HYN 102 Engineering Hydrology

Streamflow Measurement

River Hydrometry

- Refers to river level, velocity and discharge measurement
- Proper understanding of river flow measurement requires a basic knowledge of the mechanics of *open channel flow.*

Open Channel Flow

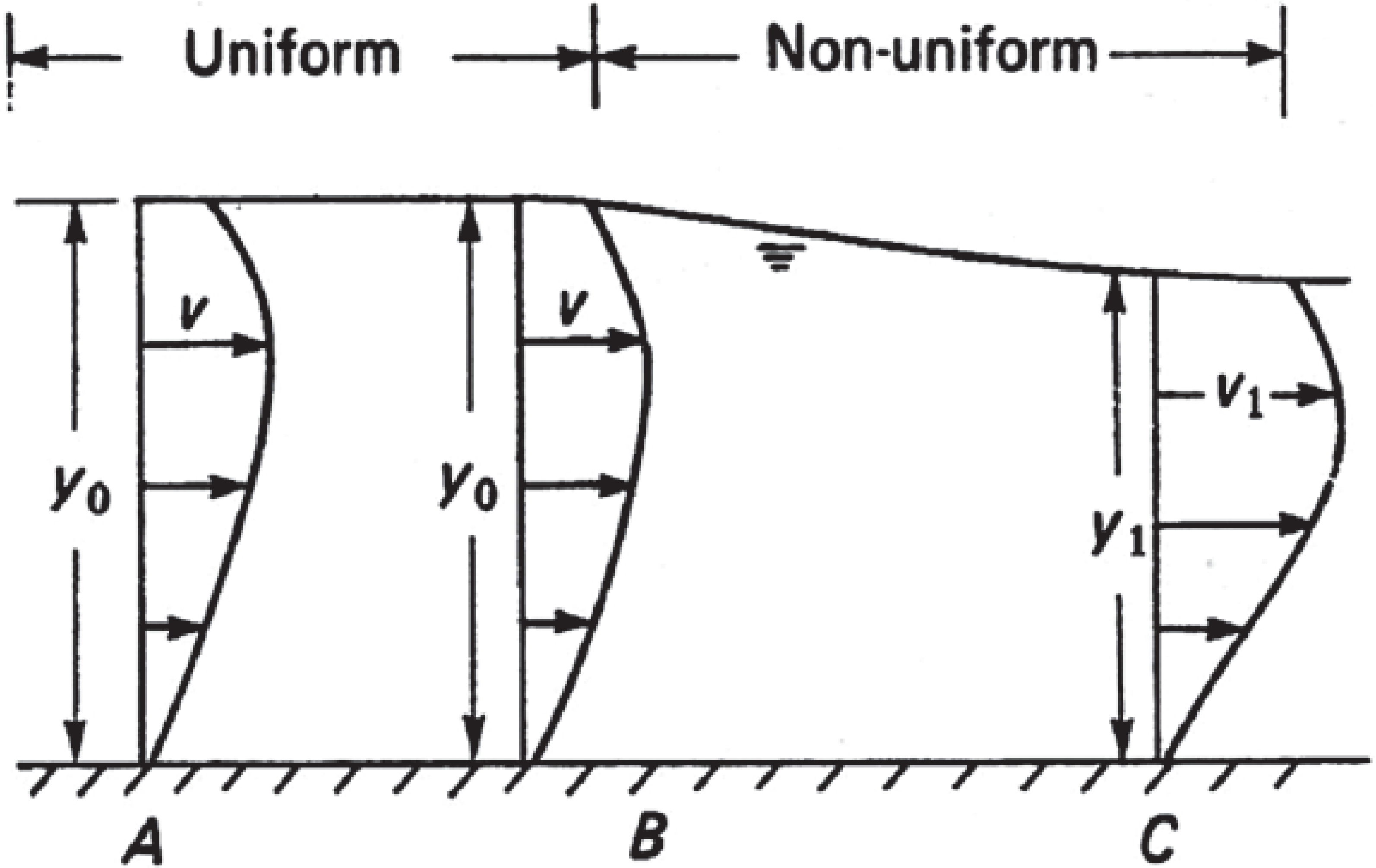
- Open channel flow
  - Water in an open channel is effectively an incompressible fluid
  - that is contained but can change its form according to the shape of the container
  - In nature, majority of surface water either in soil, as lakes, or flows in well-defined channels.
  - Also flows in man-made systems (channels/pipes) as long as there is a free water surface and gravity flow.

Open Channel Flow

- Hydrologist is interested primarily in discharge of a river in terms of cubic metres per second ($m^3\ s^{-1}$)
- In open channel flow study, although the complexity of the cross-sectional area of the channel may be readily determined
  - the velocity of the water in metres per second ($m\ s^{-1}$) is also a characteristic of prime importance.
- The variations of velocity both in space and in time provide bases for the standard classifications of flow.

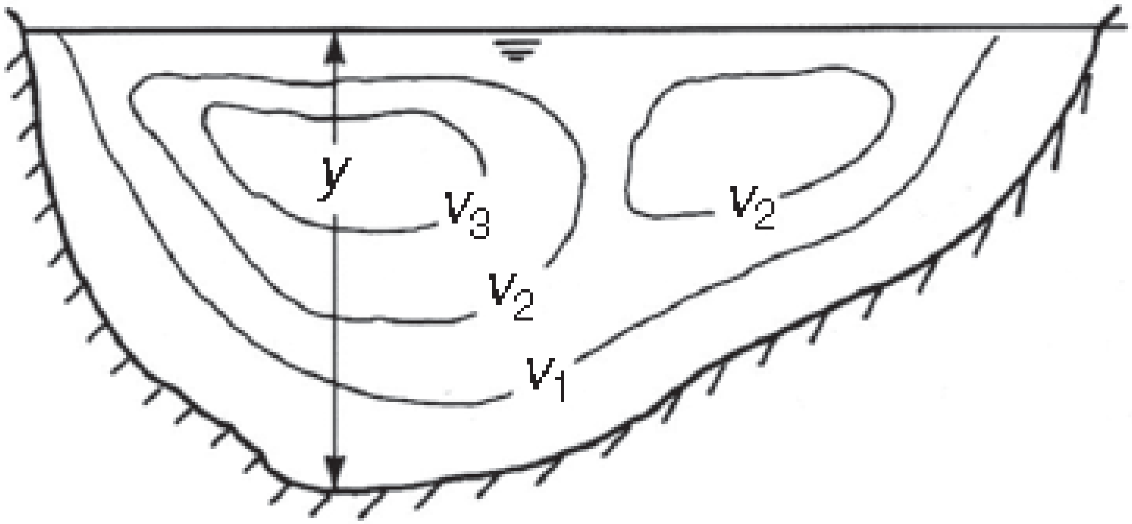
Classification of Flows

- Uniform vs Non-uniform flow
- Usually means that the velocity pattern within a constant cross-section does not change in the direction of the flow.
- Flow is uniform from *A to B in which the depth of flow,* y_o, *called the normal depth,* is constant.
- The values of velocity, *v, remain the same at equivalent depths.*
- *Between B and C, the flow shown is non-uniform; both the depth of flow and the velocity* pattern have changed.
- The depth is shown as decreasing in the direction of flow ($y1 < yo$). *A flow with depth increasing* ($y1 > yo$) *with distance would also be* non-uniform

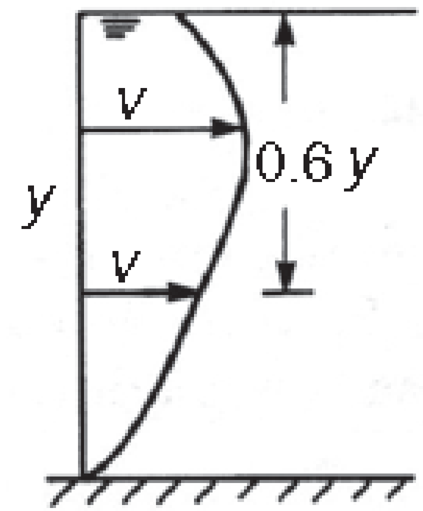

Uniform
Non-uniform
v
v
v_1
y_0
y_0
y_1
A
B
C

Velocity Distribution

- Over the cross-section of an open channel, the velocity distribution depends on the character of the river banks and of the bed and on the shape of the channel.
- The maximum velocities tend to be found just below the water surface and away from the retarding friction of the banks.
- The maximum velocities typical of conditions on the outside bend of a river.
- *The average velocity of such a profile is often assumed* to occur at or near 0.6 depth



(a)



Velocity profile

(b)

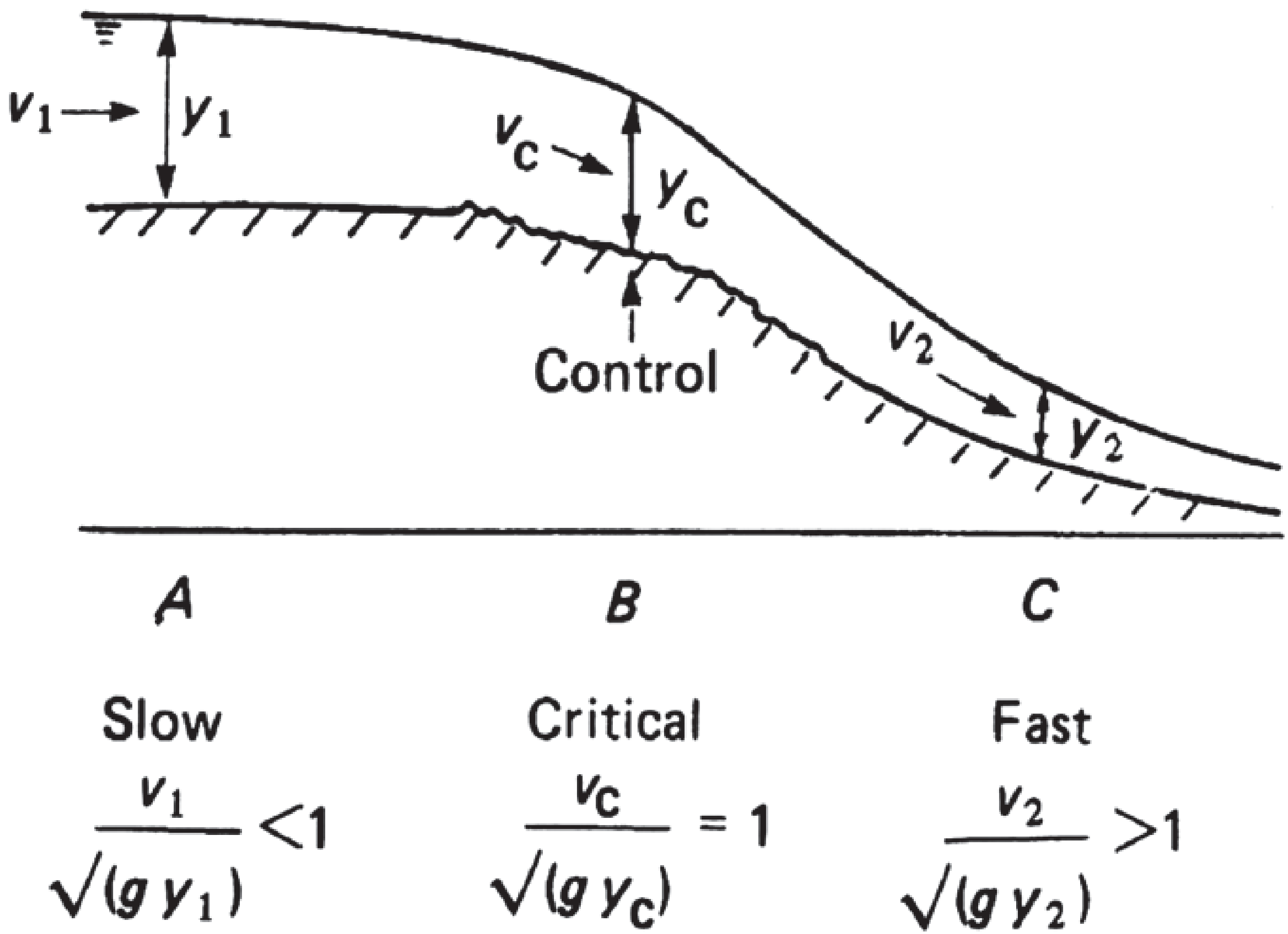
Laminar and Turbulent Flow

- When fluid particles move in smooth paths without lateral mixing, the flow is said to be *laminar.*
  - *Viscous forces dominate other forces in laminar flow and it occurs only* at very small depths and low velocities.
  - It is seen in thin films over smooth paved surfaces.
  - Laminar flow is identified by the Reynolds number **Re = $\rho_w \upsilon y/\mu$**, *where* ρ_w is the water density and μ *the dynamic viscosity. (For laminar flow in open channels,* Re is less than about 500).
- As the velocity and depth increase, Re increases and the flow becomes *turbulent, with considerable mixing laterally and vertically in the channel.*
- Nearly all open channel flows are turbulent.

Critical, Slow and Fast Flow

- Flow in an open channel is also classified according to an energy criterion.
- For a given discharge, the energy of flow is a function of its depth and velocity, and this energy is a minimum at one particular depth, the critical depth, y_c .
- Akan (2006) that the flow is characterized by the dimensionless Froude number:

$$Fr = \frac{v}{\sqrt{(gy)}}$$



The occurrence of critical flow as defined by the Froude number, $Fr = v/\sqrt{(gy)}$, where v is the velocity, g is gravitational acceleration and y is the depth of flow. Slow flow is also called subcritical flow, and fast flow is also called supercritical flow.

- For Fr < *1, flow is said to be subcritical (slow, gentle or tranquil).*
- *For Fr = 1, flow is* critical, with depth equal to y_c *the critical depth.*
- *For Fr > 1, flow is supercritical (fast* or shooting).
- Larger flows have larger values of υ_c *and* y_c.
- *The occurrence* of *critical flow is very important in the measurement of river discharge because, at* the point of *critical flow for a given discharge, there is a unique relationship between* the velocity and the discharge as $\upsilon = \sqrt{(gy)}$.
- *Thus only depth has to be measured to* calculate velocity
- Elsewhere, the flow might be either a subcritical or supercritical state, and both velocity and depth would have to be measured to derive discharge.
- if a cross-section where critical flow occurs naturally cannot be found, the installation of a weir or flume can force the flow to become critical.

- Steady Flow:
- This occurs when the velocity at any point does not change with time.
- Flow is unsteady in surges and flood waves in open channels. The analytical equations of unsteady flow are complex and difficult to solve but the hydrologist is most often concerned with these unsteady flow conditions.
- With the more simple conditions of steady flow, some open channel flow problems can be solved **using the principles of continuity, conservation of energy and conservation of momentum**

STREAMFLOW MEASUREMENT

- **Introduction**

❖ Stream flow represents runoff phase of the hydrological cycle.

