Field Methods For Hydrologic and Environmental Studies

Chapter 1

Surface Water Data Collection

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Introduction

Surface water hydrologic data collection involves sensing (or making measurements), recording, transmitting, and post-processing/analyzing the data. Each of these steps is quite involved and often there are many variations on a theme of how each step can be achieved. The exact variation is usually dependent on the circumstances present at the field site, both hydrologic and otherwise. The steps of collection of surface water data are detailed in the following pages.

Some Reasons For Collect Surface Water Hydrologic Data

- Flood Forecasting/Flood Warning
- Water Allocation (Lake Michigan Diversion, Western States Water Rights)
- Flood Studies (Flood Insurance, etc)
- Flood Control Design
- Water/Wastewater Plant Siting
- Watershed Best Management Practices
- Environmental Assessment/Abatement
- Hydraulic Structure Design
- Drinking Water Monitoring/Other Public Safety Issues
- Lake Management

Types of Surface Water Data

- Water Level or Stage (both continuous time series and partial record) of Rivers, Streams and Lakes
- Water Velocities/Depth → Volumetric Water Discharge
- Channel Bathometry
- Rainfall
- Temperature
- Physiographic Characteristics of the Watershed
- Water-Quality Parameters---suspended-sediment concentration, Dissolved Oxygen (DO), Pesticides, Nutrients, Metals, etc.
- Biological Indicators

Some Agencies That Collect Surface Water Data

- U.S. Geological Survey (USGS)—Primary data collector in Federal Government
- U.S. Army Corps of Engineers
- U.S. EPA (mainly water quality)
- Natural Resouces Conservation Service (formerly SCS)
- Illinois Department of Natural Resources, Office of Water Resources
- Illinois Department of Natural Resources, State Water Survey
- Illinois Department of Natural Resources, Natural History Survey (biology)
- Illinois EPA

The USGS collects hydrologic data across the United States and its territories as well as providing assistance to various foreign countries with their data collection activities. The USGS, Water Resources Division is divided into Districts, which usually are bounded by state lines. The Illinois District is comprised of the State of Illinois, however the Hawaii District is comprised of the State of Hawaii plus the Islands of Guam and American Somoa.

Nationwide, the USGS operates over 6000 streamflow monitoring stations that collect such surface water data as: stage, discharge, water quality constituents, and sediment transport.

In Illinois, the USGS currently collects continuous streamflow data at 157 gaging stations. Data collected at streamflow stations, as well as water quality and groundwater data, are digitally stored in the USGS data base.
Check out the Web site at→ http://www-il.usgs.gov/

Surface Water Stage (water level)

The stage (elevation) of a river can either be determined continuously (as a time series) by sensors interfaced with data loggers or intermittently by manual means. Stage data is used for many purposes such as: flood studies, assistance in the operation of a river control structure for navigation, reservoir operation, water intake structure operation, etc.. The location where stage data is collected is called a streamflow gaging station. Under the current technology, continuous time series stage data is easier than continuous volumetric discharge (discharge) data to collect. In most methods that will be discussed in this class, continuous time series discharge data is a dependent variable in relation to the independent variable of stage. This relation is determined by first making several direct measurements of discharge and the corresponding stage followed by deriving a relation between stage and discharge. This relation is known as a stage-discharge rating curve.

Sur*face Water Discharge Data*

Surface water discharge data is needed for a variety of surface water studies. For example, in studies to assess the expected impacts of a waste-water treatment plant on the health of a river system, water samples are collected for laboratory analysis of various constituents. These analyses are reported as concentrations (milligram per liter, microgram per liter, etc.). However, the total flux of the contaminant is usually necessary to complete the study. Computation of the flux requires knowledge of the quantity of water flowing past a point, which when multiplied by the concentration, yields the flux of the constituent.

Surface Water Sediment Data

Sediment data collection is also covered in this portion of the course. Sediment is transported downstream either suspended in the water column (suspended-sediment transport) or moving along bottom of the channel in contact with the bed (bedload transport). Suspended-sediment transport is determined by collecting representative samples to determine the average concentration of the sediment in suspension. This is then multiplied by the water discharge to yield the suspended-sediment load. Bedload transport is measured by various methods, both sampling and by remote sensing. The typical method in gravel bed streams is to place a sampler on the bed at several locations and collect the bedload that moves past that location in the river over a measured time interval. The bedload trasnport is then the total weight of bedload collected in the sampler divided by the time that the sampler was on the bed.

Overview of Streamflow Gaging Stations

Introduction

When gaging stations are discussed, one usually means streamflow discharge gaging station where a continuous time series of both stage and discharge data are collected. Sometimes peak stage and discharge are only needed. In this case a Crest-Stage Gage is operated and as the name entails, only the crest stage (peak stage) and possibly the discharge are determined. Other data parameters of the stream are sometimes collected at the same site such as:

- Suspended-sediment
- Water Quality Parameters
  - Temperature
  - Dissolved Oxygen
  - Nutrients
  - Etc.

The concentration (milligram per liter, part per million, microgram per liter, etc) of these parameters can be determined irrespective of the water discharge, but in order to compute the total load or flux of these constituents, the water discharge is necessary. With this in mind, one needs to understand how water discharge data is obtained and determined.

Objectives Of Streamflow Gaging Station

- Obtain continuous record of stage and discharge (stage being the water surface elevation above some datum). Gage height and stage mean the same thing.
- Location is chosen in order to obtain the best stage/discharge rating (relationship) (see figure 1). *In some sites, a unique relationship between stage and discharge is not possible because of variable backwater. In special locations like this we either install an additional gage very close so as to determine a 2nd variable in the relationship---slope, or a reference velocity meter is installed to determine the average velocity in the stream cross section for computation of the final water discharge. (more later when we discuss Acoustic Velocity Meters*
- Install instuments that sense and record the water-surface elevation
- Discharge measurements are made at periodic intervals to verify the stage-discharge relation
- At some sites, discharge is not a unique function of stage---therefore variables other than stage must be determined to obtain discharge
  - Slope
  - Rate of change of stage
  - Velocity
- Low head weirs are sometimes constructed at some stations to stabilize the stage/discharge relation at low flows (more on this when controls are discussed).

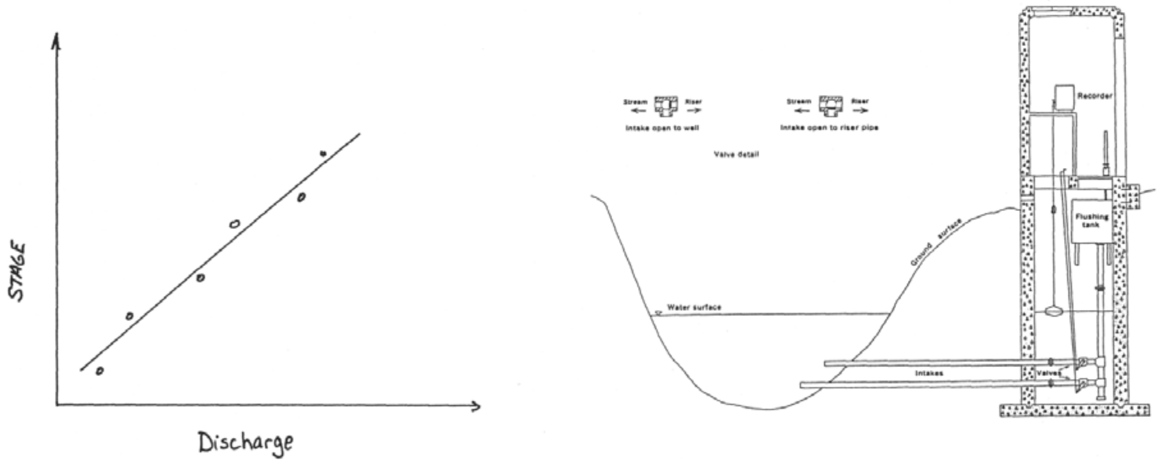


Figure 1.—Example of streamgage and associated stage-discharge rating relation.

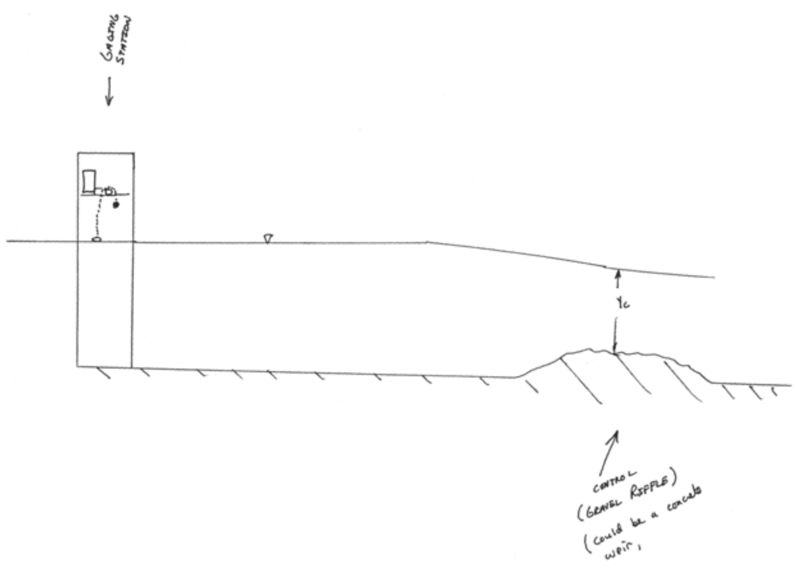


Figure 2.—Schematic of a gravel riffle

Station Components

Control

The control is a feature in the stream downstream of the gaging station in subcritical flow, that "controls" what the relation between stage and discharge is. For most streams, multiple controls usually occur and which one dominates depends on the stage of the stream. For example, at low flow a gravel riffle may be the control, at medium to high flow a culvert restriction may be the control. **Figure 2** shows a gravel riffle control downstream of a gaging station. Chow (1959, pp 70-74) and Henderson (1966, pp 40-43, 116-119) discuss controls on flow.

Datum with Reference Marks

The stage of river is the elevation of the water surface above some datum. The zero of this datum corresponds to some elevation above mean sea level. For example, the datum for the Boneyard Creek gaging station is 708.10 feet above sea level. This means that a stage of 0 at the Boneyard Creek gaging station corresponds to 708.10 feet above mean sea level. Therefore a stage of 2.30 feet corresponds to a mean sea level elevation of 710.40 feet. The relation between gage datum and mean sea level is determined by running surveying levels from a known bench mark to reference marks (RM) and reference points (RP) at the gage.

In establishing the datum, Usually an arbitrary datum is assumed which will keep the reported stage in the single to double digits, ie. 3.50 feet of stage instead of 711.60 feet of stage.

Stage Sensing Equipment

- Stilling well with a float/counterweight system **(figure 3)**
- Gas Bubble system **(figure 4)**
- Submersible Pressure sensors
- Acoustic sensors
- If Partial Record station, the stage might be determined manually by intermittent observations by an observer reading an outside staff gage or wire weight gage, or by a routine visits to check a **crest stage gage** which records the peak of a flood event only.

Recording (data logging) equipment

- Logs the time series of the stage parameters (or other parameters such as temperature, precip, Dissolved Oxygen, etc.)
- In addition, may have telemetry equipment to automatically send data back to the office (for flood warning, etc.)

Outside (independent) non-recording stage gage

- such as staff gage, wire weight gage, tape down reference point, etc.

Shelter for the data logger

Means to Determine the discharge

- Development of a stage-discharge rating curve by making discharge measurements by:
    - Conventional Current meter discharge measurements
    - Acoustic Doppler Current Profiler (ADCP)
    - Calibrated Flume
        - Parshall
        - V-Notch Weir
    - Volumetric Measurement
- Use of reference velocity by continuously sensing the velocity by acoustic or other means (Acoustic Velocity Meter (AVM) station)

Optional

- Means to collect a time series of water quality parameters (sediment, temperature, D.O., Metals, conductance)----This can be done by placing probes in the water for some parameters, others can only be determined by laboratory analysis. These samples can be collected by installing a pumping sampler or contracting with a local observer to collect samples for later analysis.

Factors In Selecting a Location for Gaging Station Sites (IDEAL)

- The course of the stream is straight for about 300 ft upstream and downstream from the site
- The total flow is confined to one channel at all stages, and no flow bypasses site
- The streambed is not subject to scour and fill and is free of aquatic growth
- Banks are permanent, high enough to contain floods, and free of brush
- Permanent, stable control that is effective at all stages. The control can either be a section or channel control or a combination of the two
- A pool upstream from the control at low stages to ensure good stage measurements (avoids high velocities and severe turbulence at high stages)
- Gage site is far enough upstream of a confluence to avoid variable backwater
- Satisfactory conditions for measuring discharge at all stages is available
- Free from ice conditions
- Concessions to reality…land owner permissions, accessibility, required data

Measurement of Stage

When determining the water level of a stream, there has to be a datum to which the measurement is referenced with. For example, if the water level is reported as 493 feet above mean sea level, the reference datum is the mean level of the ocean. In streamgaging applications, we refer to water level as the stage or gage height. The datum is usually something other than mean sea level because it was simpler with data recorders of old to have your stage readings to not be required to report the 3rd digit to the left of the decimal point. Therefore, the datum is typically somewhere just below the channel bed and the stage is in the range of 1 to 20 feet for most gaging stations. This arbitrary datum is most always surveyed in to reference it to mean sea level so that conversions can be made on the stage to mean sea level if necessary

Types of Sensors (sensing the water level)

- Manually Read---Staff Gage, Wire Weight Gage, Electric Tape Gage, Crest Stage Gage (pages 22-32, Rantz, S.E., and others, 1982; Buchanan, T.J., and Somers, W.P., 1968,)
- Automatic Sensors
  - Float Driven Sensor---Stilling Well with Float (figure 3)—The stilling well is hydraulically connected to the stream by a series of pipe intakes. The water level in the stilling well is equal to that of the stream, however the normal water level surges of a natural stream due to turbulence and wave action are minimized inside the stilling well. Inside the stilling well, the float and counterweight are connected by a steel tape. The steel tape runs over a calibrated wheel that is mounted on the shaft of a device used to convert mechanical shaft rotation into a digital reading of stage change. This conversion device sits on a shelf at the top of the stilling well. As the float raises and lowers with the water level, the wheel turns the shaft and the device deciphers how far the float has raised/lowered because the wheel is calibrated. Two of the more typical devices used to convert the shaft movement to a digital stage are: (1) incremental shaft encoder and
    (2) potentiometer. According to Latkovich and Leavesley (1993), "An incremental encoder uses an electrical counter to monitor and count increments of shaft rotation. Each increment normally represents 0.01 ft of stage change. The incremental changes are added to or subtracted from a base-stage preprogrammed into the data logger……A potentiometer is a resisting device with a rotating shaft input that can be placed in an electrical circuit to convert mechanical shaft rotation to a variable voltage output. The relation between resistance, as measured by voltage output, and stage is determined by calibration. This relation is then used to compute stage."

Figure 3.-Shaft encoder and float for stilling well

Figure 4. Gas bubble system

- Gas-Bubble Systems (figure 4)---the gas bubble system uses a regulator to bubble gas (nitrogen or air) through an orifice near the bed of the stream at a constant rate. As the stream rises and falls, the pressure necessary to maintain the bubble rate will change proportionate to the water level over the orifice. A pressure sensor is placed in the gas line inside the gage house to sense the changes in pressure necessary to maintain the bubble rate. The following are some of the gas bubble/pressure sensor systems:
    - Mercury Manometer with Nitrogen Tank (—**phasing out because of mercury problem.** A nitrogen tank and conoflow regulator system are used to bubble the gas into the stream. The manometer converts any pressure change to mechanical movement of a rotating shaft. The shaft rotation is transferred to the shaft of a mechanical or electromechanical data recorder, or to an encoder, by a chain and sprocket assembly (Latkovich and Leavesley, 1993).
    - Pressure Transducer with Nitrogen Tank --(Sutron Accubar, Design Analysis H350, others)—Being used to replace the mercury manometers. Pressure Transducers use a pressure-sensitive diaphragm which translates the pressure force exerted on the diaphragm to an electrical signal. The electrical signal can in turn be recorded by a data logger. This type of pressure transducer is nonsubmersible and just like the manometer is placed in the gas bubble line to "sense" the pressure changes due to increased pressure on the end of the orifice when water levels flucuate.
    - Transducer Pressure Sensor with compressor system (Design Analysis H355, Vitel Bubbler)---This unit operates under the same principle as the Pressure Transducer with Nitrogen Tank above, however, this system has no need for a Nitrogen Tank and conoflow as the gas feed is produced by an internal compressor and pressure tank.

