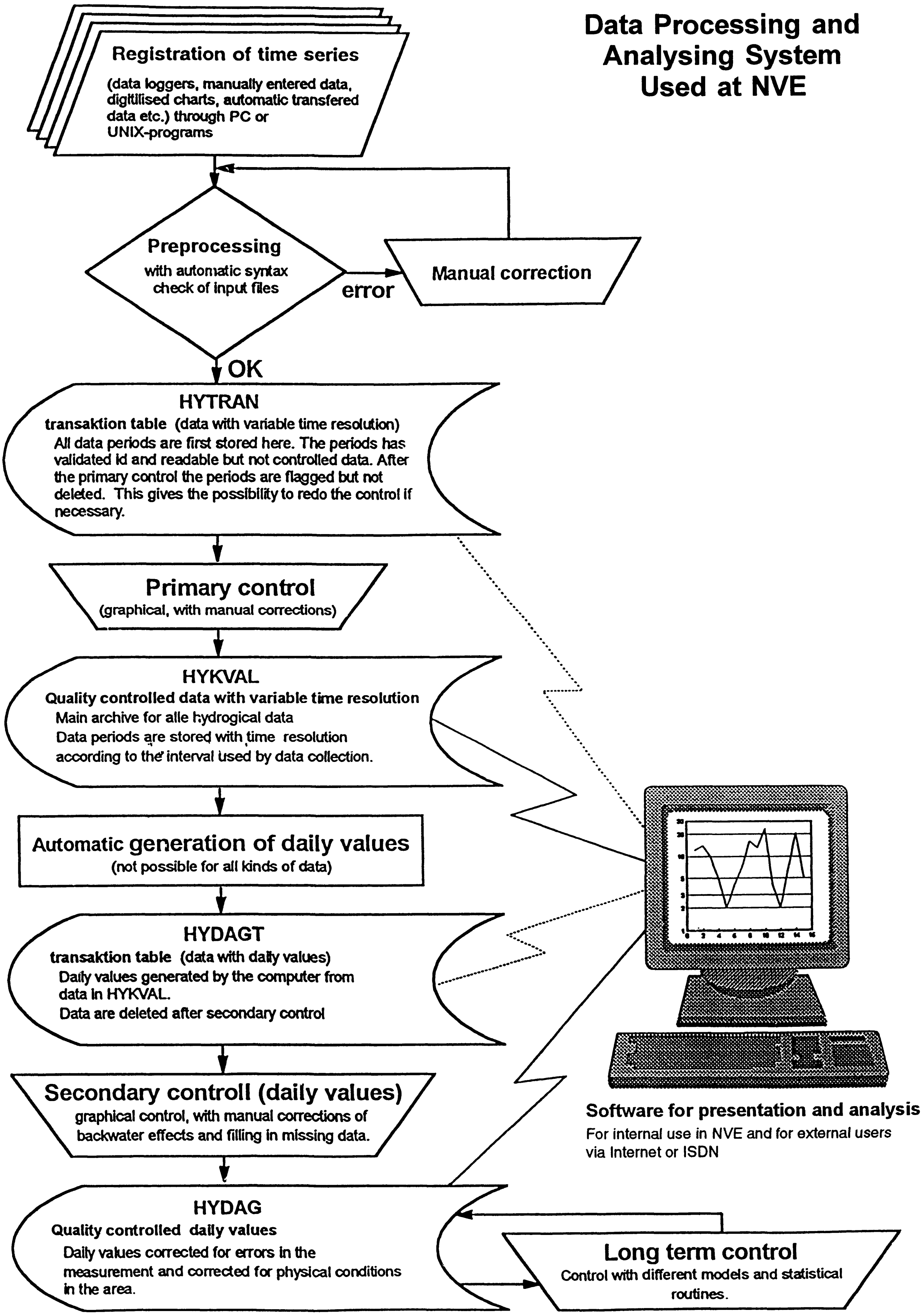


Figure 48. The figure shows a flowchart for the database HYDRA II which was developed and is in use at the Hydrology Department of the Norwegian Water Resources and Energy Administration.

BIBLIOGRAPHY AND REFERENCES

1. UNESCO-WMO-IAHS
   1974: *Three centuries of scientific hydrology: 1674–1974.*
   Key papers submitted on the occasion of the celebration of the Tercentenary of Scientific Hydrology, Paris 9–12 September 1974. Published jointly by UNESCO, WMO and IAHS. ISBN 92-3-001192-4.

2. World Meteorological Organization (WMO)
   1995: *Guide to hydrological practices.*
   Fifth edition, WMO-No. 168, Geneva.

3. World Meteorological Organization (WMO)
   1988: *Technical regulations–Volume III: Hydrology.*
   Basic Documents No. 2, WMO-No. 49, 1988 edition with later loose-leaf supplements (1992 and April 1996), Geneva.

4. World Meteorological Organization (WMO)
   1980: *Manual on stream gauging–Volume I: Fieldwork; and Volume II: Computation of discharge.*
   WMO Operational Hydrology Report No. 13, WMO-No. 519, Geneva.

5. World Meteorological Organization (WMO)
   1972: *CASEBOOK on hydrological network design practice.*
   WMO-No. 324, Geneva.

6. World Meteorological Organization (WMO)
   1971: *Use of weirs and flumes in stream gauging.*
   Technical Note No. 117, WMO-No. 280, Geneva.

7. Wiebe, K.
   1995: *Intercomparison of principal hydrometric instruments–Second phase.*
   WMO Technical Reports in Hydrology and Water Resources No. 43, WMO-No. 613, Geneva.

8. Tilrem, Ø.A.
   1986: *Level and discharge measurements under difficult conditions.*
   WMO Operational Report No. 24, WMO-No. 650, Geneva.

9. Tilrem, Ø.A.
   1986: *Methods of measurement and estimation of discharges at hydraulic structures.*
   WMO Operational Hydrology Report No. 26, WMO-No. 658, Geneva.

10. World Meteorological Organization (WMO)
    1991: *International workshop on network design practices.*
    Technical Reports in Hydrology and Water Resources, Report No. 50, WMO-No. 671, Geneva.

11. Moss, M.E.
    1982: *Concepts and techniques in hydrological network design.*
    WMO Operational Hydrology Report No. 19, WMO-No. 580, Geneva.