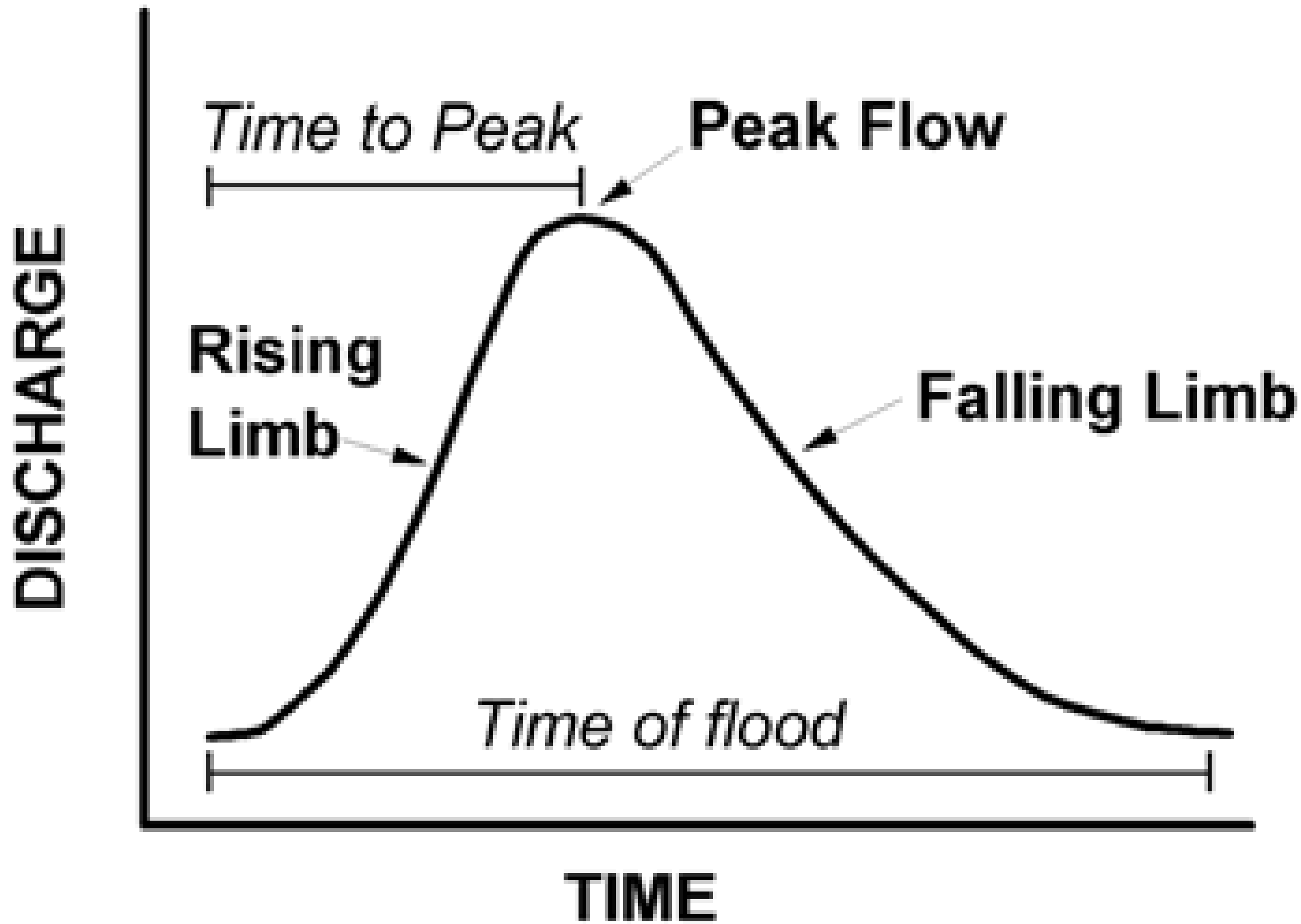
❖ Most important basic data for hydrological studies.

❖ Precipitation, evaporation, evapotranspiration, infiltration are difficult to measure and these components vary over space.

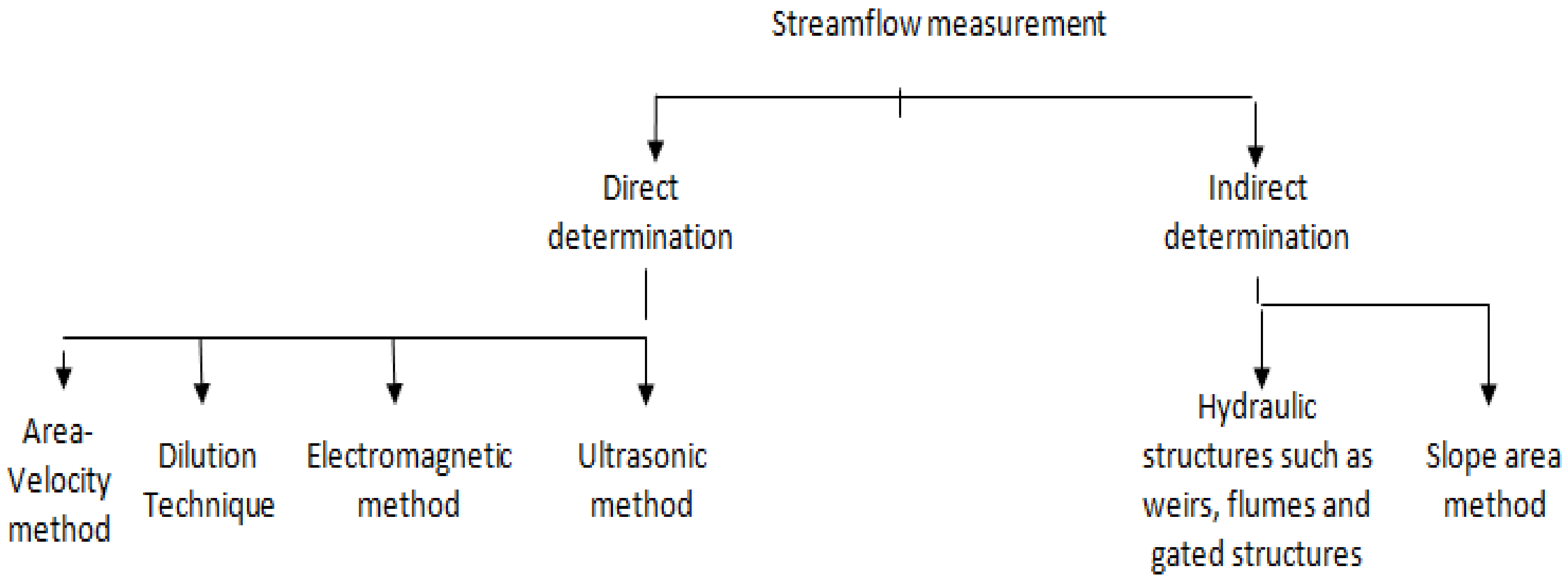
❖ Stream flow represents flow at any section and it integrates all the runoff formed at the upstream of the section of measurement.

- Stream flow is amenable to fairly accurate measurement and it is the only component of the hydrological cycle that can be measured accurately.
- Stream can be considered as a flow channel into which the surface runoff from a specified basin drains.
- Considerable exchange of flow takes place between a stream and the aquifer.
- Stream flow is measured in units of discharge(m^3/s) and it is an instantaneous value. Measured stream flow forms part of the historical data.
- The measurement of discharge in a stream forms the subject of hydrometry.
- **Hydrometry is the science and practice of water measurement.**

Hydrograph



Time to Peak
Peak Flow
Rising
Limb
Falling Limb
Time of flood
DISCHARGE
TIME

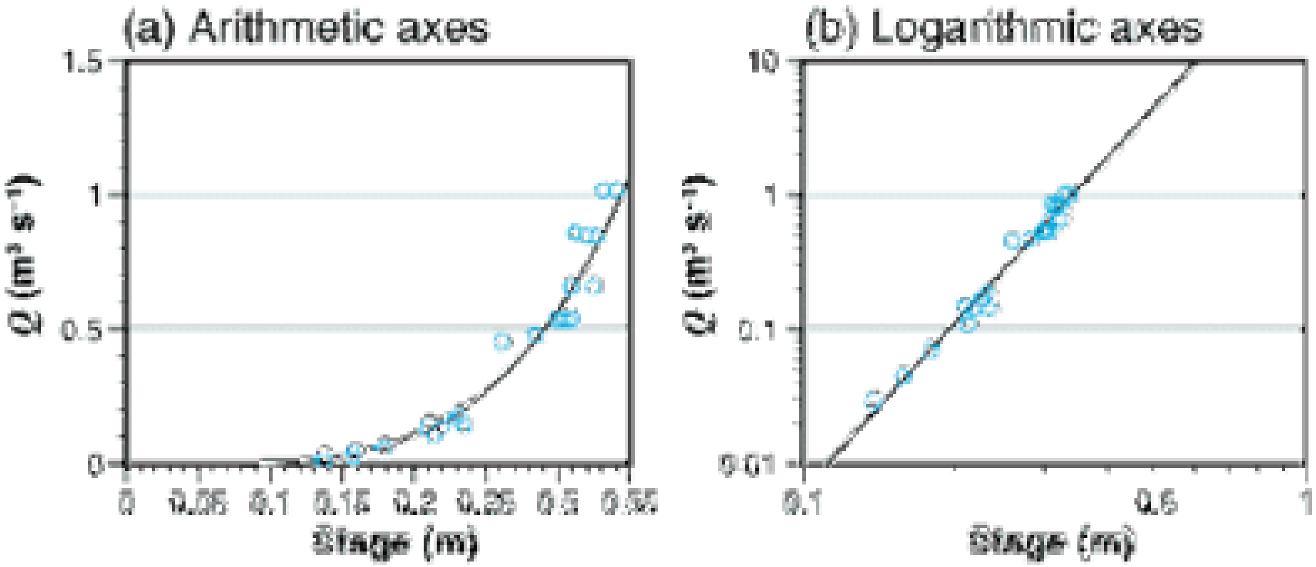

Streamflow measurement
Direct determination
Indirect determination
Area-Velocity method
Dilution Technique
Electromagnetic method
Ultrasonic method
Hydraulic structures such as weirs, flumes and gated structures
Slope area method

- Continuous measurement of stream discharge is very difficult. Direct measurement of discharge is a very time consuming and costly procedure.

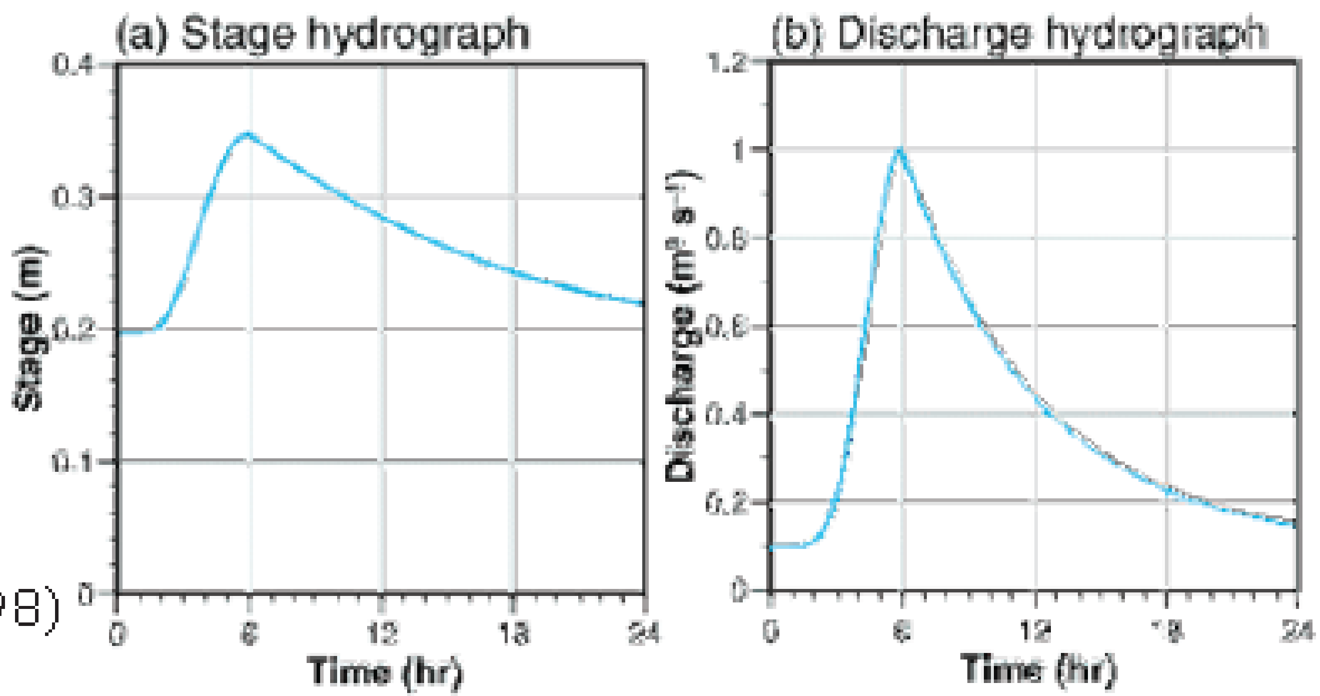
Hence, a two step procedure is followed:

1. First, the discharge in a given stream is related to the elevation of the water surface (stage) through a series of careful measurements.
2. The stage of the stream is observed routinely in a relatively inexpensive manner and the discharge is estimated by using the previously determined stage-discharge relationship.
3. The observation of stage is easy, inexpensive, and if desired, continuous readings can also be obtained.

This method of discharge determination of streams is adopted universally.


