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ETHIOPIAN INSTITUTE OF
WATER RESOURCES
ADDIS ABABA UNIVERSITY

Implementation of Water Sector Human Capacity Development Programme for Ethiopia

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Technical Level Training Course Material

Module One

Operational Hydrology: Flow and Sediment Monitoring in Streams

Ethiopian Institute of Water Resources
Addis Ababa University

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Contents

Course Description

Training Course Title	Operational Hydrology: Flow and Sediment Monitoring in Streams	
Training Course Type	Technical Level	
Target Group	Technicians in water resources monitoring	
Course Chapters/modules	Chapter/module Title	Topic Description
Chapter- 1	Establishment of Stream Gaging Gauging stations	The trainees will acquaint with field criteria, procedures and methods in selecting appropriate stream gauging station and designing hydrometric networks in major river basins. Multiple hydrological, hydraulic and economic considerations in selecting feasible gauging stations and hydrometric network design are going to be discussed both in class and field exercises.
Chapter-2	Stream Discharge Measurements	Real time water resources monitoring and observation is critical for the implementation of Integrated Water Resources Management (IWRM). Hence, under this module different techniques in operational hydrology for field measurement of river discharges will be presented. The trainees will be familiarized with theoretical and practical application of each technique feasible to Ethiopian river conditions. Hands-on practical exercise both in class and field will be conducted to enhance the technical skills of the trainees in applying those techniques.
Chapter-3	Developing Stage-Discharge Relationship at Stream Gauging station	Establishing permanent control in streams and principal stations usually facilitate continuous river flow monitoring. For that reason the field technicians require a skill to develop a stage-discharge relationship called Rating Curve both for River Discharge and suspended Sediment flow. With this module the trainees will get familiarize with multiple methods (such as graphical, analytical, etc.) both in theory and practice on actual field measured data.
Chapter-4	Sediment Transport in streams: Analysis and Monitoring	Monitoring sediment in streams is of paramount importance for the sustainable operation of hydro-infrastructures across the country. As a result this chapter will focus on the theoretical background on the sediment dynamics (erosion, transportation, and deposition) together with presenting different numerical and laboratory techniques to be used in sediment monitoring. A systematic approach will be followed to interlink sediment monitoring and river discharge monitoring during the training during in class lecture and field exercises.
Chapter-5	Operation and Maintenance of Stream Gaging stations	In order to give the trainees a practical lesson on the field operation and maintenance of gauging stations, this specific chapter is entirely be conducted in the field. Available instruments (both traditional and modern) will be used for field demonstration and exercises in monitoring stream flow. Field instrumentation for stream flow monitoring using Acoustic Doppler Current Profiler (ADCP) and Current Meter are used for field exercises to familiarize the trainees with those field instruments.

Chapter One: Establishment of Stream Gauging stations

1.1 Establishing a Stream Gauge Station

1.1.1 Procedure for Establishment

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. Before a gauging station is established, a first stage reconnaissance work at the station location shall be performed to identify most suitable site to install the gauge controls. Hence, before fixing the gauging location on the stream channel, the following points should be taken into consideration:

- Accessibility to the site at all seasons of the year
- The hydraulic conditions necessary for maintaining a permanent relation between stage and discharge
- The availability of suitable cross-section or channel reach where discharge measurements can be made
- Favourable conditions for correct placement of the water level gauge
- The availability of a competent local observer

The final decision concerning the permanent location of a new gauging station is based on the general reconnaissance with an expert in hydrology and a preliminary survey. The purpose of 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. This includes:

- A plan for the site
- The width of the river at a stated stage
- The edges of the natural banks of the channel and the toe and rest of any flood- bank
- Any obstructions against the flow of water in the channel
- Longitudinal sections of the stream reach
- The level of the deepest part of the streambed
- The level of the lowest point on a section control corresponding to the stage of zero flow
- The water level profile at low and high stages
- A detailed plan of the controlling section or reach

1.1.2 Criteria for Establishment

The ideal gauge sites satisfy the following criteria:

- The hydraulic conditions necessary for maintaining a permanent relation between state and discharge
- The total flow is confined to one channel at all stages and now flow bypasses the site as subsurface flow
- The stream-bed is not subject to scour and fill and is relatively free of aquatic vegetation
- River banks are permanent, high enough to contain floods, and are free of brush
- The gauge site is far enough upstream /downstream from the confluence
- A satisfactory reach/stream for measuring discharge at all stages within reasonable proximity of the gauge site
- Accessible for installation and operation at all seasons of the year
- Within reach of a suitable telemetry system or favourable conditions for correct placement of the water level gauge
- Instruments, shelter, and housing above all flood levels, etc.

Exercise: Field work to practice site selection to establish a hydrologic gauging station

1.2 Hydrometric Network Design

1.2.1 Integrated Water Resources Management (IWRM)

The concept of integrated water resources management (IWRM) has been developing since the beginning of the eighties. IWRM is the response to the growing pressure on our water resources systems caused by growing population and socio-economic developments. Water shortages and deteriorating water quality have forced many countries in the world to reconsider their options with respect to the management of their water resources. As a result water resources management (WRM) has been undergoing a change worldwide, moving from a mainly supply-oriented, engineering-biased approach towards a demand-oriented, multi-sectoral approach, often labeled integrated water resources management.

The concept of IWRM makes us move away from top-down 'water master planning' which focuses on water availability and development, towards 'comprehensive water policy planning' which addresses the interaction between different sub-sectors, seeks to establish priorities, considers institutional requirements and deals with the building of management capacity. IWRM considers the use of the resources in relation to social and economic activities and functions. These also determine the need for laws and regulations for the sustainable use of the water resources. Infrastructure made available, in relation to regulatory measures and mechanisms, will allow for effective use of the resource, taking due account of the environmental carrying capacity.

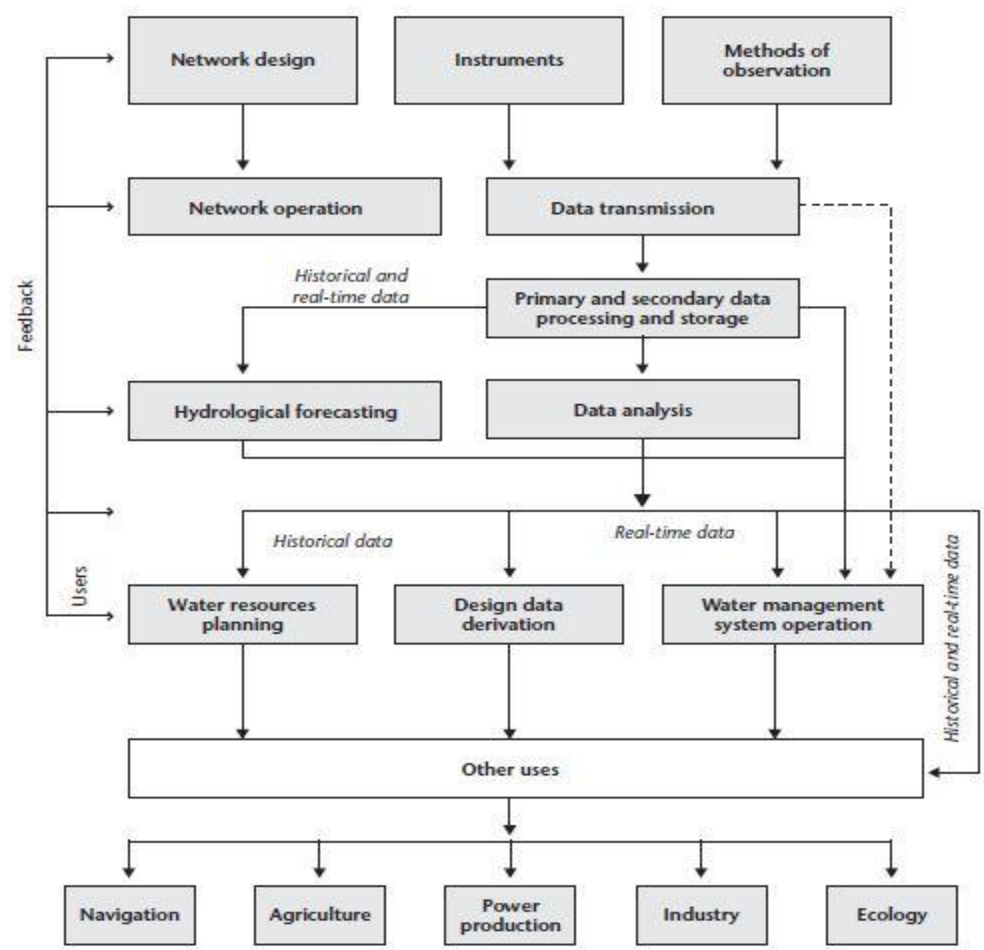


Figure [1.1]: System of Hydrology

The design of gauging sites should be guided by the needs of water management or the requirements of the hydrologic network and in order to implement IWRM at basin and sub-basin scale the following points have to be considered:

- The scale of managing water at basin level
- Water allocation base on actual measurement of availability and use

- Require real time flow measurement
- Stream network coincide with sub-systems
- Integrated water resourced development planning

River Basin Illustration Examples:

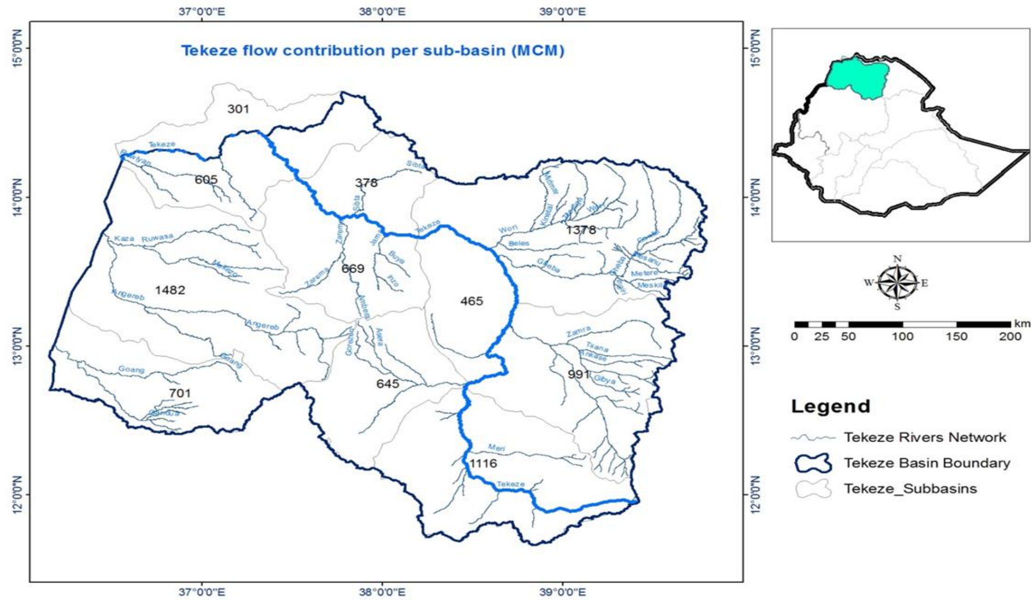


Figure [1.2]: Tekeze River Basin sub-systems suitable for Hydrologic gauging network installation

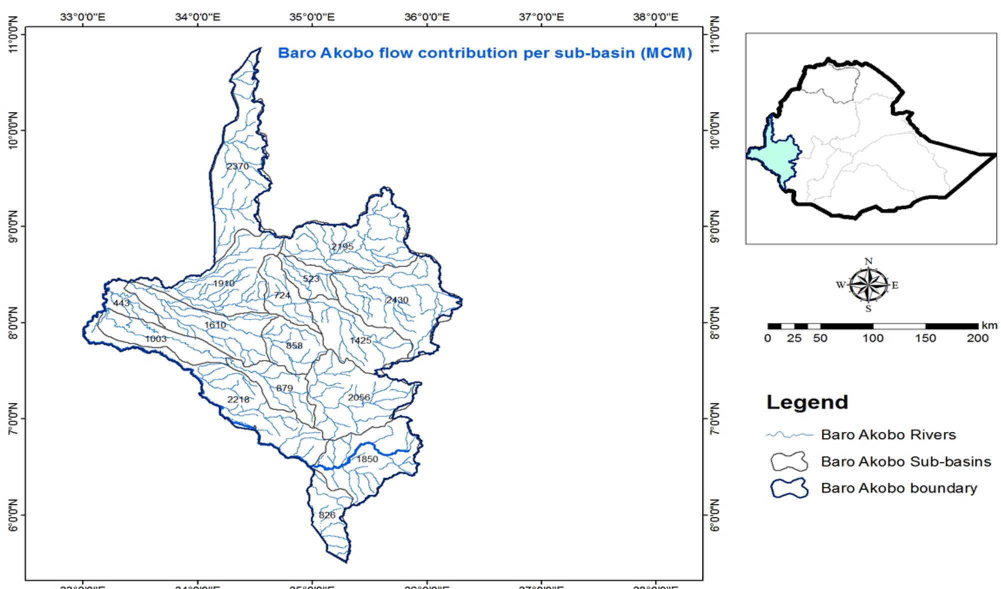


Figure [1.3]: Baro-Akobo River Basin sub-systems suitable for Hydrologic gauging network installation

1.2.2 Hydrometric Network

A hydrometric network is a system of river gauging stations in a river basin at which river stage and discharge are measured. This network provides hydrologic data needed for the planning, design and management of conservation and utilization of the waters, sediment and other natural resources of the river system. A complete network design answers the following questions pertaining to the collection of hydrological data:

1) What hydrological variables need to be observed?
2) Where do they need to be observed?
3) How often do they need to be observed?
4) What is the duration of the observation programme?
5) How accurate should the observation be?