12. Langbein, W.B.
    1968: *Hydrological bench marks.*
    Reports on WMO/IHD Projects, Report No. 8, Geneva.

13. K.R. Jones, O. Berny, D.P. Carr, E.C. Barrett and FAO Staff
    1981: *Arid zone hydrology.*
    Food and Agriculture Organization of the United Nations (FAO), FAO Irrigation and Drainage Paper 37, FAO, Rome. ISBN 92-5-101079-X.

14. Laenen, Antonius and Smith, Winchell
    1982: *Acoustic systems for the measurement of streamflow.*
    United States Geological Survey, Open-File report 82–329, Department of the Interior, Portland, Oregon.

15. United States Geological Survey
    1977: *National handbook of recommended methods for water-data acquisition.*
    A United States Contribution to the International Hydrological Program. 1977 edition with later loose-leaf supplements and revisions. Department of the Interior, Office of Water-Data Coordination, Reston, Virginia.

16. Rantz, S.E. and others
1982: *Measurement and computation of streamflow. Volume 1: Measurement and computation of stage and discharge–Volume 2: Computation of discharge.*
US Geological Survey Water-Supply Paper 2175, United States Government Printing Office, Washington, D.C.

17. Corbett, Don M. and others
1945: *Stream-gaging procedure–A manual describing methods and practices of the Geological Survey.*
US Geological Survey Water-Supply Paper 888, United States Government Printing Office, Washington, D.C.

18. Pierce, C.H.
1941: *Investigations of methods and equipment used in stream gaging–Part 2: Intakes for gage wells.*
US Geological Survey Water-Supply Paper 868-B, United States Government Printing Office, Washington, D.C.

19. Pierce, Charles H.
1947: *Equipment for river measurements–Structures for cableways.*
US Geological Survey Circular 17, Department of the Interior, Washington, D.C.

20. Schindler
1972: *SK 3 Cable-way installation.*
A. OTT, Kempten, Germany. Direct communication.

21. Kilpatrick, Frederick A. and Cobb, Ernest D.
1985: *Measurement of discharge using tracers.*
Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A16, United States Government Printing Office, Washington, D.C.

22. Smoot, G.F. and Novak, C.E.
1969: *Measurement of discharge by the moving-boat method.*
Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A11, Washington, D.C.

23. Inland Waters Directorate, Water Resources Branch, Canada
1985: *Automated moving boat measuring system.*
In the Series: Hydrometric Field Manual, Flow Measurement Method, Ottawa, Canada.

24. Carter, R.W. and Davidian, Jacob
1968: *General procedure for gaging streams.*
Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A6, United States Government Printing Office, Washington, D.C.

25. Buchanan, Thomas J. and Somers, William P.
1968: *Stage measurement at gaging stations.*
Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A7, United States Government Printing Office, Washington, D.C.

26. Buchanan, Thomas J. and Somers, William P.
1969: *Discharge measurements at gaging stations.*
Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A8, United States Government Printing Office, Washington, D.C.

27. Herschy, R.W. and others
1986: *New technology in hydrometry: Developments in the acquisition and management of streamflow data.*
Adam Hilger Ltd, Bristol and Boston.

28. Herschy, R.W.
1985: *Streamflow measurement.*
Elsewier Applied Science Publishers Ltd., Barking, Essex, UK.

29. Herschy, R.W. and others
1978: *Hydrometry: Principles and practices.*
Department of the Environment, Water Data Unit, Reading, John Wiley & Sons.

30. Herschy, R.W., White, W.R. and Whitehead, E.
1977: *The design of Crump weirs.*
Technical Memorandum No. 8, Department of the Environment, Water Data Unit, Reading, UK.

31. Department of the Environment
1977: *Weed growth on river flow measuring structures.*
Water Data Unit Technical Memorandum No. 15, Reading, UK.

32. Killingtveit, Ånund and Sælthun, Nils Roar
1995: *Hydrology–Volume 7 in the Series of Hydropower Development.*
Norwegian Institute of Technology, Division of Hydraulic Engineering, Trondheim, Norway.

33. Rodriguez-Iturbe, Ignacio
1969: *Estimation of statistical parameters for annual river flows.*
Water Resources Research, Vol. 5, No. 6, pp. 1418–1421.

34. Grover, N.C. and Harrington, A.W.
1966: *Stream flow–Measurements, records and their uses.*
Dover Publications Inc., New York.

35. Barbagelata, A.
1928: *Chemical-electrical measurement of water.*
Am. Soc. iv. Engrs. Proc., vol. 54, No. 3, pp. 789–802.

36. Barbagelata, A.
1926: *Il metodo chimico-elettrico per la misura delle portate dei corsi d'aqua.*
L'elettrotecnica (Assoiazione Elettrotecnica Italiana),v. XIII, no. 5, pp. 93–99.

37. Østrem, G.
1964: *A method of measuring water discharge in turbulent streams.*
NVE Hydrologisk avdeling, Meddelelse nr. 8, Oslo.

38. Aastad, J. and Søgnen, R.
1954: *Discharge measurements by means of a salt solution: the relative dilution method.*
Assemblee´Int. d'Hydrologie generale de Rome, pub. no. 38, tome III, 289–292.

39. Aastad, J. and Søgnen, R.
1928: *Ny metode for bestemmelse av vannføringen i naturlige og kunstige vannløp: Den relative fortynningsmetode.*
Teknisk Ukeblad, Årg. 75, nr. 29, 283–286, Oslo, Norway. (In Norwegian)

40. Hellstrøm, Bo
1941: *Wind effects on lakes and rivers.*
Handlingar, Ingeniørs Vetenskaps Akademien, Nr. 158, Stockholm.

41. International Organization for Standardization (ISO)
1995: *Measurement of liquid flow in open channels–Velocity-area methods.*
Draft ISO Standard ISO/DIS 748.2: 1995, Geneva.

42. International Organization for Standardization (ISO)
1996: *Measurement of liquid flow in open channels–Part 1: Establishment and operation of a gauging station.*
ISO Standard 1100–1:1996, Geneva.

43. International Organization for Standardization (ISO)
1982: *Liquid flow measurement in open channels–Part 2: Determination of the stage-discharge relation.*
ISO Standard 1100/2-1982, Geneva.

44. International Organization for Standardization (ISO)
1980: *Water flow measurement in open channels using weirs and Venturi flumes–Part 1: Thin-plate weirs.*
ISO Standard 1438-1. 1980, Geneva.

