MINISTRY OF WATER ENERGY AND MINERALS
TANZANIA

MANUAL ON PROCEDURES IN OPERATIONAL HYDROLOGY

VOLUME 1

ESTABLISHMENT OF STREAM GAUGING STATIONS

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MANUAL ON PROCEDURES IN OPERATIONAL HYDROLOGY

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ESTABLISHMENT OF STREAM GAUGING STATIONS

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PREFACE

This Manual on Procedures in Operational Hydrology has been prepared jointly by the Ministry of Water, Energy and Minerals of Tanzania and the Norwegian Agency for International Development (NORAD). The author is Østen A. Tilrem, senior hydrologist at the Norwegian Water Resources and Electricity Board, who for a period served as the Project Manager of the project *Hydrometeorological Survey of Western Tanzania*. The Manual consists of five Volumes dealing with

1. Establishment of Stream Gauging Stations
2. Operation of Stream Gauging Stations
3. Stream Discharge Measurements by Current Meter and Relative Salt Dilution
4. Stage-Discharge Relations at Stream Gauging Stations
5. Sediment Transport in Streams – Sampling, Analysis and Computation

The author has drawn on many sources for information contained in this Volume and is indebted to these. It is hoped that suitable acknowledgement is made in the form of references to these works. The author would like to thank his colleagues at the Water Resources and Electricity Board for kindly reading and criticising the manuscript. Special credit is due to W. Balaile, Principal Hydrologist at the Ministry of Water, Energy and Minerals of Tanzania for his review and suggestions.

CONTENTS

1 INTRODUCTION - GENERAL PRINCIPLES, 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 supply available 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 undertakings. 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 recources 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 – 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 the so-called water cycle or hydrogical 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 lakes and streams. Although the concept of the water cycle is oversimplified, it affords a means of illustrating the most important processes the hydrologist must consider.

Precipitation, and thereby natural flow in streams, 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 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 – that is, at least 15 to 20 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:

1. Measuring and recording, processing and compiling basic hydrological data.
2. The analysis of these data to develop and expand fundamental theories in the discipline.
3. 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 hydrometrical stations (streamflow, sediment transport, water quality, groundwater levels, rainfall, evapotranspiration, temperature),
b) Operating and maintaining these stations to collect basic hydrological data, and
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 results 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 reasonably accurate measurements to be made of the quantities involved.

The basic methods used in stream gauging have changed little over the last 70 to 80 years. Stream stages (water levels) have to be recorded and discharge measurements 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 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 locations can be found with a unique relationship between the discharge of the stream channel and the stage in the channel. To establish this relationship, it is necessary to carry out simultaneously at a selected gauging site, a sufficient number of measurements of the discharge and the corresponding stage. Knowledge of the stage-discharge relation will provide a means by which simple water-level observations can be 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 site so that for a given stage the discharge past the station will always be the same. The shape, reliability and stability of the stage-discharge relation are 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 discharge measurements defines the stage-discharge relation and is termed the *discharge rating curve* for the station.

The discharge rating curve is rarely permanent, particularly at low flow, because of changes in the stream channel such as scour and fill, aquatic growth, ice or debris or because of changes in bed roughness. Frequent discharge measurements are usually necessary to define the discharge rating curve at any time under such conditions.

If variable backwater or highly 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 established 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 must be used to describe the variation of discharge with time.

Detailed procedures for establishing the station rating curve are given in Volume 4 of this Manual.

1.2.2 Selection of Gauging Site

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

Each tentative site is given a critical examination in the field. Particular attention is paid to a) the hydraulic conditions necessary for maintaining a fixed and permanent relation between stage and discharge, b) the possible access to the site at all seasons of the year, and c) the availability of a competent local gauge reader. Also of importance is to locate a suitable cross section for use when making discharge measurements.

1.2.3 Observation and Recording of Stage

The stage of the stream is the elevation of the water level above a chosen datum plane. 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 stream structures and for planning the use of flood plains.

The stage of a stream is generally derived in two ways: a) the elevation 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, and b) a continuous record is obtained by installing automatic instruments that sense and record the height of the water level in the stream channel.

The most commonly used automatic water-stage recorder consists of a float gauge attached to which is a recording device tracing the rise and fall of the water level on a chart. The float is placed in a stilling well that is connected to the stream by intake pipes. The stilling well protects the float and dampens the fluctuation in the stream caused by wind and turbulence. Stilling wells, though usually placed in the bank of the stream, are often placed directly in the stream and attached to bridges or abutments.

1.2.4 Measurement of Discharge

In the case of new stations, discharge measurements are made without delay in order to ascertain the discharge rating curve as rapidly as possible after the establishment of the station. At stations where the discharge rating curve has already been established, regular gaugings are required to check for any changes that may have occurred in the stage-discharge relation. At some stations, where the station control is permanent, the initial rating curve may apply throughout the entire period of record for the station and only check gaugings will be required. Stations with unstable and shifting controls usually require complete re-rating at intervals, generally after major floods.

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. It is essential that a sufficient number of velocity observations are made to eliminate the effect of variations in velocity across the stream. The product of the average velocity and the area gives the discharge. The velocity is usually measured by a *current meter.* Perfected by repeated experiments during the past 90 years, the current meter is 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. 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 calibrated gauging reel into the water by the operator, from a boat, a bridge, or a cableway. Detailed procedures for the current-meter method are given in Volume 3 of this Manual.

During flood conditions, it is frequently difficult to obtain the peak discharges because of conditions beyond the hydrologist's control. The roads may be impassable, cableways or other structures for high-water current-meter measurements might not have been installed, driftwood may prevent use of the current meter or there may be lack of personnel available for taking the gaugings. Thus, many peak discharges have to be determined by indirect means after the flood has passed. Indirect methods make use of energy equations for computing stream discharge. These equations relate the discharge to the water-surface profile and the geometry of the channel. Usually, 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 channel. The slope-area method for indirect measurement of stream discharge is described in Volume 3 of this Manual.

1.2.5 Calibration of Stream Gauging Stations

The operations required when establishing the stage-discharge relation at a gauging station include making a sufficient number of discharge measurements and developing the discharge rating curve and are called the *calibration* or *rating* of the 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 discharge variation, 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 a difficult task and may take time. Thus, at a majority of gauging stations, discharge measurements are not available for the high flood stages and the rating curve must be extrapolated beyond the range of available measurements.

Very few streams have absolutely stable characteristics. The calibration, therefore, can not be carried out once and for all, but has to be repeated as frequently as required by the rate of shifts in the station control. Thus, it is the stability of the station control that governs the number of discharge measurements that are necessary to define the stage-discharge relation at any time and to follow the temporal changes in the stage-discharge relation. If the channel is stable, comparatively few measurements are required. On the other hand, in order to define the stage-discharge relation in sand-bed streams, up to several discharge measurements a month may be required because of random shifts in the stream geometry and the station control.

Sound hydrological practice requires that the discharge rating curve is established as rapidly as possible after the construction of a new gauging station. Unless the discharge rating curve is properly established and maintained, the record of stage for the station can not be converted into a reliable record of discharge.

1.2.6 Construction and Operation of Stream Gauging Stations

The construction of stream gauging stations includes all work connected with the installation of gauges, the erection of cableways or measuring bridges from which discharge measurements can be made, and the placing of bench marks from which the gauge datum can be checked. It may also involve improvement of the stream channel by building an artificial control downstream from the gauging station. 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. This involves:

1. Collection of systematic stage records.
2. Making a sufficient number of discharge measurements in order to define the discharge rating curve and periodic measurements to check the curve.
3. Periodic checks to see if the local observer is doing his work correctly and instructing him when necessary.
4. Maintenance of structures and instrumental equipment in good condition. Special attention must be given to the stability of the gauge datum which should not be altered during the life of the gauging station.

All the collected data must be stored at a central office where the final processing and analyses are carried out. Statistical streamflow records are arranged chronologically in tables and summaries giving daily mean discharges and monthly and yearly maxima, minima, and means. The arrangement of statistical data in chronological sequence is essential for many needs, especially for the purpose of intercomparisons.

Data are also presented as graphs and curves, as follows:

1. Yearly hydrographs showing daily mean stage or discharge plotted against time.
2. Mass curves showing the sum of discharge from a certain date plotted chronologically against time.
3. Duration curves showing number of days or per cent of time any selected discharge is available.
4. Frequency curves showing the frequency with which specific recorded discharge events have occurred.

There are two important points to be stressed regarding stream gauging stations. The first point relates to the selection of the station site, the second to the operation of the station.

The most important characteristics of a gauging station are those that affect the stability of the stage-discharge relation. The degree of stability of this relationship affects not only the amount of work necessary to establish and maintain the discharge rating curve and thereby the cost of operating the gauging 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-changing position and shape of the curve.

Thus, if the curve is permanent, the cost of operation will be moderate and the accuracy of the records high; if it is not permanent, then the cost of operation tends to be high and the accuracy of the records tends to be low.

Regarding the operation of gauging stations, the important thing is that observational data must be collected systematically if they are to have any value. Streamflow records must be obtained at gauging stations that are operated continuously. If not, the records will neither have the necessary reliability nor show the maxima and minima of flow, and they will not contain sufficient information to allow computation of the annual runoff.

1.2.7 Problems and Difficulties in the Collection of Streamflow Records

The theory for obtaining systematic records of streamflow 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 vegetal growth, 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 extra gauge downstream from the station site.
- At gauging stations located in reaches where the slope is very flat, the stage-discharge relation is frequently 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 a gauge reader 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 automatic recording of the water level. Conventionally, at automatic recording stations, the changing water level of the stream is registered by a cable and float-driven tracing stylus, the float being housed in a stilling well in the river bank and connected to the river by pipes. The crucial thing here is, of course, that the intake pipe and well must be kept open and free from obstructions. To solve the silting problem under conditions of heavy sediment load, the stilling well must be provided with facilities for digging and 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 a clear communication between river and stilling well.

Perhaps the greatest single factor that has frequently limited progress in streamflow data collection is the popular misconception that the collection and processing of streamflow data is easy and that anyone can do this work without prior training or experience in this discipline. In fact, it takes a long period of specialized experience in both field and office work before an engineer is trained thoroughly so that he can control correctly even the simplest operation of streamflow data collection and computation of streamflow records. The result of operating without such training will invariably show up in poor quality of the processed records.

1.3 New Developments in the Collection of Streamflow Data

During the last 10–15 years, many advances have taken place in the technology of stream gauging. These include development of new instruments, automation of streamflow records and new concepts of stream-gauging networks.

The Electromagnetic Flowmeter

The electromagnetic flowmeter operates on Faraday's principle that when an electrical conductor, in this case water, moves in a magnetic field an electrical current will be induced. As used in streamflow measurements, the meter records continuously the velocity of flow at a fixed cross section of the stream. The method uses a magnetic field generated by passing an alternating current through a horizontal coil buried in the channel bed. Voltage probes are placed in the banks to record the induced potential which is proportional to the mean velocity of the flow across the section. Present experience indicates that the application may be limited to channels up to 30 m wide. The gauging station must be calibrated and the electromagnetic output related to discharge. The current-meter method or dilution methods may be used for calibration. The electromagnetic flowmeter tolerates considerable variation in stage. The accuracy is about ±10%. [1], [2].

The Acoustic Flowmeter

The acoustic flowmeter utilizes transmission of acoustic waves in water to measure the velocity of flow in open channels. The method is most useful for continuous measurement of velocity on a permanent or semi-permanent basis as it has a relatively high installation cost.

Several acoustic flowmeter systems have been developed using variations of the same basic theory. Common to all is the measurement of flow velocity by determination of the time of travel of sound pulses transmitted diagonally in both directions across the stream between transducers mounted on each bank. The flow velocity indicated by the system is the average velocity component parallel to the diagonal path between the transducers. When the variation in water level in the channel is small, a single pair only of transducers is necessary. For larger variations in the water level, transducers are necessary at more than one level.

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

Due to scattering of the acoustic energy, sites with great amounts of entrained air, such as just below hydro-electric plants, should not be selected. Similarly, sites with a high concentration of suspended sediment are unsuitable. Sites with thermal or saline gradients should be avoided. Such gradients can cause the acoustic path to deflect from the theoretical straight line path between the transducers.

Stream channels up to 400 m wide have been gauged by the acoustic flowmeter. The accuracy depends on the preciseness of the calibration or the assumptions made in deriving the mean velocity. It is claimed that the acoustic method can achieve an accuracy of ±3% in natural river channels.

The Acoustic Flowmeter method is not in common use or standardized. Each station must be individually designed. [1], [2].

The Dilution Gauging Method

The measurement of stream discharge by the dilution 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 along a stream channel and to sample the water further downstream where turbulence has mixed the tracer uniformly over the cross section. The difference in concentration of the tracer in the injected solution and the tracer 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 entirely upon complete mixing of the injected solution with the stream water before the sampling cross section is reached and upon no adsorption of the tracer on stream bed material. The dilution method is used mostly for gauging streams with excessive turbulence which are difficult to gauge by use of the conventional current meter. [2].

Detailed procedures for The Relative Salt Dilution Method are given in Volume 3 of this Manual.

The Moving Boat Method of Measuring Stream-Discharge

A significant breakthrough in stream gauging in recent years is the *moving boat method* which is particularly suited to the accurate and rapid gauging of large rivers in remote areas. The method requires no fixed facilities and lends itself to the use of alternative sites if necessary. As with conventional current-meter measurements, the moving boat method requires information on the location of observation verticals, stream depth at each vertical, and the stream velocity normal to the cross section.

During the traverse of the motor boat across the river, an acoustic sounder records the bottom profile of the traversed section, while a continously operating current meter records the combined stream and boat velocity. A vertical vane aligns itself in a direction parallel to the movement of water past it, and an angle indicator attached to the vane assembly indicates the angle between the vane and the true course of the boat. The data from these instruments provide information necessary for computing the discharge for the cross section. Normally, data are collected at 30 to 40 observation verticals in the cross section for each run.