1.2.3 Hydrometric Network Variables

During the design of hydrometric network design a number of factors are considered. Some of the major factors emphasised during the network establishment are:

1) Monitoring objectives:
    - Determined by the data needs of the hydrological data users where the actual data need for a particular basin be obtained by interviewing the potential hydrological data users, presented in a Hydrological Information Need (HIN).
2) Temporal and spatial variability of the river flow:
    - Determined by (1) climatic (precipitation, evapotranspiration) (2) physiographic (river basin size and shape, slope, land use and drainage characteristics, and (3) geologic (river bed material, geologic fault)
3) Availability of financial, manpower and other resources
    - Determined by the country's economic condition and availability of skilled human resource for the installation and maintenance of gauging station

1.2.4 Hydrometric Network Classification

Based on the network levels sampling principles, hydrometric network for hydrologic stations is designed according to the following three types:

1) Primary stations (principal stations)
2) Secondary stations
3) Special purpose stations

Primary (Principal) Stations: considered and maintained as key stations where measurements are continued for a long period of time to generate representative flow series of the river system and provide general coverage of a region. A minimum network should include at least one principal hydrologic station in each climatologic and physiographic region. If there is a potential for future development, at least on primary station should be established.

Secondary Stations: these are essentially short duration stations intended to be operated only for such a length of period which is sufficient to establish the flow characteristics of the river relative to those of a basin gauged by a primary station.

Special purpose stations: these are usually required for the planning and design of projects or special investigation and are discontinued when their purpose is served. The purpose could vary from design, management and operation of the project to monitor and fulfil legal agreements between co-basin states as well as inventory of outflow from a river basin. In general, during the designing of a hydrologic network all types of stations mentioned above must be considered simultaneously.

1.2.5 Hydrometric Network Design Process

Since hydrometric networks are existing in most places, the network designs process in one of evaluation, reviewing and updating of an existing network. Detailed review of the existing networks to achieve the following:

- Define and/or re-define the purpose of each gauging station
- Identify gaps in the existing network
- Identify stations which are no longer required
- Establish a framework for the continual evaluation and updating of the network

The main steps in the network design process are summarized as follows:

1) Review mandates, roles and aims of the organizations involved in the operation of the Hydrologic Information System (HIS) in a particular area and evaluate the communication links
2) Collect maps and other background information
3) Define the purpose of the network (who are the data users and what will the data be used for?)

4) Define the objectives of the network (what type of data is required where and at what frequency?)
5) Evaluate the existing network (how well does the existing network meet the overall objectives?)
6) Review existing data to identify gaps, ascertain catchment behaviour and variability
7) Identify gaps and over-design in the existing network (propose new stations and existing stations)
8) Prioritize gauging stations (use simple form of classification system)
9) Estimate average capital and recurrent costs of installing and maintaining different categories of hydrometric stations (estimate overall cost of operating and maintaining the network)
10) Review the revised network in relation to overall objectives, ideal network, available budgets and the overall benefit of the data (here investigate the sustainability of the proposed network)
11) Prepare a phased implementation plan (this has to be prioritized, realistic and achievable)
12) Decide on the approximate location of sites and commence site surveys (i.e, if the site is not available review the location and see if another strategy can be adopted (e.g, gauge a tributary to estimate total flow at the required spot rather than trying to measure the total flow in the main stem river)
13) Establish a framework for regular periodic network reviews

Remark: Hydrometric network design is a dynamic process. Therefore, networks have to be continually reviewed and updated so that they react to new priorities, changes in policies and physical changes. As a result, regular formalized network review should be undertaken and recommended to take place after 3-5 years of at a shorter interval if new data needs do develop.

Chapter Two: Stream Discharge Measurement

2.1 Measuring Discharge

A prospective gauging station location should be examined for the availability for discharge measuring sites for the various stages expected. The most important aspects of this examination is to be certain that there should be a measuring site at low flow where the velocities will be in the range where the current meter can measure accurately. Hence the following points shall be in consideration where one selects a good site location for discharge measurement:

- A discharge measurement is generally made in conjunction with a water-level gauge on a stream Therefore, the measuring cross-section must not be far from the gauge
- The stream at the gauging site should not overflow its banks and should preferably be contained in a single channel
- The stream channel at the gauging site should be straight and of uniform cross-section and slope. This helps to avoid abnormal velocity distributions.
- The channel should be free from large rocks, vegetation and any other big substances that will create turbulence
- The depth should not be too shallow. For depths less than about 15cm there will be difficulties in obtaining good measurement with the use of ordinary current meter for velocity.
- The velocity should be neither too low nor too high. The most reliable measurement are obtained at velocities between 0.2 and 2.5m/s
- The general direction of flow should be normal to the measuring cross section

2.2 Measurement Approaches

There are a number of approaches for flow measurement. The following are the direct and indirect methods used to measure discharge:

Direct methods (stream gaging):

- Current-meter method
- Floats

- Tracer-dilution technique
- Ultrasonic method
- Electromagnetic method

Indirect Techniques:

- Slope-are method
- Rating curve

2.2.1 Current Meter Measurement (Velocity Measurement)

Most discharge measurements are made by conventional Current Meter Method. Stream discharge is the product of velocity and cross-sectional area of the flow. This method evaluates these two terms for a cross-section. The method belongs to the area-velocity group of discharge gauging methods and is the easiest and efficient method that anybody can operate during the evaluation process.

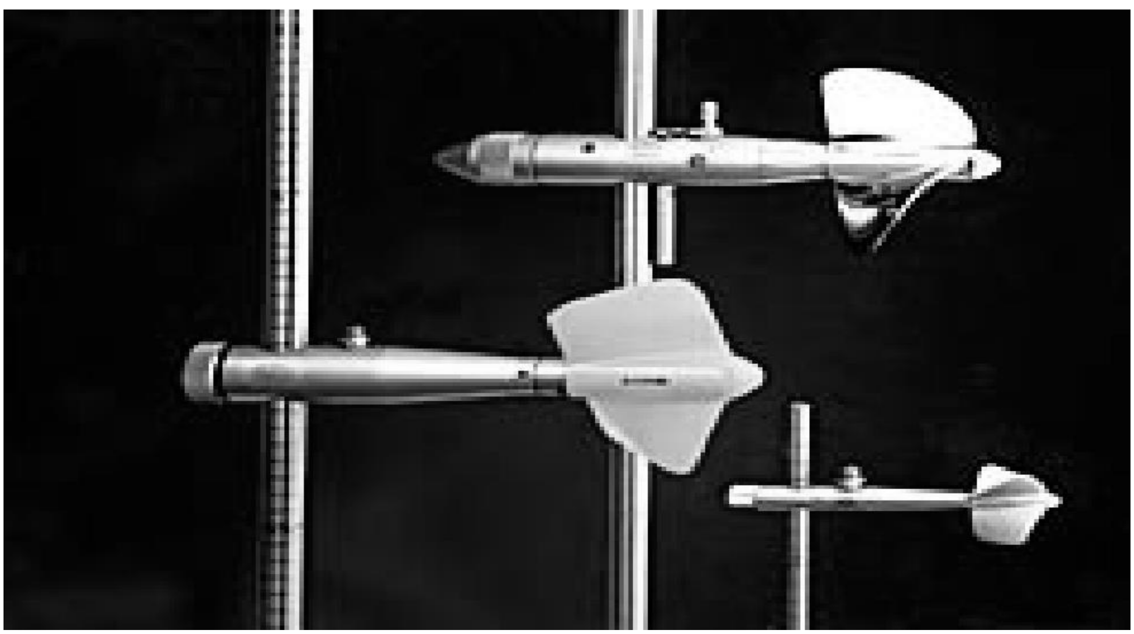


Figure [2.1]: Current meter

The mean flow-velocity is obtained by means of current-meter measurements, taken at many points in the cross-section. Then by integrating the point-velocities over the cross-sectional area the mean flow velocity is obtained. During the measurement, the current meter is mounted on a measuring rod, suspended on a weighted cable which is controlled by means of a winch with depth indicator. Usually the 0.6 (60%) depth method is employed while operating the current meter. The velocity is observed at 60% of the depth below the surface. According to both to theory and experience the velocity at this point is fair approximation of the mean velocity in the vertical.

Figure [2.2]: ADCP for direct discharge measurement

2.2.2 The Staff-Gauge Measurement

The water-level gauge or the staff-gage is usually a non-recording vertical staff gauge or an inclined staff gauge used for the measurement of stage. This type of staff gauge is ordinarily used at non-recording gauging stations.