(a) Arithmetic axes
(b) Logarithmic axes
Q (m³ s⁻¹)
Stage (m)

98)

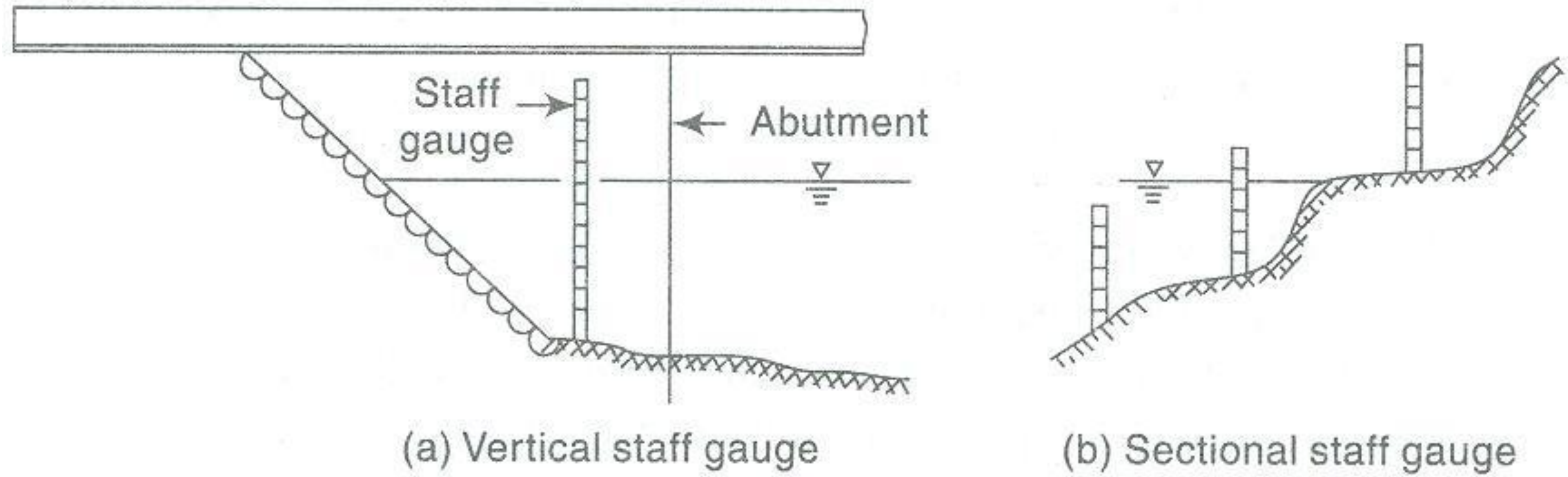

(a) Stage hydrograph
(b) Discharge hydrograph
Stage (m)
Discharge (m³ s⁻¹)
Time (hr)

- **Measurement of Stage**

The stage of a river at a particular location is defined as its water-surface elevation measured above a datum. The datum can be the mean-sea level (MSL) or any arbitrary datum connected independently to the datum.

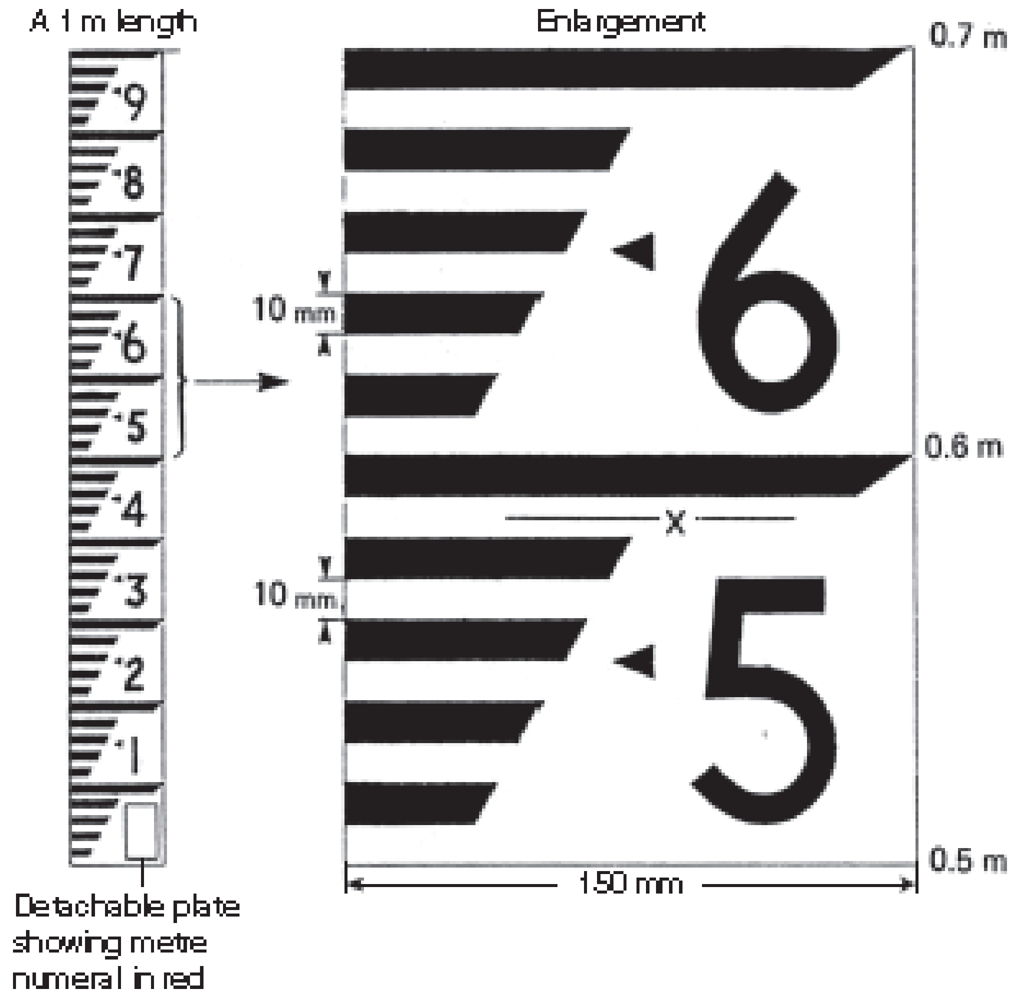
- **Manual gauges**

The simplest of stage measurements are made by noting the elevation of the water surface in contact with a fixed graduated staff



Staff Gauge

- Staff gauge is a durable material with a low coefficient of expansion with respect to temperature and moisture.
- Sectional staff gauge is used- when single gauge of longer length cannot be used as the entire range of water surface estimation cannot be used.



A staff gauge. Stage reading at $X = 0.585$ m. (Adapted from BS 3680-7: 1971, British Standards Institution.)

- **Wire gauge (Float-operated recorders)**

It is a gauge used to measure the water-surface elevation from above the surface such as from a bridge.

Lower the wire tied with the weight at one end. A mechanical counter measures the rotation of the wheel which is proportional to the length of the wire lowered to touch the water-surface of the stream flow. The operating range of this gauge is about 25m.

Wire Gauge

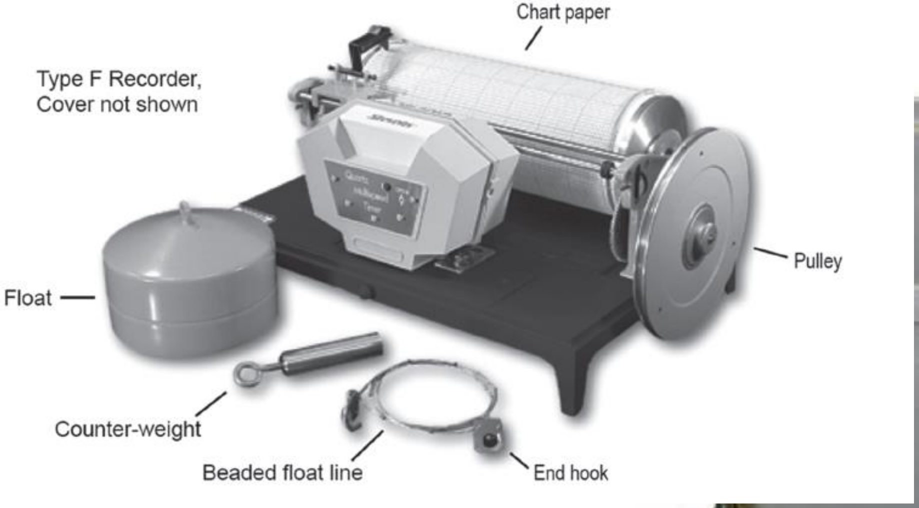
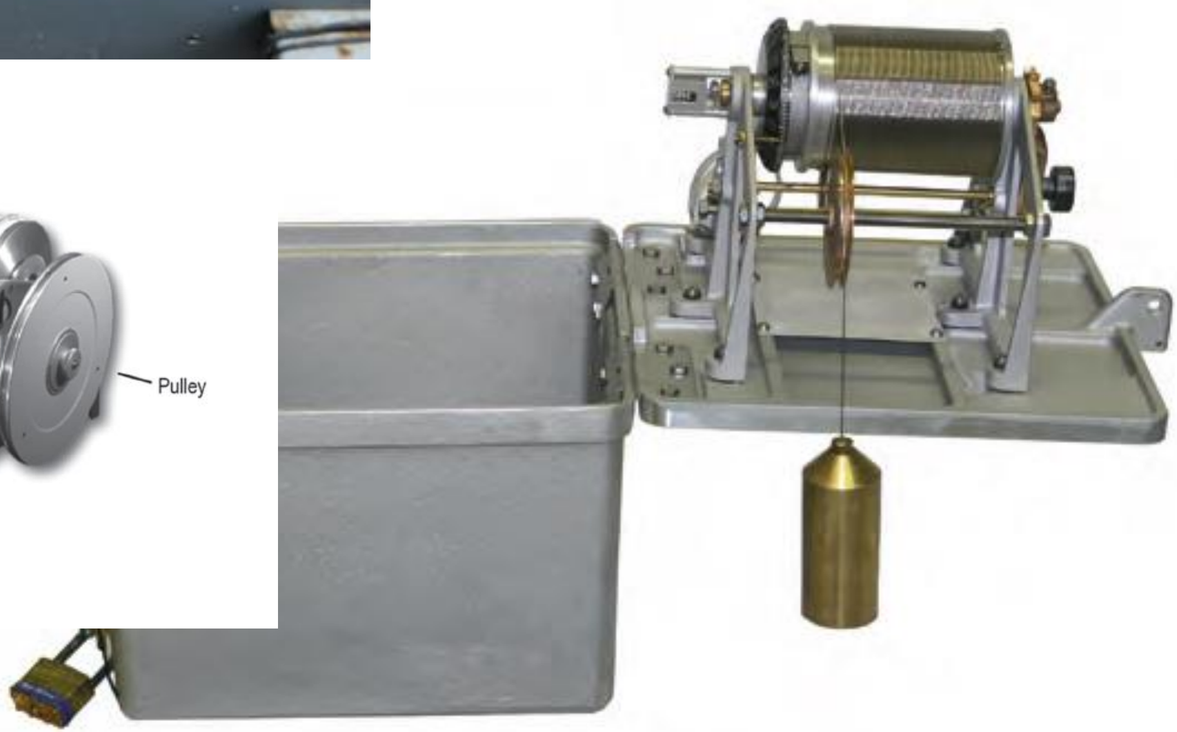
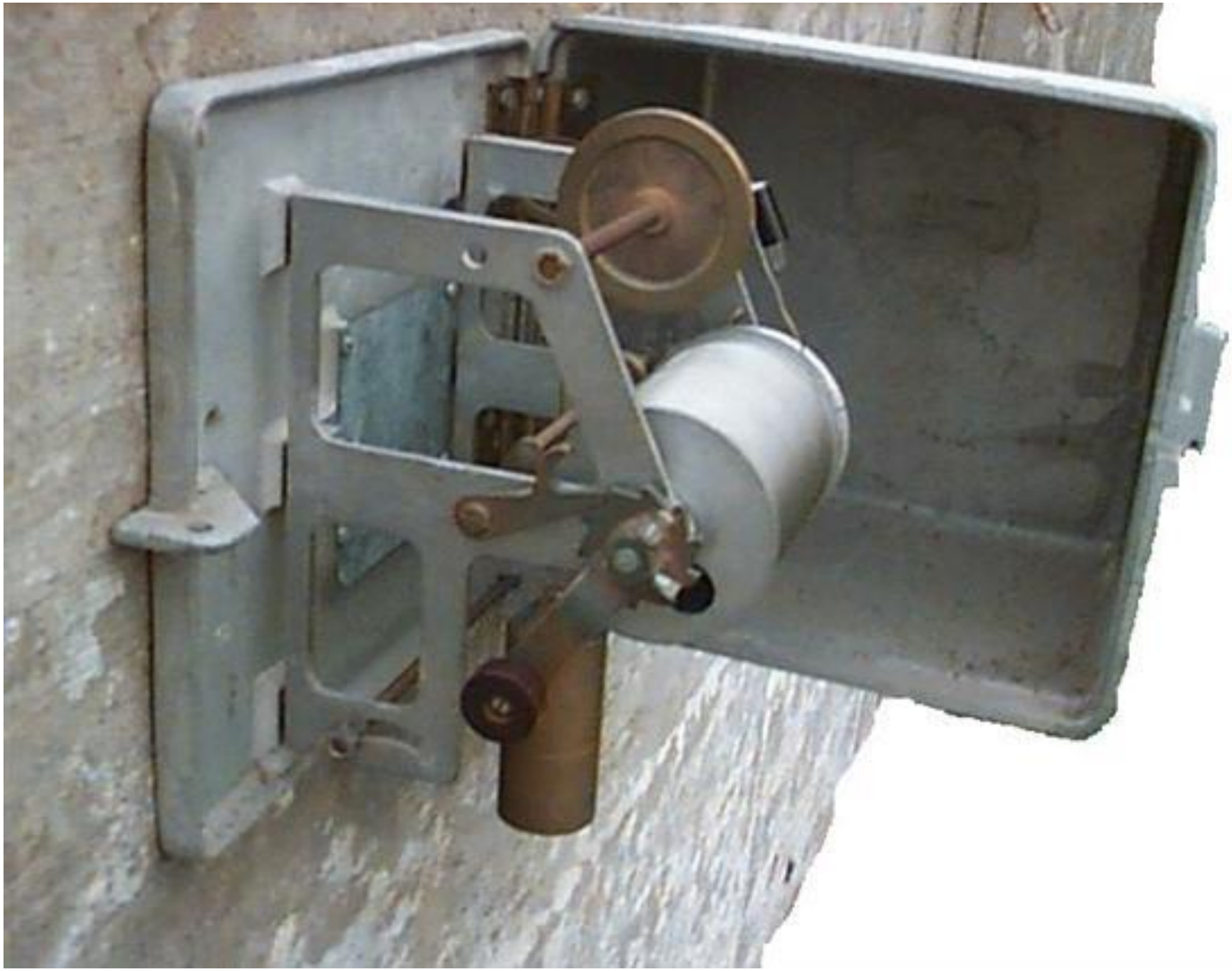


Chart paper
Type F Recorder,
Cover not shown
Pulley
Float
Counter-weight
Beaded float line
End hook





Cantilever Wire Gauge

- **Automatic Stage Recorders**

The stage gauge and wire gauge desired earlier are manual gauges. Simple, inexpensive, but they have to be read at frequent intervals to define the variation of stage and time accurately.

Automatic stage recorders overcome this basic deficiency of manual staff gauges.