In recent years, the moving-boat method has been proved, through repeated trials, to be unquestionably the most efficient and economic means for gauging large rivers in remote areas. The method has been applied successfully on the Amazon and Sao Francisco Rivers in Brazil, the Parana River in Argentina and the Mekong River in Thailand and Laos. It has the advantages of speed, high mobility and relatively low cost and thus has wide potential application throughout the developing world.

A detailed description of the Moving Boat Method is given in reference [3].

The Bubble Gauge

The bubble gauge records the water stage in a stream without need of stilling wells and intakes. It works on the following principle: If a gas is bubbled slowly through a small-calibre tube and discharged freely at an orifice located at a fixed elevation in the water, the pressure at the orifice and at any point in the tube is a function of the depth of water over the orifice. The pressure is transmitted through the tube to a recorder where it is converted to stage and recorded. [2].

Automation of Streamflow Records

Automation of streamflow records includes a digital stage recorder and a general purpose high-speed digital computer. The recorder punches a digitized record of water level on a paper tape at pre-set time intervals. By feeding the stage record together with the discharge rating curve into the appropriately programmed computer, the data may be processed, analysed and presented in any form desired. The printout from the computer is ready for reproduction by photographic methods without any further editing.

Station Networks for the Collection of Hydrological Field Data

The essence of hydrological network planning is to achieve some stated operational goal in order to meet a stated objective, not only for scientific reasons, but for administrative reasons as well.

In planning a data collection network, the experience and judgment of the hydrologist is utilized. Appropriate emphasis is placed on sampling areas with different topography, geology, vegetative cover, climate, and to existing needs for data at specific sites. As the needs for data increase and the sampling techniques are improved, networks are expanded. As the network of gauging stations in a given country grows, it becomes necessary from time to time to evaluate and re-evaluate the entire network. Firstly, the stations are classified according to the purpose they serve 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 obtaining the necessary information are considered taking into account the climatic, socioeconomic and other applicable constraints, i.e. 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 – those having essential hydrological significance and operated for indefinitely long periods.

Secondary stations – those at which continuous flow records are collected for a period of only a few years (5–10 years).

Partial-record stations – those at which flow or stage is measured only during extremes of either high or low conditions.

According to current concepts of hydrological network design, a data collection network should consist of relatively few primary stations which would be operated indefinitely in order to sample variations in time. In evaluating the location and density of the existing primary gauging station, statistical methods are used to determine the degree of independence of the stations in the network. With these criteria, it is possible to eliminate duplicating stations and pinpoint new areas needing gauging. Thus, the optimum extent of the required primary network is determined.

On the network of primary stations there is superimposed a network of secondary stations to be operated for relatively short periods of time (5–10 years) in order to sample geographical variations. The basic rationale in the use of secondary and partial-record 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 satisfactory 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 the gaps between the primary stations. Then, through regression analyses based on the primary stations and on the concurrent observation at a secondary station, the secondary station record can be extended almost to the period of the primary station network. It is to be noted 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 rainfull data from nearby long-term meteorological stations, the regression may be greatly improved.

Thus, if conditions are favourable, planning and design of water resources projects may proceed safely after a relatively short extent of data collection at the project site. Substantial amounts of money and precious time may thus be saved if 5–10 years of data collection proves sufficient instead of 15 or more years, which is often considered the absolute minimum for design of a sizable project.

A final consideration in network design is the preservation of the collected data in a place and in a form both useful and easily available. The emphasis is on reliable data, centrally filed, permanently preserved and readily available. [4], [5], [6], [7].

The Vigil Network

The Vigil Network is intended to detect complex and dramatic changes in the hydrological environment resulting from conditions imposed by man. For this network, observation stations are set up in river basins that are subject to uses such as farming, grazing, deforestation, urbanization and other activities of man. [8].

Hydrological 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 chance 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. [8].

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 digital computer and the development of mathematical modelling techniques in recent years, a new era in our ability to analyse 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 recources, especially in the developing countries.

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 hydrology in recent years is limited unless long, undisturbed and continuous series of basic data records (streamflow and rainfall) are available. Minimum length is often considered to be 40–50 years. The concept of the Hydrological Bench Mark mentioned above is an attempt to preserve and prevent already-existing streamflow records from being curtailed by, for example, water resources development and river regulations, before they attain their useful and optimal length.

References Chapter 1: [1], [2], [3], [4], [5], [6], [7], [8].

2 STREAM GAUGING STATIONS

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

Either single-gauge or twin-gauge stations may be enployed 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, in such cases there is a unique relation between the discharge and the water levels at each end of a reach of the channel. 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 record of stage into a record of discharge through the stage-discharge relation.

The stage-discharge relation is normally determined by making discharge measurements at various stages of the stream and plotting the obtained discharges against the corresponding mean gauge-height on graph paper. The smooth curve drawn through the plotted points defines the stage-discharge relation and is called the discharge rating curve for the station.

When establishing a new stream-gauging station, the first objective must be to locate a stream channel reach with those characteristics that will assure a permanent stage-discharge relation. The relation between stage and discharge is controlled by a channel reach or section downstream from the station known as the *station control.* The term control does not only mean a particular cross section through the channel downstream from the station, but the definition in respect to its function includes all elements and features of the stream channel which govern and control the stage-discharge relation.

2.2 The Station Control

The channel characteristics forming the station 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 stream bed and banks, and the *vegetal cover,* all of which collectively constitute the factors determining the *channel conveyance.*

A station 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.

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 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 consist of a constriction of the stream channel, a rock bar or ledge across the channel forming a kind of weir, the crest of a waterfall or of a reach of rapids that fixes the stage-discharge relation at the station. A section control always has a forebay or pool which may extend from a few to several hundreds of metres upstream from the control. 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 upstream lip of the control and the point where the control is most effective in maintaining the stage-discharge relation. (Figures 1–4).

Figure 1. Complete section control, sensitive; low-water part of control is permanent, while high-water part is non-permanent. (Msadia River at Usevia, Tanzania).

Figure 2. Complete section control, permanent; low-water part of control is sensitive while high-water part is non-sensitive (Torsbjørka River at Mannseter, Norway).

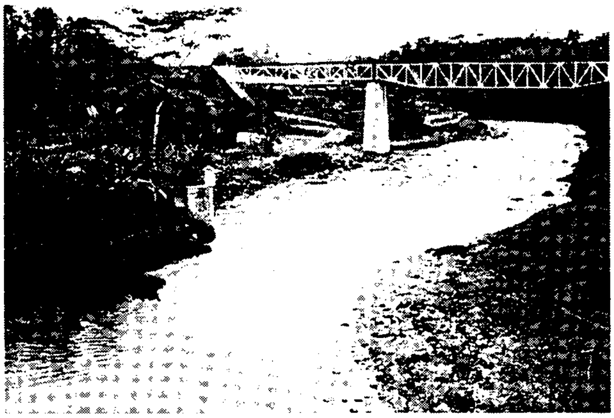


Figure 3. Complete section control with upstream pool, stable and sensitive (Progo River at Kranggan, Java, Indonesia).

Figure 4. Section control at outlet of a lake (Stryn River at Strynsvatn, Norway).

If the controlling features consist only of frictional resistance, slope and channel geometry in a relatively long reach of a stream channel, one speaks about a *channel control.* The channel type of control is inconspicuous because of the lack of a break in the slope of the water surface downstream from the station. At low discharges, a channel control is generally due to the slope in the water surface that is produced by the frictional resistance of the stream bed. (Figures 5–6).

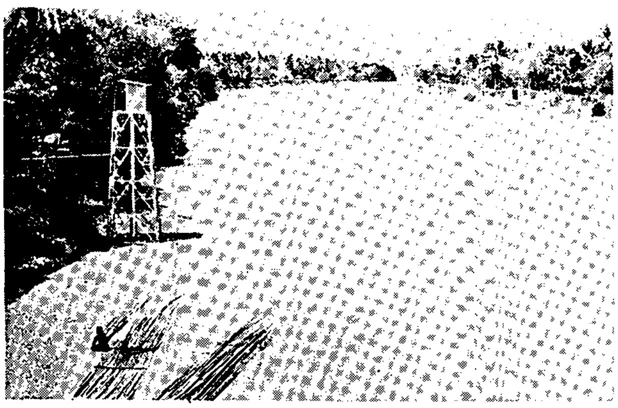


Figure 5. Channel control, moderately stable, probably shifting during and after major floods (Comal River at Comal, Java, Indonesia).

Figure 6. Channel control, stable; river flows on solid bedrock, banks consist of sand (Sao Francisco River at Petrolina/Juazeiro, Pernambuco, Brazil).

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 station 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 the discharge rating curve. On streams with steep slopes and high velocities one and the same reach of channel may be 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 at the gauge, and for a small change in discharge a relatively large change in stage will occur (as in a V-notch weir). A non-sensitive 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 per cent change in discharge.

2.2.1 The Low-Water Control

A low-water control usually consists of a natural bar or ledge across the stream bed, a rapid, or a contraction of the stream channel. Such a control causes a break in the water-surface slope 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 non-effective and it is said to be drowned out.

A channel-type low-water control is conspicuous because of the lack of a break in the water-surface slope.

Although the sensitivity of the 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 non-sensitive control.

An artificial control is a structure built by man. This may be a low broad-crested 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. (Figure 7).

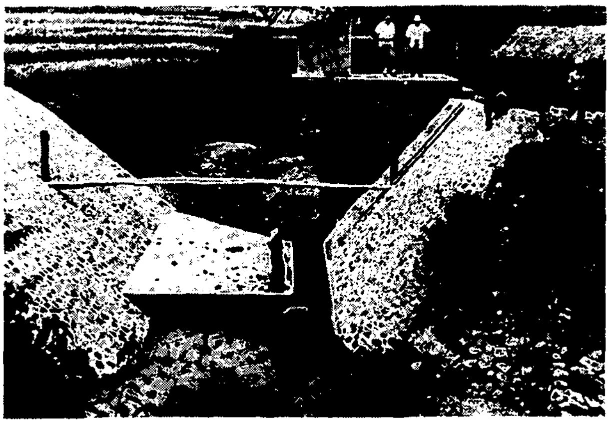


Figure 7. Artificial control to stabilize stream bed, steep gradient (Tributary of upper Solo River, Java, Indonesia).

2.2.2 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 stream bed. 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 the gauging station is of great value when analysing the relation between stage and discharge in order to establish the discharge rating curve.

Constrictions of the stream channel downstream from the 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, etc. usually act as constrictions. A sharp bend situated below the gauging station has a similar effect in that the slope shows a marked break at the bend.

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

2.2.3 Permanent Controls

Regardless of how stable and *permanent* a control may appear, it is always possible that a change may occur in the original 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 elements. 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 in the stage-discharge relation, is attainable only by comparing the results of discharge measurements with the previously established discharge rating curve.

2.2.4 *Shifting Controls*

The term shifting control as used in stream gauging signifies that the stage-discharge relation does not remain permanent but varies or changes with time. In such cases, the physical features forming the station 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 discharge rating curve as defined before the change.

It should be recognized that most natural controls shift slightly. 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 of the station. 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 vegetal and aquatic growth in the stream channel.

2.2.4.1 Erosion

Erosion (scour) of the stream bed and banks within the controlling reach of the channel will appear in the discharge rating curve as a shift to the right of the previous curve indicating an increase in the channel conveyance over that previously found 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 come into effect at the high stages maintaining the previous stage-discharge relation. On the other hand, the opposite situation may often occur where the low-water control is essentially permanent, as in the case of a rock ledge across the stream, while the high-water elements of the control, such as alluvial banks, are subject to erosion during high floods.

If a radical change has affected the controlling reach downstream from the station 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 discharge rating curve.

2.2.4.2 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.

The effect of deposition on a low-water control will be drowned out when full submergence occurs and the downstream high-water controlling elements take effect. 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 discharge rating curves spreading out fan-wise at the lower end and converging for stages above the beginning of submergence of the low-water control.

2.2.4.3 Shifts in the Channel above the Station Control

Shifts and changes in the stream channel above the station 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 channel takes place, the greater capacity of the forebay upstream from the control would result 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 would be the result.

2.2.4.4 Vegetal and Aquatic Growth in the Stream Channel

Vegetal and aquatic growth 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 growth is generally greatest in streams polluted by organic wastes.

Aquatic growth on and at 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. Floods may remove part of the effect from aquatic growth by flattening them out.

2.2.4.5 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. It is frequently practicable 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 whenever possible as it presents many complications, especially when determining the high-water segment of the rating curve.

2.2.4.6 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, that is, there are 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 a recorder, a steeper slope of the graph on a falling stage than on a rising stage 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 backwater caused by the ice.

2.2.5 Artificial Controls

A site with an unstable bed may be stabilized by the construction of an artificial control. However, a change in the hydraulic conditions which result from such a control must be expected to produce a change in the stream bed. The artificial control will increase the depth of water upstream thereby reducing the velocity of approach. If the stream does not carry any appreciable amount of sediment, the stream bed 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 sediments there may be continual changes (erosion and deposition) 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 immediately above the control may vary from time to time resulting in a variable stage-discharge relation.

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 stream bed in its existing shape as far as possible, and for this purpose the structure would raise the surface of the water the minimal 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. For larger streams, it is generally desirable to obtain the required results without a radical change in the hydraulic conditions. In small streams such a change may be, in most cases, less important.

2.2.6 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 gauge height at which the water ceases to flow over the control. Usually, this stage does not coincide with the zero of the gauge. The stage of zero flow is an important item of information and a very helpful aid in the construction of the discharge rating curve and it is included as a parameter in the discharge equation for the gauging station.

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 rocky ledge over which the water flows.

For other natural controls, particularly channel controls, the determination 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 should be 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 across the stream at the first complete break in the slope of the water surface below the gauge; 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/reach.