- Submersible Pressure Transducer---Actually submerged in the water and sense the pressure of the weight of water above the transducer directly as opposed to the non-submergible system that senses the pressure of the gas bubble system. The transducer must be vented to atmosphere to ensure that pressures measured at the transducer face are relative to atmospheric pressure. Otherwise a atmospheric pressure measurement would be required to correct the recorded data. Some manufacturers:

    - Druk
    - Design Analysis
    - Others
- Acoustic Sensors—Sensors that are mounted vertically and send out an acoustic (sound) pulse that bounces off the water surface to give a distance reading that is based on the speed of sound concept. The sensor can either be mounted above the water surface and look down at the water surface or can be mounted below the water surface and look up.
- Crest Stage Gages (Records the peak only of a flood event)---This stage sensor that uses powdered cork to record the peak stage on a graduated stick inside a 2-inch pipe. More on this follows later in the notes.

Recorders

Stage Data Logging Devices (these record the time series of the data)

Old Types

- Continuous Strip chart recorder (Page 9 of Buchanan, T.J., and Somers, W.P., 1968)—This is a continuous trace of gage height recorded by a pen on a rectangular graph strip chart (A-35)
- Automatic Digital Recorder (ADR) (Page6-7 of Buchanan, T.J., and Somers, W.P., 1968) —Gage height is recorded at regular intervals (from 1 minute to 1 hour) as a series of encoded holes on a 16-channel paper tape.
- Observer Data—Sometimes gages are not automatic, and gage heights are read manually by an observer who then records the data in a gage height log book and mails it into the office for processing.

Newer Types

- Electronic Data Loggers---Several brands and models of electronic data loggers are used in the field to collect and store unit values. Gage height must be retrieved electronically and transported or transmitted to the office for processing. A few brands/models are: **C**ambell Cr-10 (figure 5), Sutron 8200, Handar, Vitel

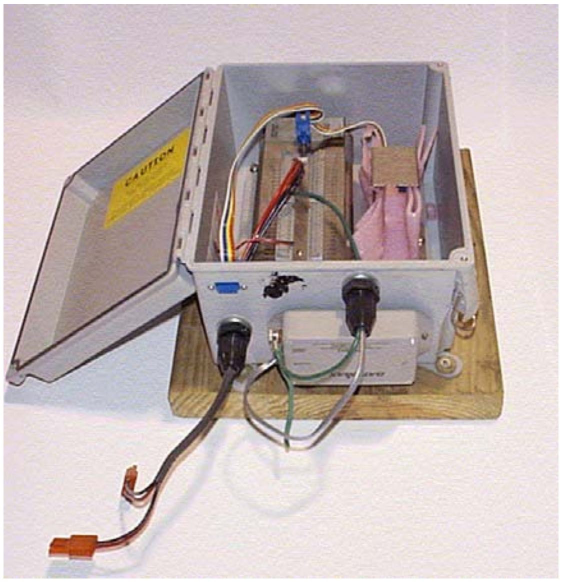


Figure 5.—CR10 Data Logger, Environmental Enclosure, and telephone modem

Telemetry/Real Time Data

- **Phone/Radio Transmitted Data---**The electronic data logger is equipped with a telephone modem or radio transmitter that regularly is interrogated by a computer system at the office.
- **Satellite Data Collection Platform Satellite Transmission (DCP)---**The electronic data logger is outfitted with a satellite transmitter that beams data back to a receiving station on regular intervals that then relays the data to an office computer.

Crest-Stage Gages

In connection with flood studies, crest-stage gages (figure 6) are operated to obtain a record of peak stages. The annual peak stage recorded is published together with the discharge, obtained either by direct or indirect methods. The gage generally consists of a 2-inch pipe with a wooden measuring stick inside and granulated cork in the bottom. Water enters holes in a cap on the bottom of the pipe and floats the cork up on the stick to the elevation of the maximum water surface. Inspecting and servicing the crest-stage gage is an exacting procedure.

The USGS places Crest-Stage Gages at some continuous discharge gaging stations to serve as a backup in case the regular gage goes down. Although the Crest-Stage Gage only provides the peak stage and discharge, this is often very useful information even if the rest of the time series data is missing. Two Crest-Stage Gages exist at the USGS Gaging Station on the University of Illinois campus. In addition, several more crest-stage gages exist along the Boneyard Creek as part of a network operated by the Illinois Department of Natural Resources, Office of Water Resources.

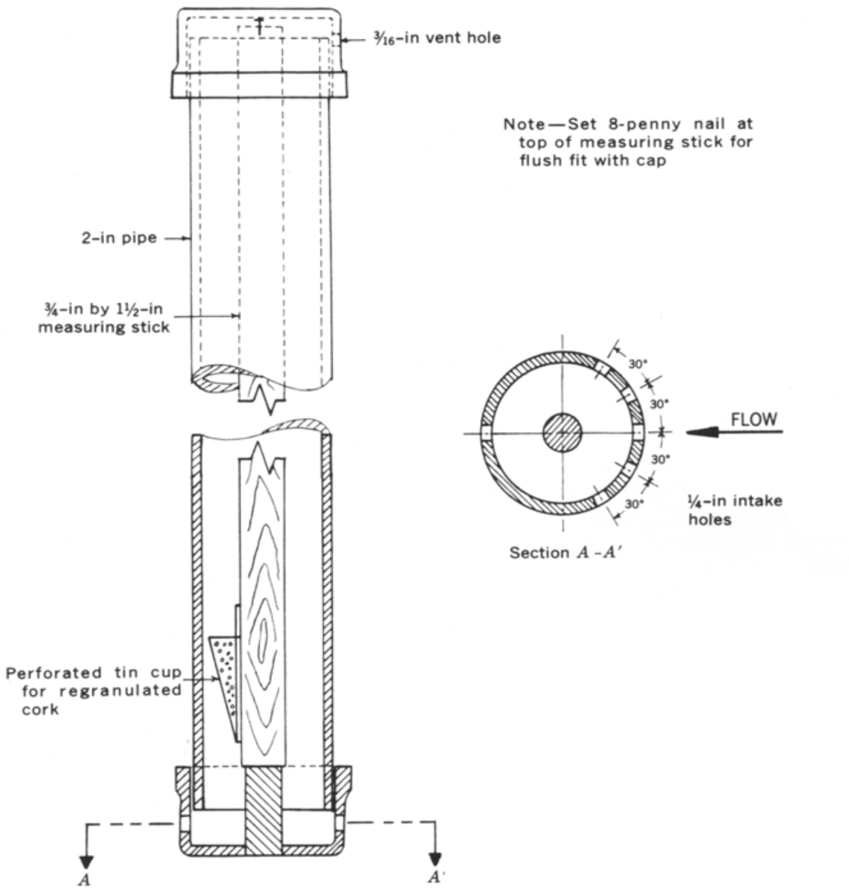
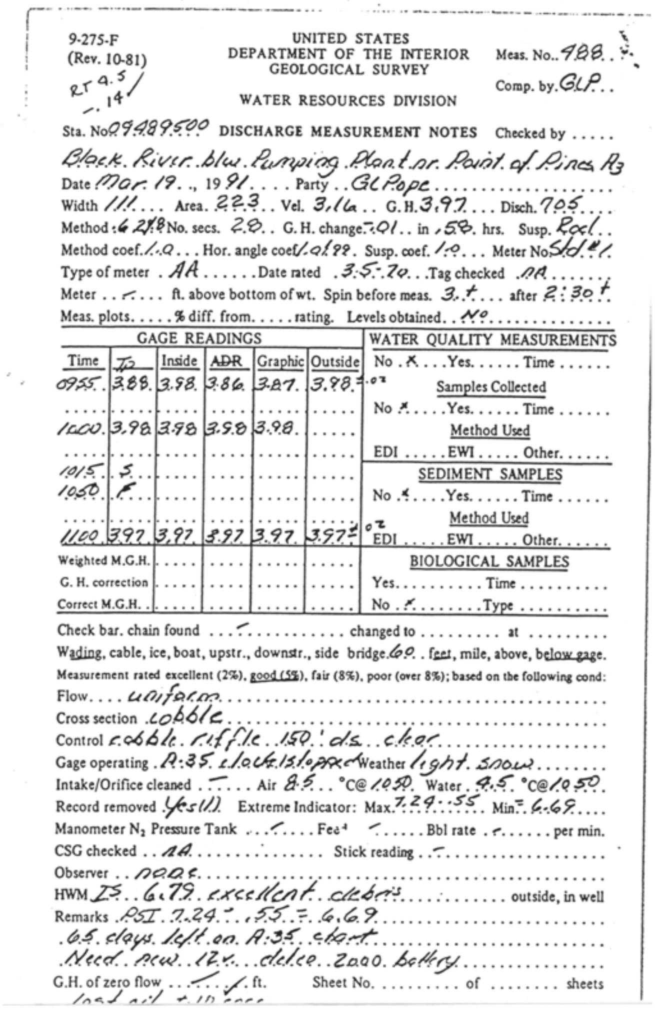


Figure 6.- Schematic of a crest stage gage

PROCEDURES FOR INSPECTING GAGES

Fill out Measurement Note Front Sheet (figure 7) with the information as follows:

- Determine all gage readings (inside and outside)
- Record watch and data logger times
- Determine if Intakes or other types of sensors are functioning properly
- Remove electronic data (if not telemetered)
- Examine back data since last visit (use graphing package on laptop)
- Obtain High Water Marks
- Check Battery voltage
- Make Discharge Measurement
- Obtain Point of Zero Flow (PZF)
- Read and record all gage readings and times again
- Ensure equipment is operating properly before leaving station



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(Rev. 10-81)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Meas. No. 488
Comp. by GLP

Sta. No 09489500 DISCHARGE MEASUREMENT NOTES Checked by

Black River blw Pumping Plant nr. Point of Pines Az

Date Mar. 19, 1991 Party GL Pope

Width 111 Area 223 Vel. 3.16 G.H. 3.97 Disch. 705

Method .6 2/8 No. secs. 28 G. H. change -.01 in .58 hrs. Susp. Rod

Method coef. 1.0 Hor. angle coef. 1.0/.99 Susp. coef. 1.0 Meter No. Std #1

Type of meter AA Date rated 3-5-70 Tag checked AA

Meter ft. above bottom of wt. Spin before meas. 3+ after 2:30+

Meas. plots % diff. from rating. Levels obtained No

Time	Tp	Inside	ADR	Graphic	Outside
0955	3.88	3.98	3.86	3.87	3.98
1000	3.98	3.98	3.98	3.98	
1015	S				
1050	F				
1100	3.97	3.97	3.97	3.97	3.97
Weighted M.G.H.					
G. H. correction					
Correct M.G.H.					

WATER QUALITY MEASUREMENTS
No X Yes Time
Samples Collected
No X Yes Time
Method Used
EDI EWI Other

SEDIMENT SAMPLES
No X Yes Time
Method Used
EDI EWI Other

BIOLOGICAL SAMPLES
Yes Time
No X Type

Check bar, chain found changed to at

Wading, cable, ice, boat, upstr., downstr., side bridge 60 feet, mile, above, below gage.

Measurement rated excellent (2%), good (5%), fair (8%), poor (over 8%); based on the following cond:

Flow uniform

Cross section cobble

Control cobble riffle 150' ds clear

Gage operating A:35 clock is slow Weather light snow

Intake/Orifice cleaned Air 8.5 °C @ 1050 Water 9.5 °C @ 1050

Record removed yes (1) Extreme Indicator: Max. 7.29-.55 Min. 6.69

Manometer N_2 Pressure Tank Feed Bbl rate per min.

CSG checked AA Stick reading

Observer none

HWM IS 6.79 excellent debris outside, in well

Remarks PSI 7.24 .55 = 6.69

65 days left on A:35 chart

Need new 12v delco 2000 battery

G.H. of zero flow ft. Sheet No. of sheets

Figure 7.—U.S. Geological Survey Discharge Measurement Note Front Sheet

Collection of High Water Marks

Anytime a field visit is made, the site should be examined for high water marks to reconcile any discrepancies that may arise with the continuous record from the sensor and data logger.

- Check stage record to see if flood event occurred since last visit.
- Reasons for obtaining high-water mark (HWM)
  - Intakes (for stilling well) may have plugged during the rising limb of the hydrograph
  - Verification with recorded peak
  - To make an indirect measurement of discharge
- Obtaining HWM's
  - If a stilling well type of gage, check inside stilling well for HWM to compare with recorded peak.

- ⇒ Install peak-stage indicator clips that fit on float-tape
- ⇒ Clean HWM from inside of well
- Obtain a HWM outside of gage well if intakes are found to be plugged. Obviously, if the gage is a gas–bubble system, HWM have to be obtained outside. Look around for mudlines, seed lines on tree, eroded leaves on banks, debris piles…NOTE. Be careful with debris piles as these are not always indicators of the highest water.
- It is especially important to get HWM if the sensing device is a gas-bubble system
- If flood reached a stage such that the discharge (estimated through rating curve extrapolation) is two or more times greater than the highest discharge measurement made to date, then several high water marks along the reach of the gage should be flagged for an indirect measurement.

Determination of Gage-Height of Zero Flow

- The gage-height of zero flow (also called the point of zero flow, PZF) is the depth of water over the lowest point of control (figure 8)

- When flow conditions permit, the gage height of zero flow should be measured because it provides valuable information that can be used for interpretation of rating position and shape, as well as for rating shift interpretation (more will be explained about this later). In fact, the gage height of zero flow can actually be interpreted as another discharge measurement, where discharge equals zero for the measured gage height (gage-height of zero flow).

- The PZF can be obtained either before or after the discharge measurement

- The PZF must be obtained and recorded for each measurement because it can change with time because of:
  - Scouring
  - Filling
  - Permanent changes

- The PZF can be used in interpreting the record during intermittent flow periods

- If there is uncertainity about the PZF, give a probable range

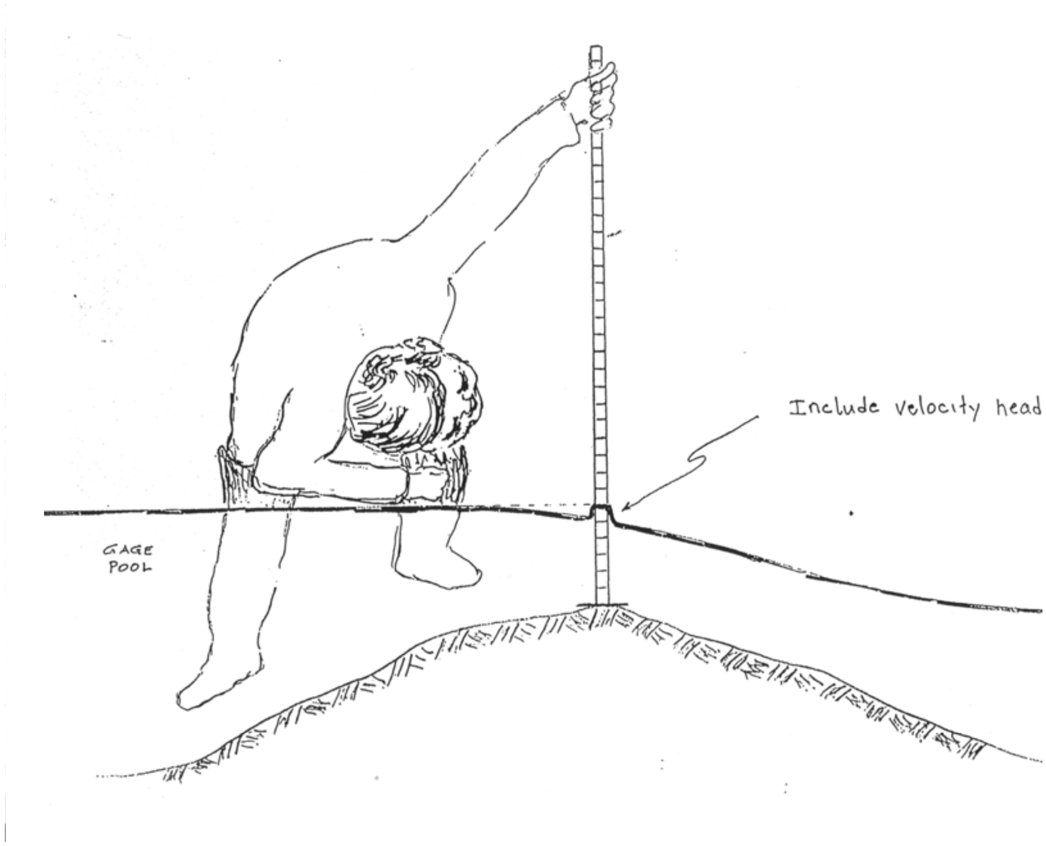


Figure 8.—Determination of Point of zero flow

Measurement of Velocity

Velocity is an important data parameter in many surface water hydrology investigations. It is absolutely essential in the determination of volumetric discharge. There are several means of measuring velocity at a point in an open channel flow.