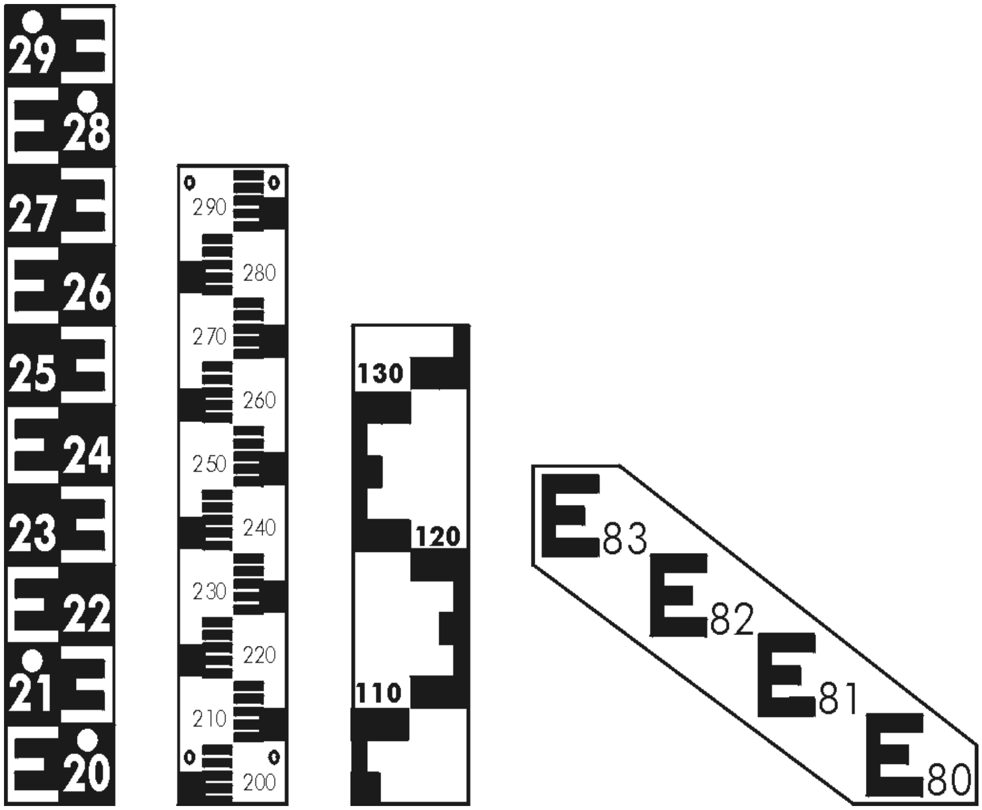


Figure [2.3]: Types of staff gauges

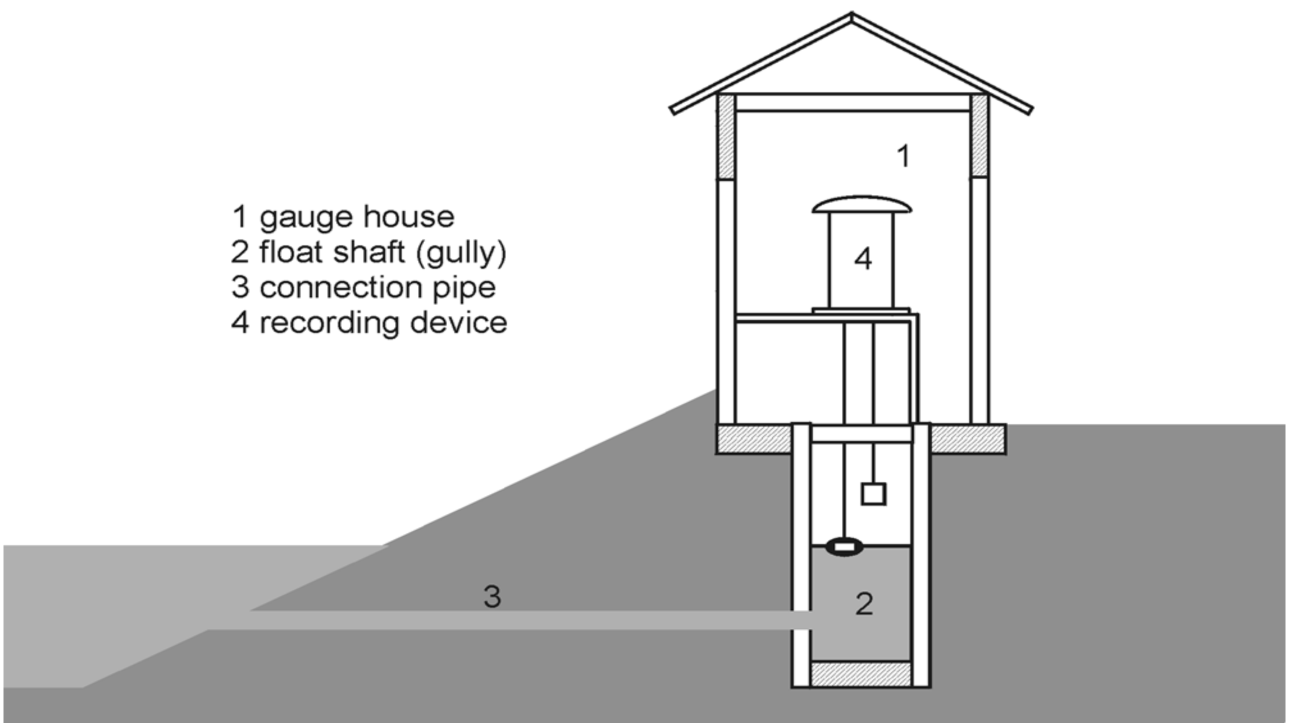


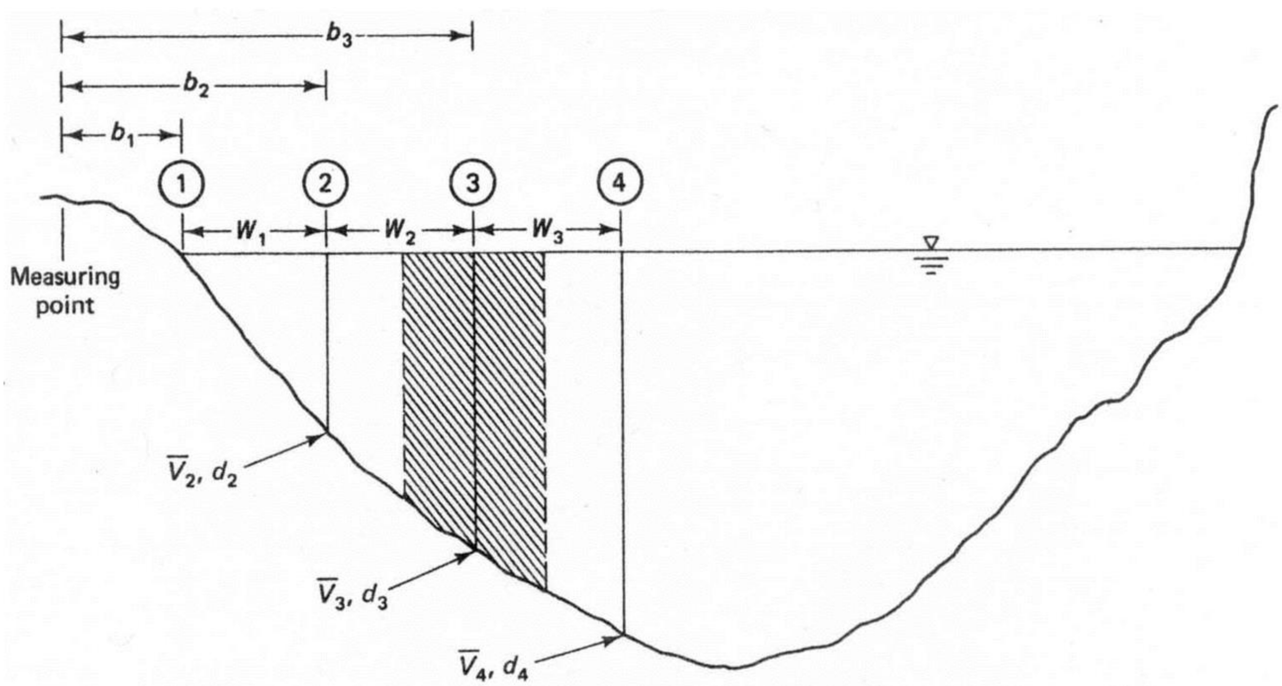
Figure [2.4]: Recording gauge type

Steps for Autographic Recorder Charts:

1. Inspection notes at the beginning & end of each chart, and there may be notes at any intermediate point.
2. Enter the dates in the margin at the top, or bottom, of the chart at the respective lines if the observer has omitted the dates.
3. Inspect the time as recorded at the beginning & end of the chart & on any intermediate days, in order to determine if any time correction should be applied.
4. The recorder pen is normally set to read the same as the reference gauge. Inspect the observations given for the reference gauge & for the pen at the beginning, intermediate points & end of the chart & at any place of resetting.
5. Examine the recorder chart to see if reversals have occurred.
6. When the recorder trace is missing for one or more days, the daily mean gauge heights are based on the available manual gauge readings.

2.3 Computation of Discharge Measurement

2.3.1 Mid-section Method



$$q_x = \bar{V}_x \left(\frac{W_{x-1} + W_{x+1}}{2} \right) d_x$$

Figure [2.5]: Cross-sections used for discharge measurement using mid-section method

2.3.2 Simplified Mid-section Method

Although there are many techniques that can be applied to compute the discharge from the current meter measurement, the simplest that can be understand easily by the local observer has been outlined. The method is called the arithmetic mid-section method. The method consists essentially of:

- Dividing the total area of the channel cross-section into partial sections and determining the area and the mean velocity of each partial section separately
- Computing the discharge in each partial section as the product of the velocity and the area
- Summing up the partial discharges to obtain the total discharge at time-t

This method is explained in detail using figure [2.2] and the following analytical derivation. The time step can be 3-hours, 6-hours or if there is no any significant variation in the stream discharge can be daily or weekly. When the time step has high resolution, the discharge estimate will approach to the reality.

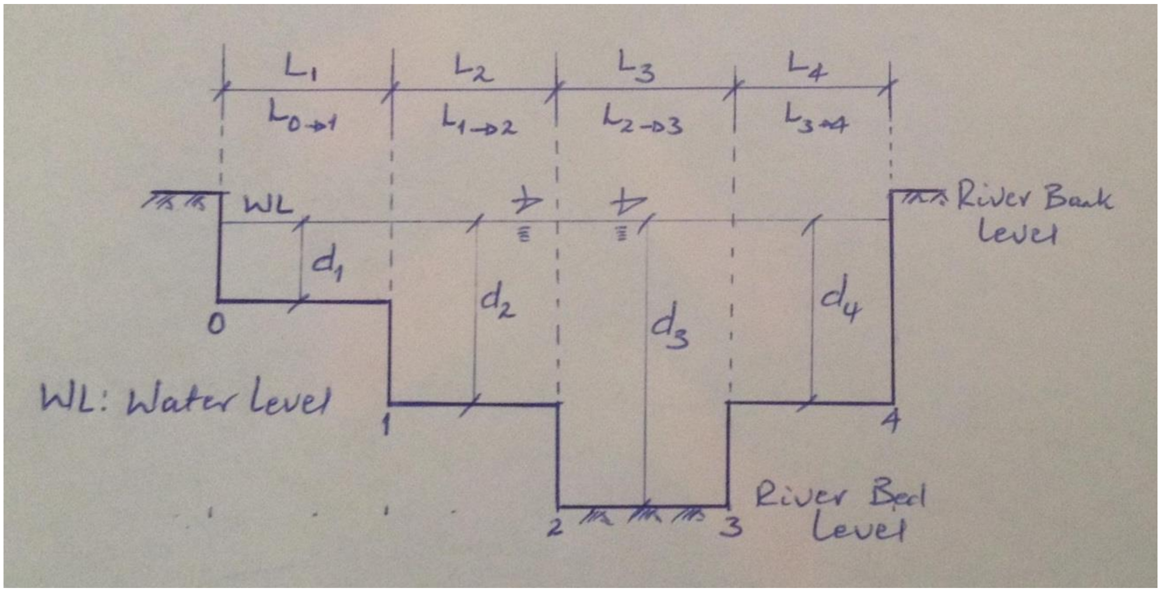


Figure [2.6]: Cross-sections used for simplified discharge measurement on a rectified stream

Considering the initial point at the bank of the stream that will be rectified to get the regular cross-section, the discharge passing through a partial section is computed as:

$$q_1 = (L_{0\rightarrow1} \cdot d_1) \cdot v_1$$

$$q_2 = (L_{1\rightarrow2} \cdot d_2) \cdot v_2$$

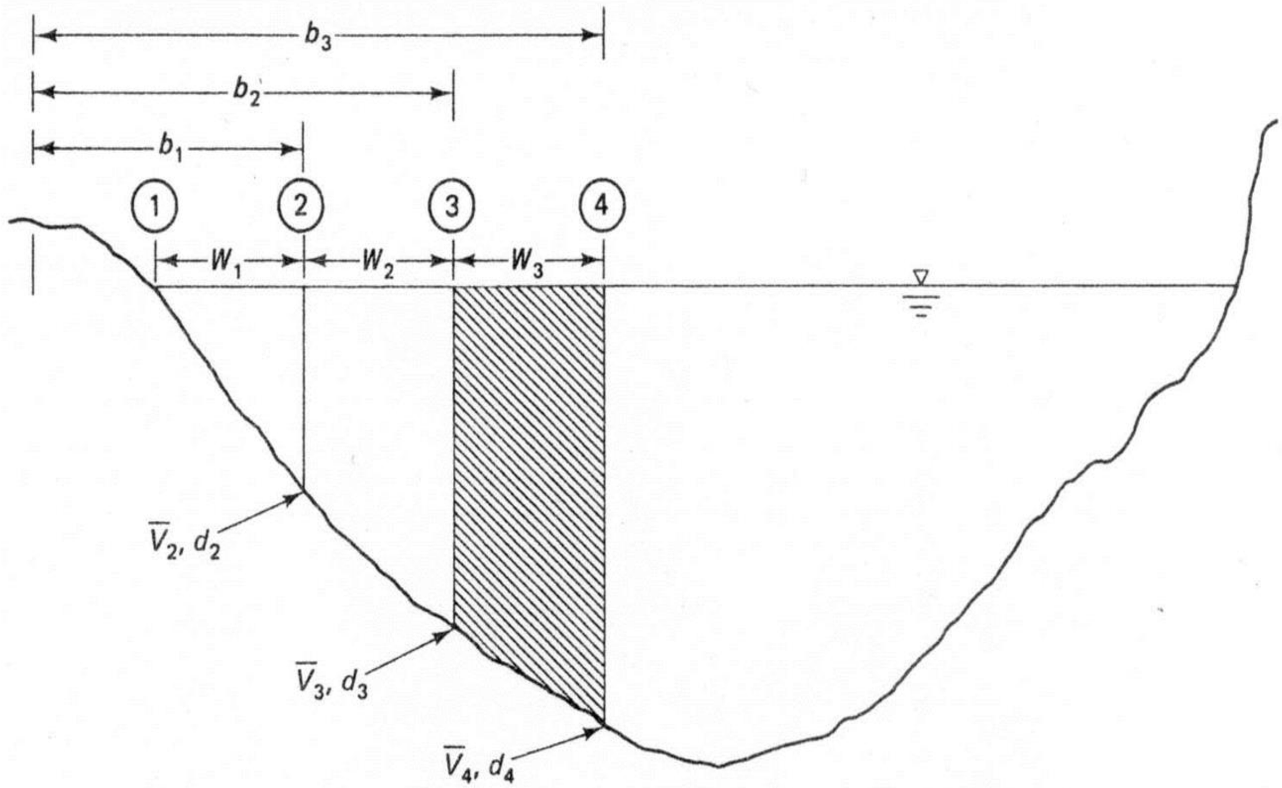
$$q_3 = (L_{2\rightarrow3} \cdot d_3) \cdot v_3$$

$$q_4 = (L_{3\rightarrow4} \cdot d_4) \cdot v_4$$

$$Q = q_1 + q_2 + q_3 + q_4$$

Where, q_1, q_2, q_3, q_4 are partial discharges passing for each cross-section and Q is the representative stream discharge passing at each gauging height (stage) and time step. The discharge for each time step is recorded alongside with the stage that measured between the references elevations (zero-level that corresponds to zero discharge) to the surface of the water that is passing through the stream section at the gauging site. The tabular format for the computation of the discharge is illustrated in Annex [2].

2.3.3 Mean Section Method



$$q_x = \left(\frac{\overline{V}_x + \overline{V}_{x+1}}{2}\right)\left(\frac{d_x + d_{x+1}}{2}\right)W_x$$

Figure [2.7]: Cross-sections used for discharge measurement using mean-section method

Exercise: Field work and demonstration of stream flow measurement using current meter Acoustic Doppler Current Profiler (ADCP)

Chapter Three: Developing Stage-Discharge Relationship

3.1 The Stage-Discharge Relation

The development of the stage-discharge relationship requires the establishment of a stream gauging station. The stream channel at the gauging station must be capable of stabilizing and regulating the flow in front of the station. This helps to get a permanent and stable discharge relation while keeping the flow past the station will always be the same. This can be done by constructing a regular shape that the area can be easily defined. The stage-discharge relation is established by plotting on graph paper measured discharges against their corresponding water level. The curve that is plotted through the plotted points defines the stage-discharge relation and usually called discharge rating curve. Annex [3] shows the tabular format that the stage-discharge relationship can be developed. Usually the linear scale is transformed into logarithmic scale. The analytical procedure that will be carried out during the establishment of a stage discharge relation is as follows.