References Chapter 2: [9], [10].

3 SELECTION OF THE STREAM GAUGING STATION SITE

3.1 General

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.

3.2 Gauging Site Considerations

When a gauging station is to be established on a stream, a general reconnaissance is made so that the most suitable site may be selected. All available topographic and geologic maps of the area drained by the stream should be studied before any field reconnaissance is begun. 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 can 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. Aerial photographs, when available, are very helpful aids in this respect.

During the field reconnaissance, all suitable sites for a gauging station in the reach of the stream where the station is to be established should be examined. The field reconnaissance should include a sketch and photographs of the physical and hydraulic features at each possible site supplemented by the hydrologist's notes, comments and evaluation of the site.

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 often possible in practice, but the sites should be visited under as many different conditions as the time allowed for 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 sand, the stage-discharge relation can normally be defined only approximately. Research on sand-bed 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 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 in the vicinity is flooded. In flood plains, stage gauges only are usually required.

When selecting the site for a gauging station, the following items should be considered:

1. A consistent, stable and sensitive control.
2. Accessibility to the site at all times and at all stages of flow.
3. Availability of discharge measuring sites.
4. Correct placement of the stage gauge.
5. Opportunity to install an artificial control.
6. Availability of a local caretaker/observer.
7. Establishment costs.

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 must be carefully considered before a decision is made regarding the location of the station.

3.2.1 The Station Control

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

1. Stability and consistency.
2. Sensitivity.
3. Freedom from variable backwater.
4. Same amount of water passing gauge and control.

The ideal control should be stable so that there will be no appreciable 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 error in the reading of 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 a tributary entering the stream at or below the control. These tributaries leave deposits in the stream which affect the control, and often cause backwater on the control because of the staggered timing of flood peaks. The control should be examined to determine what effect ice and aquatic vegetation will have on the stage-discharge relation. There should not be a lake, reservoir or power pool in the reach of stream below the control that will cause backwater on the control of the selected site.

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 flow 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 constitute the control at the various stages of the stream.

Detailed investigations carried out by an experienced hydrologist are essential to define and locate the channel characteristics which control the stage-discharge relationship. In fact, the hydrologist must have considerable background in analysing discharge rating curves, and in studying the relationship between rating curves and the characteristics of their respective controls, before he can have any basis to predict 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 existing conditions when making surveys in order to locate new stream gauging sites. Therefore, sufficient time and study should be allowed for when selecting the site where a new gauging station is to be established. Hasty selection of gauging station sites has often meant the difference between an economical and a costly operation. A careful study of each possible site must be made in order to find the most favourable location. Unless the control features are conspicuous, it may not be possible to predict the permanency or the sensitivity of a prospective 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.

The simplest and most satisfactory type of a control is formed by a rock ledge at the head of a rapid or at the crest of a waterfall. Firstly, it ensures permanency; secondly, it creates a pool or forebay in which a gauging station is often easily constructed; thirdly, favourable conditions for carrying out discharge measurements may be frequently 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 a stream gauging station.

3.2.2 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.

By comparison with the channel characteristics necessary to maintain a permanent and sensitive

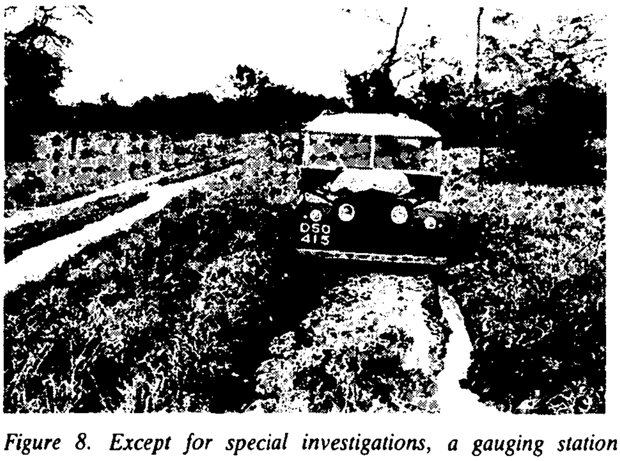


Figure 8. Except for special investigations, a gauging station should always be easily accessible by road or track during all seasons of the year. (Crossing water-logged ground between Dodoma and Ilangali on the Kisigo River during the wet season, Tanzania. Four-wheel drive vehicle and chains for all wheels are required).

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 in the selection of the gauging site. 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. (Figure 8).

Furthermore, the possibility of transporting heavy materials and equipment for the construction of the station is of primary importance. Under unfavourable conditions, the problems and cost of transporting heavy materials to the proposed site will be decisive with regard to the type of installation to be adopted.

3.2.3 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.

1. A discharge measurement is generally taken 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.
2. The stream at the gauging site should not overflow its banks and should preferably be in a single channel. If this is not possible, two straight uniform channels are preferable to one defective channel.
3. 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 upstream from the measuring cross-section should be twice that of the downstream. The channel bed and banks should be firm and stable.
4. 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.
   Sites with converging, and especially with diverging flow, should be avoided, as it is difficult to allow for the systematic errors that can arise.
5. 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.
6. The velocity should be neither too low nor too high. The most reliable measurements will be obtained at velocities from 0.2 to 2.5 m/s.
7. The general direction of flow should be normal to the measuring cross-section.

3.2.4 Placing the Stage Gauge

The gauge itself should be placed in the pool just upstream from a section control if this is available. However, it must not be placed so close to the control that it measures the stage of the rapidly-curving water surface immediately upstream from the control. Thus, the gauge or the intake orifice to an automatic stage-recorder must never be located on the crest of the control or in a place where there is a considerable slope or fall.

The gauge should be located on a straight reach of the channel rather than on a bend. It should be sited in a bay where it will be naturally protected against the force of the current and against flood water.

3.2.5 The Local Observer

Experience has shown that in order to ensure uninterrupted operation of recording stations, the routine attendance of a competent local observer 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 of sufficient ability to perform the duties of an observer are available. The necessity of having a station near adequate roads becomes more acute if an observer is needed, because few people are willing to move great distances to become a gauging station caretaker/observer.

3.2.6 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:

1. Accessibility of the site to manpower, materials and equipment.
2. Type of material to be excavated.
3. Need for protection of structure from floods.
4. Need for cableway or artificial control.
5. Type of gauge installation.

To make an accurate estimate of the cost of construction, some 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 when estimating the establishment costs of the proposed sites. 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 should be the annual cost of obtaining the field data such as the discharge measurements, datum checks, etc., the cost of the station maintenance and the cost of computing the daily discharge record.

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

3.3 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 followed by a preliminary survey to establish in detail the physical and hydraulic features of the proposed gauging 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/reach.

The plan of the station site should indicate:

1. The width of the river at a stated stage.
2. The edges of the natural banks of the channel, and the toe and crest of any flood-bank.
3. Any obstructions against the flow of water in the channel.

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

1. The level of the deepest part of the stream bed.
2. The level of the lowest point on a section control, corresponding to the stage of zero flow.
3. 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 change 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. When possible, the method of velocity distribution should be used for these measurements.

3.4 Definitive Survey of the Gauging Station Site

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

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

1. The instrument shelter or house.
2. Staff gauges and other non-recording gauges.
3. Intake pipes and static tubes.
4. Station bench mark and any auxiliary bench mark or datum marks within the instrument house for checking and setting the recorder.

The following sections are required:

1. A longitudinal section of the stream reach at the station showing the bed profile, including the lowest point on the control (stage of zero flow), the staff gauge, intakes for stilling well, and current-meter measuring section.
2. Cross sections extended up each bank of a section control, including one through the point of zero flow.
3. A cross section through the staff gauge extended up each bank.
4. Cross sections of the current-meter measurement section.

A cross section of the stilling pool is required approximately 3 m above any 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.

In those cases where the controlling section/reach is difficult to identify, a close grid of spot levels or a sufficient number of cross sections should be surveyed over the area of the assumed controlling section/reach.

References Chapter 3: [10], [11].

4 STREAM GAUGING STATION STRUCTURES

4.1 General

Four main types of structures are used at gauging stations:

1. Water-level gauge and bench mark. The gauge is usually a non-recording vertical staff gauge or an inclined staff gauge set at a chosen datum and referred to a bench mark.
2. Automatic water-level recorder. The automatic recorder is usually a float-actuated recorder with house and stilling well.
3. A structure for taking current-meter measurements, usually a cableway or a footbridge.
4. An artificial control such as a flume or a weir.

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.

The 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 the poor measuring conditions at the bridge, the inconvenience entailed in using some 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 some similar feature of the bridge for convenient spacing of the verticals during discharge measurements.

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

The construction of facilities for a gauging station should be very carefully planned to be certain that the resulting structures are correctly located, safe, and economical to operate and maintain. Most of the construction work is normally done by the Hydro Service's own personnel rather than subcontracting the work, because the jobs are usually small and the cost of preparing detailed plans and of supervising construction would have to be added to the contract cost. On the other hand, however, the use of a contractor where practical, frees the Service's own personnel for other tasks.

4.2 The Staff Gauge

The staff gauge is the type of gauge ordinarily used at non-recording gauging stations. At recording stations, the staff gauge is used as an outside reference gauge from which the recording instrument is set.

The staff gauge may be either 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. The sections are supplied in lengths of 1.00 and 0.50 metre and are graduated in 0.01 or 0.02 metre. The sections are usually screwed to a board which is fastened to a suitable support. Slotted holes in the plates are provided for final adjustment in setting the gauge.

Preferably, the gauge should be placed near the side of the stream so that a direct reading of the water level may be made (Figure 9). If this is impractical because of excessive turbulence, wind effect or inaccessibility, the observations may be made in a suitable permanent stilling bay or stilling well in which the wave actions are reduced and the level of the water surface closely follows the fluctuations of the water level in the stream. To ensure this, intakes to stilling wells should be properly designed and located.

Figure 9. Staff gauge (Bua River at Lillebudal, Norway).

The gauge should be located near to the current-meter gauging section without affecting the flow conditions at this point. It should not be placed where the water is disturbed by turbulence or where there is danger of damage by drift. Bridge abutments or piers are generally unsuitable locations. Wherever the gauge is situated, it must be readily and conveniently accessible so that the observer may make readings as near as possible at eyelevel. Where necessary, the construction of a flight of steps to give convenient access is recommended. The gauge plates should be securely fixed to the backing board, but provision should be made for removing the gauge plates for maintenance and adjustment.

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. The board should be attached to the surface of the wall so as to present a truly vertical face to receive the graduated gauge plates and it should be securely fastened to the wall. Gauges may also be fixed to piles, either driven firmly into the river bed or banks or set in concrete in order to avoid sinking, tilting or washing 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 levels exceeds the capacity of a single vertical gauge section, additional sections may be installed on the line of the cross section normal to the direction of flow (Figure 10).

Figure 10. Staff gauge in three sections (Seraju River at Rawalo, Java, Indonesia).

An inclined gauge usually consists of heavy timber securely attached to a permanent foundation. The graduations of an inclined gauge may be marked directly on the surface of the timber or may be carried on manufactured gauge plates designed to be set for particular slopes. Except where use is made of manufactured gauge plates, an inclined gauge should be calibrated in situ by accurate levelling from the station bench mark. Usually, various sizes of bronze numerals are used for the graduations. An inclined gauge should be 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 may be installed; frequently, however, it may be necessary to construct the gauge in several sections, each with a different slope. 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.

4.2.1 The Gauge Datum

The datum of the gauge may be a recognized datum such as mean sea level, or an arbitrary datum selected for the convenience of using gauge readings of relatively low numbers. In general, it is desirable to avoid negative values for gauge height readings; therefore, the gauge zero should be set below the level of zero flow in the case of a section control and below the lowest stage anticipated at the site in the case of a channel control. In this respect, it is recommended that one should always start the lowest gauge plate section at 1.00 metre instead of 0.00 metre so that minus readings are avoided if a very 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 the gauges at their correct datum, one and preferably two bench marks are required at a gauging station. A bench mark must be entirely detached from the gauges or their supports and secured against destruction and changes in elevation.

4.2.2 The Station Bench Mark

The *station bench mark* should 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 accurate 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 reciprocal levelling or with equally-balanced foresights and backsights. The level is transferred from the station bench mark 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, 10–15 cm long and 15 mm in diameter.

If the station is equipped with an automatic water-level recorder, it is practical to establish an auxiliary bench mark on the shelf for the instrument. It is then easy to check the inside gauge if it is at the correct level or the inside water level if no gauge is installed.

4.3 Auxiliary Non-Recording Gauges

In addition to the ordinary staff gauge, there are four other types of non-recording gauges that may be used at gauging stations. These are:

1. Wire-weight gauge.
2. Float-tape gauge.
3. Electric-tape gauge.
4. Crest-stage gauge.

4.3.1 The Wire-Weight Gauge

The typical wire-weight gauge 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 (Figure 11). The disc is graduated and is connected permanently to the counter and the shaft of the drum. The cable is guided to its position on the drum

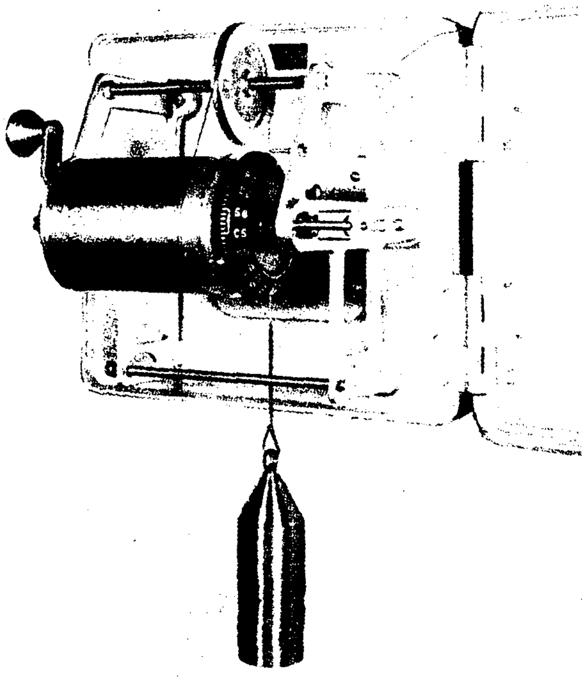


Figure 11. Wire-weight gauge (Leupold and Stevens).