45. International Organization for Standardization (ISO)
1989: *Liquid flow measurements in open channels by weirs and flumes–Rectangular broad-crest weirs.*
ISO Standard 3846:1989, Geneva.

46. International Organization for Standardization (ISO)
1984: *Liquid flow measurements in open channels by weirs and flumes–Triangular profile weirs.*
ISO Standard 4360:1984, Geneva.

47. International Organization for Standardization (ISO)
1995: *Measurement of liquid flow in open channels–Water-level measuring devices.*
ISO Standard 4373:1995, Geneva.

48. International Organization for Standardization (ISO)
1979: *Measurement of liquid flow in open channels–Automated moving-boat method.*
ISO Standard 4369:1979, Geneva: (Replacement of 1979 ed. is in preparation).

49. International Organization for Standardization (ISO)
1990: *Liquid flow measurements in open channels–Round nose horizontal broad-crested weirs.*
ISO Standard 4374:1990, Geneva.

50. International Organization for Standardization (ISO)
1979: *Measurement of liquid flow in open channels–Cableway system for stream gauging.*
ISO Standard 4375:1979, Geneva.

51. International Organization for Standardization (ISO)
1990: *Liquid flow measurement in open channels–Flat V-weirs.*
ISO Standard 4377:1990, Geneva.

52. International Organization for Standardization (ISO)
1992: *Measurement of liquid flow in open channels–Measurement of discharge by the ultrasonic (acoustic) method.*
ISO Standard 6416:1992, Geneva.

53 International Organization for Standardization (ISO)
1984: *Hydrometric data transmission systems–Part 1: General.*
ISO Standard 6419-1:1984, Geneva.

54. International Organization for Standardization (ISO)
1992: *Hydrometric telemetry systems–Part 2: Specification of system requirements.*
ISO Standard 6419-2:1992, Geneva.

55. International Organization for Standardization (ISO)
1985: *Liquid flow measurements in open channels by weirs and flumes–V-shaped broad-crested weirs.*
ISO Standard 8333:1985, Geneva.

56. International Organization for Standardization (ISO)
1985: *Liquid flow measurement in open channels–General guidelines for the selection of methods.*
ISO Standard 8363:1986, Geneva.

57. International Organization for Standardization (ISO)
1992: *Measurement of total discharge in open channels–Electromagnetic method using a full-channel-width coil.*
ISO Standard 9213:1992, Geneva.

58. International Organization for Standardization (ISO)
1994: *Measurement of liquid flow in open channels–Tracer dilution methods for the measurement of steady flow–Part 1. General.*
ISO Standard 9555-1 1994, Geneva.

59. International Organization for Standardization (ISO)
1992: *Measurement of liquid flow in open channels–Tracer dilution methods for the measurement of steady flow–Part 3.*
Chemical Tracers. ISO Standard 9555-3:1992, Geneva.

60. International Organization for Standardization (ISO)
1994: *Measurement of liquid flow in open channels–Field measurement of discharge in large rivers and floods.*
ISO Standard 9825:1994, Geneva.

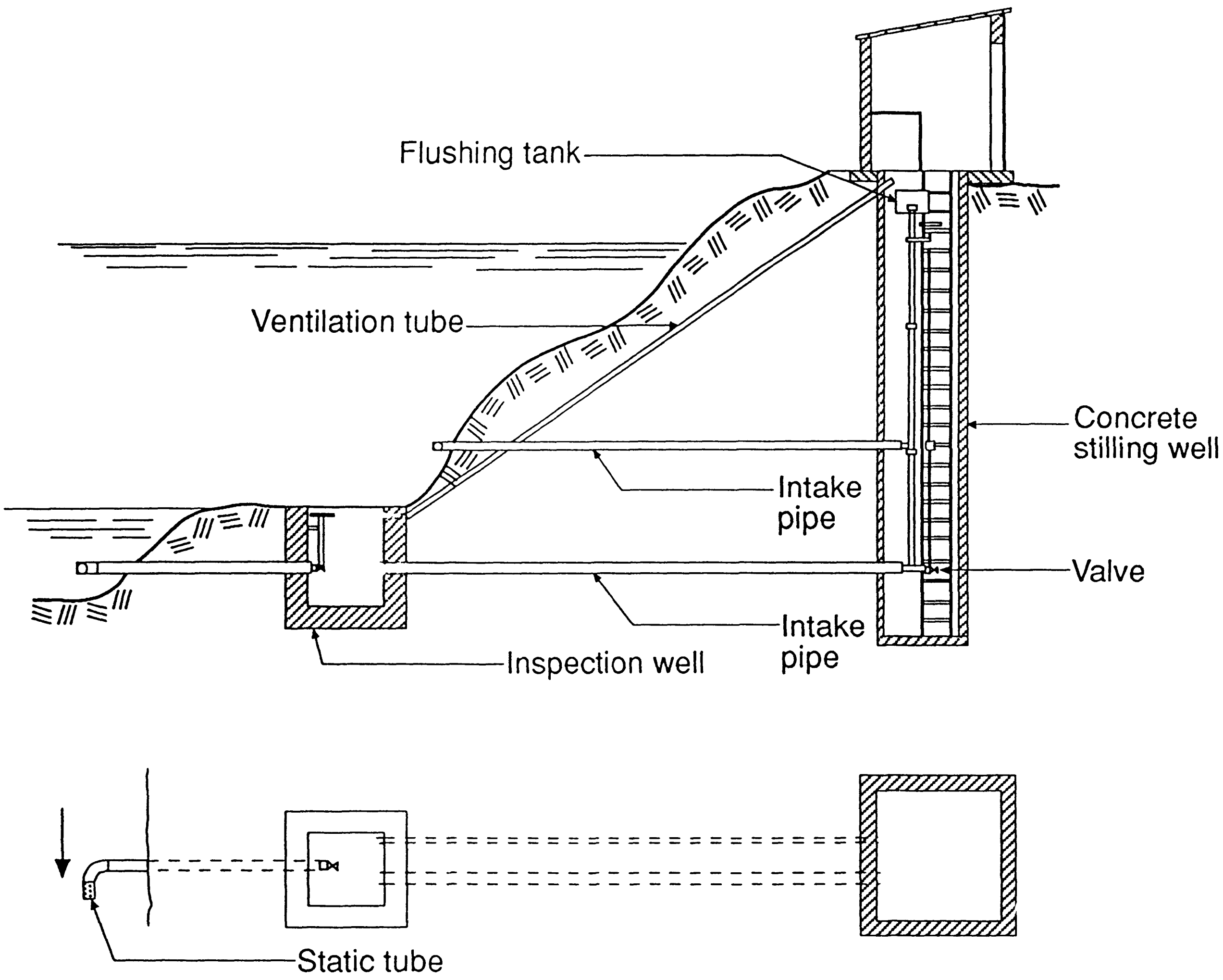
61. International Organization for Standardization (ISO)
1992: *Measurement of liquid flow in open channels–PARSHALL and SANIIRI flumes.*
ISO Standard 9826:1992, Geneva.