1. To develop **rating curve,** first we have to find zero gauge height.

   h_o= a (zero gauge height)

2. Along the cross section of the river we take a measurement at least 10-15 at different times. And it is better that **the measurement should be taken at the time of low, medium and high flow.** From each measurement we can get **gauge height & discharge.** Let us assume we took measurement **during at the time of low, medium & high flow & we took 15 measurements at different time** and **plot by Log paper** these 15 measurements and **select out the low and the high value of water level** that you have got from the plot at the same line or curve. At this time we can get water level data **(h_1, h_2) & (q_1, q_2) and** after that we can compute q3 b**y formula** $q_3 = \sqrt{q_1 \times q_2}$ **then** it is possible to read the value of **h_3** from the graph **by plotting q_3 Vs h_3.**

Then, by using the formula:

$$h_0 = \frac{h_1 \times h_3 - {h_2}^2}{h_1 + h_3 - 2h_2}$$

We can find $h_0 = a$ (zero gauge height) in:-

-low flow (October, November, December & January)

-medium flow (Feburary, March,April & May)

-high flow (June, July, August & September)

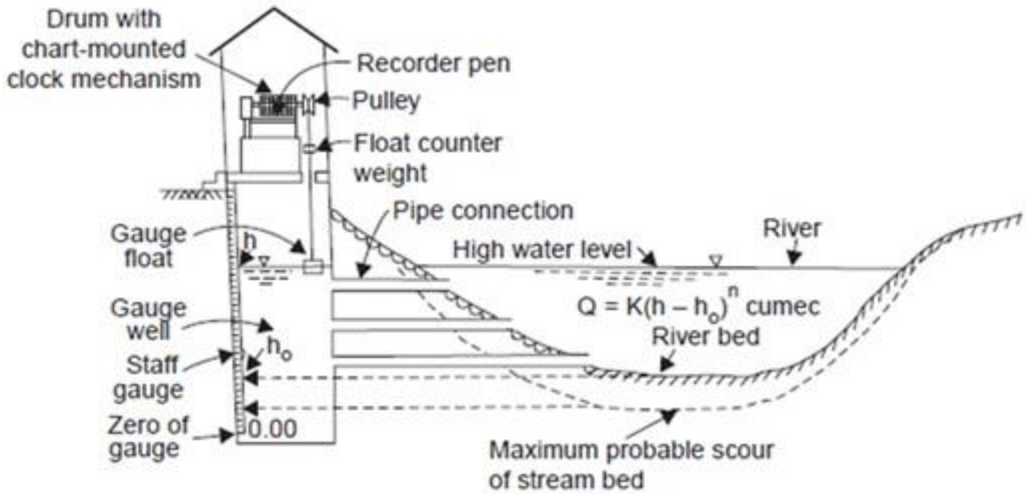


Figure [3.1]: Recording gauge showing critical components and levels

So during calculation it is possible to take zero gauge height before you start the measurement and you have to take the value according to the flows & we have to find the equation of a line in order to get the flow correctly.

But in our case most of the time we apply the measurement **of low, medium & high flow to get one equation of a line. At this time we utilize the measurement data of one year, two years, etc… according to the available of measurement data.**

The relationship between the stage and the discharge is a single-valued relation which is expressed as:

$$Q = \alpha(Z - a)^{\beta}$$

Where, Q is stream discharge, Z is gauge height (stage), a is a constant which represent the gauge reading corresponding to zero discharge, α and β are rating curve constants. This relationship can be expressed graphically by plotting the observed stage against the corresponding discharge values in arithmetic or logarithmic plot. Logarithmic plotting is advantageous as the above equation plots as a straight line in logarithmic coordinates.

The best values of α and β in the above equation for a given range of stage are obtained by the least-square-error method. Thus, by taking logarithms,

$$\log Q = \beta \log(Z - a) + \log \alpha$$

Or, similarly:

$$Y = \beta X + b$$

In which the dependent variable

$$Y = \log Q \ ,$$

independent variable

$$X = \log(Z - a)$$

and

$$b = \log \alpha$$

For the best-fit straight line of **N** observations of **X** and **Y**, by regressing

$$Y = \log Q$$

on

$$X = \log(Z - a)$$

Where,

$$\beta = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum Y)^2}$$

And,

$$\alpha = \frac{\sum Y - \beta \sum X}{N}$$

Pearson product moment correlation coefficient:

$$r = \frac{N(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[N(\sum X^2) - (\sum X)^2] \times [N(\sum Y^2) - (\sum Y)^2]}}$$

Here, **r** reflects the extent of linear relationship between the two data sets. If **r** is between 0.6 and 1.0, it is generally taken as a good correlation. Values of **X**, **Y**, and **XY** can be calculated from the data via transforming the discharge (Q) and the stage $(Z - a)$ into a logarithmic scale [Annex 3].

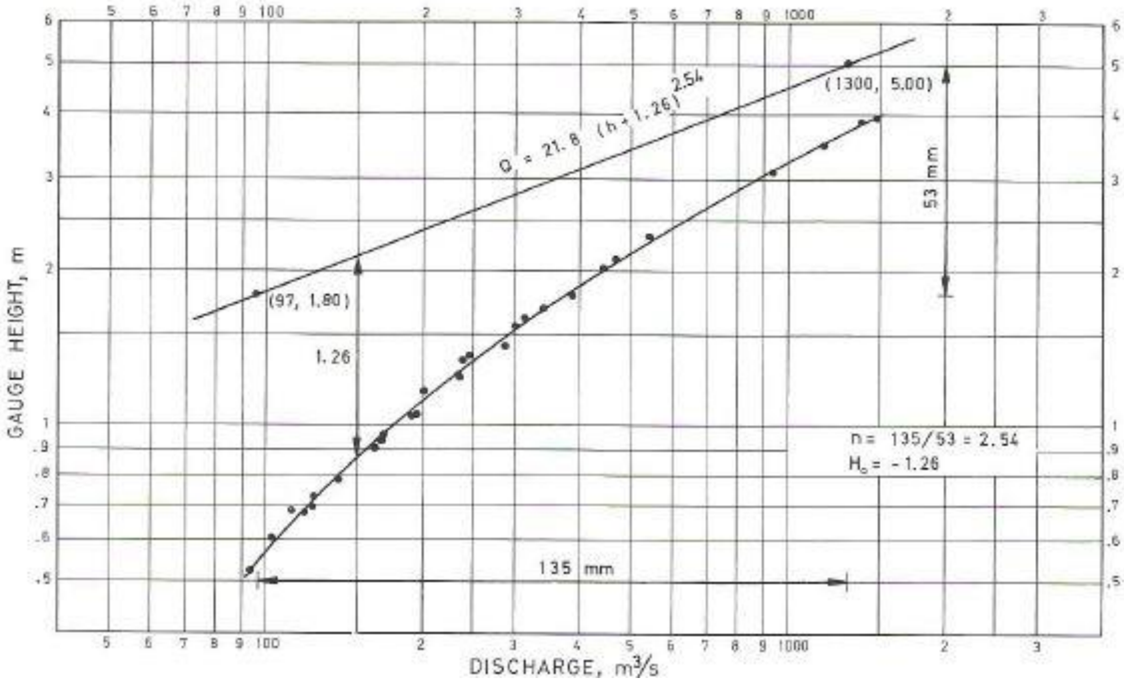


Figure [3.2]: Stage-discharge curve established by the logarithmic method

3.2 Factors Affecting the Stage-Discharge Relation

Shifting control:

The control that exists at a gauging section giving rise to unique stage-discharge relationships can change due to:-

a) Changing characteristics caused by weed growth, dredging or channel encroachment.
b) Aggradation or degradation phenomenon in an alluvial channel
c) Variable back water effects affecting the gauging section and
d) Unsteady flow effects of a rapidly changing stage.

There are no permanent corrective measure to tackle the shifting controls due to causes a& b .The only recourse in such cases is to have frequent current-meter gauging to update the rating curves. Shifting controls due to causes c& d are described below.

Back water effect:

If the shifting control is due to variable back water curves, the same stage will indicate different discharges depending upon the back water effect. To remedy this situation another gauge, called the secondary gauge or auxiliary gauge is installed some distance downstream of the gauging section and readings of both gauges are taken the difference between the main gauge and the secondary gauge gives the fall of the water surface in the reach. Now for a given main-stage reading the discharge under variable back water condition is a function of the fall.

Unsteady flow effect:

When a flood wave passes a gauging station in the advancing portion of the wave approach velocities are larger than in the steady flow at corresponding stage. Thus, for the same stage, more discharge than in a steady uniform flow occurs. In the retreating phase of the flood wave the converse situation occurs with reduced approach velocities giving lower discharges than in equivalent steady flow case, thus the stage discharge relationship for an unsteady flow will not be a single valued relationship as in steady flow but it will be a looped curve.

Storage Hysterisis:

In a natural rivers, the Stage-Discharge relationship in general appears to be a loop, rather than single valued that create a hysteresis effect where the rating curve follow a different trajectory during falling and rising stage of the stream flow.

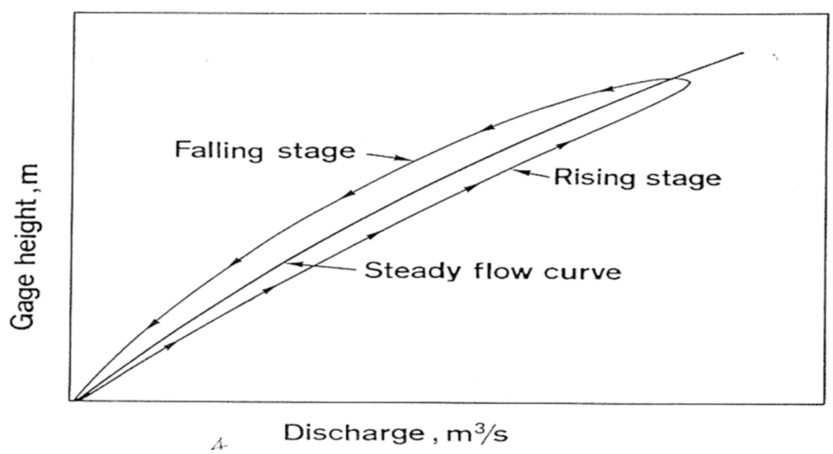


Figure [3.3]: Hysterisis effect in stream flow discharge measurement

Exercise: Practical exercise on the development of Stage-Discharge Relationship (Discharge Rating Curve) based on actual field data collected from a stream using graphical (with scale paper) and analytical technics (curve fitting)

Chapter Four: Sediment Transport in Streams: Analysis and Monitoring

4.1 Sediment Sampling and Analyses

4.1.1 Sampling Schedules

The frequency and duration of sampling sediment discharge depends on the purpose of the investigation, the variation in the sediment discharge of the streams, and the cost of the sediment investigation. The timing of the sampling may be as important as the technique of taking the samples themselves. It is important to note that the variation in sediment concentration during a rising stage is generally rapid and erratic, while the variations during the falling state are gradual and consistent. Ideally, samples should be obtained for small streams every few minutes and large streams every half hour or an hour during rising stage. However, for convenience of sediment monitoring task it is recommended to take samples along with the stage-discharge measurement. For daily-record stations suspended sediment samples are taken daily throughout the year by the local observer.

4.1.2 Sediment Sampling Equipment

The common procedure of measuring suspended sediment discharge in a stream is to sample the concentration of suspended sediment in the flow and to measure the concurrent water discharge. The suspended sediment discharge is then computed by multiplying the mean concentration of sediment by the corresponding water discharge. The major criterion of a good sampler is that it should be able to collect a representative sample from a flowing stream at any desired point. Here once should notice that putting in place the sampler and the process of collecting the sample should not disturb the flow pattern at the sampling point. The general requirements of an ideal sediment sampler are listed as follows:

- The water-sediment mixtures should enter the sampler nozzle isokinetically. That is, the water-sediment mixture approaching the nozzle undergoes no change in speed direction as it enters the orifice
- The intake should be pointed into the approaching flow
- The sampler should be streamlined and of sufficient weight to avoid excessive downstream drift

- The sampler should be of simple design to minimize the need for repairs in the field
- The sampler should be adaptable to support equipment already in use for streamflow measurements
- The sample container should fill smoothly without sudden inrush
- The sample container should be removable and suitable for transportation to the laboratory without loss or spoilage of the content

Suspended sediment samplers for general use may be classified into the following types:

- Bottle sampler
- Instantaneous sampler
- Integrating sampler
- Pumping sampler

However, from the view of its simple application and use, the bottle sampler has been recommended for sediment monitoring task. The simple bottle samplers also have an advantage in relation to operability by the local observer while taking the sample and transport to the laboratory for further sediment concentration analysis. The simplest and most readily improvised device for collecting suspended sediment samples is an ordinary milk bottle, fruit jar or other standard container, attached to a rod or to a line with a hydrometric sinker-weight [Figure 2.4]. Air escaping through the intake opening produces a bubbling effect at the entrance. An open bottle still can be used for dip sampling.