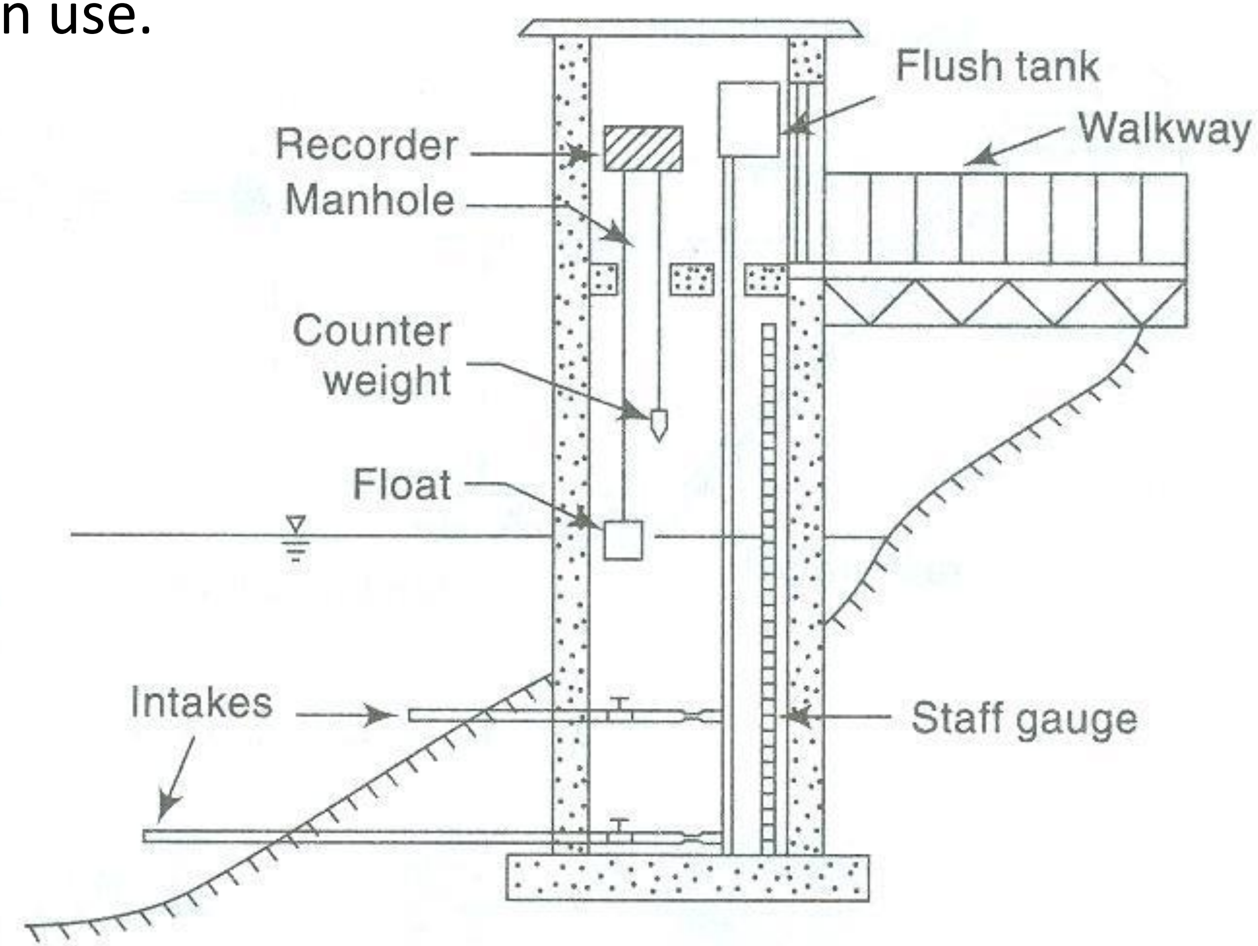
- Two types of automatic stage recorders.

  1.Float-Gauge Recorder

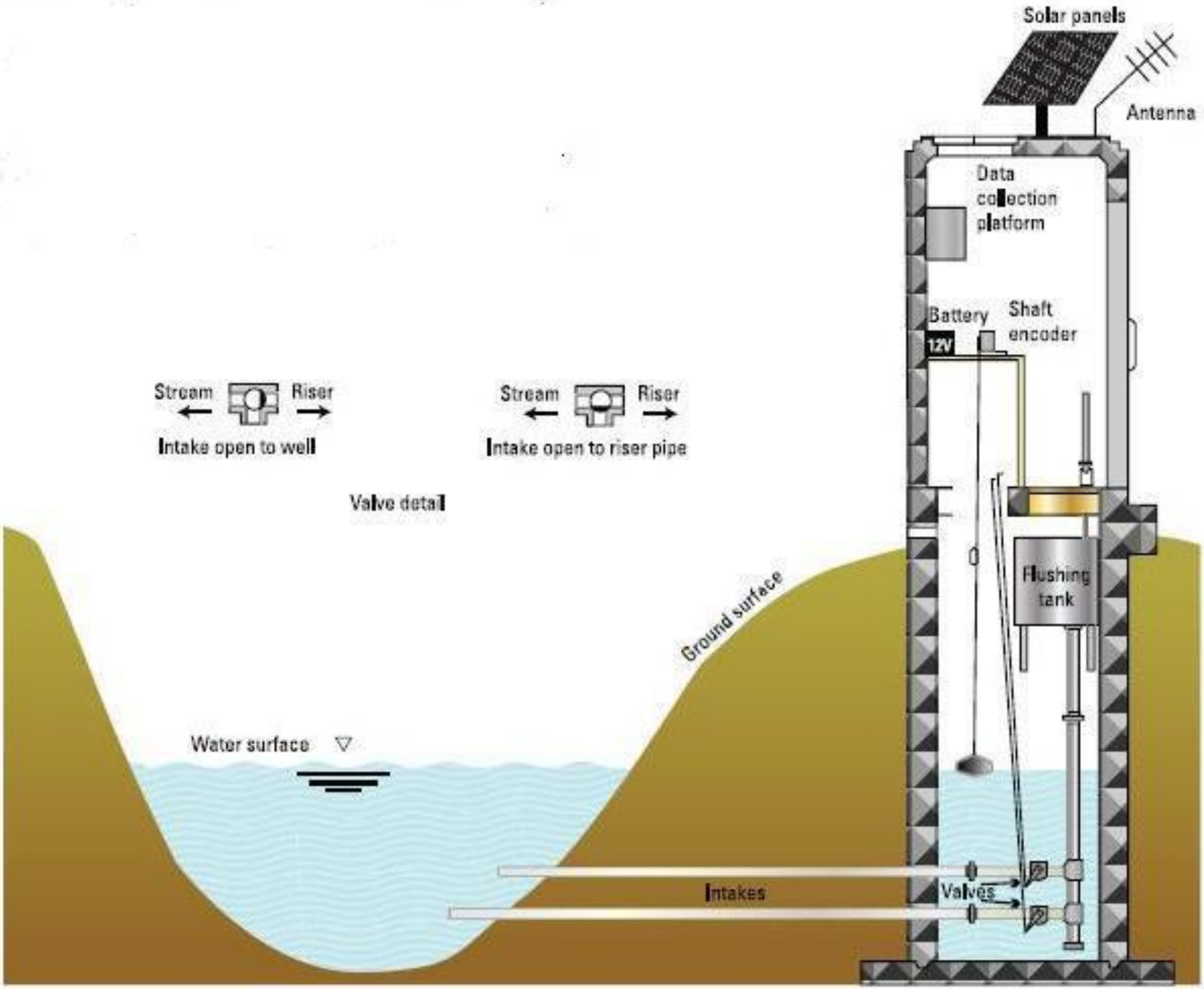
  2.Bubble Gauge

1. Float-Gauge Recorder

This is the most common type of automatic stage recorder in use.



Stilling well Installation



Solar panels
Antenna
Data collection platform
Battery
12V
Shaft encoder
Stream
Riser
Intake open to well
Stream
Riser
Intake open to riser pipe
Valve detail
Ground surface
Flushing tank
Water surface
Intakes
Valves

Shaft encoder

- The float with its geared pulley and counterweight turns a *shaft encoder (also called rotary encoder). The encoder comprises of a disc with concentric, metal rings with* breaks, plus a series of fixed contact wipers.
- As the disc rotates on the shaft, those wipers that are in electrical contact with the metal ring sections create a unique binary code, which can be recorded on an eight-bit data logger.

Shaft encoder-based float-operated recorder. (Reproduced with permission of OTT Hydrometry Ltd.)

Electronic pressure sensor

- The measurement of stage by pressure sensors, an indirect method converting the hydrostatic pressure at a submerged datum to the water level above, are widely used for gauging small rivers and streams.
- Those pressure sensors used within these applications typically use <u>piezo-resistive, silicon strain gauges</u>, and are called <u>*pressure transducers*</u>*.*
- Versions of these sensors with on-board signal amplification and current output are called <u>*pressure transmitters*</u>*.*

A submersible pressure transducer used for river-level monitoring in the UK. (Reproduced with permission of Campbell Scientific Ltd.)

- *Differential pressure transducers (or transmitters)*, where the differential pressure between water-level pressure and atmospheric pressure (observed by means of an air pipe running inside the cable connecting the sensor to data logger) are normally used.
- The calibration of the pressure sensor may change over time and this is normally checked annually.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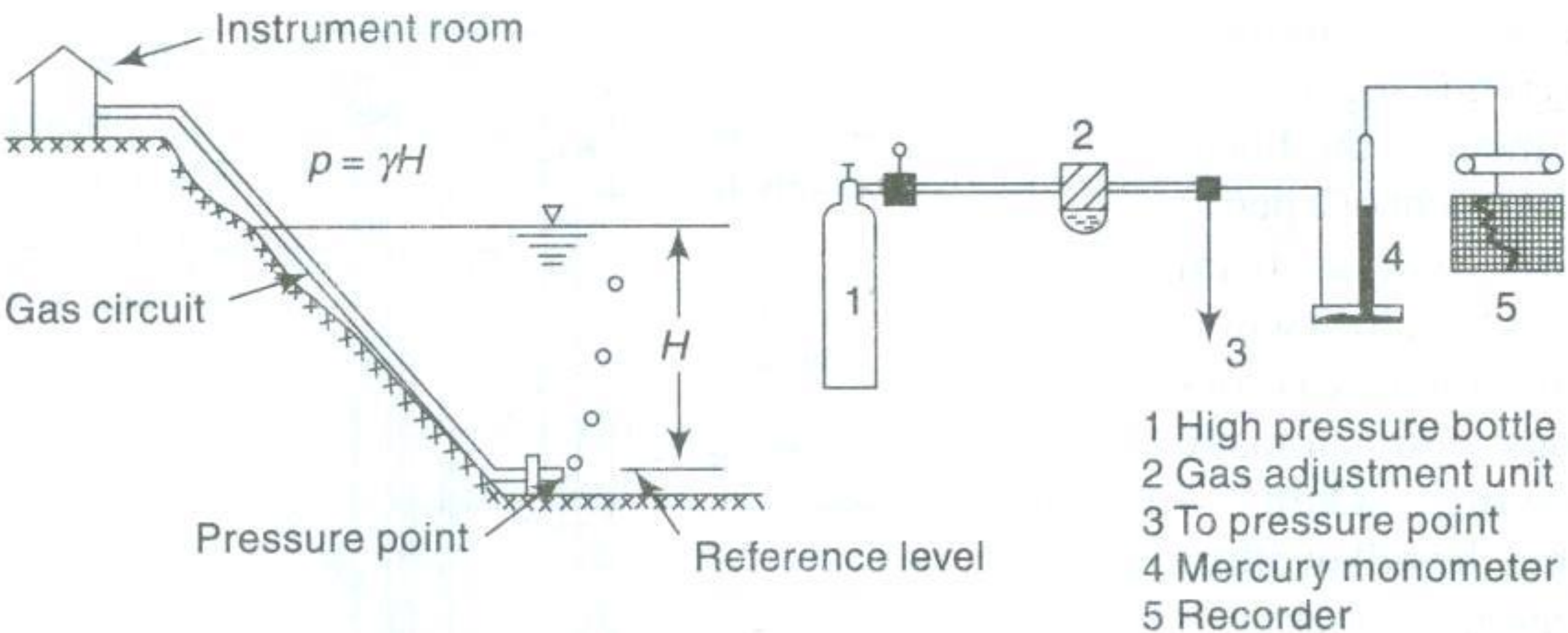
Gas purge (Bubbler) Gauge

With gas purge devices , nitrogen from a cylinder or air compressed from a pump, is allowed to bubble slowly out of the end of a tube located close to the river bed.



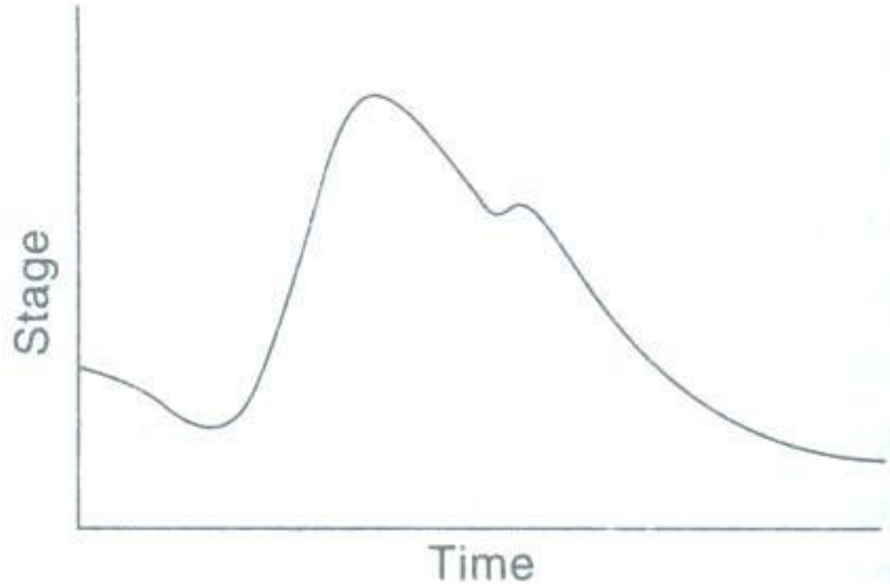
Bubble Gauge

- When the rate of bubble production is sufficiently small, the pressure in the line is static so that the pressure at the orifice is the same as the pressure at the other end of the tube in the instrument itself.
- This allows the pressure to be measured in the instrument rather than in the river, and is usually measured with an electromechanical balance (using bellows or mercury-float device) or pressure transducer.
- The principal advantage of the gas purge gauge is that no sensors need to be installed within or near the river, only a plastic pipe; the sensors can be housed within a building at some distance from the river.

Ultrasonic and radar gauge

- Ultrasonic-level gauges are expensive devices mounted above the surface of the river.
- This means that they can be used in contaminated rivers (or sewer systems) where there would be a high risk of fouling or corrosion of floats and pressure transducers.
- River level gauges using radar have the advantage over ultrasonic gauges in that they are not significantly affected by air turbulence, temperature, surface angle or dust.

A radar-based river level sensor. (Reproduced with permission from Vega UK.)