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 normally mounted where there is a bridge, dock or other structure over the water.

4.3.2 The Float-Tape Gauge

The float-tape gauge is used chiefly as an inside stilling well reference gauge for a water-level recorder and consists of a float attached to a counterweight by means of a stainless steel tape. The tape is graduated in metres and centimetres and passes over a float pulley. The float pulley consists of a wheel grooved on the circumference to accommodate the tape and mounted in a standard. An arm extends from the standard to a point slightly beyond the tape to carry an adjustable index. The tape is connected to the float by means of a clamp which may also be used for making adjustments to the tape reading too large to be accommodated by the adjustable index. A 20 cm copper float and a 0.3 kg lead counterweight are usually used. (Figure 12).

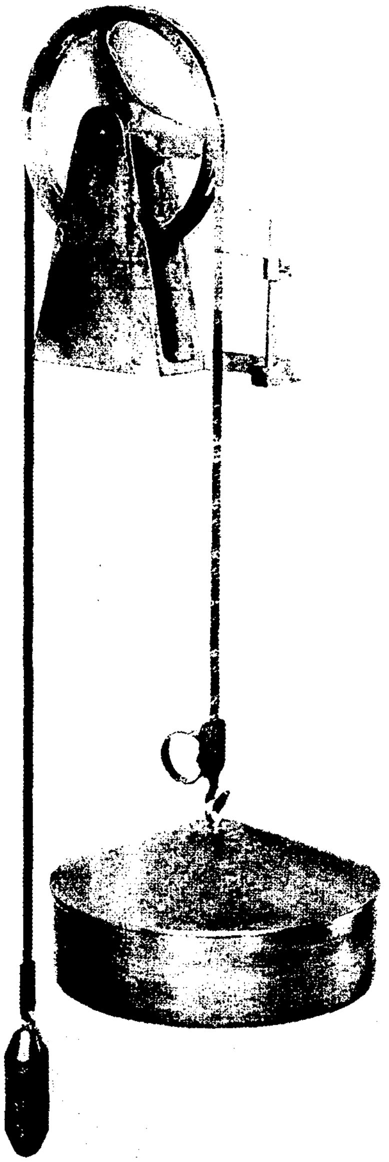


Figure 12. Float-tape gauge (Leupold and Stevens).

4.3.3 The Electric-Tape Gauge

The electric-tape gauge, like the float-tape gauge, is used almost exclusively as an inside reference gauge for water-level recorders. It offers two advantages over float gauges: a) it can be used in a stilling well which is too small to accommodate two floats and b) the possibility of errors caused by leaky floats is eliminated. This type of 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 source of electric current and an electric indicating device. All of these parts are supported by an insulated bracket. The source of the electric current commonly used is supplied by a 4.5 volt dry-cell battery.

With the gauge properly set to correct datum, the weight is lowered until it contacts the water surface, which completes the electric circuit and causes a bulb to light up. With the weight held in the position of contact, the tape reading is observed at the index provided on the reel mounting.

4.3.4 The Crest-Stage Gauge

The crest-stage gauge is a device for obtaining the elevation of the flood crest of streams; it is simple, economical, reliable and easily installed. The gauge consists of a 5 cm diameter galvanized pipe 1.5–2.0 m long containing a graduated wooden staff held in a fixed position and referred to the gauge datum. The bottom cap has several intake holes so as to keep the drawdown or superelevation inside the pipe to a minimum. The top cap contains a small vent. 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 inside the pipe, thereby retaining the highest stage of the flood. (Figure 13.)

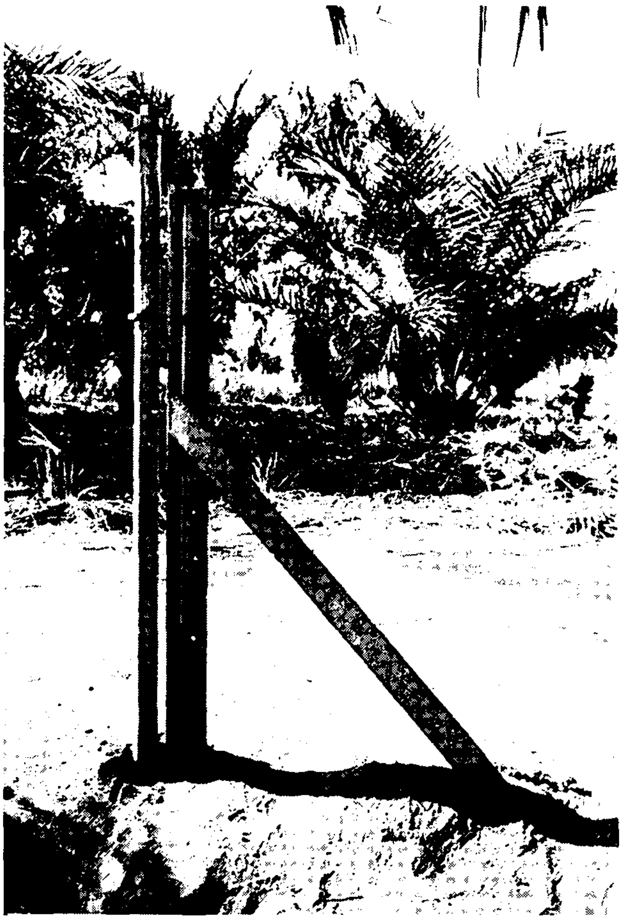


Figure 13. Crest-stage gauge. (Note. Intake covered by fine sand, pipe should be lifted).

4.4 Recording Gauges

The recording gauge consists of an instrument that senses and records the stage of a stream or lake. The instrument is commonly actuated by a float and counterweight system. To protect the float and to eliminate, or at least reduce the effect of surface waves and short period surges in the natural channel, it is customary to provide a stilling well. The stilling well is usually set back in the bank of the river and connected to it by one or more intake pipes, but sometimes placed directly in the stream. The recording instrument is sheltered in a house which rests on the top of the stilling well. Figure 14 shows a standard design of an automatic water-level recorder set in the river bank.

4.4.1 The Automatic Water Level Recorder

The automatic water-level recorder generally used is an instrument for producing a continuous graphic record of the rise and fall of a water surface with respect to time. It consists of a time element and a gauge-height element which, when operating together, produce a record of the fluctuations of the water surface on a chart. The time element is controlled by a clock which may be spring, weight or electrically-driven. The gauge-height element is actuated by a float. (Figures 15–16).

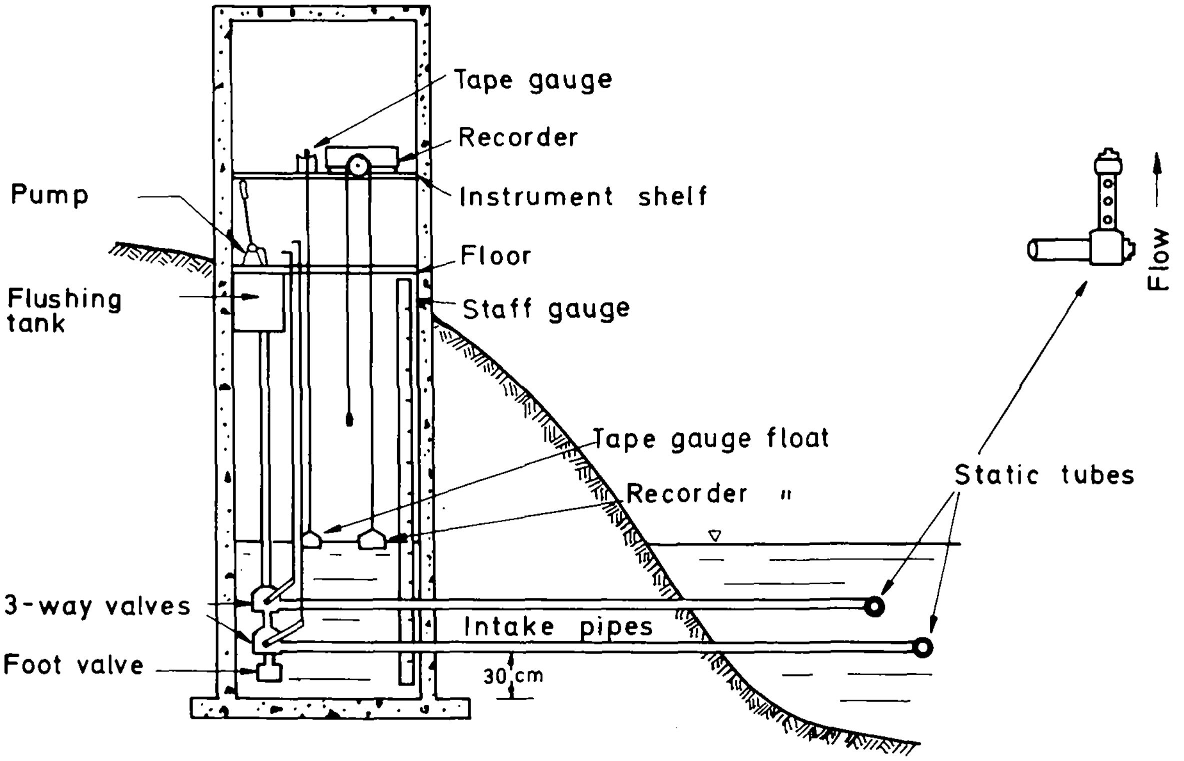


Figure 14. Standard design of automatic water level recorder station set in river bank; section of house, stilling well and intake.

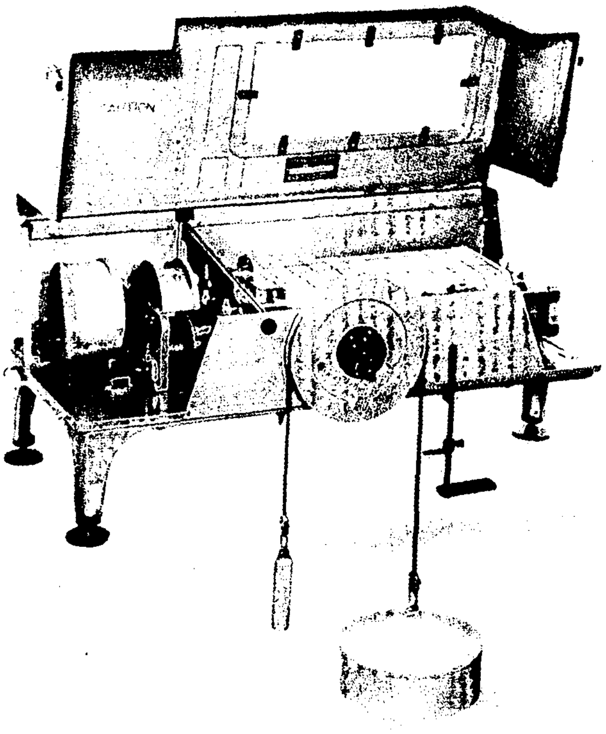


Figure 15. Continuous strip-chart water level recorder (Leupold and Stevens, Type A-35).

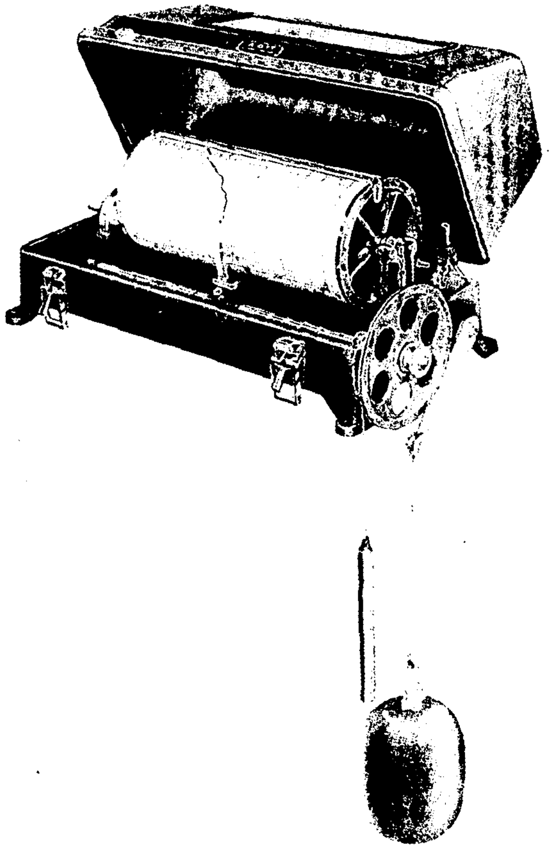


Figure 16. Drum-type water level recorder (A.OTT Type X).

Float actuation is essentially the same as for the non-recording float-tape gauge described in Section 4.3.2 except that the float pulley is attached to the water-level recorder. The float and counterweight are usually suspended from a perforated steel tape, but plain or beaded cable may also be used. Spines on the circumference of the float-tape pulley match perforations in the tape. As the float rises or falls, the float pulley turns a proportional amount thereby changing the gauge reading on the recorder. A copper float 25 cm in diameter is usually used, but smaller and larger sizes are used depending on the type of recorder, gauge-height scale, dimensions of the stilling well and accuracy requirements.

The graphic recorder supplies a continuous trace of water stage with respect to time on a chart. Generally, the gauge-height element moves the pen or pencil stylus and the time element moves the chart, but in some recorders this is reversed. Most graphic recorders are capable of recording an unlimited range in stage either by use of reversing devices on the strip-chart recorder or by reversing devices and unlimited revolutions of the drum-type recorder. Most strip-chart recorders will operate for several months without servicing, but drum-type recorders require attention at weekly or monthly intervals.