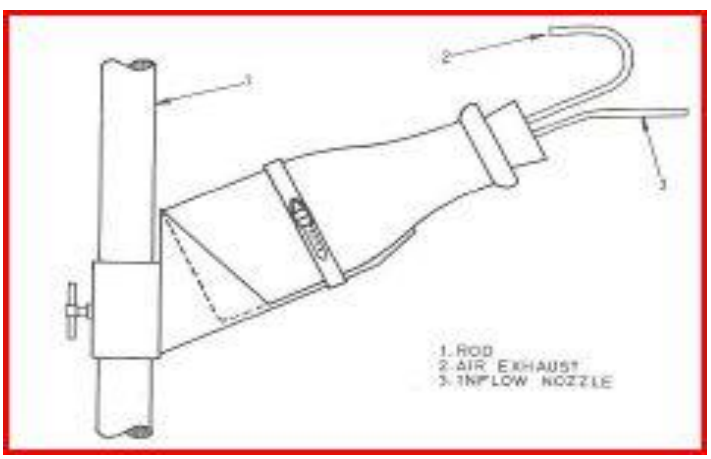


Figure [4.1] Simple bottle sampler

4.2 Sediment Concentration Analysis Procedures

The concentration of suspended sediment samples may be determined by either evaporation of filtration methods. The evaporation method consists of allowing the sediment to settle in the sample bottle, pour out the supernatant liquid, washing the sediment into an evaporating dish, and drying it in an oven at a temperature of 90^o to 95^oC. The filtration method consists of filtering the sample through an appropriate sized filter and oven drying the filter together with the filtered sediment. From its simple procedure and application, the evaporation method is recommended for sediment monitoring projects.

4.2.1 The Evaporation Method

After the sediment in the evaporating basin is dried, the weight of sediment is determined to the nearest 0.0001grams. Suspended sediment concentrations should be reported in terms of dry weight of the sediment per litre of sample (i.e. water-sediment mixture), usually in grams or milligrams per litre. The advantage of this method is its simplicity of equipment and technique. The sediment can settle to the bottom of a container, the supernatant water is poured out, and the sediment is washed into an evaporating basin and dried in an oven. The supernatant fluid must be carefully decanted or siphoned off, so that none of the sediment is removed from the settling container. The remainder is washed into an evaporation basin and dried in an oven at a temperature from 5^o to 10^oC below the boiling point (100 ^oC). at a higher temperature sediment may be lost from the basin by spattering. After all moisture has evaporated, the temperature should be raised to 110^o for about one hour. The evaporating basins must be kept in a dry state before weighting.

4.2.2 The General Procedures for Concentration Analysis

- Inspect the general condition of the sample bottles as they arrive at the laboratory from the field. Clean dirty bottle and fasten loose caps
- If storage is necessary before samples can be analysed, store samples in a cool dark room to retard evaporation and growth of organisms
- Arrange samples from a given station in chronological order when bringing them in for weighing

- Check and record the information from the sample labels on to the appropriate data forms
- Weigh the sampling bottle and record the gross weight to the nearest gram
- Leave the weighted bottles undisturbed on a table or rack for the sediment to settle. This may take from one to several days
- Siphon off most of the clear water taking care not to disturb or remove sediment
- Using distilled water; wash the remainder into a previously tare-weighted evaporating basin
- Clean the sample bottles and air-dry them. Determine the tare weight by weighting to the nearest gram. Cap the bottles and pack them in carrying cases for reuse
- Dry the evaporating basins at 90-95^{o}C in an oven.
- Cool the evaporating basins in a desiccator at room temperature
- Weigh the containers to the nearest 0.0001gm. The tare weight of the evaporating basins should be determined before each use.
- Compute the net weight of the sediment in the containers
- Calculate the concentration in parts per million by the equation:

$$ppm = \frac{Dry\ weight\ of\ sediment\ (gm)}{Weight\ of\ sediment\ laden\ water\ sample\ (gm)} \times 10^6$$

- Convert ppm to mg/lt by the equation

$$mg/lt = K \times (ppm)$$

Where, the factor **K** is obtained from Annex [1] and the above concentration analysis procedure can be found in tabular format in Annex [4].

4.3 Developing Discharge – Sediment Relationship (Sediment Rating Curve)

In determining material transport, it is important to distinguish between concentration (which is usually expresses as the mass or weight of suspended material per unit volume of water) and the load (which is the rate of discharge of the suspended material – mass per time). The concentration of suspended sediment (mass of sediment per volume of water sample collected) transported by a river is typically a strong function of discharge that can generally be characterized by a power law relation:

$$C = a \cdot Q^b$$

Where, a and b are empirical constants that are established by statistical (regression) analysis of discharge (current) measurements of C and Q for the reach of interest. This equation can also be transformed into logarithmic scale by taking both sides into logarithmic equation form in a similar way that has been done in development the stage-discharge relationship [Annex 5].

$$\log C = b \log(Q) + \log a$$

Or, similarly:

$$Y = bX + k$$

In which the dependent variable:

$$Y = \log C \text{ ,}$$

independent variable:

$$X = \log(Q)$$

and

$$k = \log a$$

For the best-fit straight line of **N** observations of **X** and **Y**, by regressing

$$Y = \log C$$

on :

$$X = \log(Q)$$

Where,

$$b = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum Y)^2}$$

And,

$$a = \frac{\sum Y - \beta \sum X}{N}$$

Pearson product moment correlation coefficient:

$$r = \frac{N(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[N(\sum X^2) - (\sum X)^2] \times [N(\sum Y^2) - (\sum Y)^2]}}$$

The rate of sediment discharge, or load (mass per time) is the product of concentration and discharge. So the equation becomes:

$$L = a \cdot Q^{b+1} \quad or\ L = C \cdot Q$$

Where, **L** is the load of suspended sediment in the stream [mass per time], **C** is the sediment concentration in the water sample collected [mass per volume of water sample], and **Q** is the rate of discharge of water [volume per time]. The tabulated format for developing the sediment rating curve is illustrated on Annex [6]. With this manual sediment monitoring technique, there must be a daily collection of sample of water with sediment at many replications as well as the measurement of daily stream flow. The daily stream flow can be measured using available techniques in literature or the rating curve that can be developed for the specific stream. The sedimentation analysis shall be done at the laboratory while given sufficient time for the material to settle in the sampling device. Here, it is important to have a scaled sampling jar to collect the sample from the river. After all the above procedures can be done; it is possible to develop the relationship stated in the above equations while determining the empirical constants. This method allows the continuous monitoring of sediment load in the stream and/or into the reservoir. The sample collection site shall be at the point before the river flows joining the reservoir and the samples are taken at different depth of the flow

Chapter Five: Operation and Maintenance of Stream Gaging Stations

This Chapter entirely a field activity based on the following main issues to practice in the field:

- Operation of stream gauge measuring devices:
    - Current meter (for flow velocity measurement)
    - Acoustic Doppler Current Profiler (ADCP) (for direct measurement of stream flow)
    - Maintenance and operation of Hydraulic Devices (weirs and notches, Orifices, and Flumes) - permanent control structures for gage readings and flow measurements

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WMO, Manual on Stream Gauging, Volume II- Computation of Discharge

Annexes

Annex 1: Factor K for converting sediment concentration from ppm to mg/lt

ppm	K	ppm	K	ppm	K
0 – 15,900	1.00	234,000 – 256,000	1.18	417,000 – 434,000	1.36
16,000 – 47,000	1.02	257,000 – 279,000	1.20	435,000 – 451,000	1.38
47,000 – 76,000	1.04	280,000 – 300,000	1.22	452,000 – 467,000	1.40
77,000 – 105,000	1.06	301,000 – 321,000	1.24	468,000 – 483,000	1.42
106,000 – 132,000	1.08	322,000 – 341,000	1.26	484,000 – 498,000	1.44
133,000 – 159,000	1.10	342,000 – 361,000	1.28	499,000 – 513,000	1.46
160,000 – 184,000	1.12	362,000 – 380,000	1.30	514,000 – 528,000	1.48
185,000 – 209,000	1.14	381,000 – 398,000	1.32	529,000 – 542,000	1.50
210,000 – 233,000	1.16	399,000 – 416,000	1.34		

(the factors are based on the assumption that the density of water is 1gm/cm^3 plus or minus 0.005, the range of temperature is 0^o – 29^{o}C, the specific gravity of sediment is 2.65, and the dissolved solids concentration is less than 10,000parts per million)

Annex 2: Computation of Discharge measurement

Time (day)	Cross-section length (L) (m)				Flow depth (d) (m)				Flow velocity (v) (m/s)				Partial discharges (q) (m^3/s)				Discharge (m^3/s)	Stage (m)
	L_1	L_2	L_3	L_4	d_1	d_2	d_3	d_4	v_1	v_2	v_3	v_4	q_1	q_2	q_3	q_4	**Q**	**Z**

Annex 3: Stage-Discharge Relationship (Discharge Rating Curve) with log transformation

Time (day)	Stage (Z) (m)	Discharge (Q) (m^3/s)	$Y = \log Q$ (m^3/s)	$X = \log(Z - a)$ (m)	XY	X^2	Y^2

$\boldsymbol{a}\ (\boldsymbol{m})$	$\boldsymbol{\beta}\ (-)$	$\boldsymbol{\alpha}\ (-)$	$\boldsymbol{b} = \log \boldsymbol{\alpha}\ (\boldsymbol{m}^3/\boldsymbol{s})$

Annex 4: Sediment Concentration Analysis

Time (day)	Stage (Z) (m)	Discharge (Q) (m^3/s)	Dry weight of sediment (gram)	Weight of the sediment laden water sample (gram)	Concentration in Parts per million (ppm)	Concentration (C) (mg/lt)

Annex 5: Discharge-Sediment Relationship (Sediment Rating Curve) with log transformation

Time (day)	Stage (Z) (m)	Discharge (Q) (m^3/s)	Concentration (C) (mg/lt)	$Y = \log C$ (mg/lt)	$X = \log(Q)$ (m^3/s)	XY	X^2	Y^2

$\boldsymbol{b}$ (−)	$\boldsymbol{a}$ (−)	$\boldsymbol{k = \log a}$ (mg/lt)

Annex 6: Suspended Sediment Load Estimation

Time (day)	Stage (Z) (m)	Discharge (Q) (m^3/s)	Concentration (C) (mg/lt)	Sediment Load (L) (tons/day)

How to establish stage discharge rating curve

Hydrology and water quality directorate

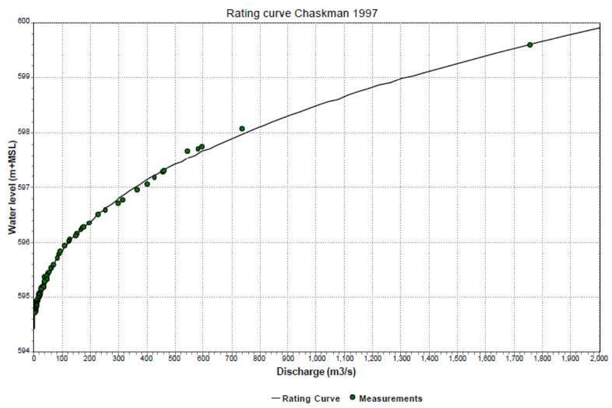
Contents

1. **General**
2. **The station control**
3. **Fitting of rating curves**

1. General

- **Flow is the variable usually required for hydrological analysis but, continuous measurement of flow past a river section is usually impractical or prohibitively expensive. However, stage can be observed continuously or at regular short time intervals with comparative ease and economy. Fortunately, a relation exists between stage and the corresponding discharge at river section. This relation is termed a stage-discharge relationship or stage-discharge rating curve or simply, rating curve.**
- **A rating curve is established by making a number of concurrent observations of stage and discharge over a period of time covering the expected range of stages at the river gauging section.**
- **At many locations, the discharge is not a unique function of stage; variables such** as surface slope or rate of change of stage with respect to time must also be known to obtain the complete relationship in such circumstances.
- **The rating relationship thus established is used to transform the observed stages into the corresponding discharges.**

- In its simplest form, a rating curve can be illustrated graphically, as shown



- If Q and h are discharge and water level, then the relationship can be analytically expressed as:

  $$Q = f(h)$$

  Where; *f(h) is an algebraic function of water level.*
- Because it is difficult to measure flow at very high and low stages due to their infrequent occurrence and also to the inherent difficulty of such measurements, extrapolation is required to cover the full range of flows**.**

2. The station control

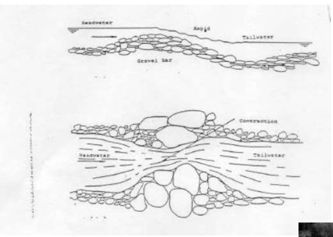
- The shape, reliability and stability of the stage-discharge relation are controlled by a section or reach of channel at or downstream from the gauging station and known as the station control. The establishment and interpretation of stage discharge
- (relationships requires an understanding of the nature of controls and the types of control at a particular station.)