Types Of Velocity Meters

Vertical Axis Meters

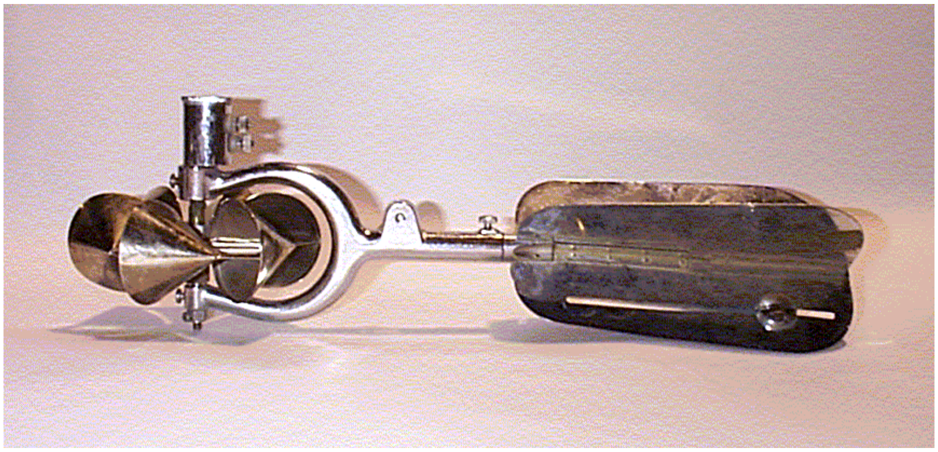
(see Buchanon and Somers, 1969, pp 4-6)

- Price AA meter (most commonly used meter in USGS)
    - Meter consists of a set of cups that rotate horizontally on a sharply pointed pivot as the flowing water drags on the cups (the cups are commonly referred to as the bucket wheel. The meter looks similar to a wind speed anemometer.
    - The meter is calibrated such that if the number of revolutions of the cups in a certain time is known (radial velocity), then the linear velocity of the water can be determined. Rating tables have been established by calibrating these meters in large tow tanks. This is basically done by pulling the meters through a tank of quiet water at various know speeds.

•The meter has either a electrical contact that communicates that one rotation of the cups has occurred. This electrical signal can either be transmitted into a headset for the user to hear and mentally count the number of revolutions or into a device called a current meter digitizer (CMD) to automatically count and time the number of revolutions.
•This electrical contact head version of the meter has both a single count contact and a penta count contact gear system. If the single count is used, then an electrical signal is sent for every revolution of the bucket wheel. If the penta count is used, then an electrical signal is sent every five revolutions. When a headset is being used in faster velocities (>3 ft/sec), the penta count is typically used as a convenience for the person trying to count the revolutions and track the time. If a CMD is used, the single count contact is used.
•Used either mounted to the top of sounding weight and lowered on a cable into the stream or mounted to a wading rod
•A tailpiece is used to align the meter parallel to flow
•For optimal meter use (as designed and calibrated), only use in water with depths greater than 1.25 feet because of boundary effects
•For optimal meter use, should not use if meter is within 0.5 feet of the water surface or bed (boundary effects)
•Meter should be raised off the pivot when not in use
•Calibrated for use in water velocities between 0.2 ft/sec and 12 ft/sec

Figure 9.—Price AA Current Meter

•Price pygmy meter (2/5 scale version of Price AA)



•Has no penta count
•Don’t use for velocities less than 0.2 fps
•Don’t use tailpiece
•Only used with wading rod

- •For optimal meter use (as designed and calibrated), Should not use for depths less than 0.75 feet
- •For optimal meter use (as designed and calibrated), should not use if within 0.3 feet of water surface and bed
- •Carry meter on a dummy pivot when not in use
- •Calibrated for use in water velocities between 0.2 ft/sec and 2.5 ft/sec

•Price OAA meter
- •Exactly like the regular AA, but has a fiber-optic counting head in replacement of the electrical contact head

•Price AA Low Velocity Meter
- •Similar to regular Price AA
- •No penta gear present, this reduces friction
- •Shaft inside of head has two eccentrics, therefore there are two counts per revolution
- •Calibrated for use in water velocities from 0.08 to 3 ft/sec
- •Recommended when velocities are less than 1.0 ft/sec

•Vane Ice meter (sheds slush ice better than AA)
- •Rotors on meter do not clog with slush ice like the regular AA bucket wheel cups do
- •Not the preferred meter for ice use by USGS
- **•USGS recommends that Price AA meter with a Water Survey of Candada Winter Style yoke be used during slush ice conditions**

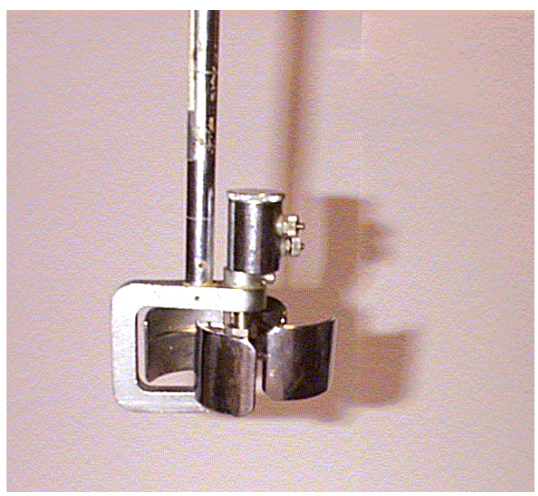


Figure 10. –Vane Ice Meter

Horizontal Axis Meters

(see Buchanon and Somers, 1969, p 7)

•Ott meter (German made, used for moving boat measurements)
•Hoff meter(Measuring velocities in pipes)
•Haskell meter(Used in deep, swift, clear streams)

- Neyrpic meter (French made)

Electromagnetic Meters

- Marsh McBirney (both single and bi-directional probes)

Acoustic meters

Acoustic meters use sound waves in the determination of velocity. Each of the instruments mentioned below uses a slightly different approach.

- **Neil Brown point velocity**
- **RD Instruments Acoustic Doppler Current Profiler (ADCP)**—Uses sound waves reflected off of particles in the water to measure the velocity of the particles, which is also assumed to be the velocity of the water that is moving the particles. It uses the doppler shift technique to determine the velocity. Figure 11 shows one type of ADCP, the broadband ADCP. ADCP are used not only to get 3-D velocity measurements, but to make complete measurements of water discharge. A boat mounted ADCP travels across the river from one side to the other, tracking its own relative position in the horizontal by use of a technique called bottom tracking, measuring depths, and measuring velocities. The software within the ADCP computes the water discharge using all the previously mentioned data.

Figure 11. Acoustic Doppler Current Profiler (ADCP) , Broadband Version

- Sontek Acoustic Doppler Velocimeter (ADV)—measures a point velocity (figure 12)

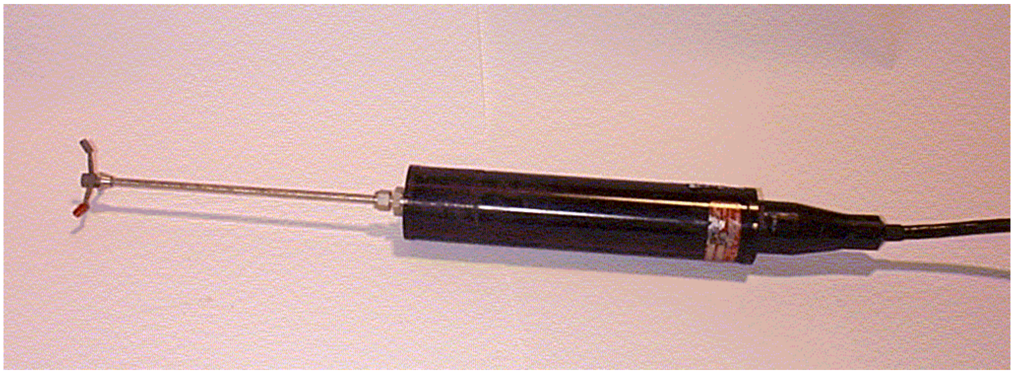


Figure 12. Acoustic Doppler Velocimeter (ADV)

•Acoustic Velocity Meter (AVM, also called UVM) path velocity meter (used to measure velocity in a horizontal plane) (Laenen, Antonius, 1985)—Determines the integrated horizontal velocity (line velocity) across the stream cross section by ultrasonically transmitting sound pulses between two transducer/receiver units. These transducers/receiver units are mounted on both sides of a stream. Sound waves emanate from one transducer and are received and sent back by the other transducer on the opposite shore. The transducer path is at an angel to the flow (figure 13). The stream velocity is the average of the amount that the speed of sound is increased (on the downstream path of the acoustic signal) and the amount the speed is decreased (on the return of the acoustic signal moving upstream).

The AVM is used to monitor continuous discharge at sites where conventional stage-discharge ratings are not possible. A relation is developed between the line velocity and the mean streamflow velocity by making several discharge measurements, calculating the mean velocity of the measurement, and relating this to the line velocity collected by the AVM during the measurement of discharge. In addition to the line velocity/mean streamflow velocity relation, a relation between stage and cross sectional area must also be developed. After these relations are developed, as the AVM collects line velocities and stage, the discharge can be determined by multiplying the mean velocity (determined from the relation between line velocity and mean velocity) and the area (determined from the relation between stage and area of the channel cross section).

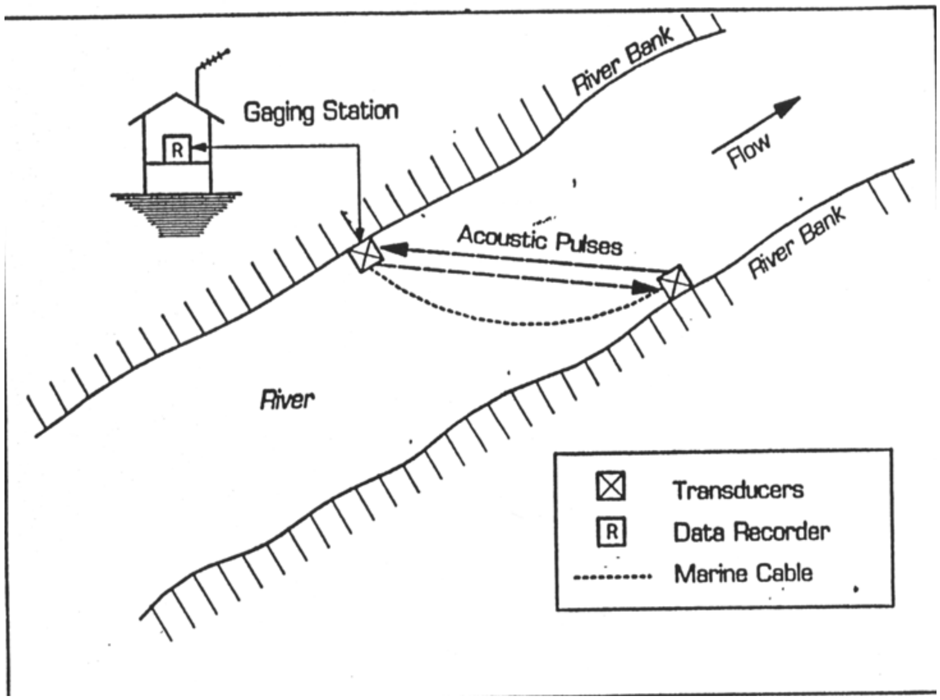


Figure 13.-Plan View of Acoustic Velocity Meter (AVM) data collection station

Quality Assurance Spin Tests For Price AA and Pygmy Meters

A spin test is conducted for each meter to ensure that the moving parts of the meter are in proper alignment and lubrication, and that the meter is functioning similar to the condition of the meter when it was manufactured and calibrated. A spin test is conducted by placing the meter on a flat surface away from any wind effects. The meter is then given a spin, simultaneously starting a stopwatch. The stopwatch is stopped when the meter cups quit rotating.

- Minimum spin test standards for meters, according to the USGS, Office of Surface Water Technical memorandum 89.07 are:

  Pygmy meters------------0:45 seconds
  AA Meters (all types)---2:00 Minutes

- Logs should be kept of all spin tests for each meter

Determination of Mean Velocity

In a turbulent open channel flow, the velocity profile in the vertical is similar to that seen in figure 1.

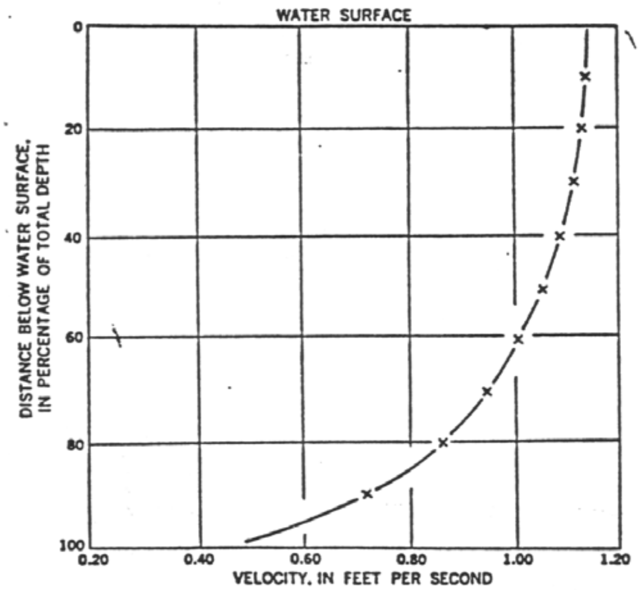


Figure 14.-Typical Velocity Profile

To determine the mean velocity in the vertical, point observations have to be made and averaged in some way as to approximate the mean velocity. The following are some of the methods that are used:

- Vertical-Velocity Method—a series of velocity observations at points well distributed between the water surface and the streambed are made at each of the verticals. The velocity values are plotted versus depth and a curve is put through the points. The area is determined between the ordinate axis and the curve, then this area is divided by the depth to get the average velocity.
- Two-Tenths Method—The velocity is determined at 0.2-depth below the surface. A coefficient is applied to the observed velocity to determine the mean velocity.
- Six-Tenths Method—The velocity is determined at 0.6-depth below the surface. This observation location is theoretically the average of a logarithmic velocity profile. This method is recommended by the USGS in the following cases: (1) depths between 0.3 and 2.5 feet, (2) when large amounts of slush ice or debris make it impossible to observe the velocity at the 0.2-depth location, thus preventing use of the two-point method, (3) When the meter is placed a distance above the sounding weight which makes it impossible to place the meter at the 0.8-depth, thus preventing use of the two-point method, or (4) when the stage in

a stream is changing rapidly and a measurement must be made quickly (Bucanon and Somers, 1969, p 33).