62. International Organization for Standardization (ISO)
1994: *Measurement of liquid flow in open channels by weirs and flumes–Streamlined triangular profile weirs.*
ISO Standard 9827:1994, Geneva.

63. International Organization for Standardization (ISO)
1993: *Measurement of liquid flow in open channels–Mixing length of a tracer.*
ISO/TR Standard 11656:1993, Geneva.

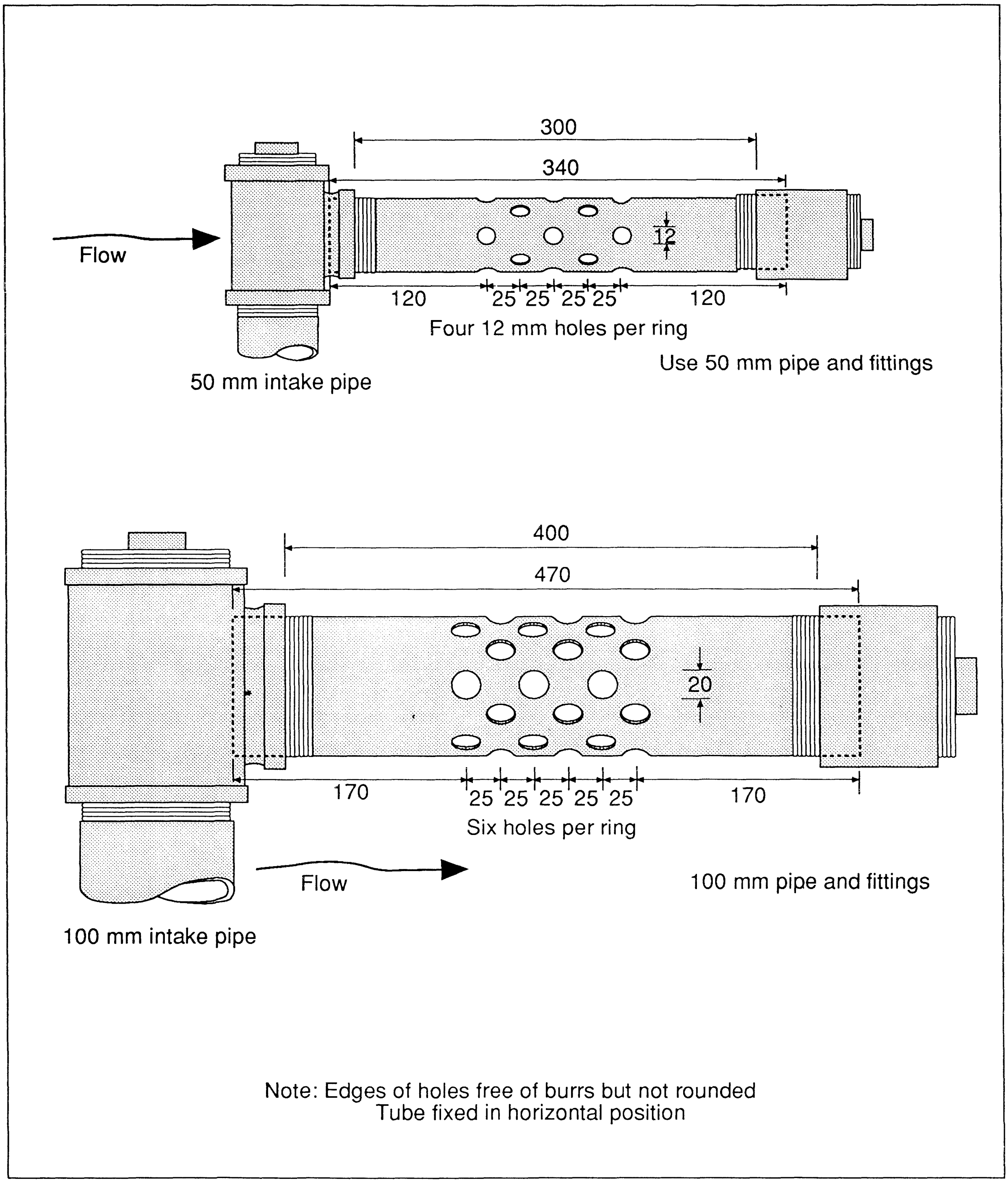
Appendix A

SEDIMENT TRAP



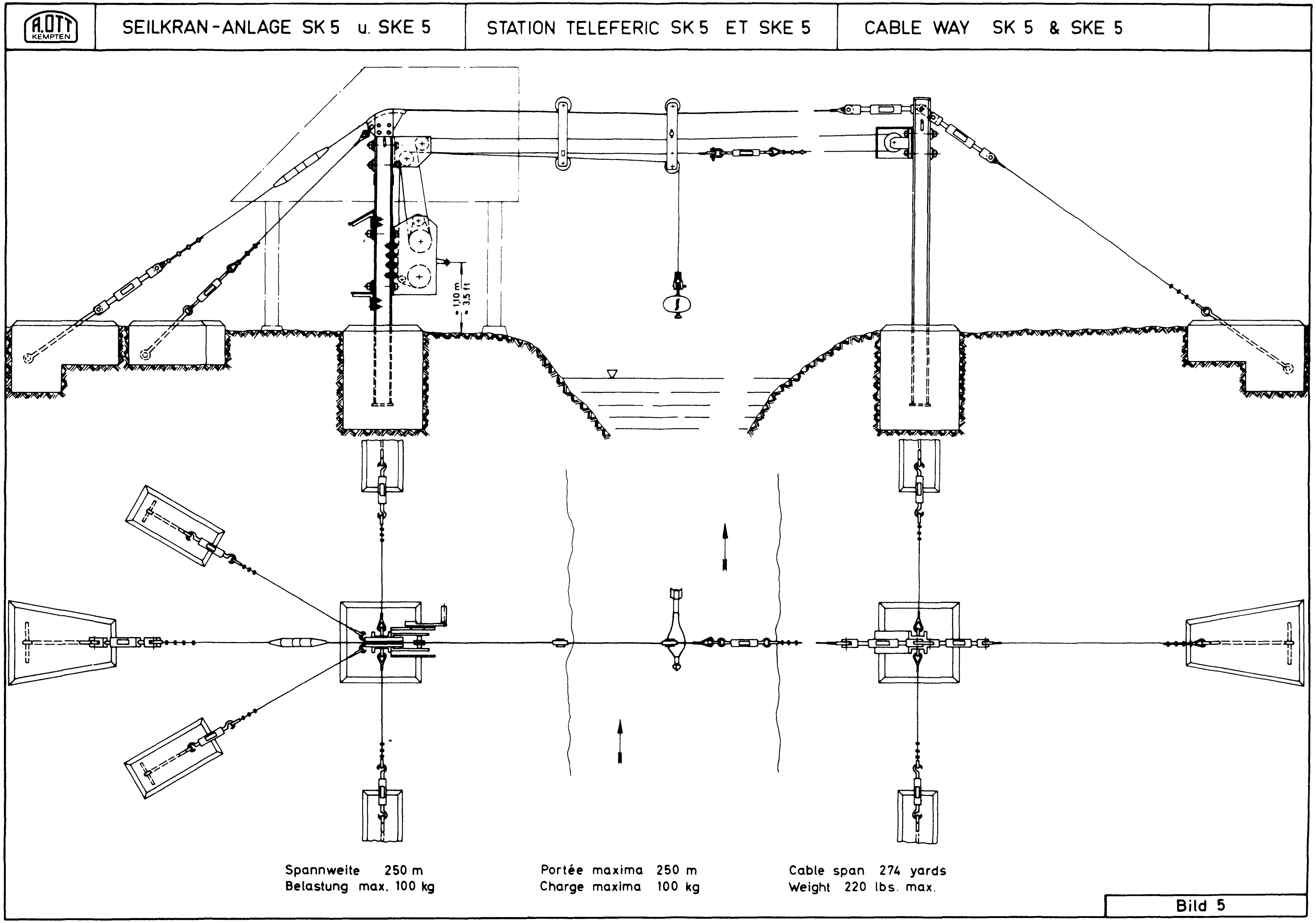
Appendix B

DETAILS OF STATIC TUBE



By courtesy of US Geological Survey

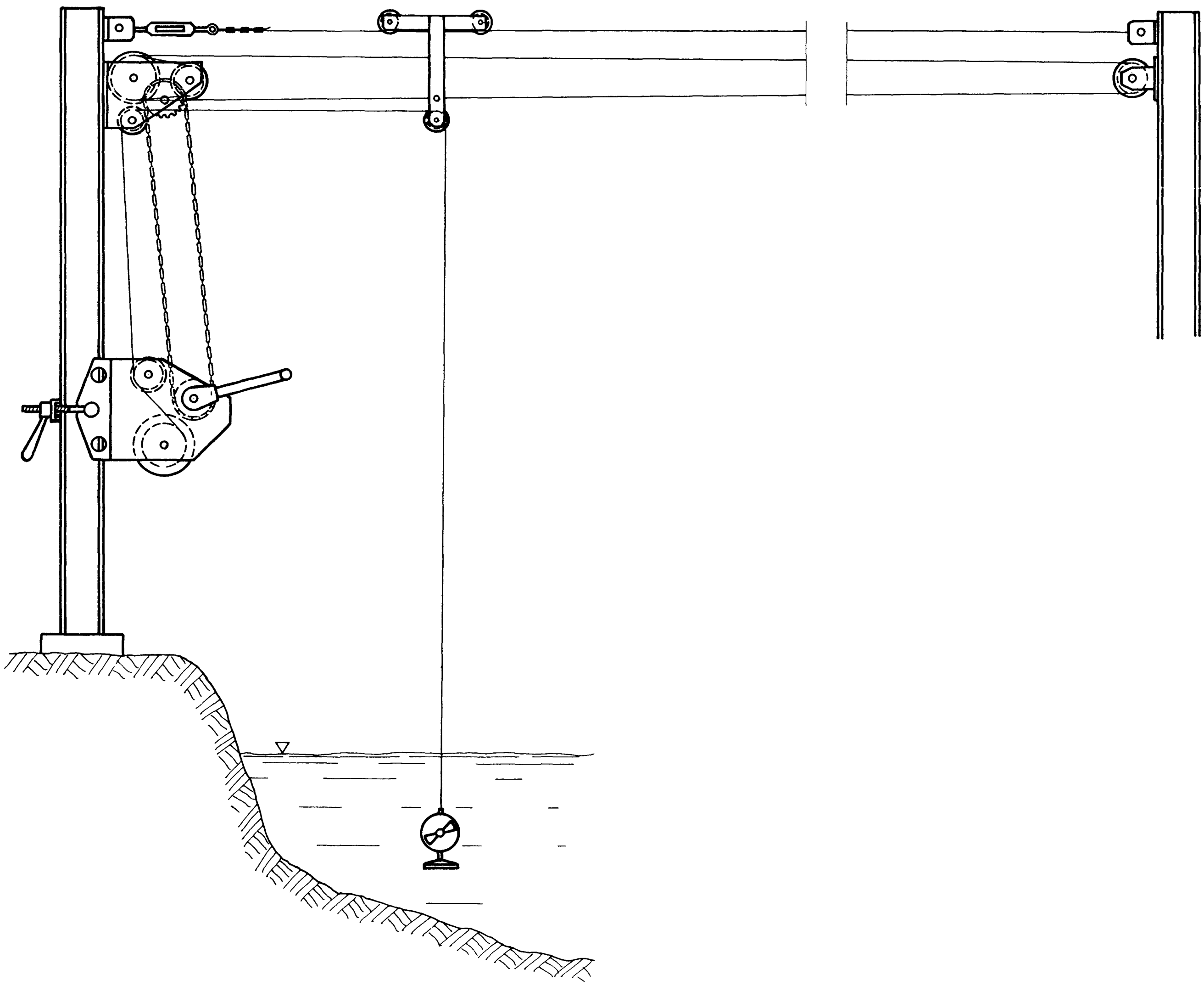
CABLEWAY WITH DOUBLE-DRUM WINCH



By courtesy of A. Ott.