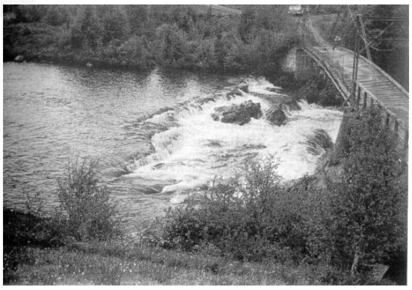
Types of station control

- section and channel controls
- natural and artificial controls
- complete, compound and partial controls
- permanent and shifting controls

Section and channel controls

- When the control is such that any change in the physical characteristics of the channel downstream to it has no effect on the flow at the gauging section itself then such control is termed as section control.
- In other words, any disturbance downstream the control will not be able to pass the control in the upstream direction.



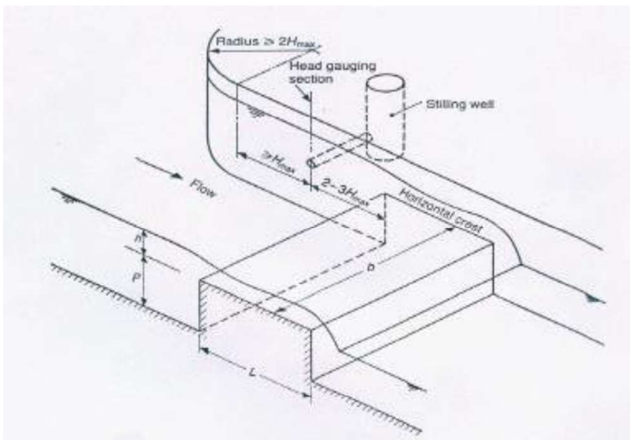


channel control

- A cross section where no acceleration of flow occurs or where the acceleration is not sufficient enough to prevent passage of disturbances from the downstream to the upstream direction then such a location is called as a channel control.
- The rating curve in such case depends upon the geometry and the roughness of the river downstream of the control

Artificial and natural controls

- An artificial section control or structure control is one which has been specifically constructed to stabilize the relationship between stage and discharge and for which a theoretical relationship is available based on physical modeling. These include weirs and flumes, discharging under free flow conditions.



Complete, compound and partial controls

- a complete control is one which governs the stage-discharge relation throughout the entire range of stage experienced. However, in many cases, station controls are a combination of section control at low stages and a channel control at high stages and are thus called compound or complex controls.
- partial control cases, station controls are a combination of section control at low stages and a is one which operates over a limited range of stage when a compound control is present, in the transition between section and channel control.

Permanent and shifting controls

- Where the geometry of a section and the resulting stage-discharge relationship does not change with time, it is described as a stable or permanent control. Shifting controls change with time and may be section controls such as boulder, gravel or sand riffles which undergo periodic or near continuous scour and deposition, or they may be channel controls with erodible bed and banks.

Shifting controls thus typically result from:

- scour and fill in an unstable channel
- growth and decay of aquatic weeds
- Over spilling and pounding in areas adjoining the stream channel.

Fitting of rating curves

- A simple stage discharge relation is one where discharge depends upon stage only. A complex rating curve occurs where additional variables such as the slope of the energy line or the rate of change of stage with respect to time are required to define the relationship.

Equations used and their physical basis

- Two types of algebraic equations are commonly fitted to stage discharge data are:

1. Power type equation which is most commonly used:

$Q = c\ (h + a)b$

2. Parabolic type of equation

$Q = c_2\ (h_w+a)^2 + c_1\ (h_w + a) + c_0$

2. Parabolic type of equation

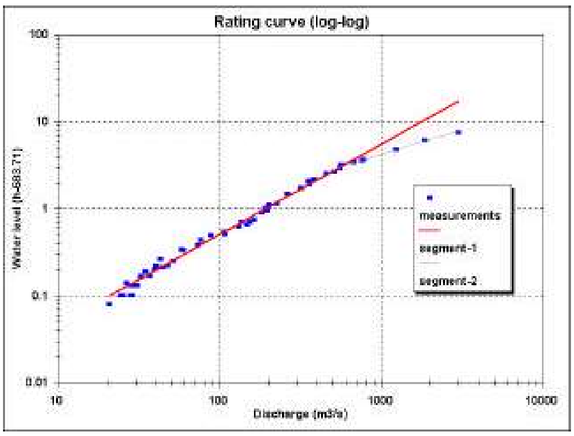
$Q = c_2\ (h_w+a)^2 + c_1\ (h_w + a) + c_0$

- where: *Q = discharge (m3/sec)*
  h = measured water level (m)
  a = water level (m) corresponding to Q = 0
  ci = coefficients derived for the relationship corresponding to the station Characteristics
- It is anticipated that the power type equation is most frequently used in Ethiopia and is recommended.

- Taking logarithms of the power type equation results in a straight line relationship of the form:
- log *(Q) = log (c) + b log (h + a)*
- *Y = A + B X*
- That is, if sets of discharge (Q) and the effective stage (h + a) are plotted on the double log scale, they will represent a straight line.
- Coefficients A and B of the straight line fit are functions of a and b.

- Since values of a and b can vary at different depths owing to changes in physical characteristics (effective roughness and geometry) at different depths, one or more straight lines will fit the data on double log plot. This is illustrated in Fig. below, which shows a distinct break in the nature of fit in two water level ranges. A plot of the cross section at the gauging section is also often helpful to interpret the changes in the characteristics at different levels.

Double logarithmic plot of rating curve showing a distict break



Arithmetic procedure:

- This procedure is based on expressing the datum correction "a" in terms of observed water levels. This is possible by way elimination of coefficients b and c from the power type equation between gauge and discharge using simple mathematical manipulation. From the median curve fitting the stage discharge observations, two points are selected in the lower and upper range (Q1 and Q3) whereas the third point Q2 is computed from Q2 =Q1.Q3, such that:

$$\frac{Q_1}{Q_2} = \frac{Q_2}{Q_3}$$

- If the corresponding gauge heights for these discharges read from the plot are h_1, h_2 and h_3 then using the power type, we obtain:

$$\frac{c\,(h_1 + a)}{c\,(h_2 + a)} = \frac{c\,(h_2 + a)}{c\,(h_3 + a)}$$

Which yields:

$$a = \frac{h_2^2 - h_1 h_3}{h_1 + h_3 - 2h_2}$$

- From this equation an estimated value of "a" can be obtained directly. This procedure is known as Johnson method which is described in the WMO Operational Hydrology manual on stream gauging

- The least-squares line uses a straight line

$$y = a + bx$$

- The leto approximate the given set of data, , , ..., , where . The best fitting curve has the least square error, i.e., ast-squares line uses a straight line

$$\Pi = \sum_{i=1}^{n}[y_i - f(x_i)]^2 = \sum_{i=1}^{n}[y_i - (a + bx_i)]^2 = \min.$$

Please note that a and b are unknown coefficients while all y_i and x_i are given. To obtain the least square error, the unknown coefficients a and b must yield zero first derivatives.

$$\begin{cases} \dfrac{\partial \Pi}{\partial a} = 2\sum_{i=1}^{n}[y_i - (a + bx_i)] = 0 \\ \dfrac{\partial \Pi}{\partial b} = 2\sum_{i=1}^{n} x_i\,[y_i - (a + bx_i)] = 0 \end{cases}$$

- Expanding the above equations, we have:

$$\begin{cases} \sum_{i=1}^{n} y_i = a\sum_{i=1}^{n} 1 + b\sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i y_i = a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x_i^2 \end{cases}$$

- The unknown coefficients a and b can therefore be obtained:

$$\begin{cases} a = \dfrac{\left(\sum y\right)\left(\sum x^2\right) - \left(\sum x\right)\left(\sum xy\right)}{n\sum x^2 - \left(\sum x\right)^2} \\ b = \dfrac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{n\sum x^2 - \left(\sum x\right)^2} \end{cases}$$

where $\sum \cdots$ stands for $\sum_{i=1}^{n} \cdots$

Discharge Measurement

Introduction

- Discharge is the volumetric rate at which fluid passes a given location
- It is measures in m3/s or l/s
- Key reasons for measuring discharge are
  - Studies of occurrence of floods
  - Studies of occurrence of low flows
  - Water availability study (water balance studies)

Streamflow measurement

- **Measurement of streamflow**
  - **Velocity- Area methods**
  - **Based on Stage – discharge relationship**
  - **Dilution method**
  - **Weirs**
  - **flumes**

1. Velocity – Area methods

- Velocty area method estimated discharge by using the following relationship

$$Q = V_{av} A$$

- where Q is total stream discharge, V_{av} is the average flow velocity and A is the cross sectional area of flow

1. Velocity – Area methods

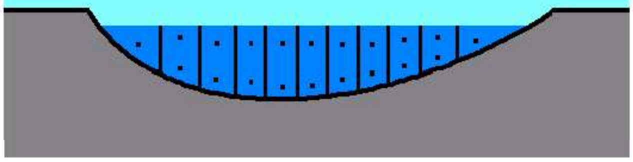
- for natural channels, flow velocity varies with position in the channel
  - flow varies vertically, with maximum velocities occurring at the surface and minimum velocities at the channel bed
  - flow also varies laterally - flow is generally greatest at the deepest part of the channel
  - Vertical as well as lateral variation of velocity
- a suitable control section must be selected
  - channel control - a long straight uniform section of channel is required

1. Velocity – Area methods

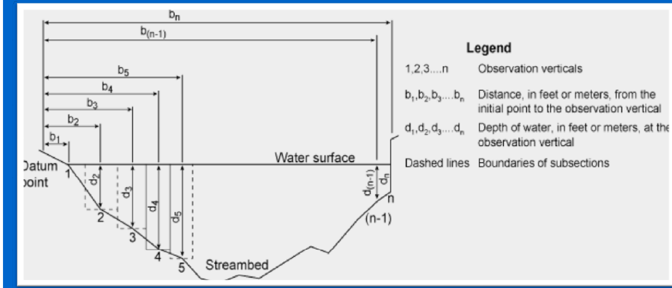
- To account for lateral variation, the cross-section is divided into suitable cross-sections of a1, a2, a3, …..
- The veridical velocity variation is accounted by taking velocity at different depths
  - ***One point*** - at 0.6 h
  - ***Two point method*** - at 0.2h and 0.8h
  - ***Three point method*** – at 0.2h, 0.6h and 0.8h
  - ***Depth - Integrated velocity measurement*** – device when lowered and raised at a constant rate through a vertical section integrates velocity and provides a means of measuring the average velocity of the section

1. Velocity – Area methods

To account for variations in flow velocity the channel is divided into vertical sections. Within each section, average flow velocity has been found equal to the average of flows at 0.2 and 0.8 of the stream depth measured from the surface. For shallow sections, 0.6 of the depth may be used as an approximation of average flow.



1. Velocity – Area methods



Devices for Flow Velocity Measurement

- **Current Meters**
  - Cups
  - Propellers

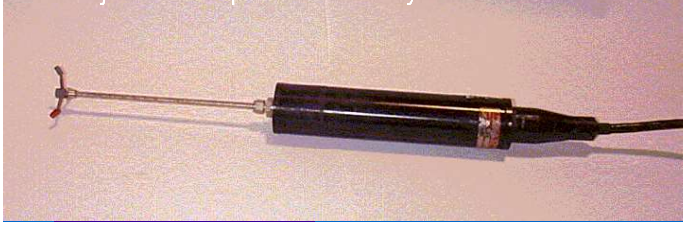
$$V = a + b \times N$$

where V = flow velocity; a = starting velocity to overcome mechanical friction; b = equipment calibration constant; N = revolutions/sec.

Electromagnetic Velocity Meter

Acoustic Doppler Velocimeter

- Uses sound to measure 3D velocity at different depths
- Measures the velocity of the whole vertical profile at once
- Not just at one point as velocity meters do



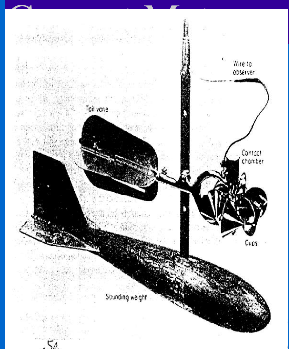


Figure 4-5 Price current meter and "30-lb" C-type sounding weight. (U.S. Geological Survey.)

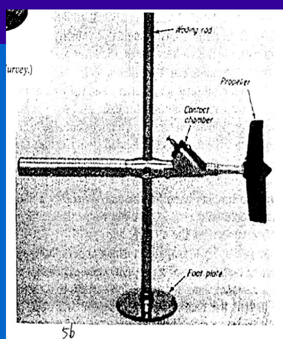


Figure 4-6 Propeller-type current meter on wading rod.

Mechanical velocity meters

- **Measure velocity in one direction at a point**

Measuring Velocity in Big Streams

Mean Flow Velocity Estimation

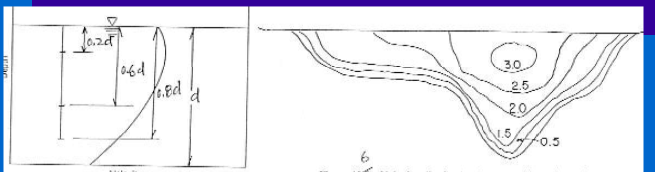


Figure 12.8 Velocity distribution in a nonuniform channel.