Stage Hydrograph

Stage data is useful for

1. Design of hydraulic structures
2. Flood warning
3. Flood protection works.

Discharge by velocity-area method

- The most direct method of obtaining a value of discharge to correspond with a stage measurement is by the *velocity–area method in which the river velocity is measured* at selected verticals of known depth across a measured section of the river.
- Around 90 per cent of the world’s rivers gauging sites depend on this method (Shaw, 1994).

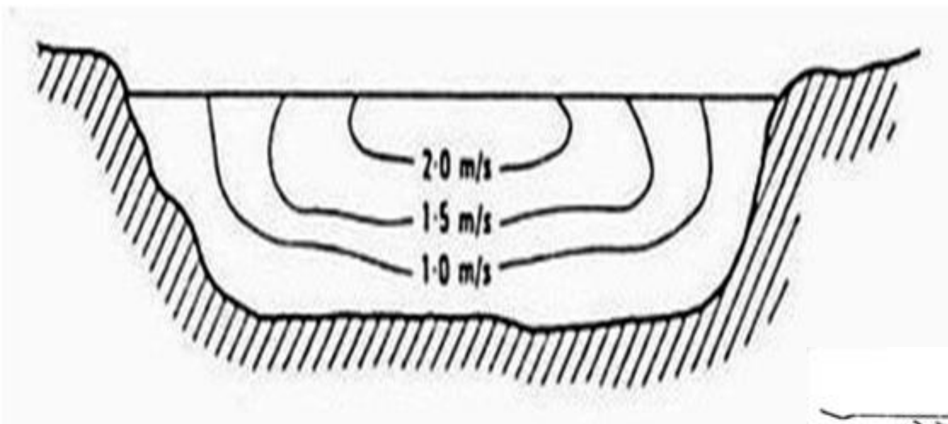
Flow Velocity Distribution

- Flow velocity in a channel is non uniform over width and depth of channel
- Velocity is greatest just under the water surface at the deepest part of the channel and is zero along the boundary of flow.
- Velocity distribution along depth in uniform flow is parabolic in nature.
- Average of velocity fall at approximately 0.6 d.

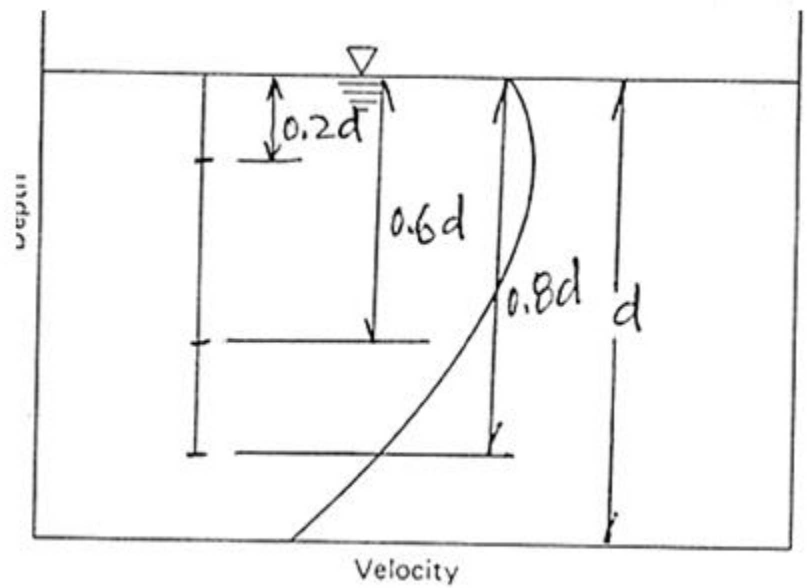
- At a river gauging station, the cross-section of the channel is surveyed and considered constant unless major modifications during flood flows are suspected, after which it must be resurveyed.
- The more difficult component of the discharge computation is the series of velocity measurements across the section.

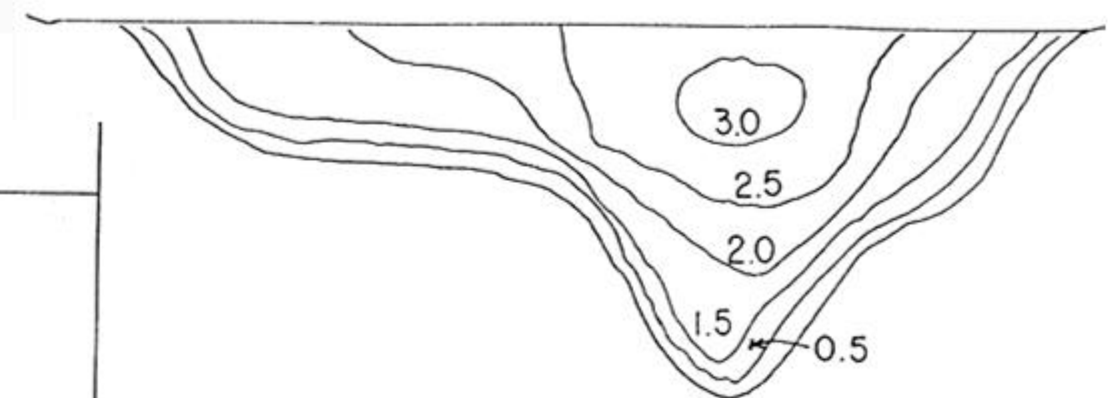
- The variability in velocity both across the channel and in the vertical must be considered.
- To ensure adequate sampling of velocity across the river, the ideal measuring section should have a symmetrical flow distribution about the mid-vertical, and this requires a straight and uniform approach-channel upstream, in length at least twice the maximum river width.
- Then measurements are made over verticals spaced at intervals no greater than 1/15th of the width across the flow.
- With any irregularities in the banks or bed, the spacings should be no greater than 1/20th of the width (BSEN ISO 748, 2007).
- Guidance in the number and location of sampling points is obtained from the form of the cross-section with verticals being sited at peaks or troughs.

Flow Velocity Distribution



Uniform section





Non-uniform section

Guidelines to compute average flow velocity

- Average flow velocity along a vertical section can be given as
$$\bar{v} = \frac{1}{d}\int_{s=0}^{s=d} v(s)\,ds$$
- Where, v(s) = velocity varying with depth s; $0 \le s \le d$; d = depth of flow at a given section
- <u>Only surface velocity (Vs) measurement is available</u> then $$\bar{v} = 0.85 v_s$$
- <u>**One point measurement**</u>: suitable for shallow streams where depth of flow is not more than 0.6 m
$$\bar{v} = v_{0.6d}$$

Guidelines to compute average flow velocity

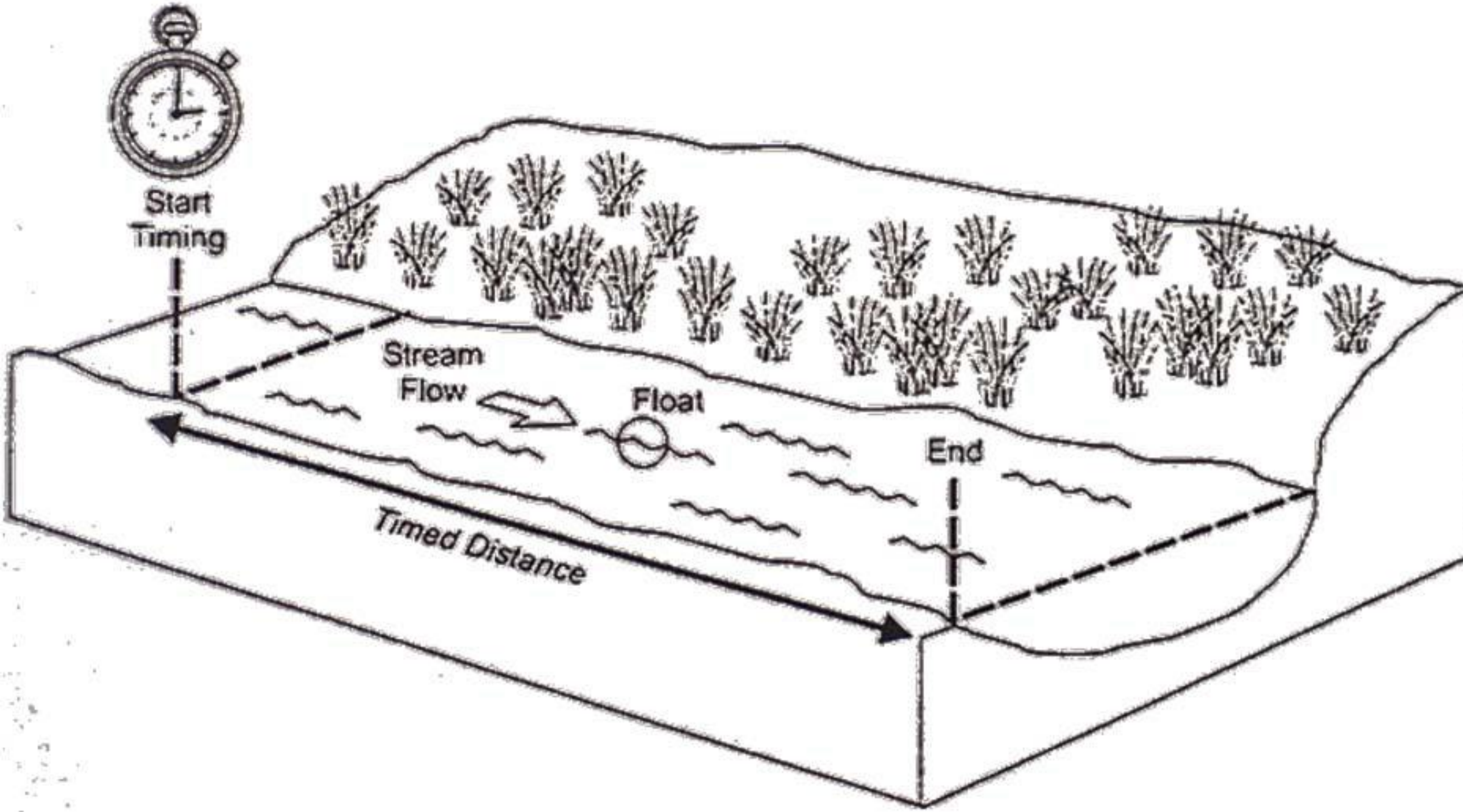
- **Two point measurement**: for moderately deep rivers $0.6 \leq d \leq 2$ m.
$$\bar{v} = \frac{v_{0.2d} + v_{0.8d}}{2}$$
- **Three point measurement**: for deep rivers $d > 2$ m.
$$\bar{v} = \frac{v_{0.2d} + 2v_{0.6d} + v_{0.8d}}{4}$$
- **Multi-point measurement**: for very deep rivers, every 1 m and average velocity is computed by averaging these values.
- **In case of high floods**: single measurement at 0.5 m below water surface and average velocity is given as:
$$\bar{v} = c_f v_{0.5} \quad \text{where } c_f = \text{reduction factor } (0.85 - 0.95)$$

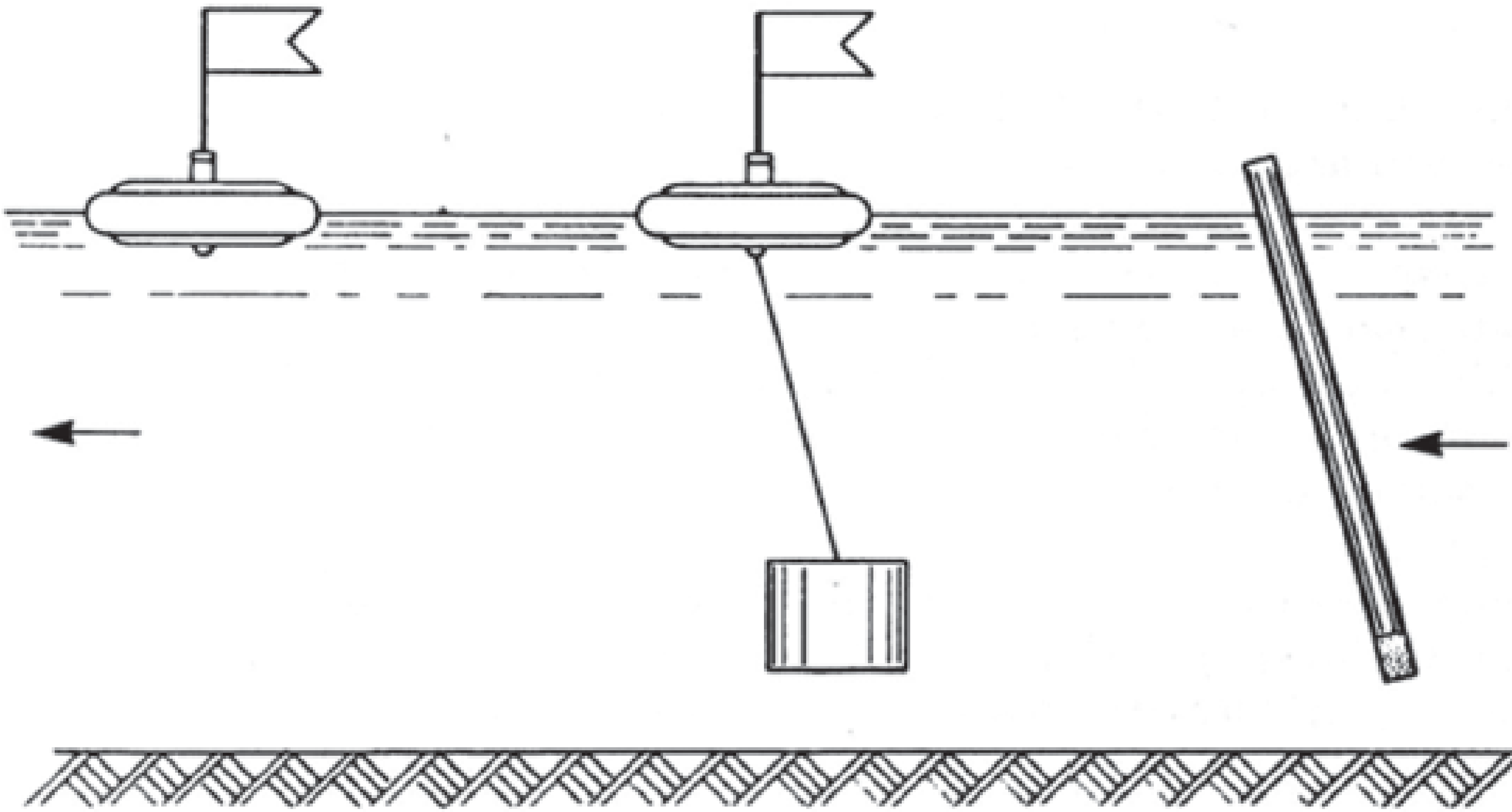
Measurement of velocity of flow

Using Floats

- Approximate stream flow velocity.
- Time of travel of an object at the surface of the water over a measured distance.
- Ball, a stick, specially designed floats etc.
- Useful in special circumstances such as:
  - A small stream in flood
  - Small stream with rapid change in water surface elevation
  - Primary or exploratory estimation.
- Not a very accurate method. But can be used for approximate determination of flow velocity.