- Subsurface-Velocity Method—The velocity is observed at some distance below the water surface. This distance should be at least 2 feet below the surface to avoid the effect of surface disturbances. The subsurface method is used when it is impossible to measure velocity and depth much below the surface (because of debris in river, ice flow, etc). A coefficient must be applied to this observed velocity to determine the mean velocity. The coefficients are difficult to determine and may vary with stage.
- Two-Point Method—Velocity is observed at 0.2-depth and 0.8-depth below the water surface. The mean velocity is the average of these two values, which for the theoretical logarithmic velocity distribution is the average. Much field data observations have shown that this method gives more consistent and accurate results than any of the other methods (Buchanon and Somers, 1969, p 32). As such, this method is the preferred method by the USGS. The two-point method is not used in depths less than 2.5 feet because the current meter would be too close to the water surface and to the streambed to give dependable results. In this case, the 0.6-depth method is used.
- Three-Point Method—This method combines the two-point method with the 0.6-depth method. Velocity is observed at 0.2, 0.6, and 0.8 of the depth from the water surface. The average of the 0.2- and 0.8-depth is determined then that value is averaged with the 0.6-depth observation. This method is used when the velocity in the vertical is abnormally distributed.

Each of these methods is explained in Buchanon and Somers (1969, pp 31-37).

Typically, as has been previously stated, the two-point and six-tenths methods are used most frequently, as they can be demonstrated to represent the mean of the theoretical logarithmic velocity profile. Consider the following from Rantz (1982, p 134) that further discusses those situations where these methods need to be altered:

> *“The vertical-velocity curve will be distorted by overhanging vegetation that is in contact with the water or submerged objects, such as large rocks and aquatic growth, if those elements are in close proximity, either in the upstream or downstream direction, to the vertical in which velocity is being measured. Where that occurs the two-point method will not give a reliable value of the mean velocity in the vertical, and an additional velocity observation at the 0.6 depth should be made. The three observed velocities should then be used in the three-point method. A rough test of whether or not the velocities at the 0.2 and 0.8 depths are sufficient for determining the mean vertical velocity is given in the following criteria: the 0.2-depth velocity should be greater than the 0.8-depth velocity but less than twice as great.”*

Continuity Principle

Before we can discuss measurement of discharge, the principle of conservation of mass (continuity principle) must be discussed.

This principle says that:

$$Q=A*V$$

Where: Q= Discharge through the Cross Section
A= Cross Section Area
V= Mean Velocity of the Cross Section

Consider the following discussion and derivation of the Continuity Equation:

The application of the principle of conservation of mass (matter can neither be created nor destroyed) to a steady flow in a streamtube results in the equation of continuity, which expresses the continuity of flow from section to section of the streamtube. Consider the streamtube shown in figure 15 through which passes a steady flow of fluid. At section 1 the cross-sectional area is A1 and at section 2 the area is A2. If the mass of fluid occupying position BB' moves to position CC' in time dt, the conservation of mass principle yields

ρ A1 ds1 = ρ A2 ds2,

where ds1 and ds2 are the displacement lengths at sections 1 and 2, respectively. Dividing by ρ dt (this assumes that ρ is constant) yields

$$A_1 \frac{ds_1}{dt} = A_2 \frac{ds_2}{dt}$$

however, ds_1/dt and ds_2/dt are the mean velocities of flow past sections 1 and 2, respectively; therefore,

$$A_1V_1 = A_2V_2 = Q, \qquad (4\text{-}1)$$

which is the equation of continuity. The product A x V is designated as the flow rate, Q, and has units of cubic feet per second.

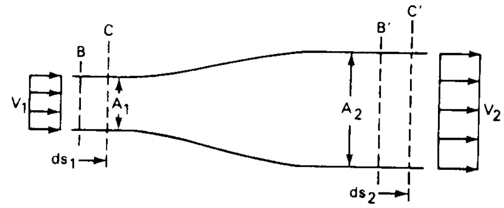


Figure 15.--Steady flow through a streamtube.

Measurement of Discharge

A continuous streamflow gaging station produces both stage and discharge data. Stage time series data are produced directly by determining the water level through some type of sensor and data logger. Discharge time series data are typically produced by stage as the independent variable to a stage-discharge relation to determine the discharge for a particular stage. There are other ways of producing discharge time series data, such as use of AVM's to collect line velocity data, however most of these methods require discrete direct measurements of discharge at various stages and hydrologic situations.

Conventional Current Meter Method For Discharge Determination

(Buchanan, T.J., and Somers, W.P., 1969)

A conventional current meter measurement consists of:

1. Selecting a suitable measurement site. The following are things to consider
   - Straight reach is most ideal
   - Velocities greater than 0.5 ft/sec
   - Flow is relatively uniform
   - Minimize affects of tributary inflow
   - Exercise judgement in meeting above criteria
2. Subdividing the channel cross section, perpendicular to flow, into several subsections, to make measurements of area and mean velocity within these subsections. *The accuracy of the measurement will increase proportionate to the ability of the velocity observations in each subsection to accurately reflect the true mean velocity in that subsection*. Figures 16 illustrates how a typically cross section is subdivided.

3. Determine the depth and width of each subsection by using both a sounding device (wading rod, lead weight, etc) and some sort of horizontal position marker (tag line, markings on a bridge rail, etc). The initial point for width measurement is at one bank, using either a tag line or special pre-marked stationing on a bridge or cableway. The subsection area is the product of the width and average subsection depth. The mean velocity of the subsection is then determined by point velocity observations. This is typically done at the mid-point of the subsection using either the two-point method or 6-tenths method (discussed in previous sections).
   - Wading Rods for sounding---marked every 0.1 feet for depth determination

   - Sounding Weights
     - Selection of Sounding Weights

- Weight Used ≥ (V_{max} * D_{max}) Where: V_{max} =Maximum Velocity in Cross Section; D_{max} =Maximum Depth in Cross Section

  For some measurements, the maximum weight available will not be adequate to prevent errors in depth measurement when the sounding weight drifts downstream. This will necessitate the use of wet line/air line correction methods which are discussed in Buchanon and Somers (1969, pp 47-52)

- Sounding for depth using a sounding weight and reel
  - Lower meter until the meter cups are ½ submerged at the water surface, then zero the depth indicator on the reel
  - Lower weight until the streambed is touched (*for soft beds, the weight will continue to sink into the bed, therefore, when you first "feel" the weight touch, use that as the bed level)*, then read the depth indicator
  - To get the total depth, add the appropriate length that corresponds to the distance between the centerline of the meter cups and the bottom of the sounding weight. When using a 100 pound sounding weight, this distance is 1 foot.
- Taglines
  - Kevlar Taglines are marked as follows: 1mark every 2 feet, 2 marks every 10 feet, 3 marks every 100 feet
  - Steel taglines are marked as follows: 1mark every 2 feet for first 50 feet, every 5 feet between 50 and 150 feet, every 10 feet beyond 150 feet. Two or three marks placed at selected points.
  - Distances between marks are estimated
- Each velocity observation should be a minimum of 40 seconds unless: rapid stage change, debris or ice heavy, or other special circumstances regarding safety.
- When the flow in a subsection is not perpendicular to the tag line, bridge, or cableway, an angle of flow must be determined to adjust the velocity observation. This is done by use of the angle coefficients marked on the back of the measurement note sheets (figure 17).

4. For each subsection, the pertinent notes are recorded on a discharge measurement note sheet (figure 18).
   - Record the time at the beginning and end of the measurement along with gage height of all gages (inside, outside, and recorder) on the note sheet. If stage is changing rapidly, show time every 15 minutes or so. This will be used for a determination of Weighted Mean Gage Height.

- Show the side of the stream corresponding to the beginning and end of the measurement, e.g. LEW or REW for left or right edge of water.

5. An effort is made to have no more than 5% of the total discharge in any one subsection.

Measurement Sectioning

"The verticals should be so spaced that no subsection has more than 10% of the total discharge. The ideal measurement is one in which no subsection has more than 5 % of the total discharge, but that is seldom the achieved when 25 subsections are used. It is not recommended that all observation verticals be spaced equally unless the discharge is evenly distributed across the stream. The spacing between verticals should be closer in those parts of the cross section that have the greater depths and velocities" (Rantz and others, 1982, p. 140)

- If the stream has an established rating, before the measurement, estimate Q from the rating then shoot for 5% per subsection as you do your computations during the measurement.
- If the stream has no established rating, make an estimate of the Q by visual estimation of velocity, mean depth and width (utilizing continuity Q=A*V, where A=D*W). Shoot for no more than 5% of this value in each subsection.
- **Common sense** is the **rule,** no 50 subsection measurements just to achieve the under 5% in each subsection.
- **There are times during floods that the aforementioned guidelines on the previous pages are violated.**

Rating of the Quality of the Discharge Measurement

Discharge measurements should be rated to indicated the accuracy based on conditions noted at the time they are made (Excellent, Good, Fair, Poor). The USGS typically considers an Excellent measurement to be within 2% of the actual discharge (2% error), a Good measurement to be within 5% of the actual discharge, a Fair Measurement to be within 8% of the actual discharge, and a Poor Measurement to be greater than 8% error. Do not consider your performance in the evaluation, unless you are not following the established guidelines. Do NOT base it on "a gut feeling"---carefully note the conditions affecting the accuracy of the measurement.

Measurements should be rated down, accordingly, for the following adverse conditions:

- Significant variation in the interval between "clicks" or revolutions of the current meter cups. This would indicate turbulent flow.
- Significant variation between velocities of adjacent sections
- Abnormal velocity distributions
- Very sluggish velocities

- Poor distribution of observation sections (too much flow in some sections….failure to achieve the goal of no more than 5% in any section)
- Angular flow
- Poor measuring section:
  - Uneven bottom or other poor section shape
  - Wide overflow
  - Considerable aquatic growth/debris

Some of the potential error sources in conventional discharge measurements:

- Width measurement
- Depth measurement
- Current meter
- Vertical velocity profile
- Horizontal velocity profile
- Oblique flow
- Computation methodology

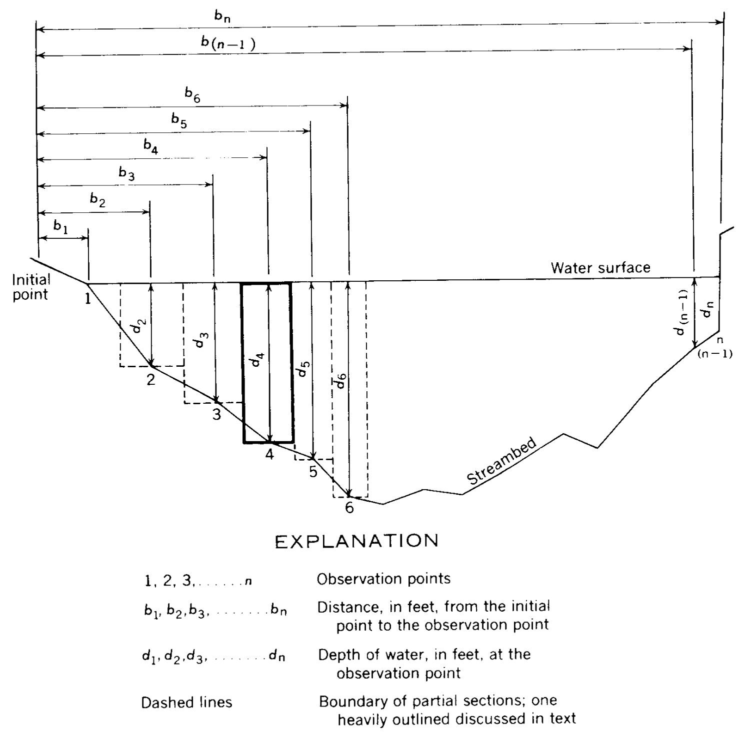


Figure 16.—Schematic showing mid-section discharge measurement method

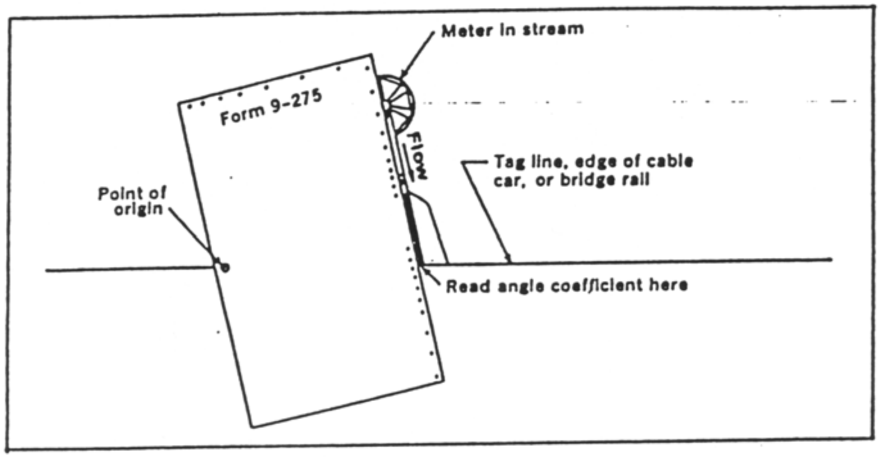
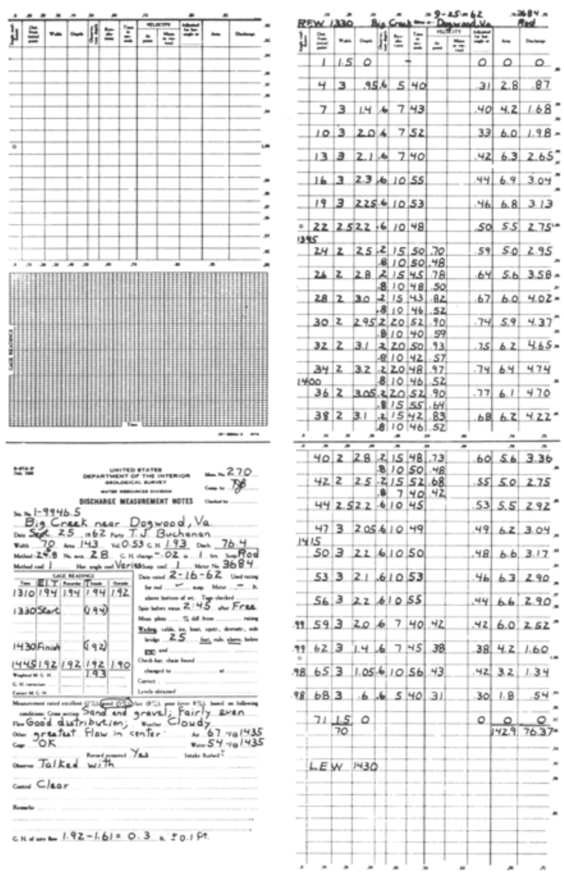


Figure 17.-Measurement of horizontal angle with measurement notes



UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION
DISCHARGE MEASUREMENT NOTES

Meas. No. 270
Comp. by TJB
Sta. No. 1-9946.5
Big Creek near Dogwood, Va.
Date Sept. 25 1962 Party T.J. Buchanan
Width 70 Area 143 Vel. 0.53 G.H. 1.93 Disch. 76.4
Method 2-.8 No. secs. 28 G.H. change -.02 in 1 hrs. Susp. Rod
Method coef. 1 Hor. angle coef. Varies Susp. coef. 1 Meter No. 3684
Date rated 2-16-62
Spin before meas. 2:45 after Free
Wading ... bridge 25

Time	ELT	Recorder	Inside	Outside
1310	1.94	1.94	1.94	1.92
1330 Start			(1.94)	
1430 Finish			(1.92)	
1445	1.92	1.92	1.92	1.90
Weighted M. G. H.			1.93	

Measurement rated excellent (2%), good (5%), fair (8%), poor (over 8%), based on following conditions: Cross section Sand and gravel; Fairly even
Flow Good distribution; Weather Cloudy
Other greatest flow in center Air 67 °F @ 1435
Gage OK Water 54 °F @ 1435
Record removed Yes
Observer Talked with
Control Clear
Remarks
G. H. of zero flow 1.92-1.61 = 0.3 ft ±0.1 ft.