Deph < 0.6m $\quad \bar{V} = V_{0.6d}$; 0.6 water depth from the water surface

0.6m ≤ Depth ≤ 2m $\quad \bar{V} = \dfrac{V_{0.2d} + V_{0.8d}}{2}$

Depth ≥ 2m $\quad \bar{V} = \dfrac{V_{0.2d} + 2V_{0.6d} + V_{0.8d}}{4}$

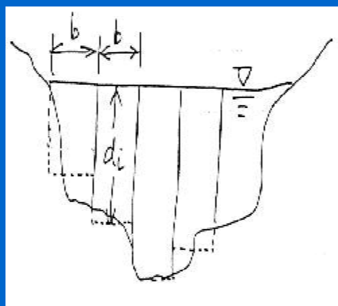
Measurement of Stream Flow Discharge - 1

- a. Mid-Section Method

$$A_i = b d_i$$

$$Q_i = \bar{V}_i A_i$$

$$Q = \sum_i Q_i = \sum \bar{V}_i A_i$$



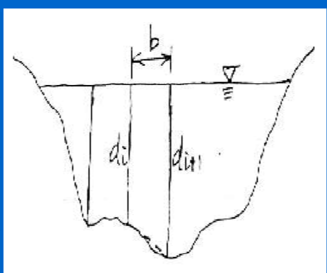
(b) Mean-Section Method

$$A_i = \frac{b}{2}(d_i + d_{i+1})$$

$$v_i = \frac{(v_{0.2} + v_{0.8})}{2}$$

$$Q_i = \bar{\bar{V}}_i A_i$$

$$Q = \sum_i Q_i$$

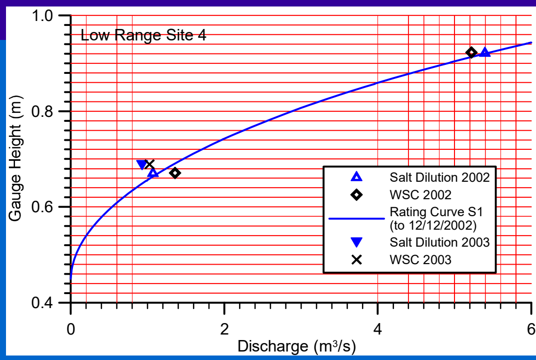


2. Stage – discharge relationship and the Rating Curve

- **For a stable channel, there is a relationship between stream discharge and stage - this relation is called *the rating curve***
  - stage is the water level above a reference elevation
    - reference elevation is often taken as the channel bed, but not necessarily, as the bed elevation in alluvial channels may change

Rating curve

- **For natural channels, stage or gauge height (Y-axis) is plotted against flow (X-axis)**
  - the curve is a parabola or other
  - curve fitting
  - it is essential that the stage measurement be tied in to some fixed stable benchmark
    - changes in bed elevation due to scour or aggradation are reflected in a curve shift



Rating curves

- A best estimate of the relationship between stage and discharge at a given place in a river.
- The relationship should be on the form $Q=C(h-h_0)^n$ or a segmented version of that. *Q*=discharge, *h*=stage
- For a known zero-stage, the rating curve can be written as $y=b+nx$,
  - where $y=log(Q)$, $x=log(h-h_0)$ and $b=log(C)$.
- How do we estimate the rating curve parameters of C, b and *ho?*

Establishing a rating curve

- **Least square solution method**
  - trial and error approach
  - Three point dicharge appraoch
- **Graphical methods**

Establishing a rating curve

1.LSS method

- Assume Ho and estimate the coefficients C and n that gives the best r^2 and minimum standard error
- The LSS equations are given next slide
  - Log Q=log C+ nlog (H-Ho)
  - Y = b + nX
- **Change the value of Ho and evaluate the Se and r^2**
- **Continue until you have global minimum Se and best r^2**

Establishing a rating curve

LSS Equations

$Q=C(H-H_0)^n$

Log Q=log C+ n Log (H-Ho)

↓ ↓ ↓

y = b + n x

Linear equation

$$n = \frac{N(\sum xy) - (\sum x)(\sum y)}{N(\sum x^2) - (\sum x)^2}$$

$$b = \log C = \frac{(\sum y) - n(\sum x)}{N}$$

$$S_e = \left\{ \frac{1}{N} \sum (Q - Q_{\cdot})^2 \right\}^{1/2}$$

$$r^2 = \left(1 - \frac{\sum (Q - Q_{\cdot})^2}{(Q - \bar{Q})^2} \right) * 100\ \%$$

Establishing a rating curve

- 2. Three point discharge method
- Three discharge values are selected from H-Q curve and in such a way that Q1/Q2 = Q2/Q3
- Ho is determined from this relation as

$$H_o = \frac{H_1 H_2 - H_2}{H_1 + H_3 - 2H_2}$$

Examples of rating curve equation

Code	River	Station	Period	a	b	Ho	r2
1002	Gilgel Abbay	Merawi	Mar 59/Jun 62	33.49	1.979	0.25	0.989
			Dec 62/Jul 84	34.58	2.069	0.25	0.994
			Aug 84/Feb 94	35.61	2.04	0.2	0.997
1003	Koga	Merawi	1959/1981	13.41	2.029	0.5	0.964
			except Sep/Dec 69			0.3	0.964
			1982/1995	19.98	2.239	0.15	0.99
1005	Ribb	Addis Zemen	Aug 59/Sep 71	7.23	1.908	0.65	0.946
			Nov 71/Dec 75	3.48	2.046	0.75	0.961
			1976/1977	3.04	2.194	0.8	0.981
			1978/1979	3.5	2.102	1.15	0.995
			1980/1981	2.48	2.288	1.15	0.976
			1981/1983	3.85	2.069	1.55	0.974
			1984/1985	3.49	1.754	1.8	0.953
			1986/1988	4.39	1.976	2	0.977
			1988/1990	1.29	2.6	2.1	0.899
			1990/1994	0.54	3.305	2.2	0.974
1006	Gumara	Bahir Dar	59/66	14.9	1.683	0.55	0.956
			67/68	5.8	2.373	0.1	0.965
			69/95	8.7	1.929	-0.15	0.947

Requirement of a good H- Q site

- The river reach must be stable and fairly straight on both u/s and d/s for a length of 0.75 to 1km
- H-Q relation should always be uniform – site is subjected to shift control
- Easily accessible during all the time of the year
- The site should be sensitive to all H-Q
- Back water and tidal effects should be minimum
- Site should be away from bridge
- When a tributary joins, the site should be located 0.8 km u/s and d/s of their confluence
- Disturbance due to animals should be minimum
- Site should have stable and high banks to contain floods
- Rock outcrops and vegetal growth at the reach should be minimum

Requirement of a good H- Q site

- Islands should not be present at the gauging station
- Cross section of the entire reach of the river should be fairly inform
- Cross currents, vortex and eddies formation, reverse slope in parts of the channel bed should be absent at the site
- Velocity at all points are parallel to one another and at straight angle to the x-section of the stream
- The velocity is greater than 0.15m/s
- The depth of the flow is greater than 0.3m
- No aquatic growth
- Straight and stable reach

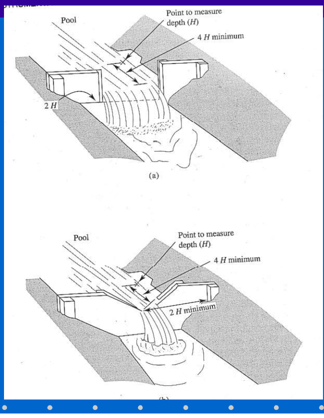
Network design

- There is no definite relation or rule to the number of stations to establish
- A basin should have two types of stations
- i – the base or permanent stations:
  - For which long term data for the important tributaries and the main rivers are always collected
- ii – auxiliary or secondary station:
  - To collect short term data and form network
  - The stations should be located at existing or potential dam site, flood forecasting purpose
  - Data from this station are correlated with data frim primary stations to extend the record

Measuring Q for small channels

- **Weirs and flumes**
  - a weir is an engineered structure that is built into a channel to control the stage - discharge relationship
  - used in small channels where the measurement error in relation to the total flow would be unacceptable, and/or where suitable natural control does not exist
  - discharge is related to head over the weir crest using a simple mathematical formula

Weirs



Example of a weir formula

– for example, a sharp crested V-notch weir (a type commonly used in research on small creeks) has the following formula:

$$Q = 4.28 C_w'' h^{5/2} \tan\frac{\theta}{2}$$

where θ is the angle of the notch, h is the head over the weir crest and C_w'' is a weir coefficient (approximately 0.32 for SI units) that varies slightly with head and notch angle.

Weirs

- Have a more definite relationship between stage and flow
- Higher accuracy than velocity X-sections
- Only can be used for smaller streams

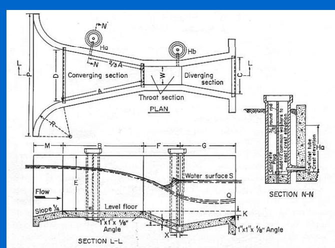
Sharp-Crested rectangular Notch Weirs

- $Q = C_d LH^{3/2}$
- Q = discharge cfs
- C_d = coefficient
- L = Width of notch feet
- H = Depth of flow feet
-

Flumes

- **Have relationship between stage and flow defined by hydraulics of the flume**
- **Higher accuracy than velocity X-sections**
- **Only can be used for smaller streams**
- **Measure water surface at two points in flume to calculate flow**

Flumes



Dilution Gauging

- A solution of a stable tracer is injected into the stream at either constant rate or all at once
- Useful for small streams and streams with lots of boulders, wood, or other roughness elements
- Some limitations on the size of the stream to be measured
- Is suitable for mountainous streams

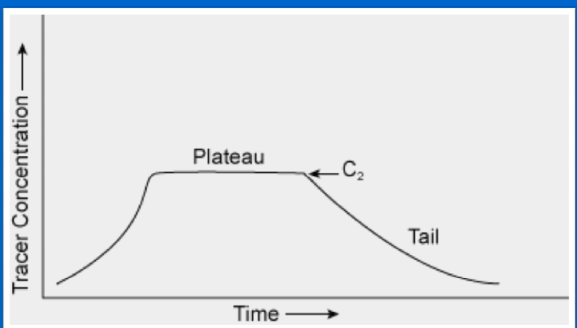
Dilution Gauging

- **Computation requires:**
  - The rate of injection should be known
  - The concentration of the tracer in the injected solution should be known
  - The concentration of the tracer in the stream after it has been mixed should be known
  -

Constant Injection

- Inject tracer with a known concentration (C_1) at a known flow rate (Q_1) into the stream and Co is initial concentration of the streamflow
- Measure the stream concentration (C_o) after complete mixing at d/s section
- Calculate the stream flow
  - **$Q_2 = q_{1}(C_1 - C_o)/(C_2 - C_o)$**
  - If the initial concentration of the tracer in the streamflow is insignificant then $Q_2 = (q_1C_1)/(C_2)$

Constant Injection



Measurement of discharge under difficult condition

- Unstable channels
- Tidal reaches
- Flood measurement
- Weed growth in stream channels

Measurement of discharge under difficult condition

1. **Unstable channels**
   - Characterized by a systematic shift of the bed, high silt concentration and presence of various types of debris
   - This is hindrance for operation of permanent gauging station/structure
   - How do you minimize this problem?
     - By selecting midway along a uniform and straight section of the channel away from any obstruction such as bridge, etc.
     - The greatest channel bank is obtained where the channel has narrow width

- If the method stage discharge method is used, the velocity distribution varies periodically, therefore, updated rating curve should be utilized
- E.g of unstable channel Is **Ribb river**
- On small streams where there is no transport of large stones and debris
  - Portable or permanently installed flumes can be used – artificial improvement of the channel

1. **Mountain Streams**
   - Characterized by high flow velocity
   - Shallow and uneven beds blocked by boulders and debris
   - Transverse and uneven water surface slopes
   - Transport of stones and debris
   - Mostly the dilution methods can be convenient
   - Improvement of the channel my be requires

Measurement of unsteady flows

- **Measurements of discharged during floods:**
  - Flood measurements should best be done from bridges, cableways or boats.
  - For large rives with no bridges or cableways, large vessels or ferries ca be used

Assignment V

1. A common salt dilution of concentration 200 mg\l was added to a stream at a constant rate of 0.2 cm3/s. concentration of this salt in the stream water was measured as 0.05 ppm. Estimate the stream discharge
2. The following data are observed in a stream by a current meter. The current meter rating equation is given as V = 0.33 + 0.03N (N= is no. of revolution per second). Calculate river discharge

Distance from bank, m	0	3	5	7	9	12	15	18	21	23	25	27
Depth, m	0	0.6	1.2	2.05	2.35	2.1	1.9	1.6	1.4	1.0	0.4	0
No. of rev at 0.6d	0	90	95	135	142	125	115	110	95	90	76	0
Time, sec	0	184	125	125	125	125	125	125	125	125.4	125	0

3. Stage discharge data at site are given below. Find the stage corresponding to zero discharge.

Stage, m	25.9	26.89	27.91	29.06	31	35.52	34.4	35.38	36.42	38.01	39.05	39.55
Discharge, m3/s	8.9	23	36	47	120.8	285.3	380	456	533	590	680	690

Assignment V

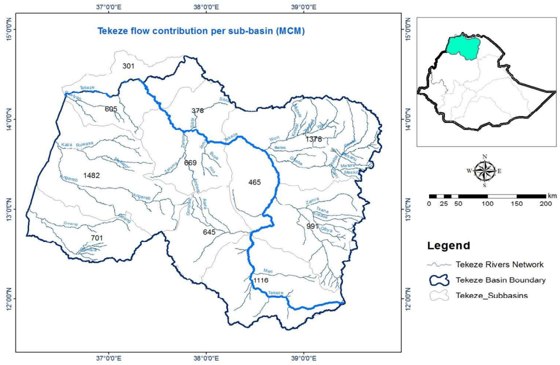
4. If you are required to measure discharge under difficult conditions (such as mountainous rivers), describe the hydraulic condition of the reaches and suggestion how you can proceed to measure discharge?
5. Your organization wants to establish a rating curve for newly established gauging station in remote reach of Beles River. Show clearly the procedure to establish the rating curve. The discharge of the river is above 100 m3/s and the river has a depth of 2 to 5 m depending on the seasons. How long it take to create a working rating curve and Why?