Appendix D

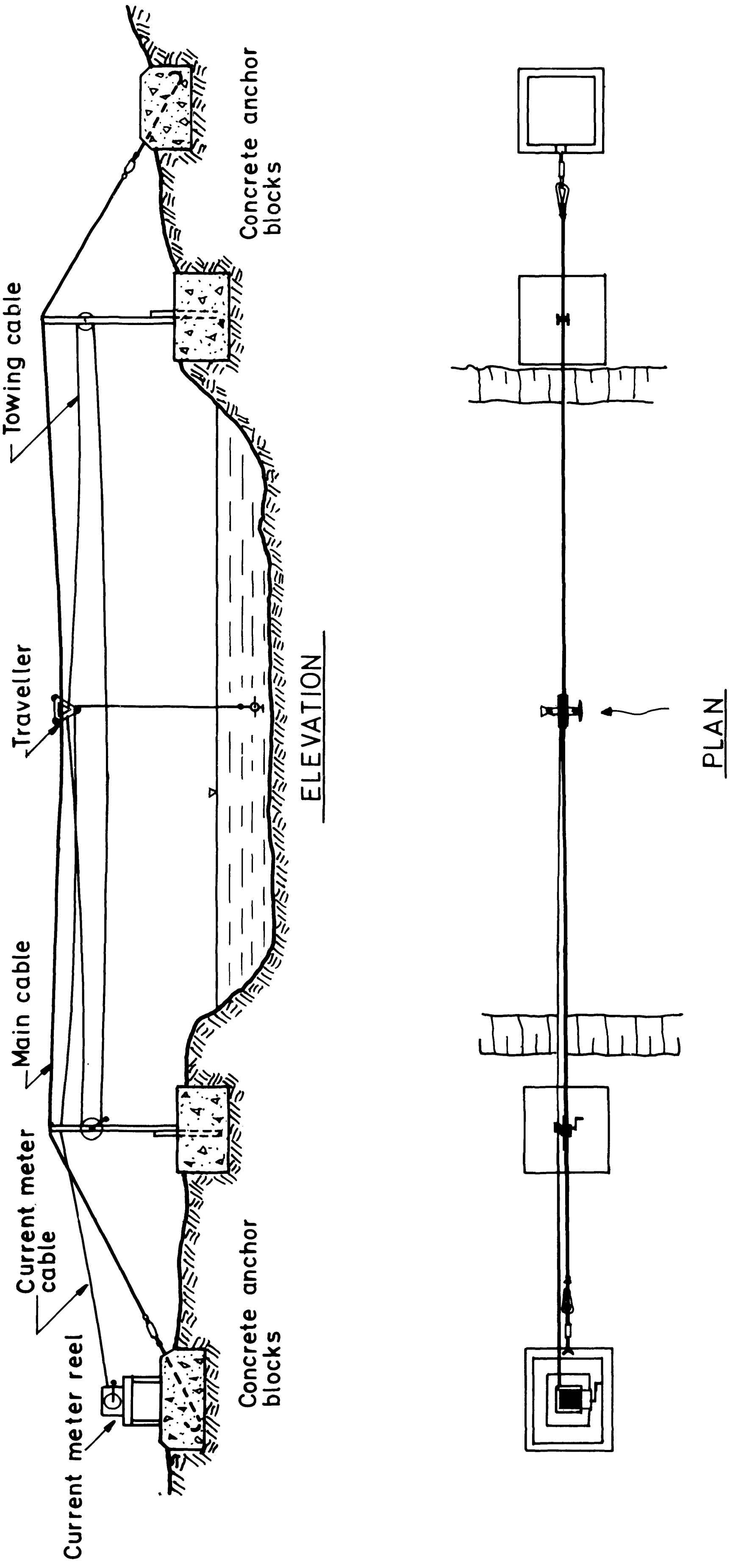
CABLEWAY WITH SINGLE-DRUM PORTABLE WINCH



By courtesy of A. Ott.