Float Method



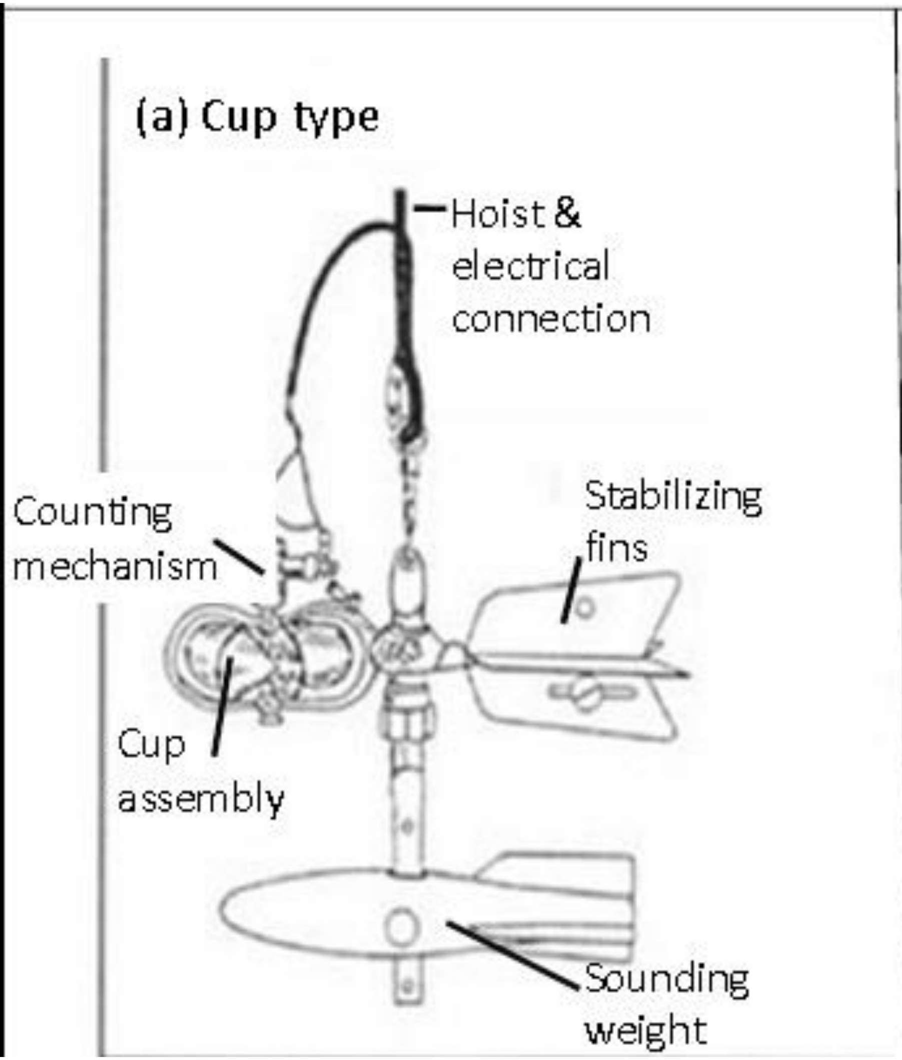


Floats: (a) surface float; (b) canister float for mean velocity; (c) rod float by mean velocity. (Reproduced with permission from R. W. Herschy (ed.) (2009) *Streamflow Measurement*, 3rd edn, © 2009, by permission of Taylor & Francis, Oxford.)

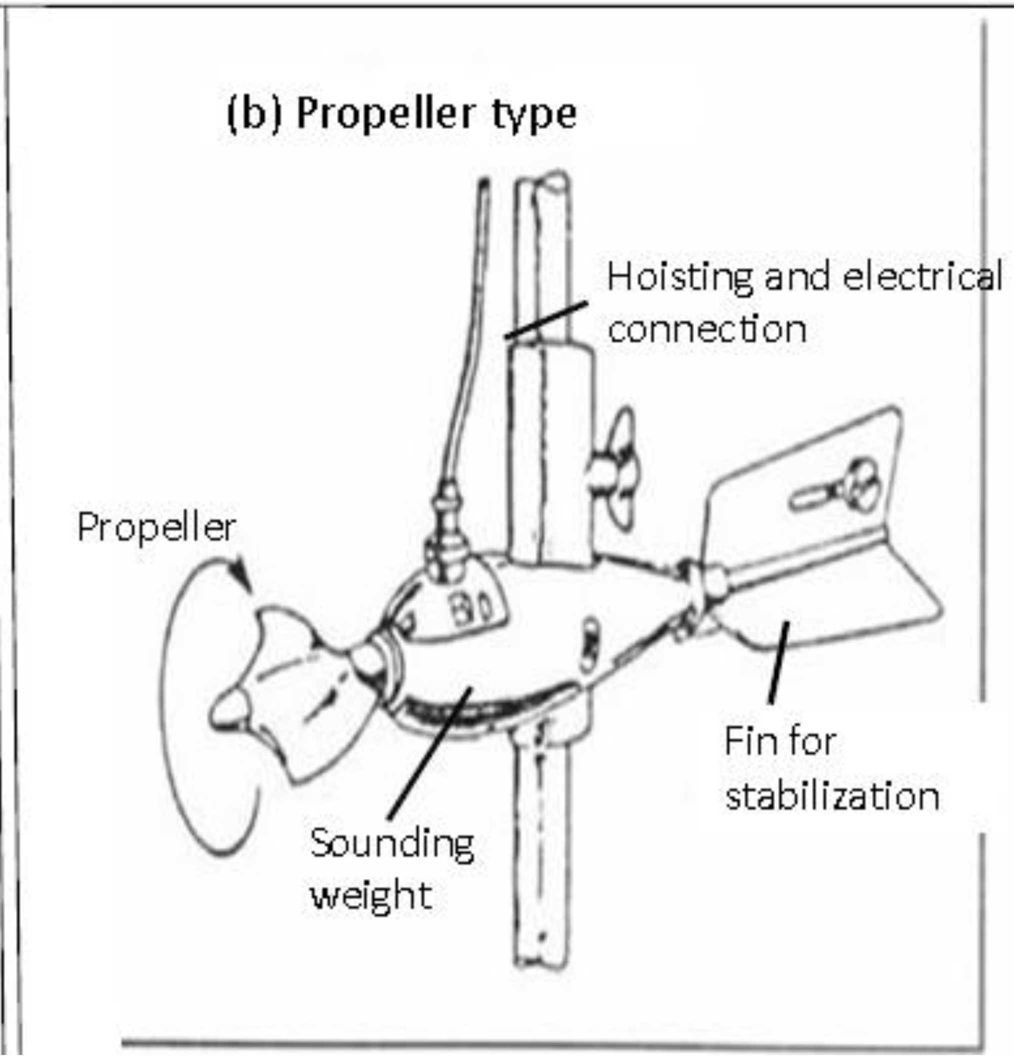
Measurement of velocity of flow

- *Current Meters*
  - A mechanical device, consisting essentially of rotating element.
  - Most commonly used instrument.
  - Accurate determination of stream velocity field.
  - Measure the velocity at a point in the flow cross-section
- *TYPES*
  - Price Current Meter or Cup type (Vertical Axis)
  - Propeller type or Horizontal Axis meter
  - Electromagnetic

Main types of current meters

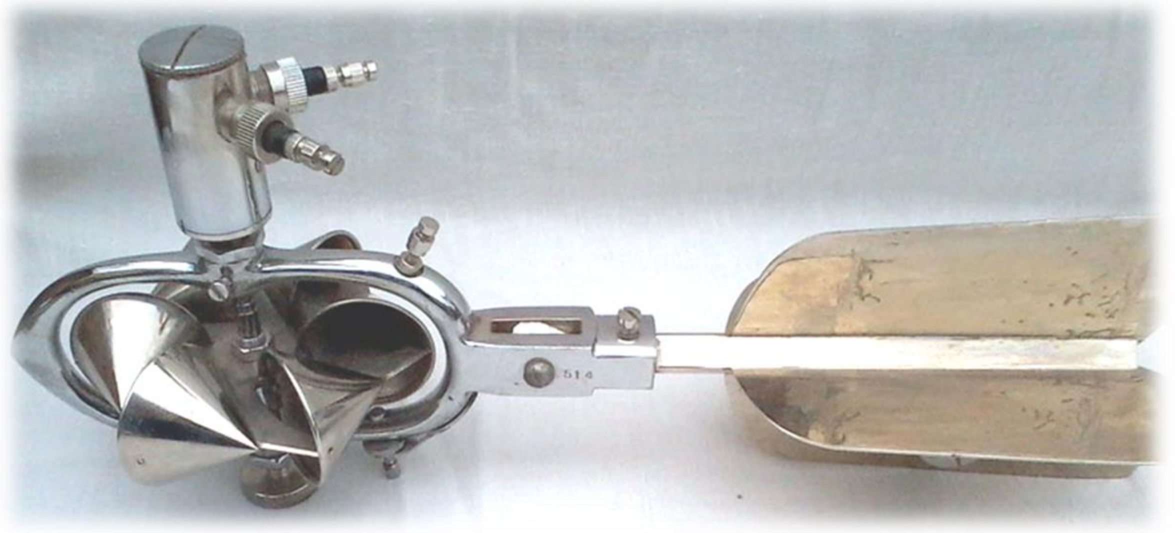


Vertical axis meter (Price)



Horizontal axis meter (Price)

Vertical axis meters



- Cups rotates in a horizontal plane
- Wires attached to the vertical axis
- Spindle records generated signals- proportional to the revolutions of the cup assembly.
- Normal range of velocity- 0.15 to 4.0 m/s.
- Accuracy 1.50% at the threshold-

  improves to about 0.3% at speeds in excess of 1.0 m/s.

$$V = aN_s + b$$

V=Stream velocity at instrument location in m/s

N_s=Revolutions per second

a= 0.65, b=0.03 for standard size 12.5cm diameter (cup type)

For pigmy meters: a=0.3, b=0.003.

Velocity computation by current meter

- Flow velocity from current meter is given as

$$V = aN_s + b \text{ for } N_s > 0$$

$$V = 0 \text{ for } N_s = 0$$

where, v = flow velocity (m/s)

a , b = constants for current meter and depends on size and type of meter.

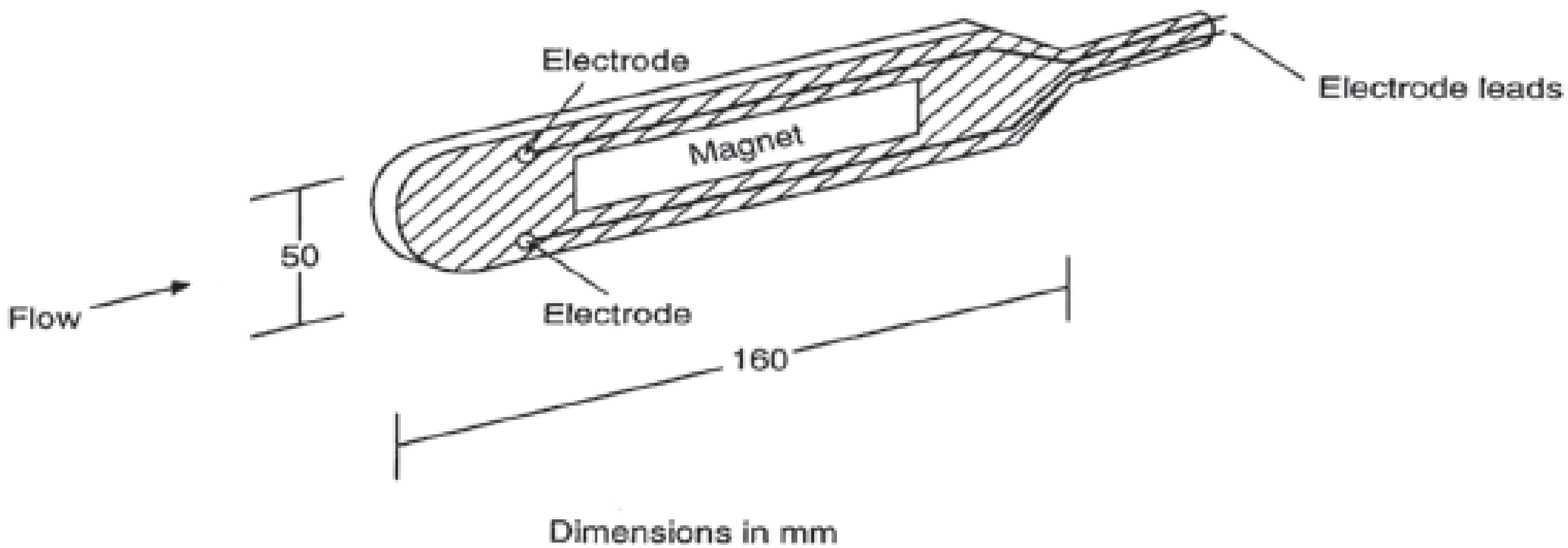
a= 0.65, b=0.03 for standard size 12.5cm diameter (cup type)

For pigmy meters: a=0.3, b=0.003.

N_s = revolutions per second by rotating cup/propeller of current meter.

Comparison of current meters

Propeller type	Cup type
Not suitable for silty water	Suitable for silty water
Delicate instrument	Robust instrument
Less steady	More steady
More sensitive	Less sensitive
Not affected by oblique flow as much as 15 deg.	Affected by oblique flow
More accurate (about 0.25% at 0.3 m/s or more)	Less accurate (about 0.3% at 1m/s or more)



A Valeport electromagnetic (EM) current meter showing the location of two electrodes and magnet. (Reproduced with permission of Valeport Ltd.)