4.4.2 The Recorder House

The recorder instrument should be housed in a weather-proof and securely-locked house on top of the stilling well. 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 should be mounted on a rigid shelf or table firmly fixed to the foundations of the house. All operating instruments should be inside the house.

A recorder house with inside dimensions 120 cm by 120 cm with ceiling height 210 cm above the floor of the house is about the ideal size. (Figure 17). «Look-in» shelters may be used in special cases where short-time streamflow records are of interest and therefore provisional arrangements are satisfactory. (Figure 18). The house is usually 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 close-fitting 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.

Figure 17. Water level recorder station set in river bank; house made of concrete block (Rinna River at Rinna Dam, Norway).

4.4.3 The Stilling Well

The functional requirements of the stilling well are as follows:

1. To protect the float system.
2. To provide within the well an accurate representation of the water level in the stream.
3. 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 of concrete or steel. 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 big 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. Figures 19–23 show gauging stations with different types of stilling wells.

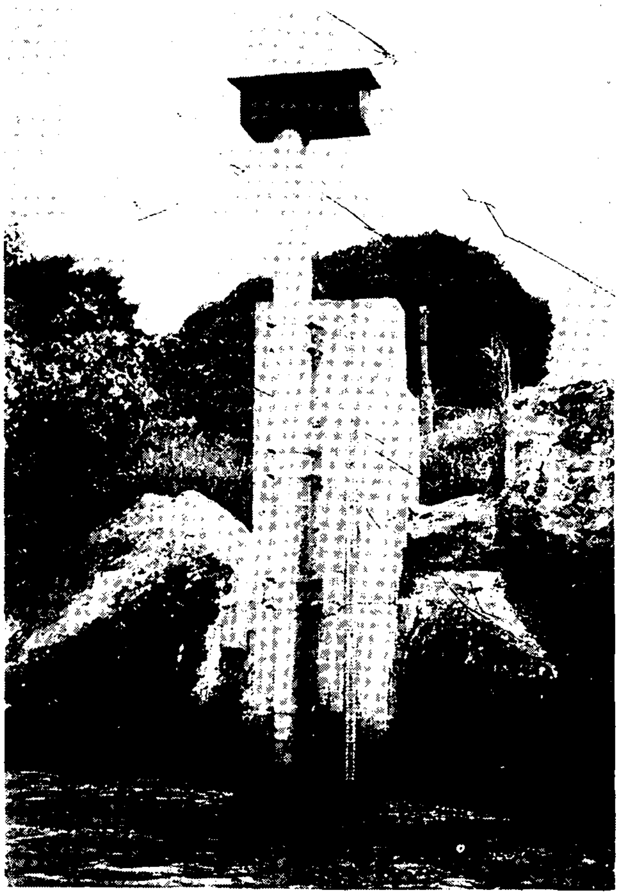


Figure 18. Water level recorder station; stilling well made of steel pipe, wooden «look-in» instrument shelter, supported by concrete pier (Little Ruaha at Ihimbu, Tanzania).

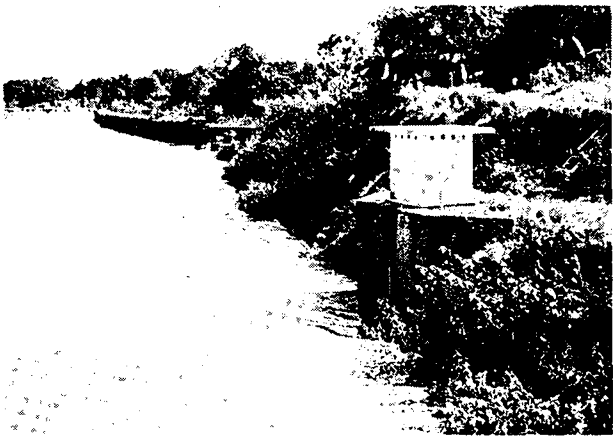


Figure 19. Water level recorder station set in river bank; stilling well made of masonry, house made of plastered brick, river bank protected against erosion by masonry wall (Cimanuk River at Tomo, Java, Indonesia).

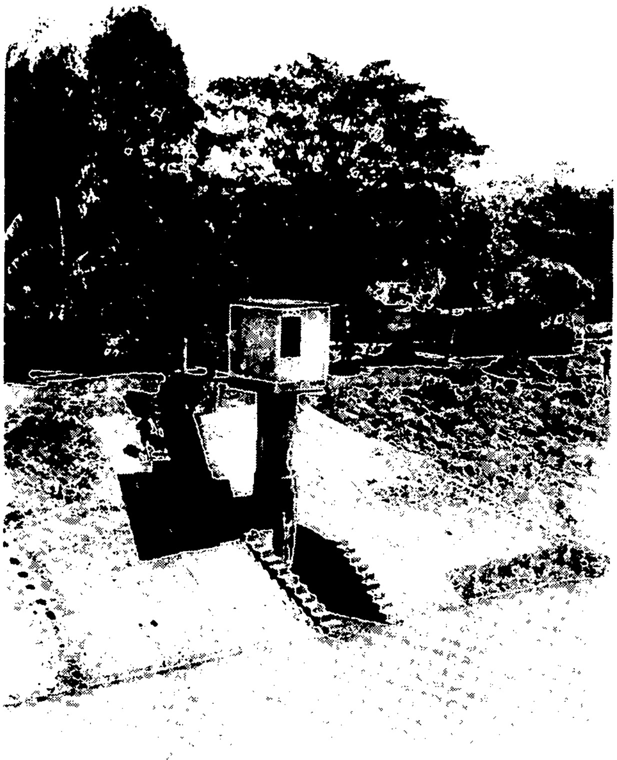


Figure 20. Water level recorder station; stilling well made of heavy concrete pipe, house made of plastered brick, bank-protection made of masonry (Cimanuk River at Djatibarang, Java, Indonesia).

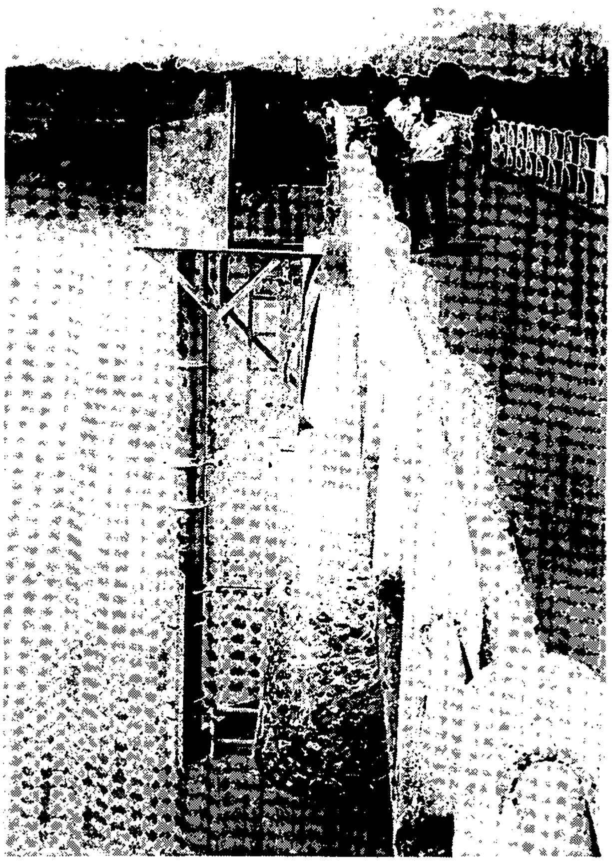


Figure 21. Water level recorder station; stilling well made of steel pipe, house made of sheet iron, attached to downstream side of bridge pier (Cimanuk River at Mandjot, Java, Indonesia).

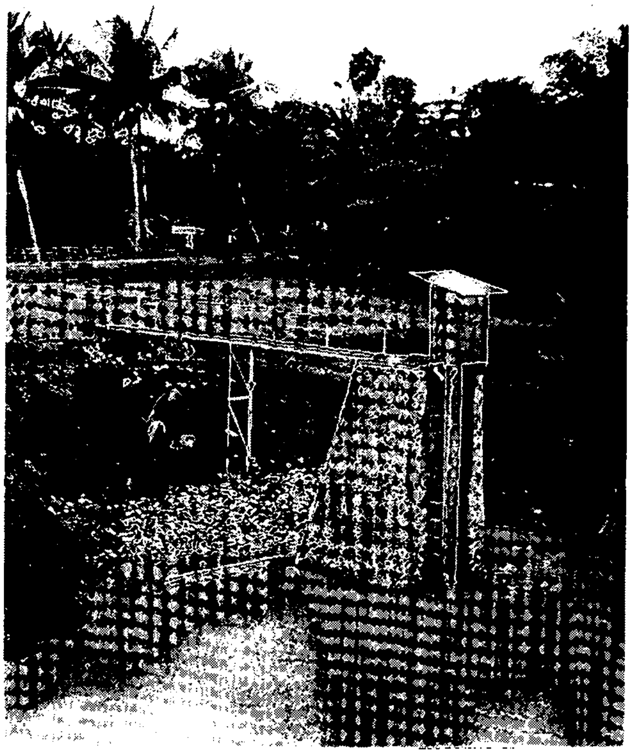


Figure 22. Water level recorder station; stilling well made of steel pipe, house made of sheet iron, supported by specially designed masonry pier, bank-protection by laid stones (Seraju River at Banjumas, Java, Indonesia).

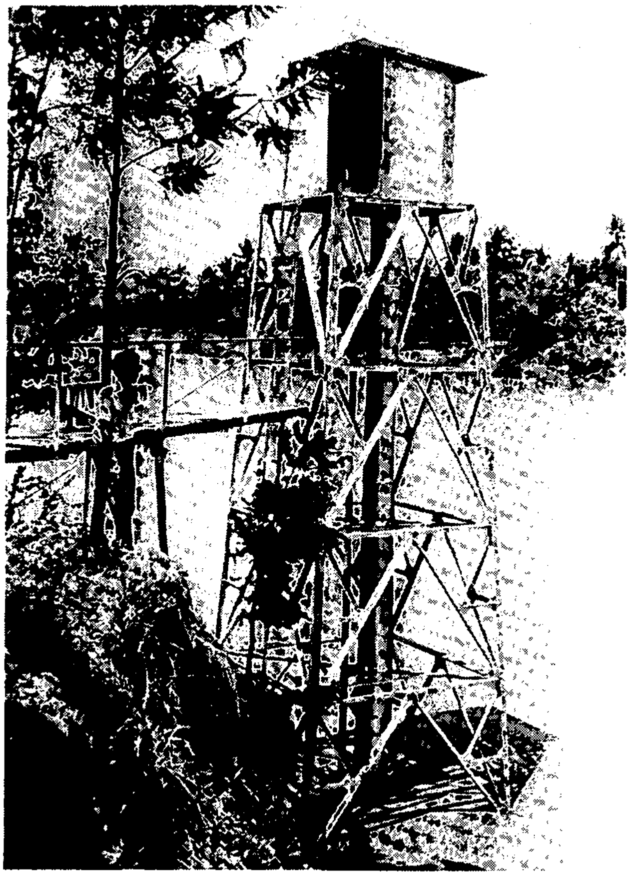


Figure 23. Water level recorder station; stilling well made of steel pipe, house made of sheet iron, supported by specially designed steel tower (Comal River at Comal, Java, Indonesia).

Normally, the dimensions of the stilling well should be large enough to provide ample space for the hydrographer to enter it and clean it or to make repairs. A pipe 120 cm in diameter or a well with inside dimensions of 120 cm by 120 cm is of suitable size. The smallest inside dimensions permitting entry and some space for cleaning out deposited mud are about 60 cm by 90 cm. The smaller metal pipe wells and high wells may have doors at various elevations to facilitate cleaning and repairing. (Figure 24). 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.

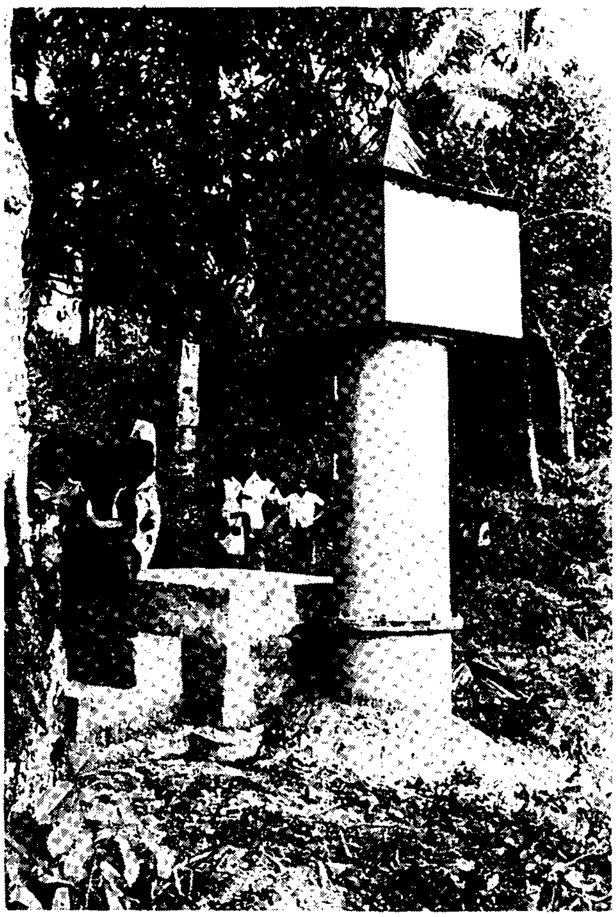


Figure 24. Water level recorder station set in river bank; stilling well made of steel pipe, «look-in» instrument shelter made of steel plates, door in stilling well to facilitate cleaning out sediment deposits (Tributary of Musi River, Sumatra, Indonesia).