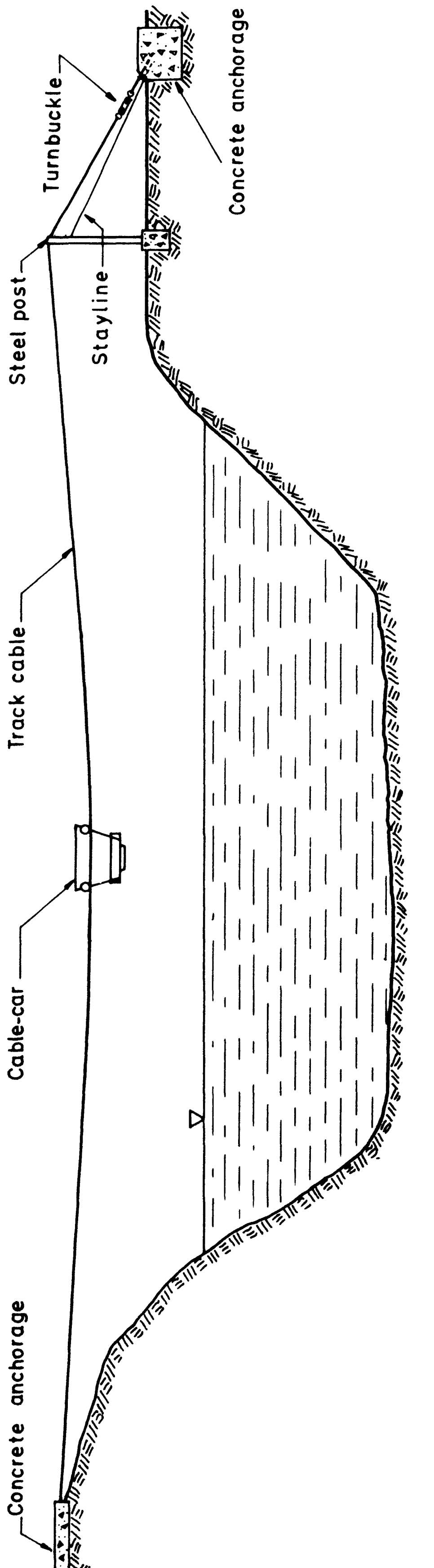
Appendix E

CABLEWAY WITH TWO SEPARATE WINCHES



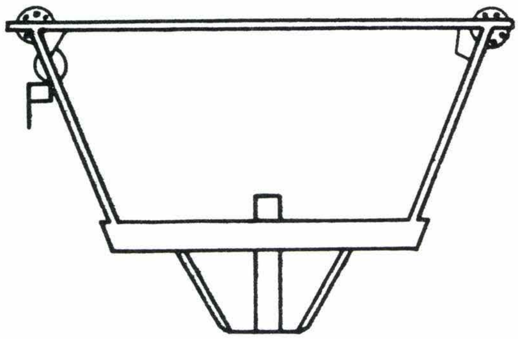
Appendix F

MANNED CABLEWAY WITH CABLE CAR

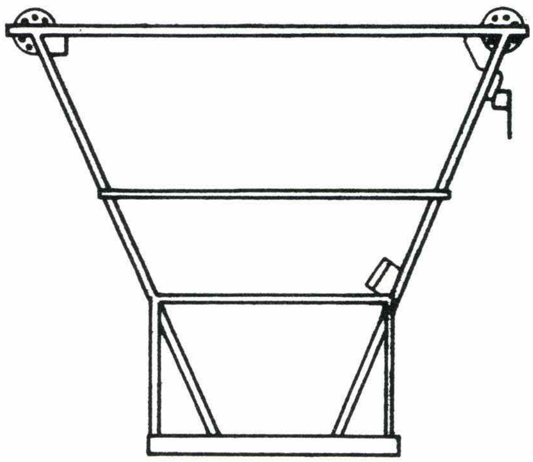


Appendix G

ONE-MAN AND TWO-MAN CABLE CARS



Seated position

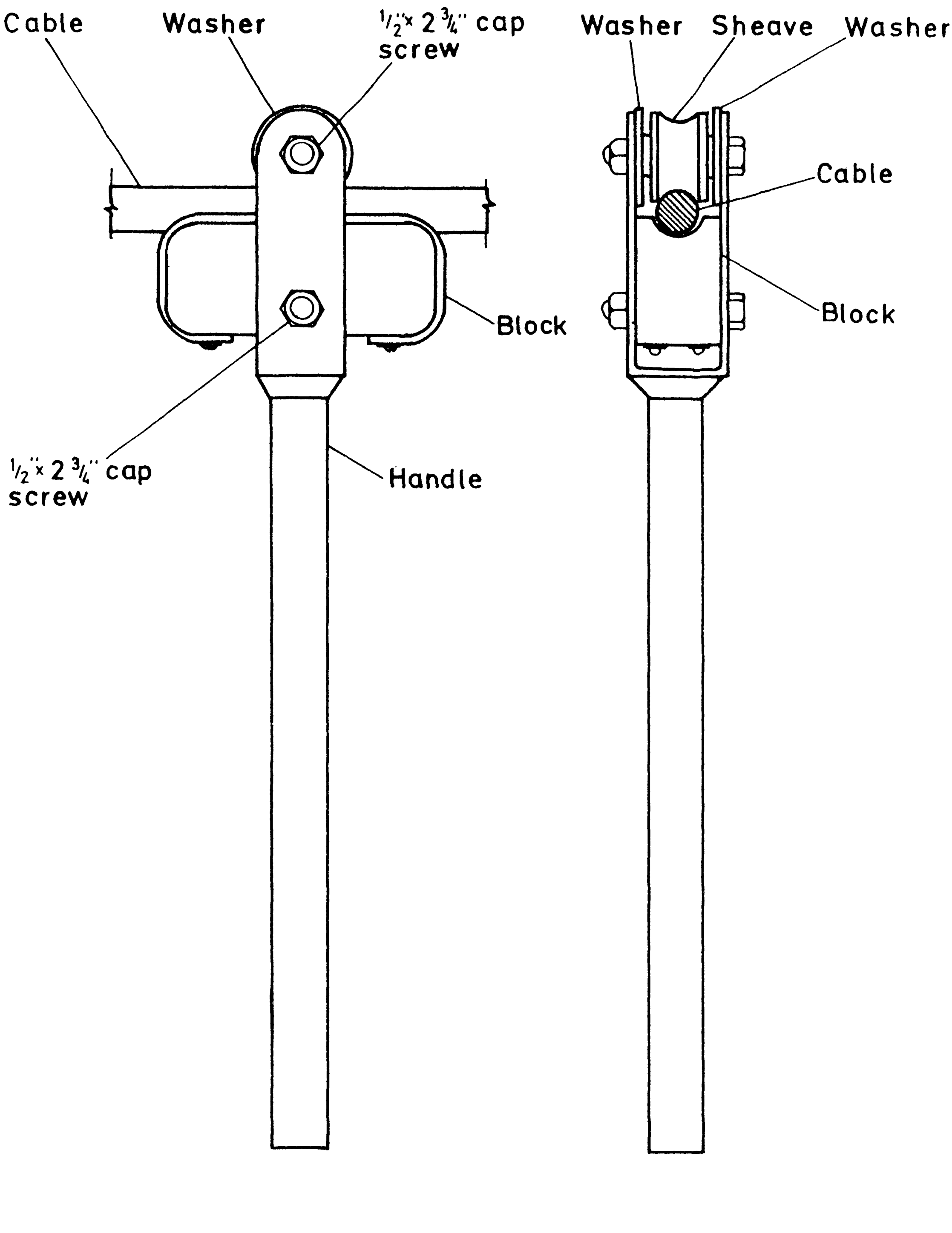


Standing position

By courtesy of US Geological Survey

Appendix H