Electromagnetic Current Meter

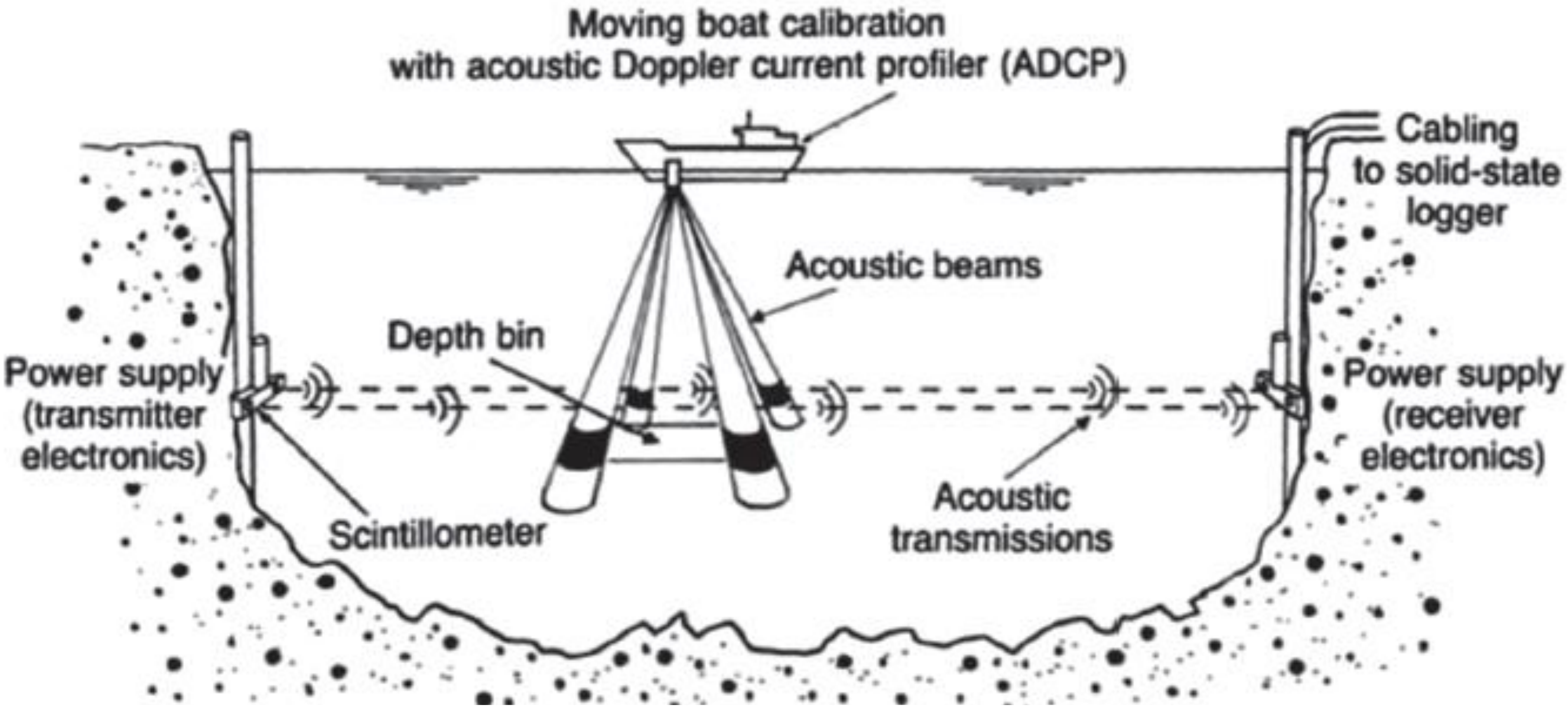
- The operation of an electromagnetic current meter utilises the Faraday principle, where water flow cuts lines of magnetic flux, inducing an electromagnetic force (emf) that is sensed by two electrodes.
- These current meters can be used to measure river velocities as slow as $0.03 ms^{-1}$ (and up to $4 ms^{-1}$).
- They also have the advantage of not having moving parts that can be caught in weeds or damaged against rocks

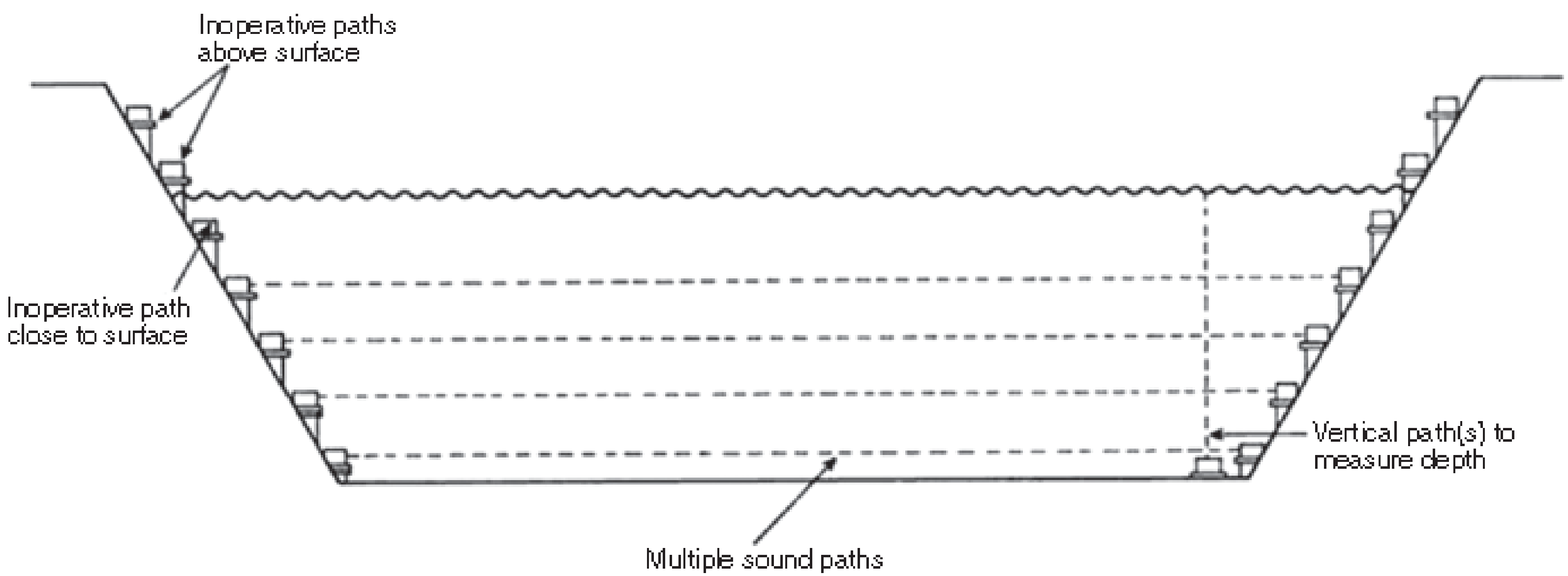
ADCP

An acoustic Doppler current profiler (ADCP) showing the transducers. (Reproduced with permission of Teledyne RD Instruments.)

Ultrasonic (Doppler) flow meters

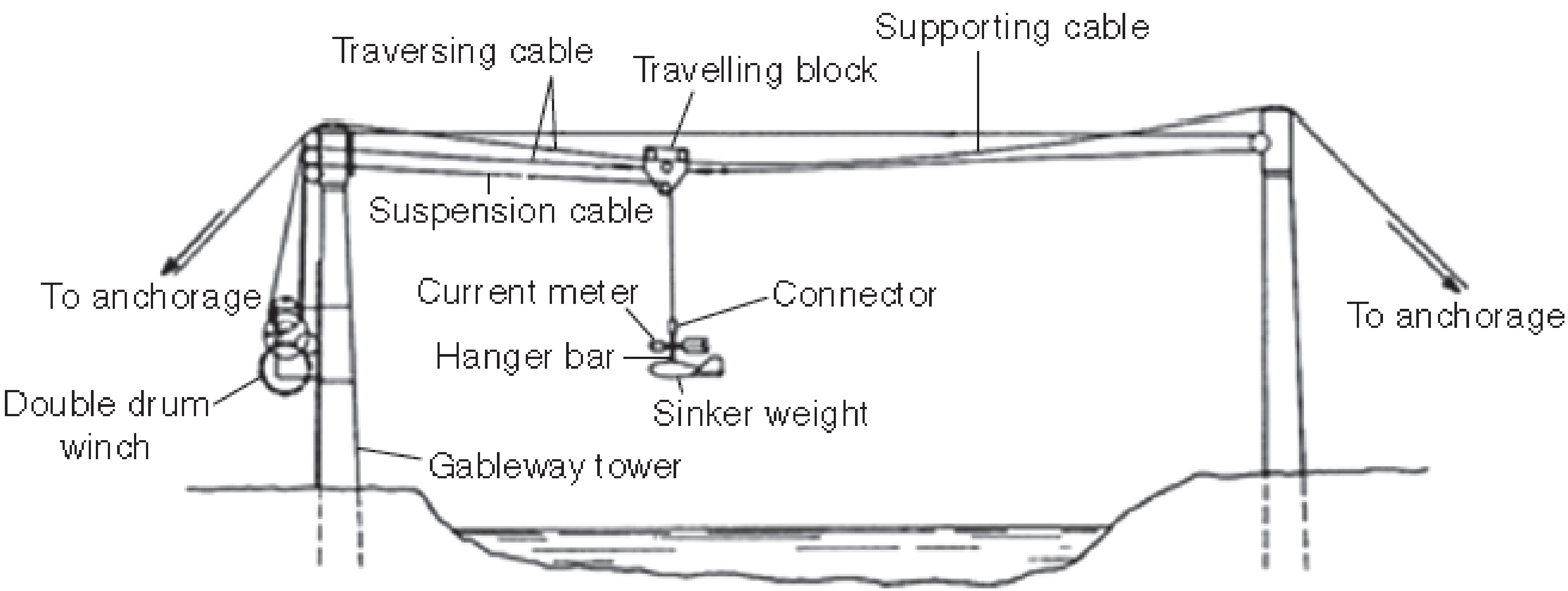
- These devices use transducers (‘loud speakers’), and measure the sound returned (echo) by scatters (e.g. fine sediment) within the water.
- The *Unidata Starflow* unit can measure a river velocity of range of 0.02–4.5ms^{-1} with an accuracy of ± 2 per cent.
- The *acoustic Doppler current profiler (ADCP) uses the same principle,* but can give a very detailed distribution of river velocity at many locations over the river cross-section when mounted on a boat or float.


Moving boat calibration
with acoustic Doppler current profiler (ADCP)
Cabling
to solid-state
logger
Acoustic beams
Depth bin
Power supply
(transmitter
electronics)
Power supply
(receiver
electronics)
Scintillometer
Acoustic
transmissions


Inoperative paths
above surface
Inoperative path
close to surface
Vertical path(s) to
measure depth
Multiple sound paths

Operational considerations

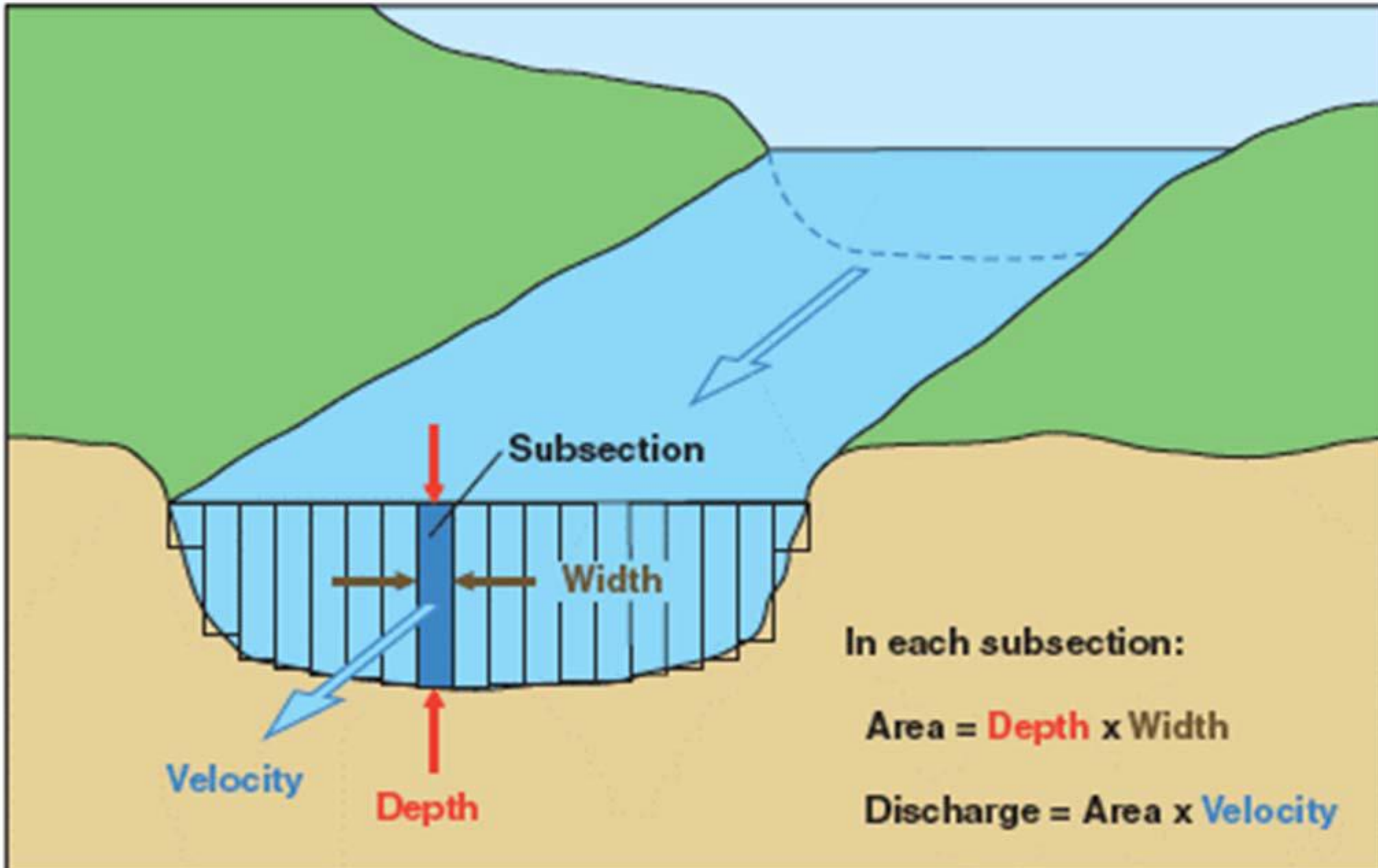
- Method of velocity sampling across a gauging section depends on the size of the river and its accessibility.
- Methods include the use of *wading rods, bridges, boats, floats and cableways*.


Supporting cable
Traversing cable
Travelling block
Suspension cable
To anchorage
Current meter
Connector
To anchorage
Hanger bar
Sinker weight
Double drum
winch
Gableway tower

Standard area- velocity method or current meter method

- The river section is divided into number of subsections by verticals.
- The average velocity in these subsections are measured by current meters.
- Accuracy of discharge estimation increases with the number of subsections used.
- Larger number of segments – larger is the effort, time and expenditure.

Area – Velocity Method



Guidelines for segmenting river section

- The segment width should not be greater than 1/15 to 1/20 of the width of the river.
- The discharge in each segment should be less than 10% of the total discharge.
- The difference of velocities in adjacent segments should not be more than 20%.
- The verticals for velocity measurement may placed at different spacing.