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 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 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 should be 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 with silt, but the higher ones will function freely. The intake pipes should be large enough for the water in the well to follow the rise and fall of stage without significant delay. The following relationship may be used to determine the lag for an intake pipe for a given rate of change of stage:

$$\Delta h = \frac{0.01}{g} \cdot \frac{L}{D} \cdot \left(\frac{A_w}{A_p}\right)^2 \cdot \left(\frac{dh}{dt}\right)^2 \qquad (4.1)$$

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),

$\frac{dh}{dt}$ = rate of change of stage (m/s).

Intake pipes should be laid at 90° to the direction of flow and at a slight slope (1 : 100) to prevent air-pockets from forming inside the pipe. A valve should be fitted at the well end to control surge in the well.

If the velocity past the end of the intake is high, drawdown of the water level in the stilling well may occur. In order to reduce this drawdown, static tubes are often placed on the stream end of the intake pipes. The static tube consists of a short length of pipe, 50 cm long, 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 or leaves through holes drilled in its sidewall. (Figure 14).

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 this inside gauge is the same as for the outside reference gauge in the stream. For convenience, a permanent reference point inside the recorder house is often provided for easy periodic check surveys. This reference point must be 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 serviced. 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 maintenance can be carried out, corrections can be made and loss of records can be prevented.

Stations installed on streams carrying a significant amount of fine sediment (silt and clay) should be provided with the means of cleaning stilling well and intake pipes. The following means are in general use:

1. 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. (Figure 14.)
2. Pumping water through the intake pipes.
3. Building up a head of water and stirring up deposited silt in the well with a stationary hand-pump or a small engine-driven portable pump to force an obstruction out of the intakes.
4. Hand-cleaning of well and intake pipes by use of shovel and bucket, and flexible steel rods.

Stilling wells will often fill with sediment, especially those located in arid or semi-arid regions. A well placed on a stream carrying heavy loads of sediment must be cleaned out often. In such cases, a sediment trap can greatly reduce the work of removing the sediment. A sediment trap consists of a large box-like structure located between the intake and the stilling well. Inside it, baffles are fitted to promote settling before the sediment reaches the stilling well. The trap is made to open for easy access and removal of the deposited material.

To reduce and eliminate the silting problem of stilling wells, the vertically hung pipe well has proved practical (Figures 21–23). This is a 40 cm diameter steel pipe provided with a so-called hopper bottom that will, in general, keep itself clear of silt. Figure 25 shows a hopper bottom of a 40 cm diameter steel-pipe 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 combined with small oscillations and fluctuations of the water surface will not permit the deposition of silt inside.

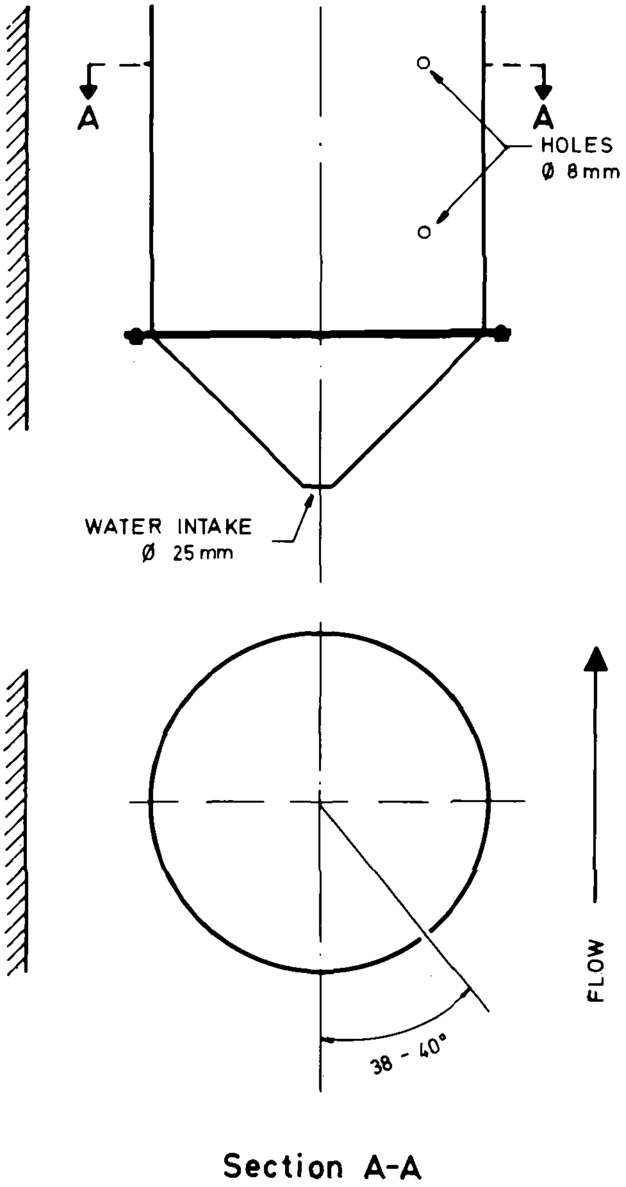


Figure 25. Hopper bottom for pipe stilling well.

Sometimes not even a hopper bottom can keep the well clear of silt. In these cases, a self-seating 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 (Figure 26). Instead of a cone, a light weight may be provided as illustrated in Figure 27. With this arrangement, the chain is worked up and down through the intake hole and the accumulated silt cleared away.

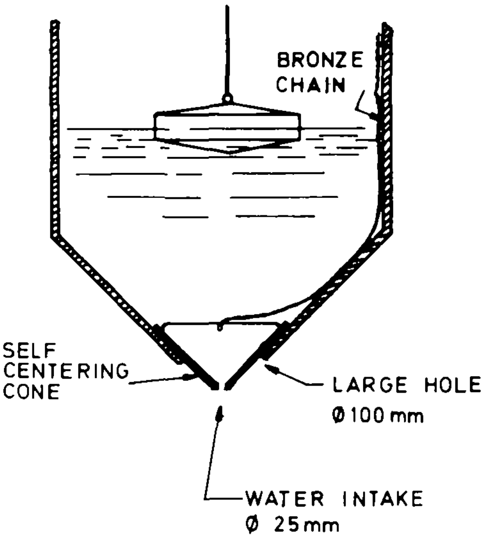


Figure 26. Section of hopper bottom for pipe stilling well with cone and chain for cleaning out sediment deposits.

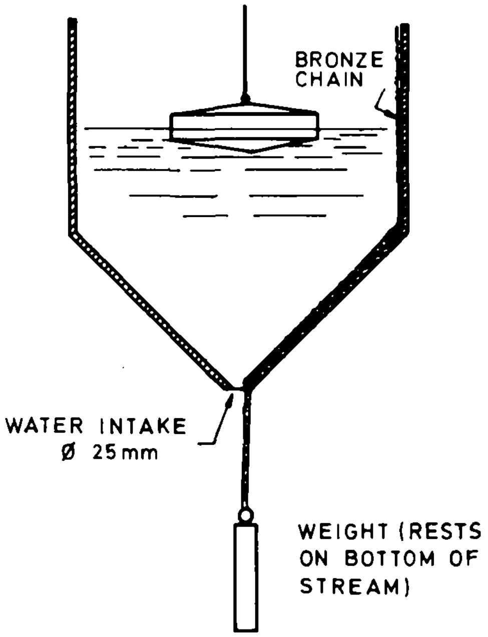


Figure 27. Section of hopper bottom for pipe stilling well with weight and chain for cleaning out sediment deposits.

The velocity of the water at the point of the hopper must not exceed about 1 m/s; otherwise the water level in the well will be drawn down. Superelevation of the inside water level may also occur at some sites. The drawdown or superelevation inside the pipe can be kept to a minimum by drilling a few small intake holes in the side-wall of the pipe at various levels and at an angle of 30–45 degrees with the direction of flow. In general, for a stilling pipe mounted on a pier or wall, the angle should be 38–40 degrees as indicated in Figure 24. However, the self-cleaning effect of the hopper bottom will be reduced when the side-wall of the pipewell is punctured and it is no longer watertight.

4.5 Selection of Stage Gauge Equipment

Often, the funds available for the establishment of new gauging stations limit the choice of the equipment to the non-recording type of gauge. Non-recording gauges are cheap to install and supply reliable data if the observer is dependable and the stream stage does not change rapidly. Non-recording gauges on flashy streams (those having rapid stage changes) often provide inaccurate records because two or three observations per day are not enough to properly define flood hydrographs. The daily readings, however, may be supplemented by the stage of the flood peak which can be obtained from a crest-stage gauge.

The main advantage of non-recording 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 non-recording 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.

Non-recording gauges are always used as auxiliary gauges at automatic water-stage recorder installations to serve the following purposes:

1. They serve as a reference gauge to indicate the water surface elevation in the stream.
2. 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 is being obtained in the well.
3. When the intakes are plugged or there is equipment failure, the outside reference gauge can be observed daily or more often by a local observer 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 a short period, 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 served and maintained only by well-trained inspectors.

4.6 Cableways

To obtain the discharge measurements and sediment samples required at gauging stations, it is necessary to suspend the measuring and sampling equipment at numerous points across the stream channel. The most practical way of suspending the equipment is by a cableway spanning the channel. Suspension from cableways avoids the difficulties met in gauging from bridges with piers and from boats.

Figure 28. Cableway with instrument carriage (Solo River at Wonogiri, Java, Indonesia).

There are two basic types of cableways, namely:

1. Those with an instrument carriage controlled from the bank by means of a winch. (Figures 28–29).

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

2. Those with a manned carriage in which the operator travels across the stream and makes the observations (Figures 30–31).

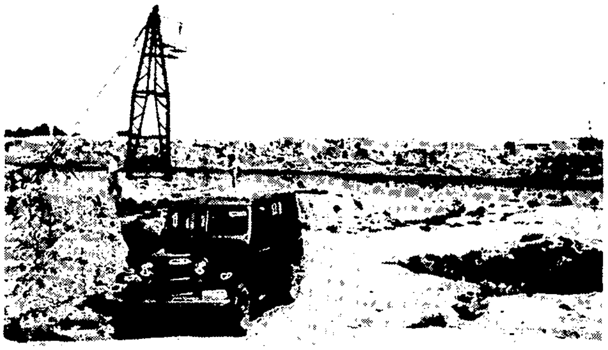


Figure 30. Heavy cableway with personnel carriage (Karun River near Ahwas, Iran).

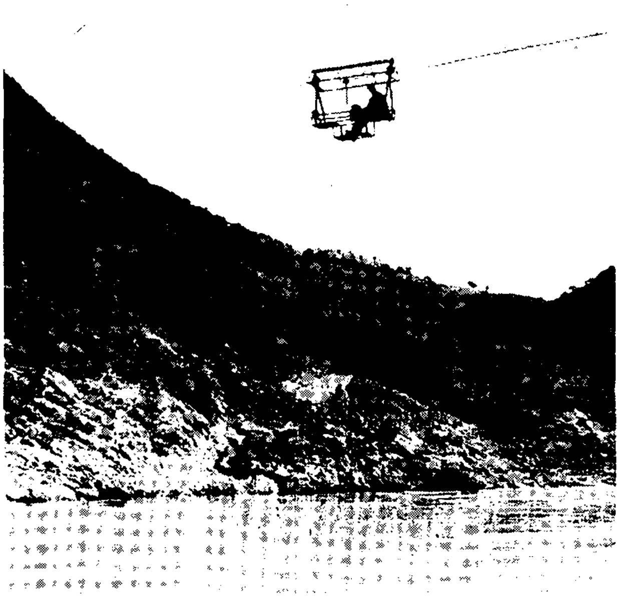


Figure 31. Cableway with personnel carriage (Dez River at Tang-e-Panj, Iran).

4.6.1 Cableway with Instrument Carriage

The cableway system with instrument carriage consists of (Figures 32–33):

1. Supporting posts (towers).
2. Track (main) cable.
3. Anchorages.
4. Staylines (backstay).
5. Towing cable.
6. Instrument suspension cable.
7. Instrument carriage.
8. Double-drum winch or two independent winches.

4.6.1.1 The Supporting Posts and Towers

The supporting posts are erected one on each bank of the channel. The posts support the main cable at a sufficient height as the suspended equipment travels along the main cable between the posts. The post 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 track or main cable should pass freely over a saddle on top of the post at the operating bank with negligible bending movement on the post. The post 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 posts should be at the same level. Instead of a post, the support on the opposite bank may often consist of a side-hill anchorage where the bank is steep.