Integrated Water Resources Management (IWRM)

- The scale of managing water at basin level
- Water allocation based on actual measurement of availability and use
- Require real time flow measurement
- Stream network coincide with sub-systems
- Integrated water resources development planning

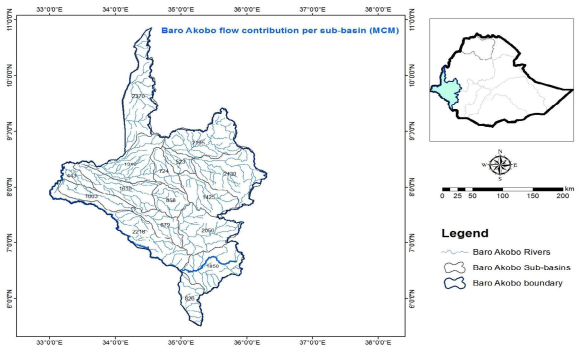
Note: the design of gauging sites is dictated by needs of **water management** or the **requirements of the hydrologic network**

Integrated Water Resources Management (IWRM)



Example: Tekeze River Basin sub-systems

Integrated Water Resources Management (IWRM)



Example: Baro-Akobo River Basin sub-systems

Network design for water resources development

- Two types of gauging stations:
  - 1) <u>**Hydrologic stations:**</u> established to determine the basic stream flow characteristics of the region
    - Two types:
      - » **Principal/primary stations:** operated permanently
      - » **Secondary stations:** operated only long enough to establish the flow characteristics of their watershed
  - 2) <u>**Special stations:**</u> established to provide specific information, such as:
    - Inventory the outflow from a basin
    - Management and operation of existing project
    - Fulfilment of legal requirements, agreements, or basin compact
    - Design of a proposed project

Network design for water resources development

- In designing the network, all types of stations should be considered
- A minimum network should include at least one principal hydrologic stations in each climatologic and physiographic regions:
  - Runoff characteristics of streams are related to the characteristics:
    - Climatology
    - Topographic
    - Geologic
- A minimum network will also include some special stations
- The design of the gauging stations network must be tailored to the drainage characteristics of the region/basin or its sub-regions/sub-basins
- The gauging station network, once designed requires evaluation and upgrading within certain interval of time

The ideal gauge sites satisfies the following criteria:

- the hydraulic conditions necessary for maintaining a permanent relation between state and discharge
- The total flow is confined to one channel at all stages and now flow bypasses the site as subsurface flow
- The stream-bed is not subject to scour and fill and is relatively free of aquatic vegetation
- River banks are permanent, high enough to contain floods, and are free of brush
- The gauge site is far enough upstream /downstream from the confluence
- A satisfactory reach/stream for measuring discharge at all stages within reasonable proximity of the gauge site
- Accessible for installation and operation at all seasons of the year
- Within reach of a suitable telemetry system or favourable conditions for correct placement of the water level gauge
- Instruments, shelter, and housing above all flood levels, etc.

Field Demonstrations!

Contents

Introduction

- Sediment process:
  - Erosion
  - Transport
  - Deposition
- Sediment process is a direct function of water movement
  - Suspended material
  - Bed-load
- In lakes and reservoirs, suspended materials originate from the watershed and river inputs
- Sediment effects:
  - On-site effect
  - Off-site effect

Introduction

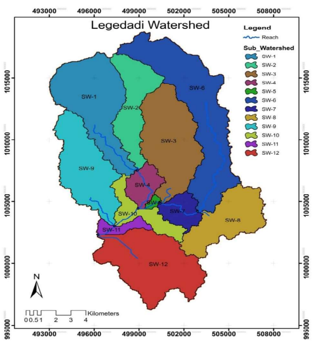
- The success of sediment monitoring program depends on:
  - Experimental design
  - Site selection
  - In-field activities
- A wide range of techniques are available for sampling suspended sediment in rivers, however the appropriateness of each technique is determined by:
  - The flow and sediment dynamics
  - Sample and data requirements
  - Resource available
- Sampling suspended sediments are broadly classified as:
  - Manual (example: sediment trap, stream and sediment discharge measurement)
  - Automatic (example: automated pump and time-integrating)

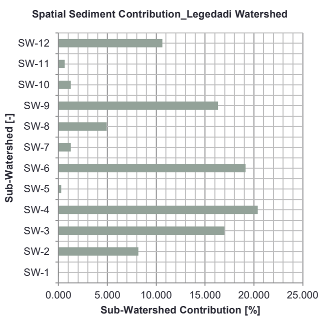
Introduction

- Advantages of manual technique:
  - Most effective and direct means of obtaining a suspended sediment sample
  - It is considered the standard – for comparison of automated and indirect approaches
  - Require less resource during sampling of sediment in the field
- However, points need attention regarding manual sampling:
  - Safe access during high inflow must be guaranteed
  - Financial and time constraints associated with travel to and from the site
  - Important storm flows are infrequent and often difficult to predict

Introduction

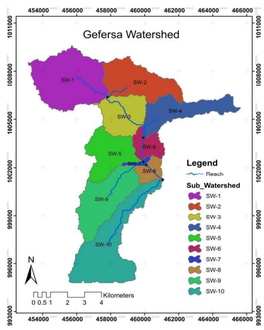
Background modeling work:
Legedadi Watershed

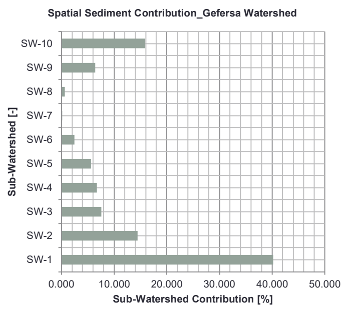




Introduction

Background modeling work:
Gefersa Watershed

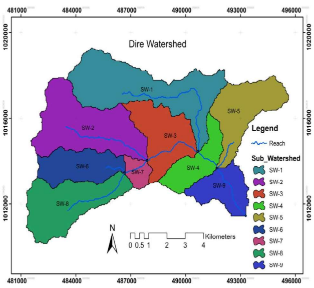


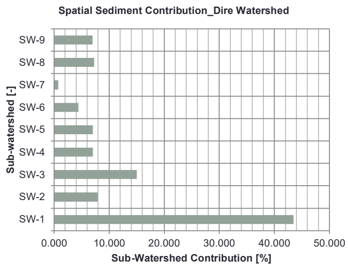


Introduction

Background modeling work:

Dire Watershed





Developing a Stage-Discharge Relationship

Discharge Rating Curve development:

- The relationship between stage and discharge is a single-valued relation:

$$Q = \alpha(Z - a)^{\beta}$$

- Where, Q is stream discharge, Z is gauge height (stage), a is a constant which represent the gauge reading corresponding to zero discharge, α and β are rating curve constants.
- The relationship can be plotted in arithmetic or logarithmic scale
- The best values of α and β in the above equation for a given range of stage are obtained by the least-square-error method

Developing a Stage-Discharge Relationship

Discharge Rating Curve development:

- By taking logarithms:

$$\log Q = \beta \log(Z - a) + \log \alpha$$

- Similarly,

$$Y = \beta X + b$$

- In which the dependent variable $Y = \log Q$, independent variable $X = \log(Z - a)$ and $b = \log \alpha$

Developing a Stage-Discharge Relationship

Discharge Rating Curve development:

- For the best-fit straight line of **N** observations of **X** and **Y**, by regressing $Y = \log Q$ on $X = \log(Z - a)$
- Where,

$$\beta = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum Y)^2}$$

And,

$$\alpha = \frac{\sum Y - \beta \sum X}{N}$$

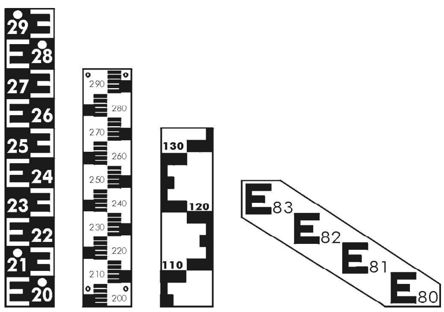
- Pearson product moment correlation coefficient:

$$r = \frac{N(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[N(\sum X^2) - (\sum X)^2] \times [N(\sum Y^2) - (\sum Y)^2]}}$$

Example: table Annex-6

Developing a Stage-Discharge Relationship

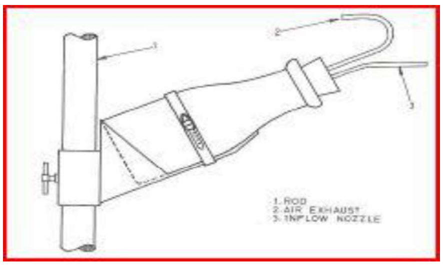
Discharge Rating Curve development:



Types of staff gauges

Sediment Sampling and Analysis

Sampling equipment:



Simple bottle sampler

Sediment Sampling and Analysis

Sediment Concentration Analysis:

Evaporation Method:

- Suspended sediment concentration should be reported in terms of dry weight of the sediment per liter of sample (i.e. water-sediment mixture)
  - Usually grams or milligrams per liter
- Advantage:
  - Simplicity of equipment
  - Simplicity of technique
- Main steps:
  - Allow the sediment to settle
  - Poured out the supernatant water
  - Washed the remainder into an evaporation basin
  - Dried in an oven at a temperature from (90 to 95ºC)
- General steps (see the handout)

Developing Discharge-Sediment Relationship

Sediment Rating curve:

- The concentration of suspended sediment (mass of sediment per volume of water sample collected) transported by a river is typically a strong function of discharge that can generally be characterized by a power law relation:

$$C = a \cdot Q^b$$

- Where, a and b are empirical constants that are established by statistical (regression) analysis of discharge (current) measurements of C and Q for the reach of interest
- This equation can also be transformed into logarithmic scale by taking both sides into logarithmic equation form in a similar way that has been done in development the stage-discharge relationship

Developing Discharge-Sediment Relationship

Sediment Rating curve:

$$\log C = b \log(Q) + \log a$$

Or, similarly:

$$Y = bX + k$$

- In which the dependent variable $Y = \log C$, independent variable $X = \log(Q)$ and $k = \log a$
- For the best-fit straight line of **N** observations of **X** and **Y**, by regressing $Y = \log C$ on $X = \log(Q)$

Developing Discharge-Sediment Relationship

Sediment Rating curve:

Where,

$$b = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum Y)^2}$$

And,

$$a = \frac{\sum Y - \beta \sum X}{N}$$

Pearson product moment correlation coefficient:

$$r = \frac{N(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[N(\sum X^2) - (\sum X)^2] \times [N(\sum Y^2) - (\sum Y)^2]}}$$

Developing Discharge-Sediment Relationship

Sediment Rating curve:

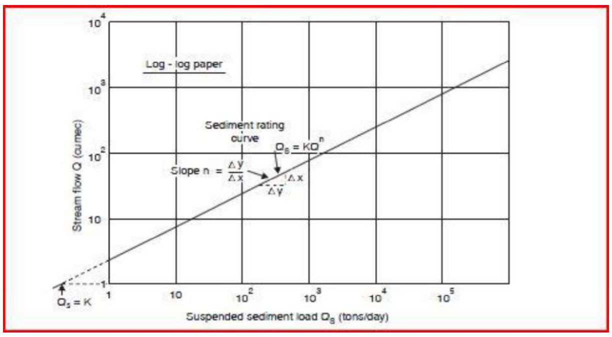
- The rate of sediment discharge, or load (mass per time) is the product of concentration and discharge. So the equation becomes:

$$L = a \cdot Q^{b+1} \quad or\ L = C \cdot Q$$

- Where, **L** is the load of suspended sediment into the reservoir [mass per time], C is the sediment concentration in the water sample collected [mass per volume of water sample], and Q is the rate of discharge of water [volume per time]
- Example: table Annex-8 &9

Developing Discharge-Sediment Relationship

Sediment Rating curve:



Session 2: Practical Sessions

Module 1.5: Operation and Maintenance of Stream Gauging Stations

1.5.1: On-site Operation and maintenance

1.5.2: Processing of Flow Discharge Records