REW 1330 Big Creek near Dogwood, Va. 9-25-62 3684 Rod

	1	1.5	0					0	0	0
	4	3	.95	.6	5	40		.31	2.8	.87
	7	3	1.4	.6	7	43		.40	4.2	1.68
	10	3	2.0	.6	7	52		.33	6.0	1.98
	13	3	2.1	.6	7	40		.42	6.3	2.65
	16	3	2.3	.6	10	55		.44	6.9	3.04
	19	3	2.25	.6	10	53		.46	6.8	3.13
	22	2.5	2.2	.6	10	48		.50	5.5	2.75
1345										
	24	2	2.5	.2	15	50	.70	.59	5.0	2.95
				.8	10	50	.48			
	26	2	2.8	.2	15	45	.78	.64	5.6	3.58
				.8	10	48	.50			
	28	2	3.0	.2	15	43	.82	.67	6.0	4.02
				.8	10	46	.52			
	30	2	2.95	.2	20	52	.90	.74	5.9	4.37
				.8	10	40	.59			
	32	2	3.1	.2	20	50	.93	.75	6.2	4.65
				.8	10	42	.57			
	34	2	3.2	.2	20	48	.97	.74	6.4	4.74
1400				.8	10	46	.52			
	36	2	3.05	.2	20	52	.90	.77	6.1	4.70
				.8	15	55	.64			
	38	2	3.1	.2	15	42	.83	.68	6.2	4.22
				.8	10	46	.52			
	40	2	2.8	.2	15	48	.73	.60	5.6	3.36
				.8	10	50	.48			
	42	2	2.5	.2	15	52	.68	.55	5.0	2.75
				.8	7	40	.42			
	44	2.5	2.2	.6	10	45		.53	5.5	2.92
	47	3	2.05	.6	10	49		.49	6.2	3.04
1415										
	50	3	2.2	.6	10	50		.48	6.6	3.17
	53	3	2.1	.6	10	53		.46	6.3	2.90
	56	3	2.2	.6	10	55		.44	6.6	2.90
.99	59	3	2.0	.6	7	40	.42	.42	6.0	2.52
.99	62	3	1.4	.6	7	45	.38	.38	4.2	1.60
.98	65	3	1.05	.6	10	56	.43	.42	3.2	1.34
.98	68	3	.6	.6	5	40	.31	.30	1.8	.54
	71	1.5	0					0	0	0
		70							142.9	76.37

LEW 1430

Figure 18.-Example of discharge measurement notes

Non-Conventional Discharge Methods

- ADCP (Acoustic Doppler Current Profiler)—The ADCP is seeing continued growth in applications and utility. The ADCP has been typically used only on larger rivers because of minimum depth limitations of this unit. The new generation ADCP's are lighter and more versatile to shallower environments.

  Frequencies and Models (manufactured by RD Instruments) used for data collection

Frequency	**Models**
300 kHz	**Broadband**
600 kHz	**Workhorse**
1200 kHz	**Rio Grande**
2400 kHz	

- **Dye Dilution** (Kilpatrick, F.A., and Cobb, E.D.1985) **—**Injection of a solution of a known tracer concentration into the river flow. By measuring the dilution of the concentration of the tracer with distance and time, the discharge can be calculated. There are two methods in common use:
  - **Slug Injection Method—**the tracer concentration is injected instantaneously
  - **Constant-Rate Injection Method—**the tracer concentration is injected at a constant rate for a sufficient period of time to obtain steady state tracer conditions at the sampling site.
- **Volumetric –**Using a rigid container of known volume, determine the time it takes for the flow to fill the container. The discharge is the volume divided by the time.
- **Calibrated Flume (**Kilpatrick, F.A., and Schneider, V.R., 1983)
  - **Portable Sharp Crested Weir Plates—**This usually consists of a 90° V-notch weir that has a free flowing nappe. The stage is measured upstream of the weir, out of the drawdown zone. The stage is the head above the low point of the V-notch. The equation of flow is:

$$Q = Ch^{\frac{5}{2}}.$$

Where: Q-discharge over the weir

C-coefficient of discharge and is about 2.47 but should be specifically determined for each weir

h-head above the bottom of the V-notch

Any leakage around the sides or the bottom of the weir will result in errors in discharge measurement. With a large weir, flows ranging from 0.02 to 2.0 cubic feet per second are possible.

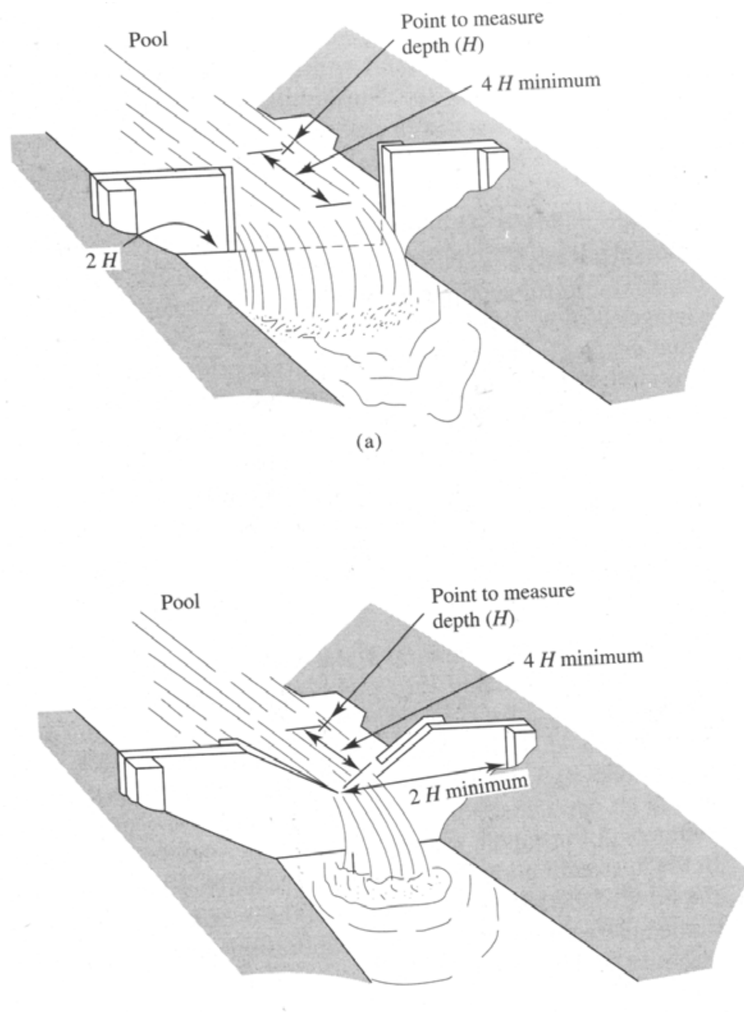


Figure 19.—Example of sharp-crested v-notch and rectangular weirs

- **Portable Parshall Flume—**This type of flume is good for shallow depths and low velocities. The flume converges down to a throat that has an adverse slope, thus forcing critical depth in this throat section. It is important that the flume be level. (Figure 20)

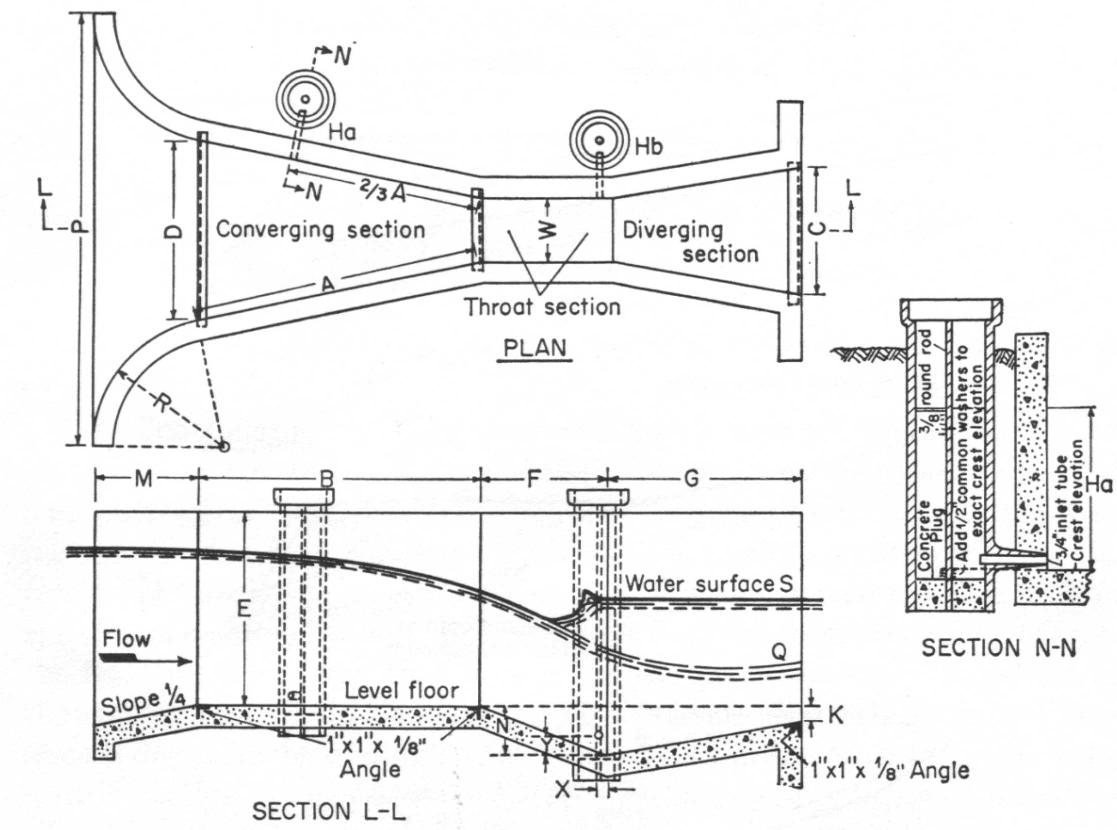


Figure 20—Parshall Flume (modified from Chow, 1959)

Stage-Discharge Relations (Rating Curves)

A Rating Curve is used to determine the discharge from an observation of the gage height (stage) of a river or stream. The rating curve is, therefore, the fundamental tool that allows the computation of discharge from a continuous or periodic record of stage. These rating curves are typically derived from both hydraulic theory and actual field measurements of discharge taken at various gage heights.

Controls

The control is a feature in the stream downstream of the gaging station in subcritical flow, that "controls" what the relation between stage and discharge is. There are two main types of controls: Section Control and Channel Control.

Section control is a specific cross section of a stream channel, located downstream from a gage, that controls the relation between gage height and discharge at the gage. The section control could be a natural feature such as a rock ledge, a sand bar, a severe channel constriction (culvert, bridge opening, etc), or an accumulation of debris. It can also be a man-made feature such as a weir, flume or an overflow spillway. Section controls can frequently be visually identified in the field by observing a riffle, or pronounced drop in water surface, as the flow passes over the control. Section controls usually control low flows, but may sometimes control medium and even high flows. The governing equation for section control takes the form:

$$Q=Cbh^{1.5}$$

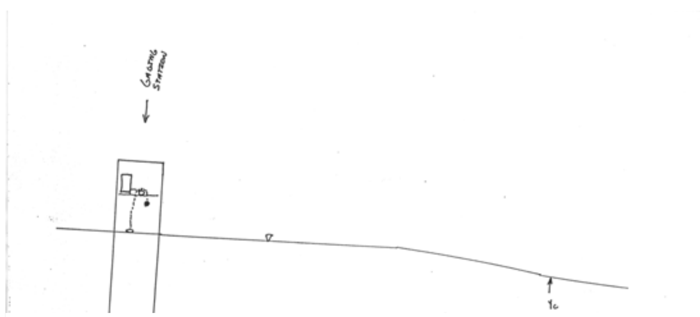
Where Q=discharge
C= coefficient of discharge
b= channel width
h=stage

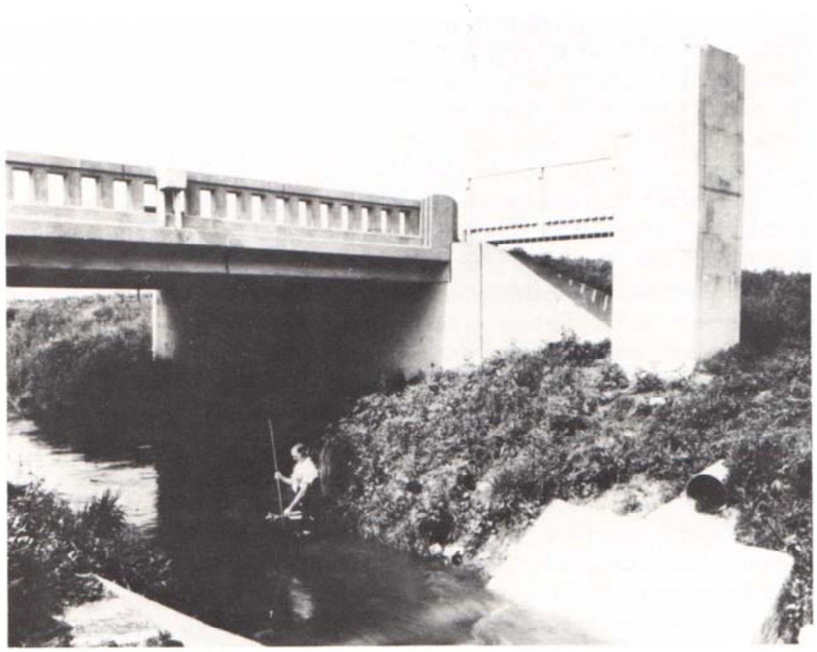
Channel control consists of a combination of features throughout a reach downstream from a gage. These features include channel size, shape, curvature, slope and roughness. The length of channel reach that controls a stage-discharge relation varies. For steep streams, the control reach may be relatively short, whereas for mild or flat sloped streams, the control reach may be very long. The precise definition of the length of channel control reach is usually not possible, or necessary. Channel controls usually control the higher magnitude flows. The governing equation for channel control takes the form of the well known Manning Equation:

$$Q = \frac{1.4986}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}}$$

Where Q=discharge
n = Manning's roughness coefficient
A = Cross Sectional Area
R = Hydraulic Radius = A/P
P = Wetted Perimeter
S = Bed Slope (for uniform flow)
=Friction Slope (for non-uniform flow)

On most streams, control changes from section to channel control as the stage increases. For example, at low flow a gravel riffle may be the control, at medium to high flow the channel may be the control. For a short range in stage between the two dominating controls, the rating curve is governed by a combination of section and channel control. This part of the rating is commonly referred to as the transition zone of the rating, and represents the change from section control to channel control. In other instances, a combination control may consist of two section controls, where each has partial controlling effects. Figure 21 shows a gravel riffle control downstream of a gaging station. Figure 22 shows a gage house upstream of a concrete broad-crested weir. Chow (1959, pp 70-74) and Henderson (1966, pp 40-43, 116-119) discuss controls on flow.





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Rating Curve Theory

As has been discussed in the preceding discussion, stage-discharge ratings are based on basic hydraulic principles. Most ratings however are developed empirically by plotting several discharge measurements versus stage for a variety of stages. Once enough measurements are plotted, a curve fit to the data typically takes on the form of a power function that looks like:

$$Q = p\,(h-e)^{b}$$

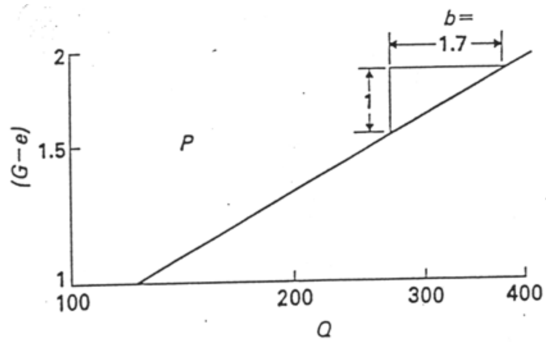
Where p = constant which is numerically equal to the discharge when the (h-e) = 1.0
h = gage height
e = gage height of zero flow(also called the point of zero flow(PZF)) for a section control of regular shape, or the gage height of effective zero flow for a channel control or a section control of irregular shape
b = slope of the rating curve
Note: (h-e) is the head or depth of water on the control.

The effective gage height of zero flow (e) is a value that, when subtracted from the mean gage height of the discharge measurements, will cause the logarithmic rating curve to plot as a straight line. This value (e) is also called the **scale offset**. For regular shaped section controls, the effective gage height of zero flow will be nearly the same as the actual gage height of zero flow. For irregular shaped section controls, the effective gage height of zero flow is greater than the actual gage height of zero flow. For those parts of the rating curve where the control changes from one section to another (or to channel control), the effective gage height of zero flow will usually change also. This results in the need to analyze the rating curves in segments (separate log-log plots for each control condition).