Calculation of Discharge using area – velocity method

- Arithmetic mean method

  a) Mean section method

  b) Mid-section method

For routine gauging at Standard station

- Graphical method

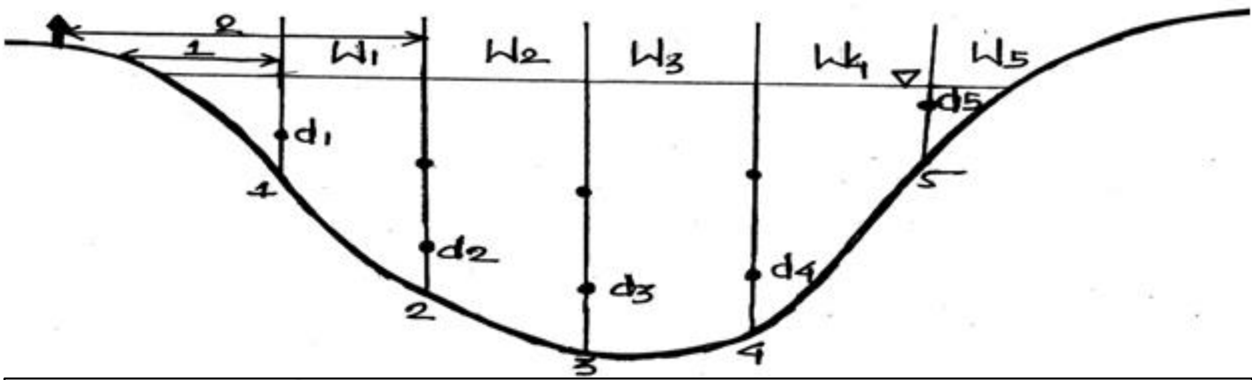
  a) depth velocity integration

  b) velocity contour method

Only appropriate when Multi-point velocity Observations are taken.
Used for checking flow Characteristics when Setting up of a station.

Mean section method

- Cross-section is regarded as being made up of number of segments.
- Each segment is bounded by adjacent verticals.



- **Discharge through each section is given by**

$$q_{1-2} = \left(\frac{\bar{v}_1 + \bar{v}_2}{2}\right) \cdot \left(\frac{d_1 + d_2}{2}\right) \cdot w$$

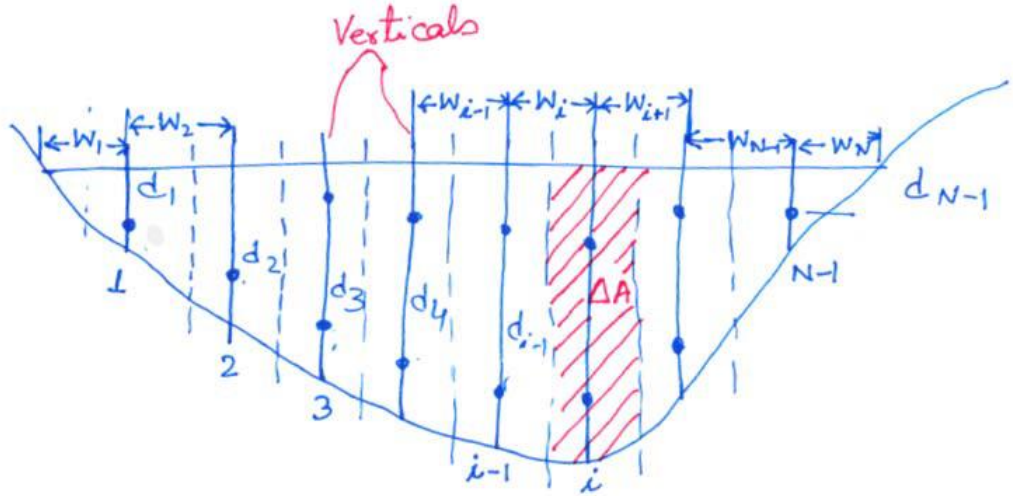
where:
q_{1-2} = discharge through section 1-2.
$\bar{v}_1$ $\bar{v}_2$ = mean velocities in first and second verticals respectively
d_1, d_2 = depths at first and second verticals respectively
w = width of the segment.

Mid-section method

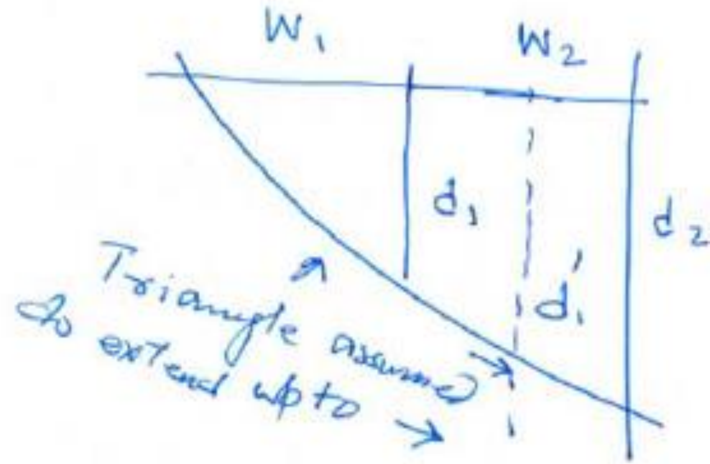
- The river section is divided into N sections by drawing N-1 verticals.
- Area represented by ith vertical is given as

$$a_i = (depth\ at\ i^{th}\ vertical) \times \left(\tfrac{1}{2}\, width\ to\ \text{left} + \tfrac{1}{2}\, width\ to\ \text{right}\right)$$

$$a_i = d_i \frac{w_i + w_{i+1}}{2} \qquad \text{for} \quad i = 2, 3, \ldots\ldots, N-2$$



1st section is assumed from bank to mid point of w_2



slope of triangle bottom $= \dfrac{d_1}{w_1}$

$$\therefore\ d_1' = \left(w_1 + w_2/2\right)\frac{d_1}{w_1}$$

Area of triangular section

$$= \frac{1}{2}\cdot\left(w_1 + \frac{w_2}{2}\right) \times d_1'$$

$$= \frac{1}{2}\left(w_1 + \frac{w_2}{2}\right)\cdot\left(w_1 + \frac{w_2}{2}\right)\cdot\frac{d_1}{w_1}$$

$$a_1 = \frac{\left(w_1 + \frac{w_2}{2}\right)^2}{2\cdot w_1}\cdot d_1$$

Similarly

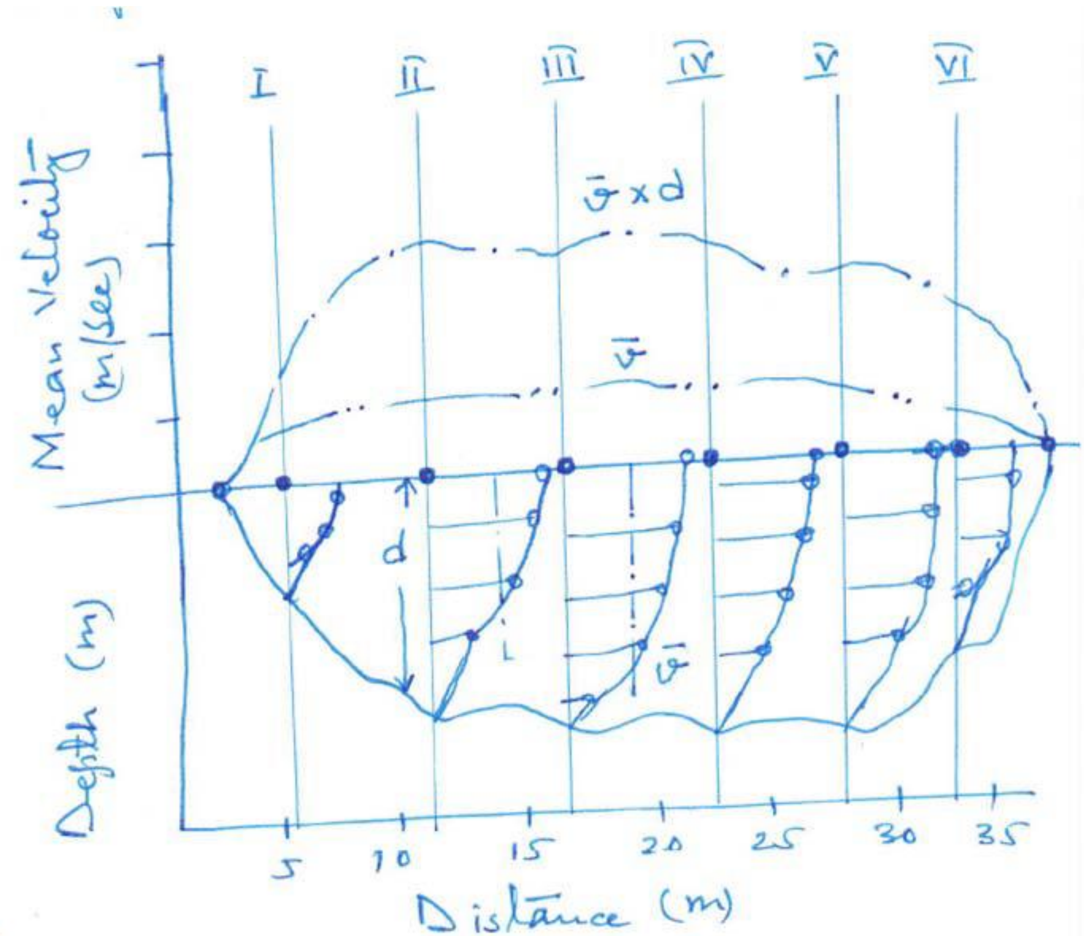
$$a_{N-1} = \frac{\left(w_N + \frac{w_{N-1}}{2}\right)^2}{2\,w_N}\cdot d_{N-1}$$

Total discharge is given as

$$Q = \sum_{i=1}^{N-1} a_i \times \bar{v}_i$$

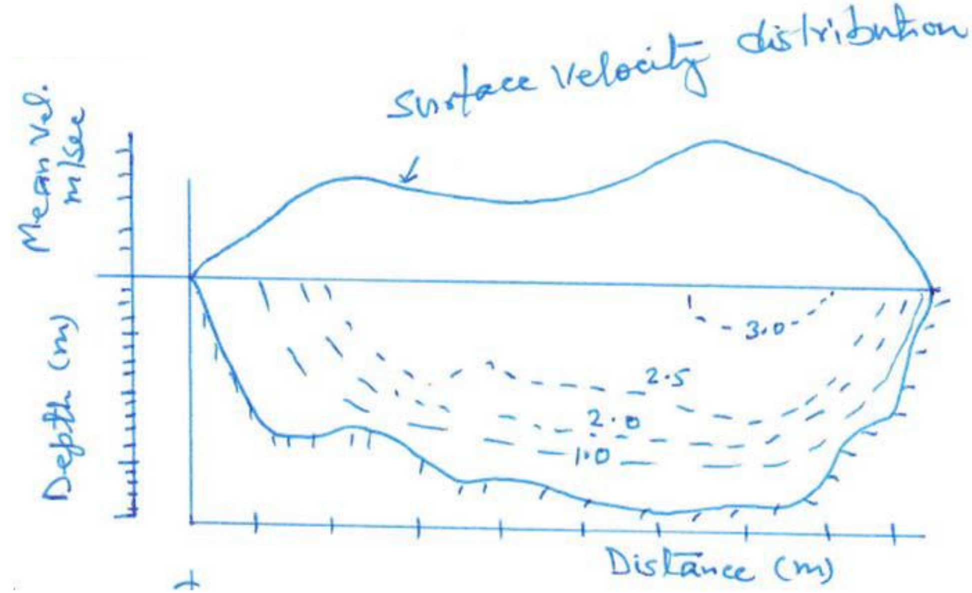
Depth-Velocity Integration Method

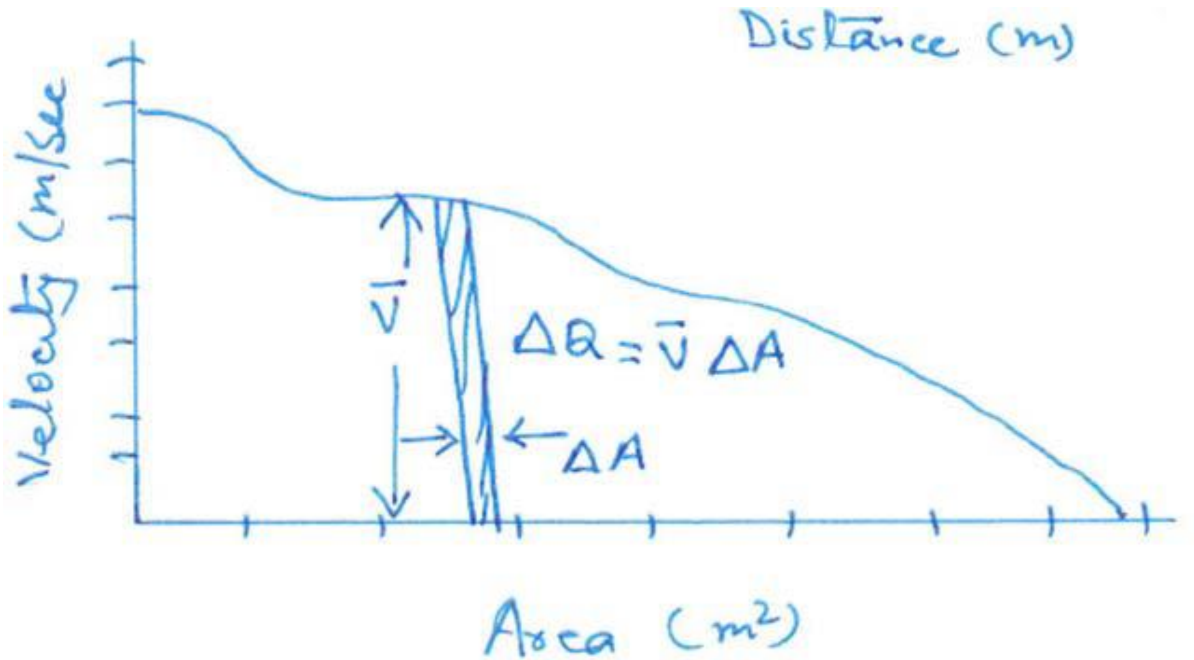
- Depth – velocity profiles at each vertical
- Area enclosed by each curve measured by planimeter = $\bar{v} \times d$
- Measured area plotted over water surface as smooth curve
- Area enclosed with this curve and water surface represents discharge



Velocity-Contour Method

- A velocity distribution diagram of the entire section is prepared
- The area enclosed by velocity contour and water surface is planimetered
- Measured area on abscissa and velocity on ordinate are plotted on a graph paper.





- The area enclosed by velocity-area curve represents discharge.

$$Q = \sum_{0}^{A} \bar{v} \cdot \Delta A$$