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

The posts or towers must be designed to take all loads which are to be supported in addition to their own weight; wind loads must be 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 tower should 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 m above the highest flood level and ensure that the cableway

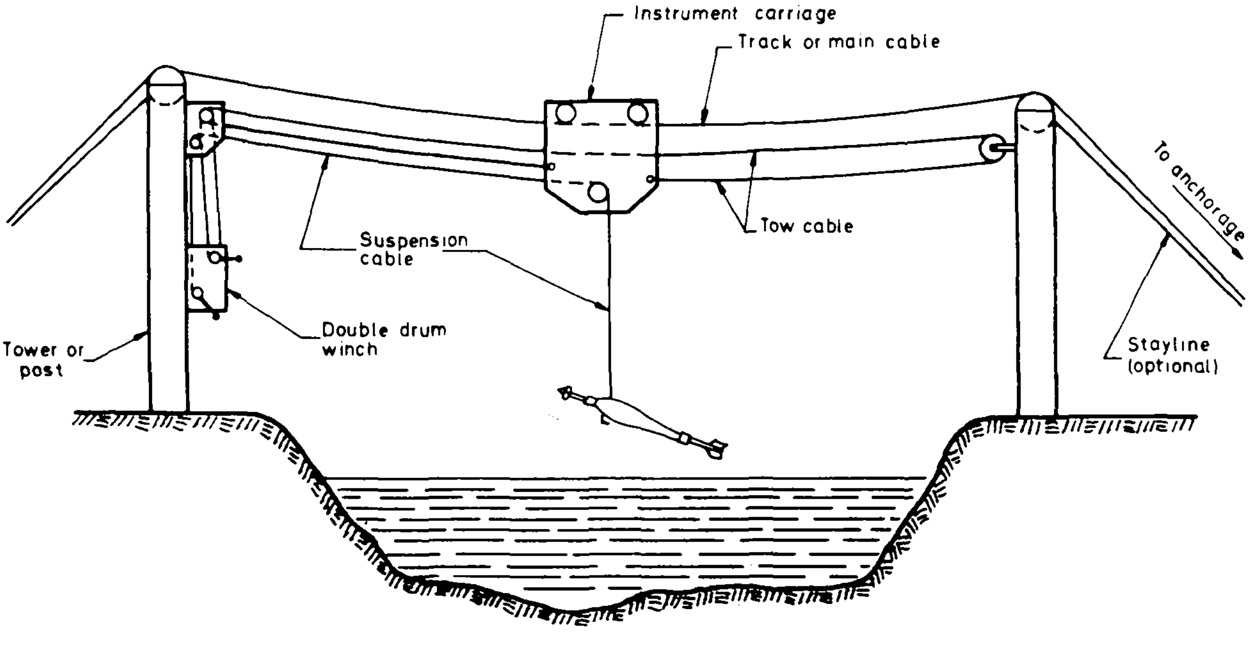


Figure 32. Cableway system; double-drum winch and instrument carriage with towing cable in endless circuit, separate suspension cable.

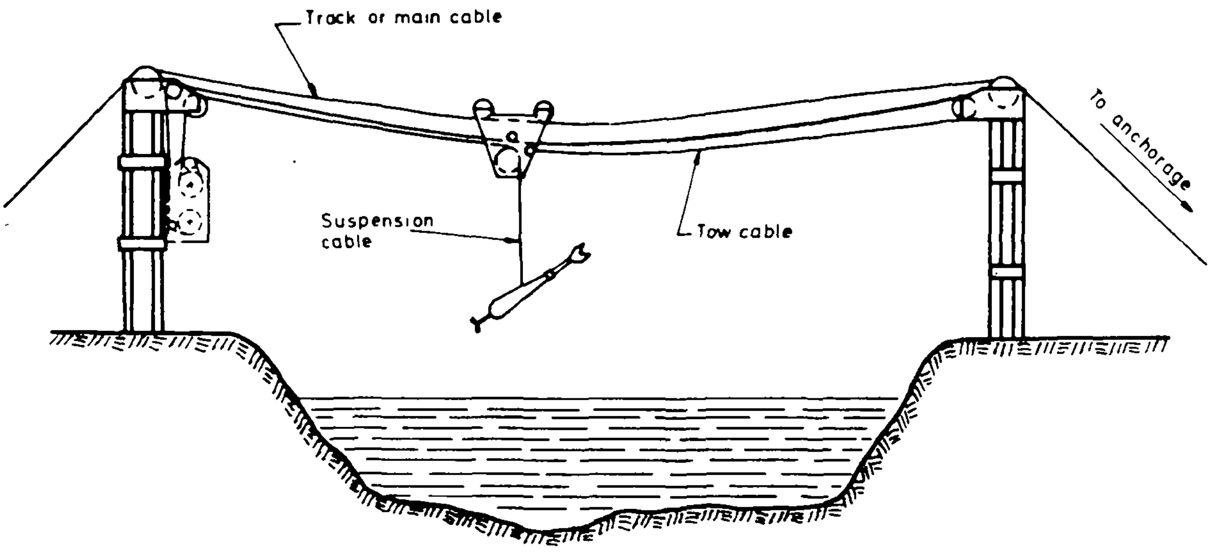


Figure 33. Cableway system; double-drum winch and instrument carriage with towing cable and suspension cable in endless circuit.

does not interfere with navigation along the channel. Aircraft warning signs may be provided according to local regulations.

Various types of constructions are used as supporting posts. For long spans, high towers may be 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 the 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.

4.6.1.2 The Track or Main Cable

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

The track cable should be corrosion-resistant. 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» cables should be provided.

The horizontal component of the tension in a cable suspended between supports of equal height is given by the formula:

$$H = \frac{wS^2}{8D} + \frac{PS}{4D} \qquad (4.2)$$

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

The actual tension in the cable is given by the formula:

$$T = H\sqrt{1 + \frac{16D^2}{S^2}} \qquad (4.3)$$

Some typical tensile strength and load values for an instrument-carriage cableway can be given as follows:

1. Track cable: diameter 15 mm, tensile strength 12,000 kg.
2. Suspension cable with insulated two-conductor core: diameter 2.5 mm, tensile strength 450 kg.
3. Load per running metre of cable (weight of cable + wind) for 15 mm cable: 1.0 kg per metre.
4. Concentrated moving load (weight of current meter + trolley + pressure head):
   with 25 kg suspended equipment, P = 65 kg
   with 50 kg suspended equipment, P = 100 kg
   with 100 kg suspended equipment, P = 170 kg

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

4.6.1.3 The Anchorages

The anchorages are fixtures to which the track cable and staylines are attached. The anchorage must be adequate to take up the maximum load for which the cableway is designed. It must be set in direct line with the track cable and it must be so placed that it can be easily inspected.

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, anchor-bolts or rods properly set in the rock may be used.

When a rigid connection is made to an anchorage by means of an anchor-bolt, the anchor-bolt must be set in a direct line and in the same plane with the connecting stayline so that there will be no bending moment in the anchor-bolt.

4.6.1.4 The Staylines

Staylines (backstay) are cables attached to the top of each supporting post or tower and to the anchorages to counteract the load of the track cable and to ensure stability for the supports. The staylines should be of corrosion-resistant steel and of sufficient strength to maintain the tower in a vertical position under all loading conditions. Means for adjusting the tension in the staylines must be provided.

4.6.1.5 The Towing Cable

The towing cable is attached to one of the drums in the double-drum winch or to a separate winch, and passes over the sheaves fixed to the towers. The two ends of the towing cable are fixed to the instrument carriage making it an endless circuit to move the carriage across the stream (Figure 32). Alternatively, one end of the towing cable may be attached to the carriage and the other end wound on the drum (Figure 33). The towing cable must have means of adjusting the tension in the cable (turnbuckle) if it makes an endless circuit. In the alternative case, the tension in the cable is given by the weight of the suspended instruments. The towing cable should be corrosion-resistant and as light and flexible as possible.

4.6.1.6 The Suspension Cable

The suspension cable is wound on the second drum in the double winch or on a separate winch, and passes over the sheave on the post at the operating bank, and then passes over the pulley in the instrument carriage. The measuring or sampling instruments are attached to the end of the suspension cable. The suspension cable has an insulated inner core which serves as an electrical conductor for the measuring instruments.

The suspension cable should be of corrosion-resistant material; it should be preformed and reverse laid to prevent spinning and rotation. The cable must be of sufficient strength to suspend the current meter and sounding weight. A breaking strength of five times the maximum load to be used should provide 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 should be equipped with a suitable connector for attachment of the measuring equipment.

4.6.1.7 The Instrument Carriage

Two track pulleys are 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 should be provided to prevent too large a sag in the suspension cable.

4.6.1.8 The Gauging Winch

A double-drum winch or two independent winches may be used. In the double-drum winch, the suspension cable is wound on one of the drums and the endless towing cable passes round the other, then over the sheave on the supporting post on the opposite bank. Alternatively, the towing cable may be wound on the latter drum. Horizontal and vertical travel of the measuring equipment attached to the suspension cable are controlled by a lever which either couples only the suspension cable drum 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 indicating the depth of the suspended instrument. (Figure 34). Instead of a double-drum winch, two separate winches may be used for horizontal and vertical movements (Figures 35–36).

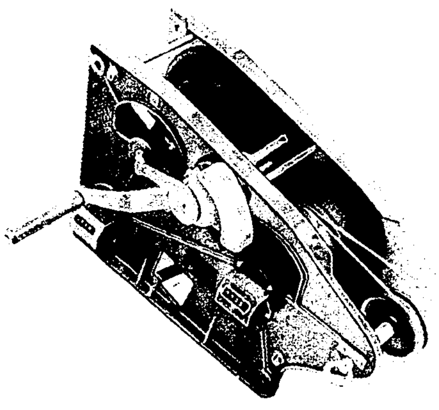


Figure 34. Double-drum winch (A.OTT).

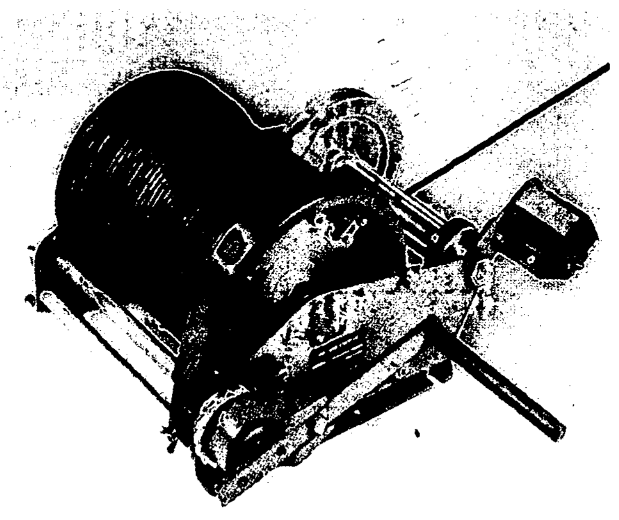


Figure 35. Single-drum winch for vertical movement of current meter (NEYRPIC).

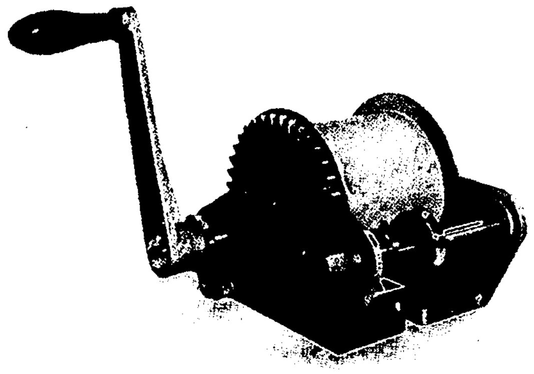


Figure 36. Single-drum winch for horizontal movement of current meter (NEYRPIC).

4.6.1.9 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.

4.6.2 Cableway with Personnel Carriage

The manned-carriage cableway system consists of (Figure 37):

1. Supporting towers.
2. Track cable.
3. Anchorages.
4. Staylines.
5. Personnel carriage.

Item Nos. 1, 2, 3 and 4 are similar to those described for cableways with instrument carriage.

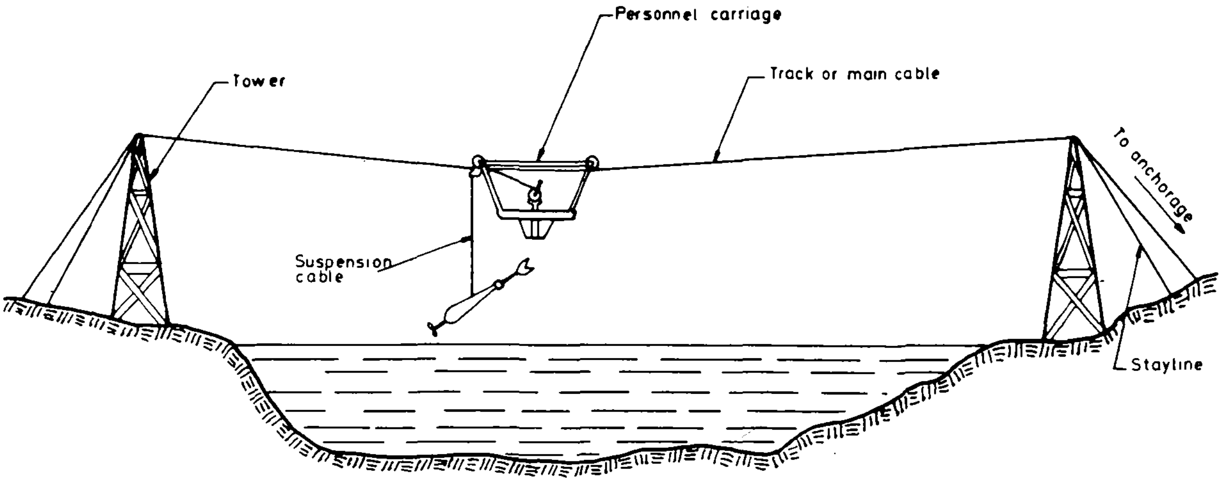


Figure 37. Cableway system; heavy cableway with personnel carriage.

4.6.2.1 The Personnel Carriage

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

4.6.2.2 Design and Safety Considerations for Cableways with Personnel Carriage

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.

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 or track cable that will meet the requirements most satisfactorily.

The loads to be considered in the design are: a) the dead-load weight per running metre of cable which may be the limiting load for long spans, b) the concentrated load carried by the cable car, and c) loads caused by wind and ice.

The concentrated load that is carried by the cable car consists of the weight of the car and the equipment and two men, 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 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.

Two different types of cable are used for the track cable of cableways. These are: a) wire rope and b) tramway track cable. Generally, the smallest diameter used for the track cable is ¾ inch 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 of 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. Ordinarily, a wire rope with a hemp core should be 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 erection, hemp-core 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 its several parts. The parts of the structure for which individual designs are necessary are: a) the track cable, b) the supports, c) the anchorages, d) footings for the supports, e) 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.