The ratings are typically plotted in log-log space the medium to high flow and on arithmetic coordinate space for low flow. Log-log space for medium to high flow is used because it makes a power function into a straight line of the form:

$$\text{Log } Q = \text{Log } p + b \text{ Log}(h-e)$$

which is the equation for a straight line (figure 23).



Where:

b is the slope of the straight line.

e is the constant which when subtracted from *G* will result in a straight line on logarithmic paper for the plot *Q* vs (*G−e*). The value of "*e*" is usually the gage height of zero flow or the effective *GZF*. The value of "*e*" used, or any other constant that is subtracted from *G* is called the "Scale Offset."

G is the gage height.

P is the intercept equal to *Q* when (*G−e*) is equal to 1.0.

Q is the discharge.

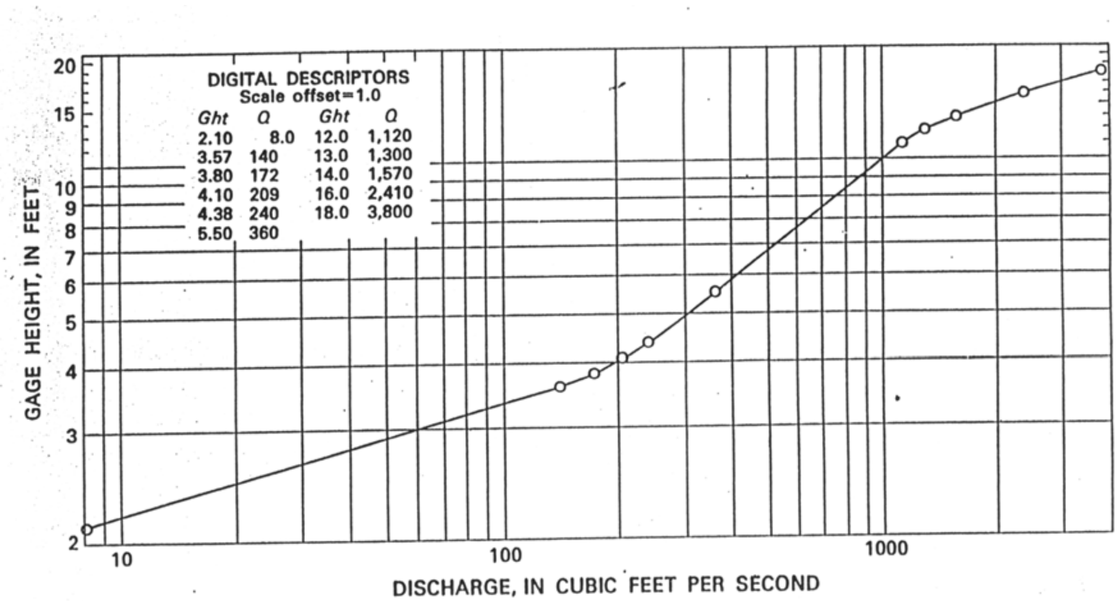
The general equation for curves of this type is

$$Q=P\ (G-e)^b$$

The equation of the curve shown is $Q=125\ (G-e)^{1.7}$

Figure 23.—Example of a stage-discharge rating which is linear in log space

If the scale offset is chosen properly, then the measurements plotted in log-log space will be approximately linear. To utilize the scale offset on log paper, the value of the offset is added to each of the regular values on the gage height axis. Figure 24 demonstrates how this is done for a scale offset of 1.0. The 1.0 location on the log scale now becomes 2.0, the 2.0 now becomes 3.0, the 10.0 values now becomes 11.0, etc. The offset is adjusted until the curve is as linear as possible. This allows the engineer to adjust the rating curve with fewer discharge measurements.

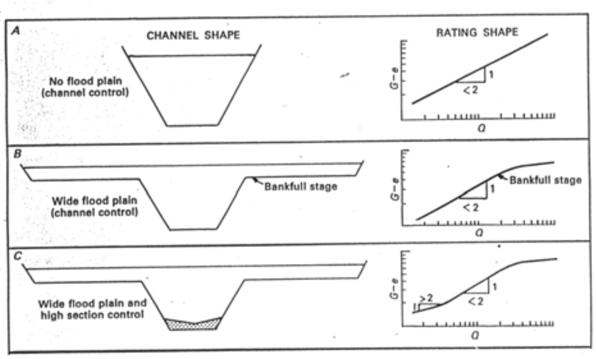


Typical logarithmic rating curve with corresponding digital descriptors.
(From USGS TWRI Book 3, Chapter A10)

Figure 24.-Stage-discharge relation using a scale offset of 1.0

For the low flow, the rating is plotted in arithmetic coordinates, because zero discharge cannot be plotted in log-log space. Knowing the point of zero flow (the measurement of which was discussed in an earlier section of these notes), helps to draw the low flow rating curve in arithmetic coordinates.

Figures 25 shows how the rating curves should be shaped with various control situations. For section controls, the slope (measured in this case as the run over the rise instead of the typical rise over run) will almost always be greater than 2. For channel controls, the

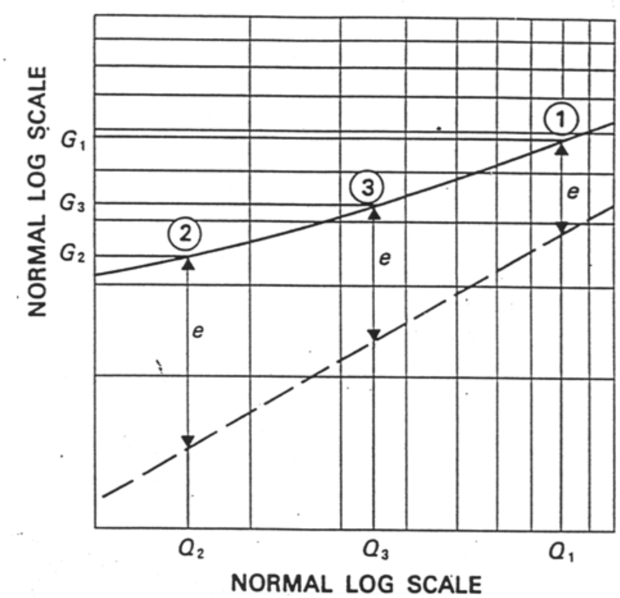


slope will usually be between 1.5 and 2.0.

Figure 25.-Relation of rating curve shape to cross section properties

Steps In Developing a Rating Curve

1. Gather all available discharge measurements. Also, gather any old rating curves for the stream that may be available. These can help determine shape of the rating curve.
2. Obtain all pertinent measurements of "Point of Zero Flow" (PZF).
3. Draw the low flow portion of the rating on arithmetic coordinates, tying the curve into zero discharge at the PZF.
4. For the medium and high flows, select the log scales so that the entire range of stage and discharge is included.
5. Separate scales, or plots, may be needed for high and low parts of the rating.
6. Discharge scale should always be the abscissa, and the gage height scale should always be the ordinate.
7. Determine the offset for the gage height scale (the discharge will always use a normal log scale (scale offset =0))
    - Generally the scale offset will be near the PZF
    - Formula for determining Offset by Johnson's method, see figure 26
    - The best scale offset is one that produces a log-log rating that is a straight line in the range of most frequent use. For the lower flow end of the log-log rating, the PZF works fairly well as the scale offset.
    - Figure 27 shows the impact of various scale offsets on a rating curve shape



$Q_3^2 = Q_1 Q_2$ **and when the dashed line is straight**

$(G_3 - e)^2 = (G_1 - e)(G_2 - e)$, **solving for** e

$$e = \frac{G_1 G_2 - G_3^2}{G_1 + G_2 - 2G_3}$$

Figure 26.-Determination of scale offset by Johnson's method

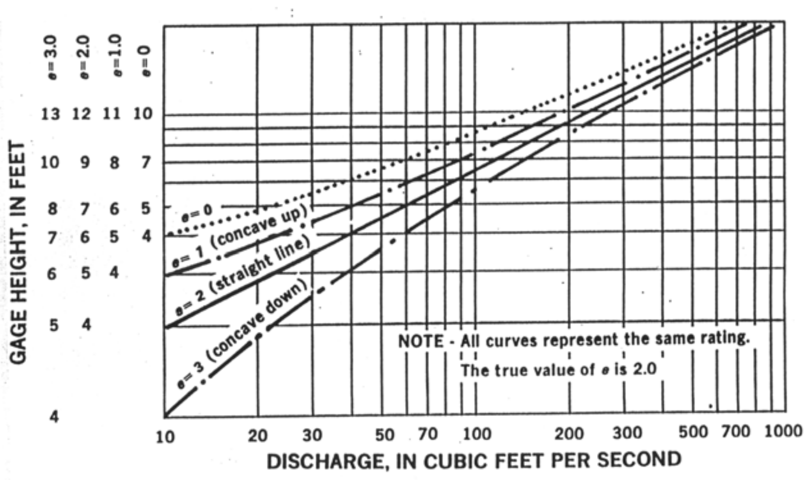


Figure 27.-Rating curve shapes resulting from various scale offsets

8. Plot the applicable measurements
   - Those that define the stable control
   - All those greater than a certain discharge
   - Lowest measurement or two
   - PZF measurement
9. If old rating curve existed for this site, draw the old rating as a dashed line
10. Draw new rating curve based on:
    - Control characteristics
    - Measurement accuracy
    - Measurement Date
    - PZF
11. Have curve reviewed and measurement plotting accuracy checked
12. Generate a table from the graphical rating curve
    - Pick points from curve to be used for computation of expanded rating table (USGS has a data base/analysis package called ADAPS that does this)
    - Check the expanded rating table against the rating curve
13. Document the rating
    - List all measurements, along with the dates made, to determine the rating curve

Kennedy (1984) contains much more details regarding stage-discharge rating curves.

Complex Ratings

The preceding discussion only involved simple stage-discharge ratings. There are other types of ratings, including loop ratings, slope ratings, and velocity-index ratings. A complex rating is one where the water-surface profile is variable, therefore, no simple relation exists between stage and discharge. Complex ratings often require more discharge measurements than simple ratings to define the rating.

Loop Rating

A loop rating is a rating where the the for the same stage, more discharge occurs on the rising limb than on the falling limb of a flood event hydrograph. This has a couple of possible causes. The most understandable is that the energy slope is greater on the rising limb of the hydrograph than on the falling limb. Recall that in the Manning Equation, discharge is proportional to the energy slope. Figure 28 is an example of a loop rating.

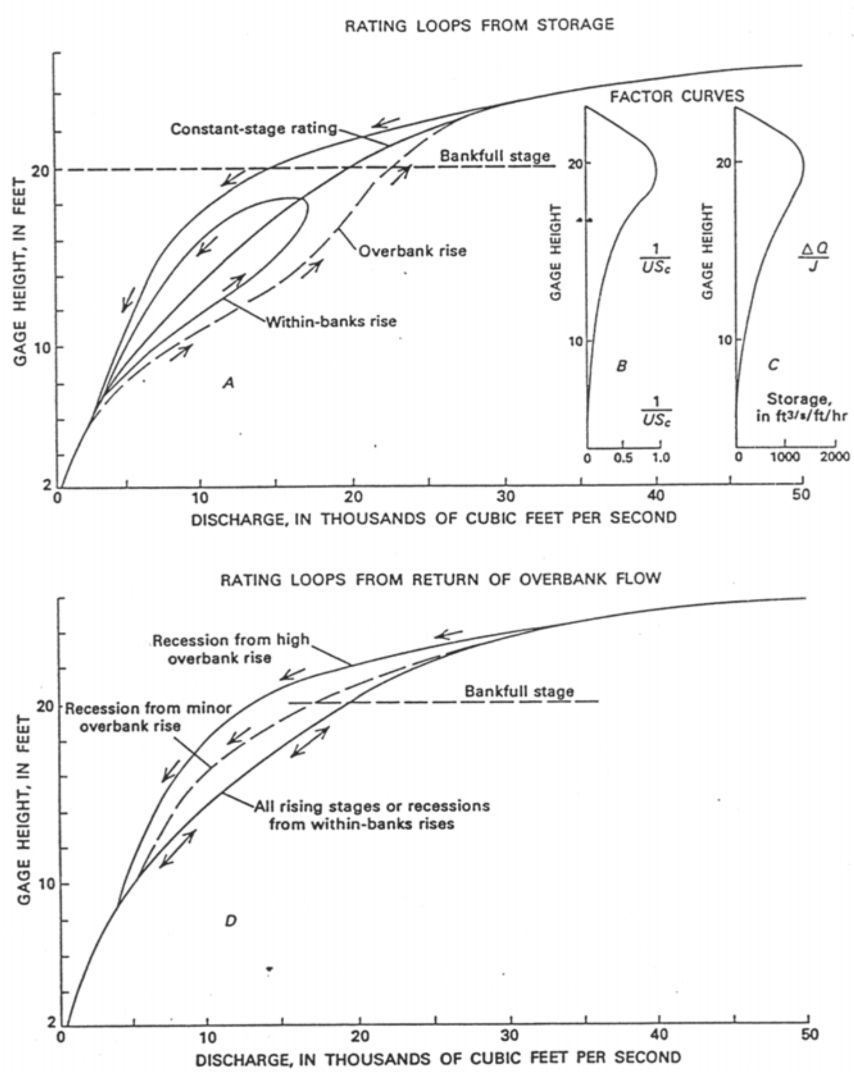


Figure 28.-Typical shapes of single-storm loop ratings and factor curves

Slope Rating

Slope ratings occur on streams affected by variable backwater or on flat gradient streams that are subject to backwater from tributaries or return of overbank flow. Two gages in the reach of interest are needed to define slope. The discharge is dependent on two independent variables, stage and the slope of the water surface.

Velocity Index Rating

Generally used where variable backwater exists and the water surface is to flat to develop a slope rating. Also used where reverse flow exists. Basically this is the method used for the AVM that was discussed previously. The AVM is used to monitor continuous discharge at sites where conventional stage-discharge ratings are not possible. A relation is developed between the line velocity and the mean streamflow velocity by making several discharge measurements, calculating the mean velocity of the measurement, and relating this to the line velocity collected by the AVM during the measurement of discharge. In addition to the line velocity/mean streamflow velocity relation, a relation between stage and cross sectional area must also be developed. After these relations are developed, as the AVM collects line velocities and stage, the discharge can be determined by multiplying the mean velocity (determined from the relation between line velocity and mean velocity) and the area (determined from the relation between stage and area of the channel cross section).

Computation of Discharge

Once a rating curve is established, the rating curve is applied to the time series of gage height record to determine the time series of discharge. However, this is not always straightforward in the field situations because of control shifts throughout the year. For example, a rating has been established for a particular stream that has a concrete weir. In mid winter, a beaver colony built a dam on top of the weir to back water up a little higher, but a spring flood washed the dam out. The beaver dam affected the stage-discharge relation for the period when the dam was intact. However, since the dam was washed out during the spring, instead of drawing a new rating for the period when the beaver dam was present, we determine a temporary shift to the rating curve to compute the discharge during this period.

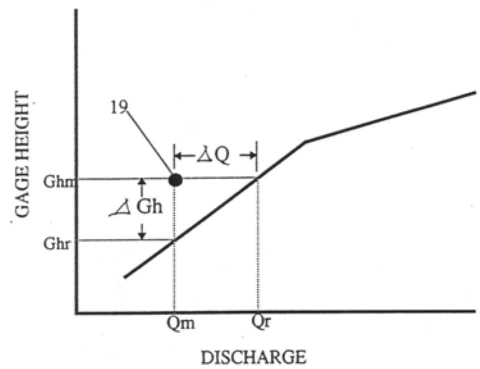
Shifts

Some of the natural events that may cause shifts in the rating curve to occur:

- Scouring of channel bottom
- Deposition of sediment
- Drift lodging on control
- Sloughing of banks
- Aquatic growth
- Flood-plain encroachment
- Beaver dams
- Ice

Figure 29 shows graphically how a shift is determined for a measurement.