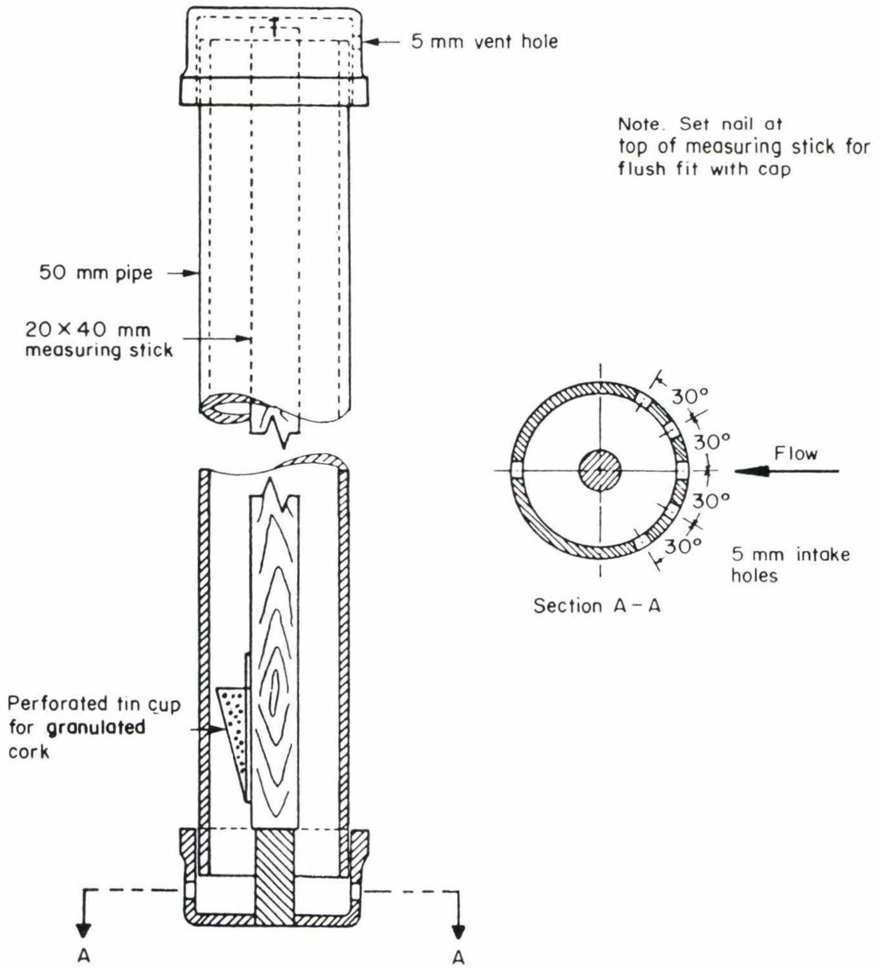
CABLE CAR PULLER



By courtesy of US Geological Survey

Appendix I

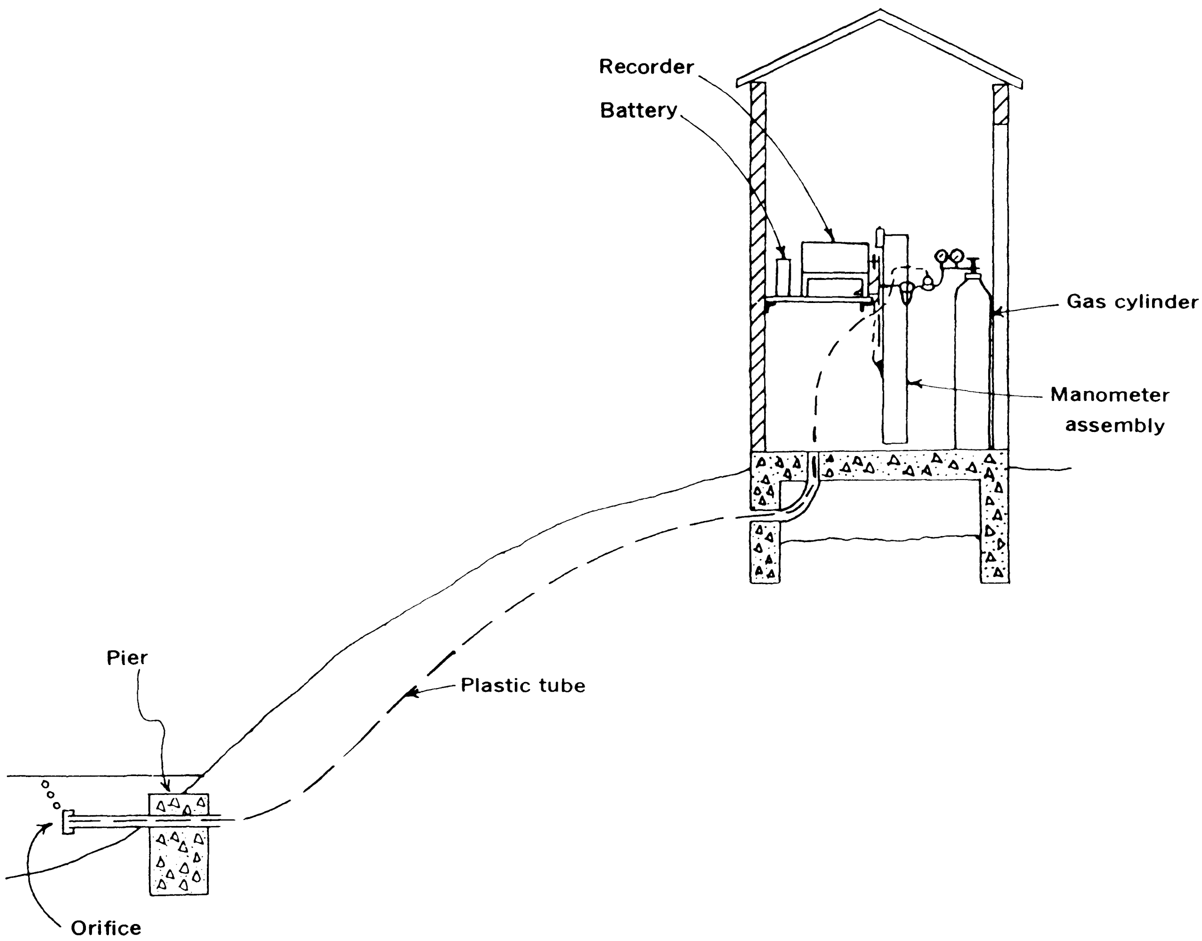
CREST-STAGE GAUGE



By courtesy of US Geological Survey

Appendix J

GAS-PURGE (BUBBLER) GAUGE



By courtesy of US Geological Survey

Head Office: Middelthuns gate 29, Oslo
Postal address: P.O. Box 5091, Majorstua
NO-0301 Oslo, Norway