A-frames and towers that are constructed of galvanized light-weight structural members shall be designed for twice the expected working loads, the allowable tensile stress used in the design shall not exceed 1100 kg/cm^2. The l/r ratio for columns and struts shall 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 T are recommended for the main or track cable: a) one-fifth the breaking strength of galvanized improved plow-steel wire rope and b) 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 should be 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 weldings shall be permitted on any parts of eyebars, turnbuckles or anchorage rods. The specifications shall 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 must be 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 shall be at least five for the ¾ inch diameter rope with a minimum spacing of 12 cm between the clips, and six clips for the 1 inch diameter rope with a minimum spacing of 16 cm. 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.

4.6.3 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.

4.6.4 Maintenance of Cableways

All steel cables must be regularly inspected and lubricated. All other connections and structural components made of steel must be protected against corrosion by painting. The sag of the track cable should be checked at regular intervals, particularly when great changes in temperature occur, and adjustments made accordingly.

Anchorages should be regularly inspected and repaired where necessary.

4.7 Artificial Controls

At gauging stations where the natural controlling features do not provide the stability and sensitivity required of the station control, artificial controls may be used. Artificial controls are structures built in a stream channel to stabilize the channel at a section. They may be low dams, broad-crested weirs conforming to the general shape and height of the stream bed, or flumes similar in design to the Parshall flume. Refer Sections 2.2.1 and 2.2.5.

A great variety of designs is possible and it is important to realise that practical experience is essential before the design of artificial controls can be attempted. As a general rule, particular attention should be paid to the following points, refer Section 2.2.5:

1. Discharge capacity of the structure at all stages.
2. Likelihood of keeping the crest clear of debris and bed material.
3. Sensitivity of the stage-discharge relation.
4. Avoidance of turbulence.
5. Prevention of excessive seepage under and around the structure.
6. Structural stability.
7. Construction and maintenance costs.

There are three distinctive control structures that are often used in natural channels when conditions are favourable. The three types are the Trenton, Columbus and Asheville. The Asheville type is adapted for locations where the control can be placed on bedrock and where no apron is necessary, whereas the other two types are adapted for most natural channels. (Figure 38).

Artificial controls installed in canals and ditches consist of sharp-crested weirs and critical depth meters. The shape of the sharp-crested weirs are usually 90° V-notch, rectangular or trapezoidal. Where there is sufficient available fall in a canal and the quantity of water to be measured is not too large, the 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 or too much floating debris, or the discharge is too large for a weir, critical depth meters are used. One type of critical depth meter used is the Parshall flume or some variation of this flume. Debris and silt tend to be swept through the critical depth meters by the increased velocity which results from the constriction.

References Chapter 4: [12], [13], [14], [15], [16], [17].

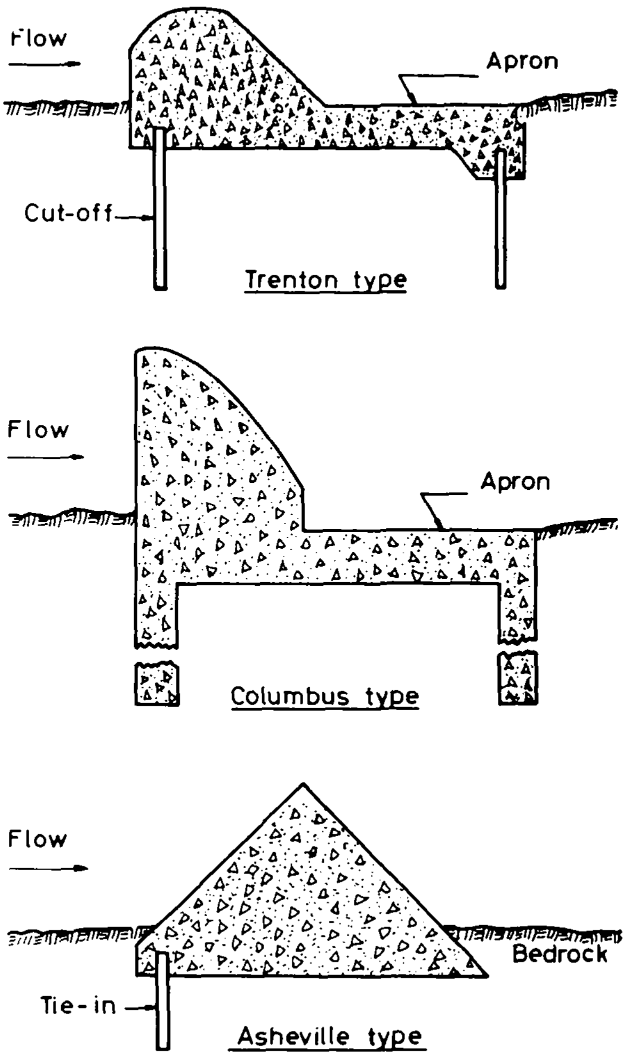


Figure 38. Different types of artificial controls.

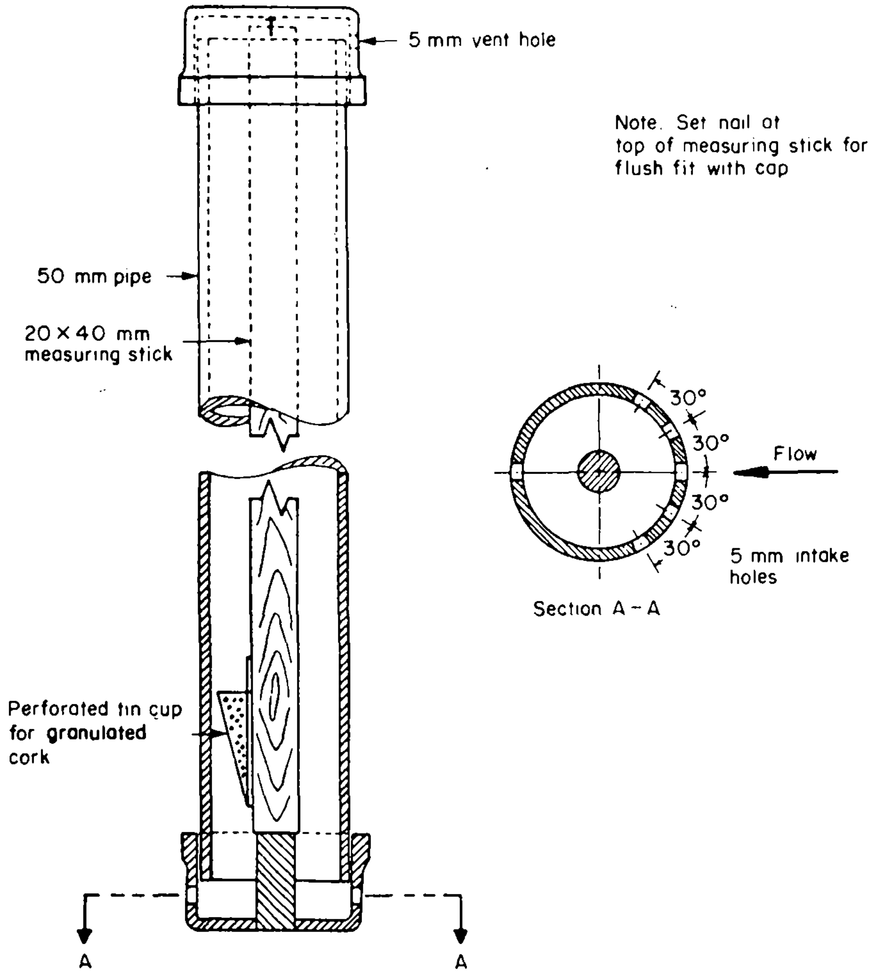
REFERENCES

1. Green, M.J. and Herschy, R.W.
   1976: Site calibration of electromagnetic and ultrasonic river gauging stations. - Proc. International Symposium on Hydrometry Padua 1975, World Meteorological Organization (WMO - N0. 427), Geneva.
2. Charlton, F.G.
   1978: Measuring flow in open channels: a review of methods. - Construction Industry Research and Information Association (CIRIA), London, 160 p.
3. Smoot, G.F. and Novak, C.E.
   1969: Measurement of discharge by the moving boat method. - United States Geological Survey, Techniques of Water Resources Investigations, Book 3, Chapter A 11, Washington D.C., 22 p.
4. Kohler, M.A.
   1958: Design of hydrological networks. - World Meteorological Organization, Technical Note No. 25 (WMO - No. 82. TP. 32), Geneva, 16 p.
5. Rodda, J.C.
   1969: Hydrological network design - Needs, problems and approaches. - World Meteorological Organization, WMO/IHP Report No. 12, Geneva, 57 p.
6. World Meteorological Organization
   1972: Casebook on hydrological network design practice. - (WMO - No. 324), Geneva.
7. World Meteorological Organization
   1975: Hydrological network design and information transfer. - Operational Hydrology Report No. 8 (WMO - No. 433), Geneva, 185 p.
8. Langbein, W.B.
   1968: Hydrological bench marks. - World Meteorological Organization, WMO/IHD Report No. 8, Geneva, 8 p.
9. Corbett, D.M. and others
   1945: Stream-gauging procedure. - United States Geological Survey Water-Supply Paper 888, Washington D.C., 245 p.
10. Grover, N.C. and Harrington, A.W.
    1966: Stream flow - measurements, records and their uses. - Dover Publications Inc., New York, 363 p.
11. International Organization for Standardization (ISO)
    1973: Liquid flow measurements in open channels - Establishment and operation of a gauging-station and determination of the stage-discharge relation. - Ref. No. ISO 1100-1973 (E), Geneva.
12. Buchanan, T.J. and Somers, W.P.
    1968: Stage measurements at gauging stations. - United States Geological Survey, Techniques of Water Resources Investigations, Book 3, Chapter A7, Washington D.C., 28 p.
13. International Organization for Standardization (ISO)
    1978: Liquid flow measurement in open channels - water-level measuring equipment. - Ref. No. ISO 4373-1978 (E), Geneva.
14. Pierce, C.H.
    1947: Equipment for river measurements - Structures for cableways. - United States Geological Survey Circular 17, Washington D.C., 38 p.
15. Powell, K. and others
    1978: Portable current meter cableways and winches. - United Kingdom Department of the Environment Water Data Unit, Technical Memorandum No. 17, Reading, 12 p.
16. International Organization for Standardization (ISO)
    1978: Liquid flow measurement in open channels - cableway system for stream gauging. - Ref. No. ISO 4375-1978 (E), Geneva.
17. World Meteorological Organization
    1971: Use of weirs and flumes in stream gauging. - Technical Note No. 117 (WMO - No. 280), Geneva, 55 p.

APPENDIX A

DETAILS OF CREST-STAGE GAUGE

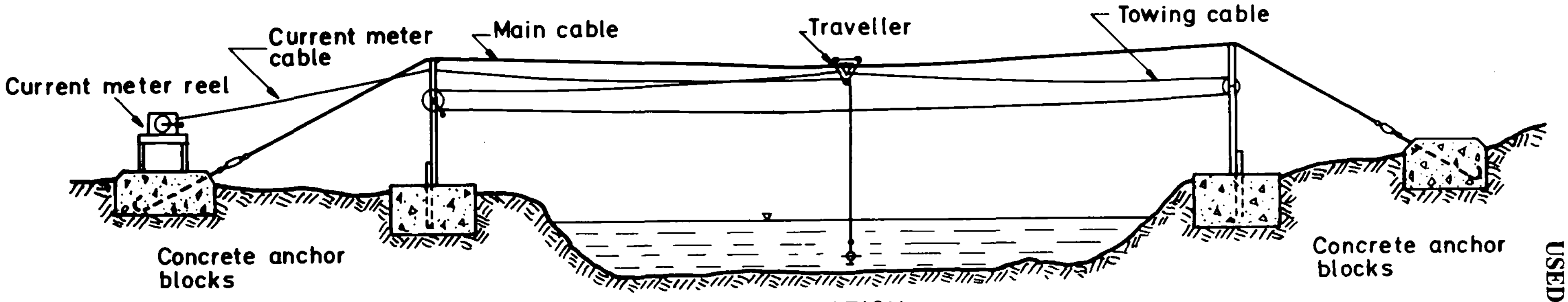
DETAILS OF CREST-STAGE GAUGE



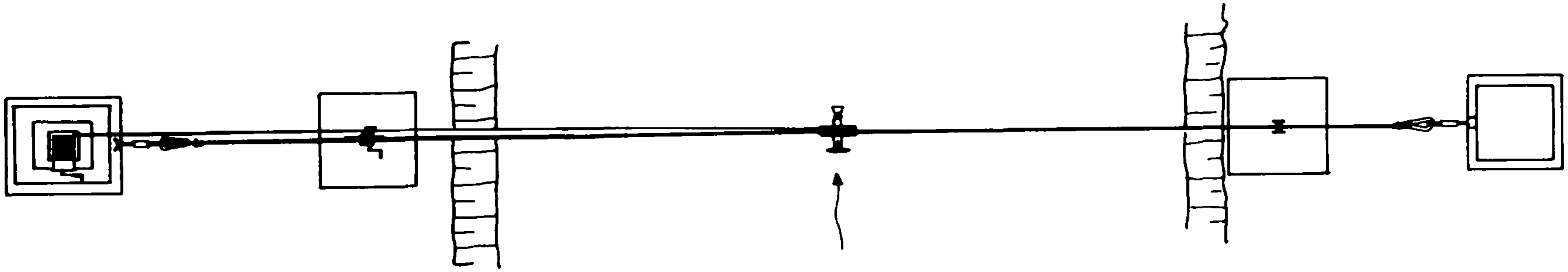
(Design: US Geological Survey)

APPENDIX B

SINGLE-DRUM WINCH CABLEWAY SYSTEM USED IN TANZANIA



ELEVATION



PLAN

SINGLE-DRUM WINCH CABLEWAY SYSTEM USED IN TANZANIA