Assume that measurement 19 had a stage of 500 ft^3/sec for a gage height of 4.75 ft. Assume that the rating in figure 29, for a gage height of 4.75 ft, the rating discharge was supposed to be 550 ft^3/sec. Using these values the percent difference would be –10% (see figure 29 for formula). The percent difference is a useful measure to assess the validity of both the measurement and the rating curve. If a measurement is made, the engineer rates the measurement good, one would expect that if the rating is still good, the percent difference would be no more than 5%. If a measurement is made and has a percent difference of 8%, then the engineer would want to consider making a check measurement to make sure no errors were made in the measurement.



Determination of Measurement 19 error from rating curve:

% Difference = [Measurement Q - Rating Q] x 100 / Rating Q

% Difference = $[(Q_m - Q_r) \times 100\ \%] / Qr$

$Gh_r - Gh_m$ = Shift (+/-) ; for measured Q

Figure 29.—Example of shift determination for a discharge measurement

For the same measurement, assume that for a discharge of 500 ft^3/sec, the gage height according to the rating curve should have been 4.50 ft. The computed shift would then be –0.25 ft. This would mean that for the period of time that this measurement was made, for all the stage collected on the data logger, the engineer would need to subtract 0.25 ft from the stage before applying the rating curve to the stage to get the discharge.

To apply shifts when working records, shift curves are developed. These curves are then applied by stage at various times of the year to the stage data before applying the rating curve to determine the discharge. Figure 30 illustrates a shift curve at the top and how it effects the rating curve at the bottom. Kennedy (1983) contains a complete discussion of discharge records computation. Figure 31 is a schematic of the process followed to compute records of discharge by the USGS.

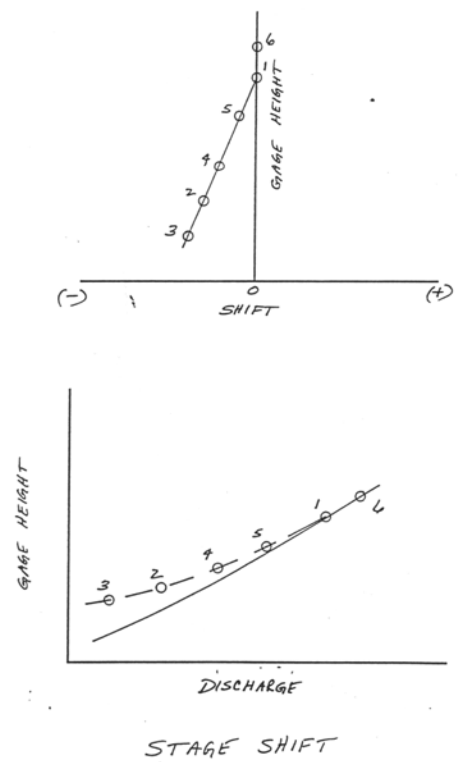


Figure 30.—Example of a shift curve

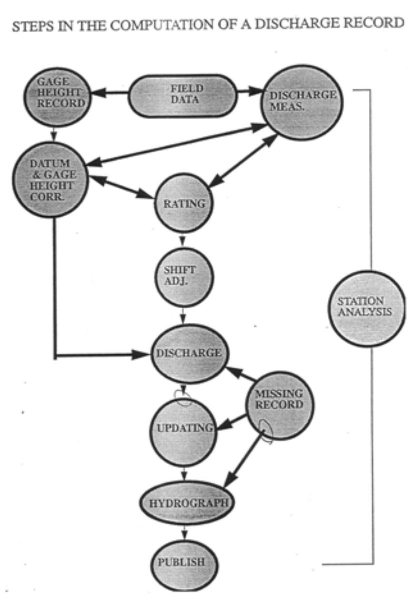


Figure 31.—Steps in the computation of a discharge record

Sediment Transport

It is important to know the nature and magnitude of sediment transport in streams and rivers for a number of reasons:

- Water Quality Assessment
- Biological Assessment of the impact on wildlife
- Reservoir Design
- Channel Stability
- Bridge Design

Fluvial sediment moves in two modes:

- Suspended-Sediment Load—That part of the sediment load which is carried in suspension in the water column
- Bed-load—That sediment which is carried in contact with the bed by skipping, sliding, and rolling

The sediment load past a point can also be categorized by the source material that the sediment stems from:

- Bed-material Load---That part of the total stream sediment load which is comprised of particle sizes found in appreciable quantities in the bed material of the stream.
- Wash Load---The part of the total stream sediment load comprised of particles which are found only in small quantities in the bed material of the stream. Typically usually finer than 0.062 mm (less than sand size).

Various sizes of sediment are characterized by the USGS as follows:

- Clay sized particles--<0.004 mm
- Silt sized particles—ranges from .004 mm to .062 mm
- Sand sized particles---ranges from .062 mm to 2 mm
- Gravel sized particles—2 mm to 64 mm

It is beyond the scope of this course to discuss in much detail the mechanics behind sediment transport. Some useful references to further investigate this phenomena are:

Graf, W.H., 1971, Hydraulics of Sediment Transport, McGraw-Hill, New York, 513p.
Vanoni, V.A., 1975, Sedimentation Engineering, ASCE Manual and Report on Engineering Practice Number 54, New York, 745 p.
Yalin, M.S., 1977, Mechanics of Sediment Transport, Pergamon Press, New York, 298 p.

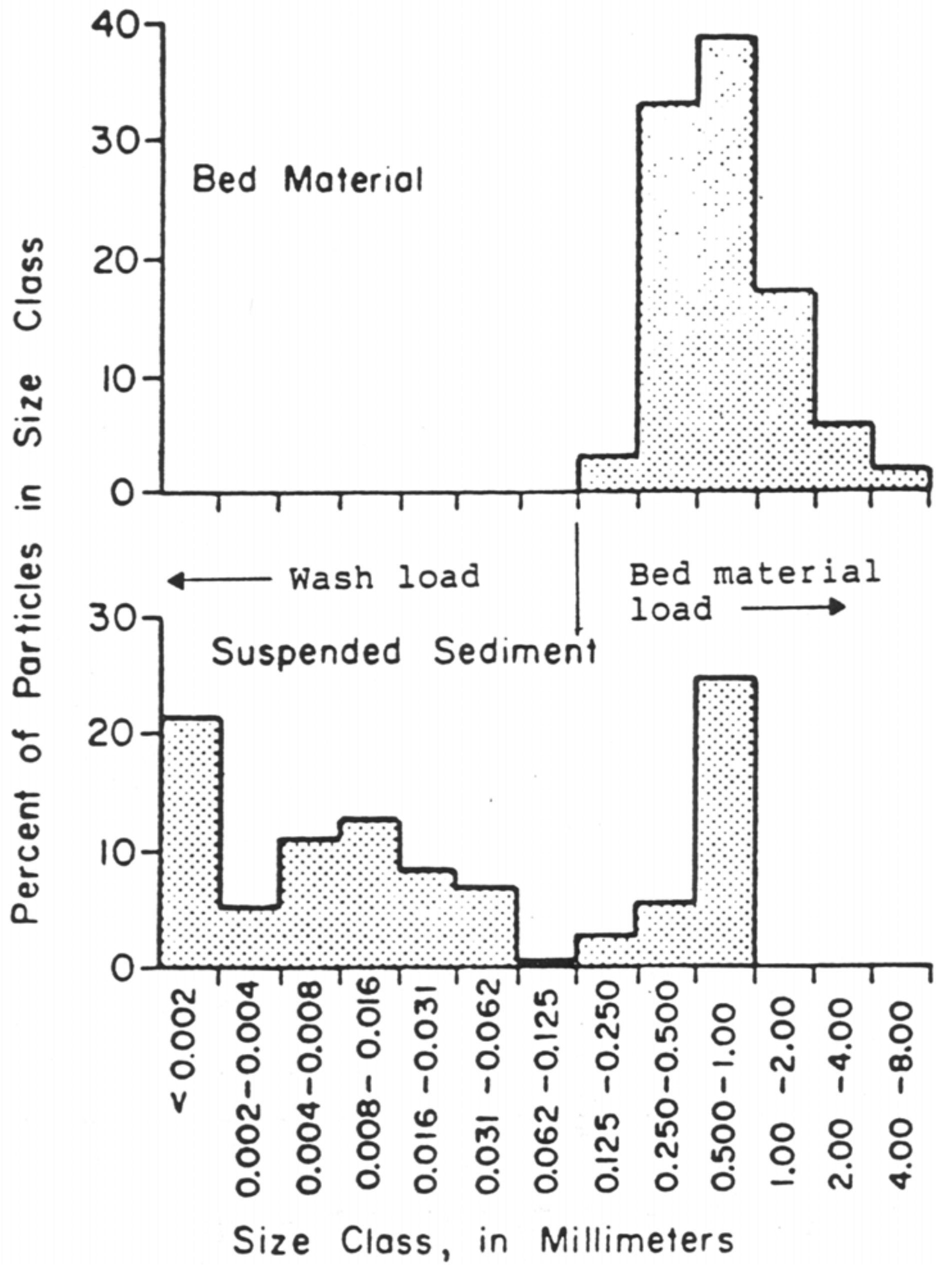


Figure 32.—Size distribution of suspended sediment and bed material showing distinction between wash load and bed material load

Sampling Theory

To determine the amount of a constituent (sediment in this case) being transported downstream, the best method for doing this would be to capture the entire flow for a period for a discrete segment of time and analyse the entire sample for the concentration of the sediment. Obviously, this is impossible for all but the smallest of streams. Therefore, a sampling procedure and methodology must be designed whereby the samples are collected that are representative of the sediment concentration of the entire stream.

Stepping back a moment, consider if the problem was to determine the mean age of everyone in a particular classroom. This could be done in one of two ways.

1. Conduct a survey to determine everyone's age and compute the "true" mean age from the entire population.
2. Obtain a small "representative" sample of the population, compute the average age of the sample and assign that age to the whole population. This would obviously have some error, unless we got real lucky.

The question becomes, how do we obtain a representative sample? There are two broad classes of sampling to choose from:

1. Random Sampling-allows data analysis using generally accepted standard statistical techniques for defining data characteristics and errors (i.e., mean, median, standard deviation, modality, standard error, etc.)
2. Non-Random or Systematic Sampling-this requires some prior knowledge about the population

For the classroom age problem, no special knowledge of the population was available, therefore a random sampling of the population (classroom) would be conducted, the ages determined, an average of that sample set computed, and the assumption that the sample average equaled the population average.

For the problem of determining the average concentration of suspended sediment in stream cross-section, a systematic sampling procedure is desirable because some characteristics of the suspended sediment in streams are know.

1. Suspended sediment moves with the flow.
2. Suspended sediment moves faster in areas of the stream having higher velocities than in areas of the stream having lower velocities.
3. If the stream carries a load of suspended sand, distribution of that concentration may be very non-uniform, both laterally and with depth. Generally, higher concentrations are found nearest the streambed and in parts

of the cross section having higher velocity (although often the variations are also very supply dependent).

- Slower velocities of sediment movement at the bottom
- Higher concentration of sediment at the bottom
- Sediment particles should be coarser near the bed and fine upward
- Laterally across the stream, the suspended sediment may be coarser in the areas of higher velocity

4. If the stream carries a load of suspended silt and clay, distribution of its concentration within the cross section is expected to be more uniform both laterally and with depth.
5. A stream transporting a mixture of both fine (silt-clay) and coarse (sand) suspended sediment, will exhibit variations in concentration showing both characteristics mentioned in 3 and 4.
6. In looking at 1-5 above, one can see that although the sediment moves with the flow, relations governing the transport of sediment are very complex.

From the characteristics above, the design of sampling schemes for suspended-sediment revolves around weighting the samples either by velocity or by discharge, because flow influences the distribution of the sediment in suspension. The methods for obtaining a representative average suspended-sediment concentration will be discussed later in these course notes under Suspended-Sediment Sampling Methods.

Sediment Samplers

Sediment samplers were standardized through the efforts of several Federal Agencies starting in 1939. Before this standardization effort, each fluvial sediment investigator and agency developed samplers and methods as needed (Edwards and Glysson, 1988). The standardization effort helped move the science of sedimentation into allowing more consistent data for comparison between agencies and projects. In 1956, the group of agencies is now called the Federal Interagency Sedimentation Project (F.I.S.P).

The samplers developed by the F.I.S.P. are designated by the following codes:

- US—United States standard sampler—In these lecture notes, this is typically dropped from the designation of the sampler
- D—Depth Integrating
- P—Point Integrating
- H—Hand held by rod or line (this code is placed after the primary letter designation and is omitted when referring to cable- and reel-suspended samlpers)
- BM—Bed Material Sampler
- Year—last two digits of the year in which the sampler was developed

There are many samplers available from the F.I.S.P. and the Hydrologic Instrumentation Facility of the USGS.

Suspended-Sediment Samplers

As was noted in the discussion on velocity distribution in the vertical and shown on figure 14, the magnitude of water velocity decreases as the bed of the channel is approached. The reverse is true for the suspended-sediment concentration, the suspended-sediment concentration increases (especially for sand-sized and greater particles) as the bed is approached (figure 33).

As should be noted, the coarser the sediment, the more marked this increase in concentration as the bed is approached (figure 33). The clay and silt sized particles have a concentration distribution that is more uniform because these particles stay in suspension longer and are typically being “washed” through the system, hence the term wash load.

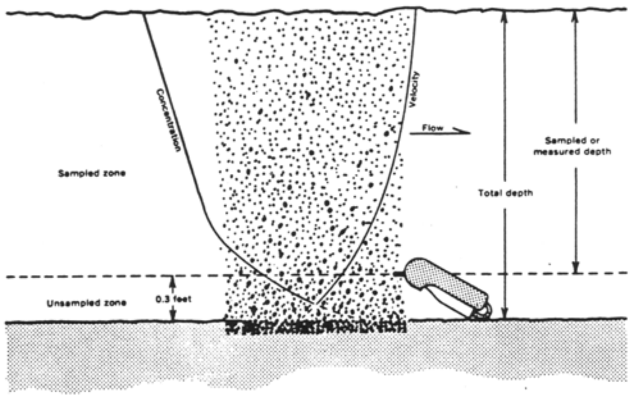


Figure 3.—Measured and unmeasured sampling zones in a stream sampling vertical with respect to velocity of flow and sediment concentration. J. K. Culbertson (written commun., May 1968).

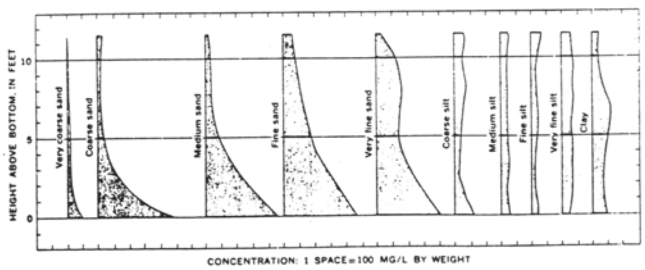


Figure 4—Discharge-weighted concentration of suspended sediment for different particle-size groups at a sampling vertical in the Missouri River at Kansas City, Mo.

Figure 33.—Distribution of the velocity and the suspended-sediment concentration (top diagram). Distribution of various particle sizes through the water column for the Missouri River at Kansas City, MO (bottom diagram)

A Suspended-sediment sampler primarily consist of a weighted hydrodynamic apparatus constructed in such a way to allow a sample container to collect a representative sample throughout the water column. The sample is weighted according to velocity. A nozzle serves as the conduit to allow the water into the sampler container. For many of the samplers, multiple size nozzles are available to interchange dependent on sampling conditions. According to Edwards and Glysson (1988, p 6), "the purpose of a suspended-sediment sampler is to obtain a representative sample of the water-sediment mixture moving in the stream in the vicinity of the sampler." To fulfill this goal, the F.I.S.P. set up the following criteria:

1. Allow the water to enter the nozzle isokinetically, ie the water entering the nozzle undergoes no change in velocity from that of the stream velocity (Figure 34)
2. Permit the sampler nozzle to reach a point as near to the streambed as possible
3. Minimize the sampler disturbance to the flow field in the stream.
4. Adapt the samplers to existing streamgaging equipment
5. Simplicity and maintenance free.
6. Accommodate a standard bottle (glass pint, glass quart, etc)

A submerged sampler has the nozzle pointed directly into the flow, thus water enters the nozzle and fills the bottle, with air exhausting out of the bottle by way of a separate exhaust hole. The "rules" of sampling have been set so as to ensure that the samplers perform as intended. Ensuring that the sampler is collecting an isokinetic sample is very important, especially when sand-sized sediments are entrained in the flow and are being sampled. If the velocity in the nozzle is faster than the ambient stream velocity near the sampler, the concentration of the suspended sediment will be lower than that of the ambient stream suspended-sediment concentration. Vice versa, if the velocity in the nozzle is lower than the ambient stream velocity, the concentration of suspended sediment will be lower than the ambient concentration of the stream.

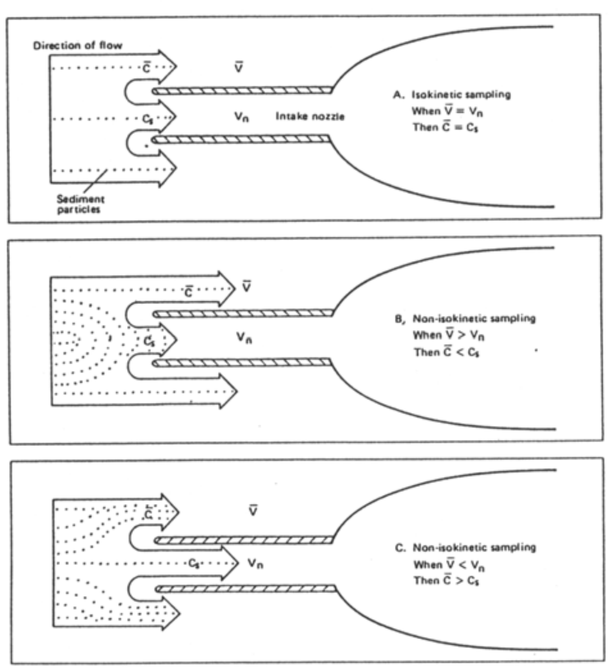


Figure 34.—Relation between intake velocity and sample concentration for isokinetic and non-isokinetic sample collection

The sample obtained by passing the sampler throughout the full depth of a stream is quantitatively weighted according to the velocity through which it passes. Therefore, if the sampling vertical represents a specific width of flow, the sample is considered to be discharge-weighted because, with a uniform transit rate, suspended sediment carried by the discharge throughout the sampled vertical is given equal time to enter the sampler. As will be emphasized later, because of this weighting by discharge (velocity) it is very important to keep the transit rate constant throughout at least a single direction of travel (ie, the descending or the ascending).

There are two types of suspended-sediment samplers: depth-integrating samplers and point-integrating samplers. The depth-integrating sampler is designed to isokinetically and continuously accumulate a representative sample from the stream vertical while transiting the stream at a uniform rate. **The depth-integrating sampler collects a velocity weighted sample as it is lowered and raised, because the faster the water is moving, the more water will enter at that point in the vertical.** The sampler is lowered to the bed and raised back to the surface, at a rate that is slow enough to allow an isokinetic sampler and fast enough that the bottle does not overfill. Overfilling of the sample bottle causes errors in the determination of the suspended-sediment concentration.

In all of the suspended-sediment samplers, there is a 3 inch unsampled zone at the bottom of the stream because of the design of the sampler (figure 33). Some of the available depth-integrating samplers are:

- DH-48—handheld wading sampler, pint bottle, ¼ inch nozzle only option -- 8.86 depth limitation
- DHS-48—DH-48 with fins and suspended on a hand line for sampling off of a structure (bridge, culvert head wall, etc), pint bottle, 5 lbs is sampler weight, ¼ inch nozzle only (figure 35)
- DH-59—hand line sampler, 22 lbs, pint bottle, 1/8,3/16,1/4 inch nozzle –9-19 ft depth limitation
- D-74—62 lbs, uses quart or pint bottles, 1/8,3/16,1/4 inch nozzles, 19 ft depth limitation
- D-77—75 lbs, uses 3 liter bottle, 5/16 inch nozzle—15.5 ft depth limitation
- DH-81—Wading version of the D-77, 1/8, 3/16, 1/4, 5/16 nozzles available, pint bottle (figure 36)---9 ft depth limitation

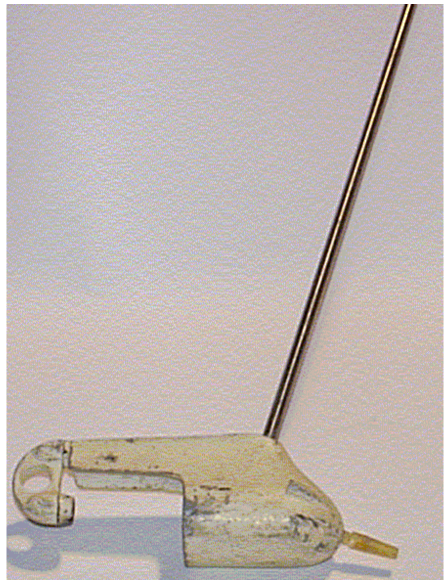


Figure 35—US DH-48 depth-integrating sampler

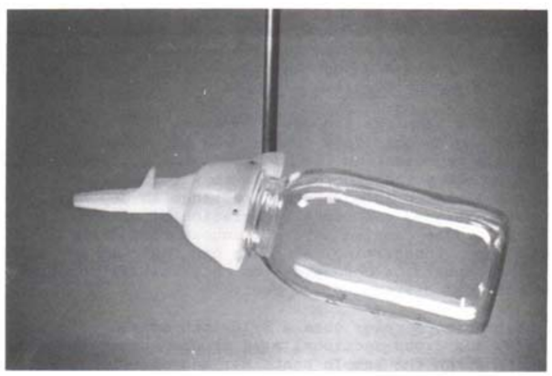


Figure 36.—US DH-81 hand held depth-integrating suspended-sediment sampler

The point-integrating sampler uses an electrically activated valve, which allows the selection of the location in the vertical at which an isokinetic sample could be collected. By activating the valve to the open position, the point-integrating sampler can be used as a depth-integrating sampler. The point sampler can sample in much deeper flows, because of the added versatility of the electrically activated valve. For example, if the stream was 30 feet deep, the typical depth-integrating sampler could not be used as the bottle would overfill before the sampler could complete the transit to the bed and back to the water surface. With the point-integrating sampler, the water column could be sampled until the sampler neared the bed, then the valve could be shut, thus not allowing any more water to enter the sampler. Once the sampler was brought to the surface, a new bottle could be inserted and the sampler lowered to the bed (with the valve shut). Once near the bed, the valve could be opened and raised to the surface, collecting an additional depth integrated sample. The point-integrating samplers are:

- P-61—105 lb, pint or quart bottles, 3/16 inch nozzle, 180 ft depth limitation because has the diving bell pressure eqaulization
- P-63—200 lb, pint or quart bottles, 3/16 inch nozzle, 180 ft depth limitation
- P-72—41 lb, pint or quart bottles, 3/16 inch nozzle, 72.2 ft depth limitation (figure 37)

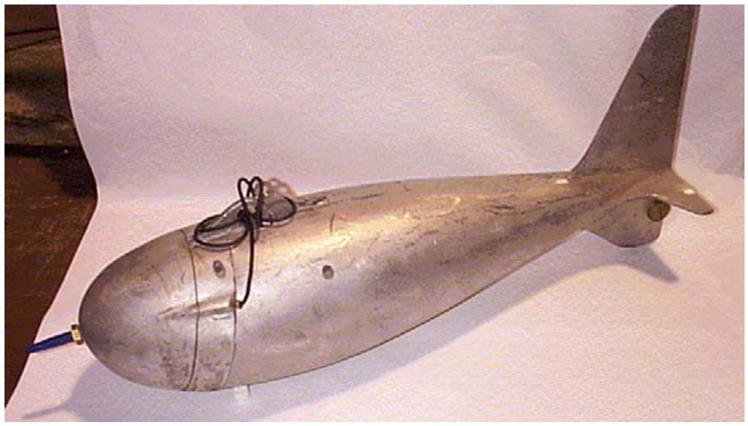


Figure 37.—P-72 point-integrating sampler

Quality Assurance of Suspended-Sediment Samplers

Before sampling it is necessary to assure that the sampler is functioning properly. Before beginning sampling:

1. Check the seal
   - ---For depth-integrating sampler, place the sample bottle inside sampler, attach tubing to nozzle and cover the exhaust port. A good seal will not allow one to blow into the tubing while covering the exhaust port.
   - --For point-integrating sampler, place the sample bottle inside the sampler and lower the sampler to the bed of the river and back with the valve closed. The bottle should be checked for water contents, no water inside bottle indicates a good seal.
2. Inspect nozzle
   - Should have no chips or ground down ends
   - Should be aligned with flow

Bed Material Samplers

Knowledge of bed material is important. Following are some of the available bed material samplers:

- BMH-53—Hand-held piston type bed sampler designed to use when wading and sampling in sand and finer grain material, poor in gravel sized bed sediments

- BM-54---Cable suspended 100 lbs, rotary type sampler, maximum bed particle size that can be accurately sampled is 16 mm gravel, When sampler hoisted to surface, ensure that bucket was completely shut as any gap in bucket will allow fines to be washed out
- BM-60—Cable suspended 32 lbs version of BM-54
- BMH-80—Hand-held with hand-activated rotary scoop designed for use in sampling sand and fine gravel (figure 38)
- Shovel—Obvious limitations because it can only be used in shallow water depths
- Ponar (dredge sampler)—Suspended from a cable, designed for use in sampling fine, soft sediments, such as sand, silt, and clay found in lakebed or estuary. Bulky, non-streamlined sampler, not for use in flowing water.

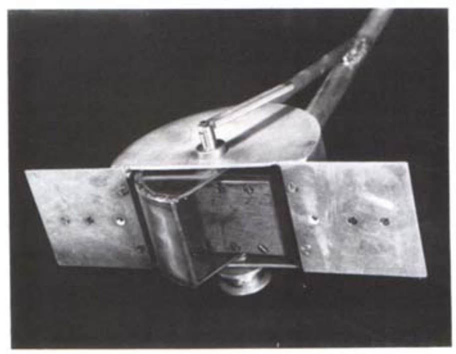


Figure 38.—US BMH-80 Bed-Material Sampler

Bedload Samplers

Bedload has traditionally been sampled by placing samplers in contact with the bed and allowing the bedload to accumulate inside the sampler before it is raised to the surface. More recently, advances in remote sensing allows determination of bedload transport by non-contact methods. Some of the contact bedload samplers are:

- Helley-Smith---66 lb sampler with a 3x3 inch opening and a flare ratio of 3.22, and a sample bag with mesh size of 0.2 mm serves as the catch for the bed material (figure 39)
- FISP sampler—3x3 opening and a flare ratio of 1.40
- TR2---220 lb sampler with a 6x12 inch opening, designed and used by the USGS on the North Fork of the Toutle River below Mt. St. Helens

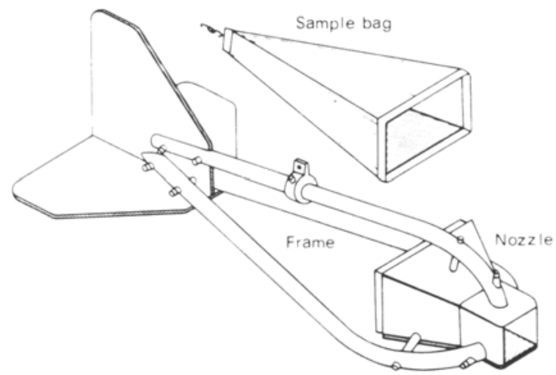


Figure 39.—Helley-Smith Bedload Sampler

Suspended-Sediment Sampling Methods

Edwards and Glysson (1988) describe various methods for sampling of fluvial sediments. A major purpose of sampling sediments is to determine the mean instantaneous suspended-sediment concentration of the cross section. Two methods exist for sampling a stream cross section to determine the mean suspended-sediment concentration: Equal-Discharge Increment method (EDI) and Equal-Width Increment Method (EWI). Both these methods involve taking samples of water at discrete locations along the cross section, but differ in the way the location of sampling verticals are selected.

The EWI method (Edwards and Glysson, 1988, pp61-64) divides the cross section into between 10 and 20 equal width increments. At each of the increments, a sample is collected using the same transit rate (speed that the sampler is lowered and raised through the water column) at each of the vertical. By using the same transit rate consistently across the cross section, the samples are being weighted according to the velocity of the stream. For example, in parts of the stream where the water is moving faster, the samples contain more of that water because since the transit rate is the same, more water moves into the sampler. EWI is typically used when no apriori information at new sites where discharge measurements have not been made. When laboratory analysis is done, all the bottles from an EWI cross section are composited for determination of the average suspended-sediment concentration. Generally, the more variable the concentration across the stream requires more verticals. Figure 40 contains the EWI sampling scheme.

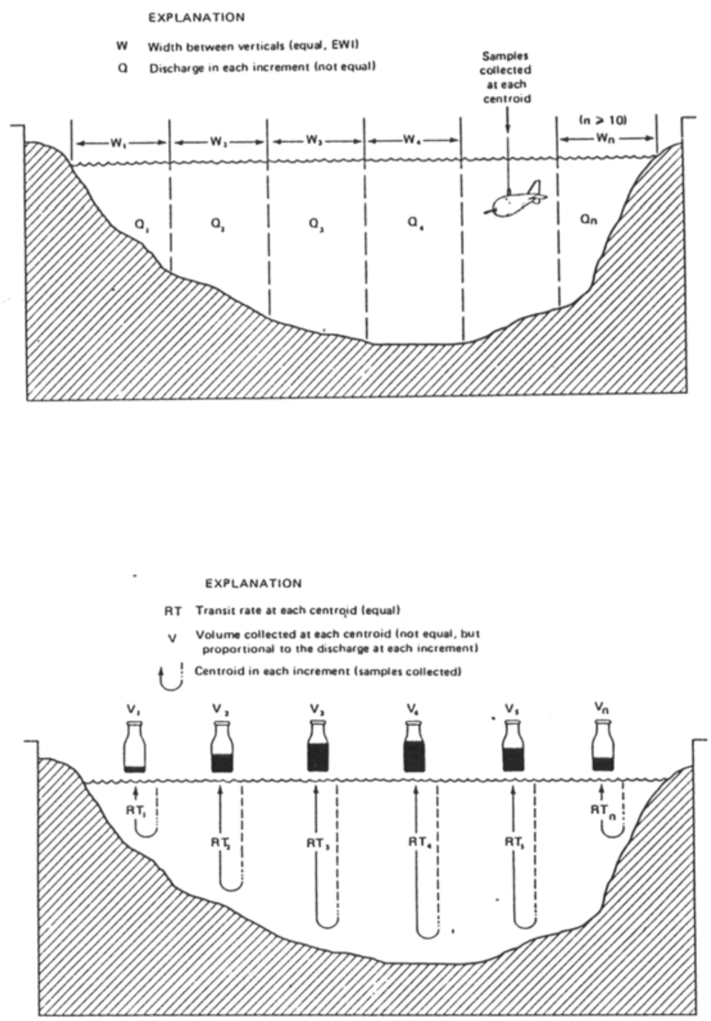


Figure 40.—EWI Method

The EDI method (Edwards and Glysson, 1988, pp 54-61) samples at points in the cross section of equal discharge. This requires the knowledge of the distribution of the discharge in the cross section before sampling can be conducted. This method requires a minimum of 4 verticals and a maximum of 9 verticals. The verticals are located at the centroids of equal discharge. This method assumes that the sample collected at the centroid of the subsection is representative of the mean concentration in that subsection. The transit rate us varied from subsection to subsection, as the goal is to get the same amount of sample volume in each sample. The samples are being weighted by the placement of the verticals in the centroid of equal discharge as opposed to the EWI has the stream velocity do the weighting. Figure 41 contains the EDI sampling scheme. Once the number of verticals to be sampled is determined, the total discharge is divided by the number of vertical (Q/n=q). The first vertical is located at q/2 to be sampling at the centroid of the first equal discharge increment. The second vertical is located at the vertical that corresponds to q/2 + q, the third vertical is located at q/2+q+q, and so on.

The transit rate is not constant for all verticals. Because the samples are already weighted by determining equal increments of discharge, the main objective is to select the transit rate such that the volume of water collected in each vertical is the same.

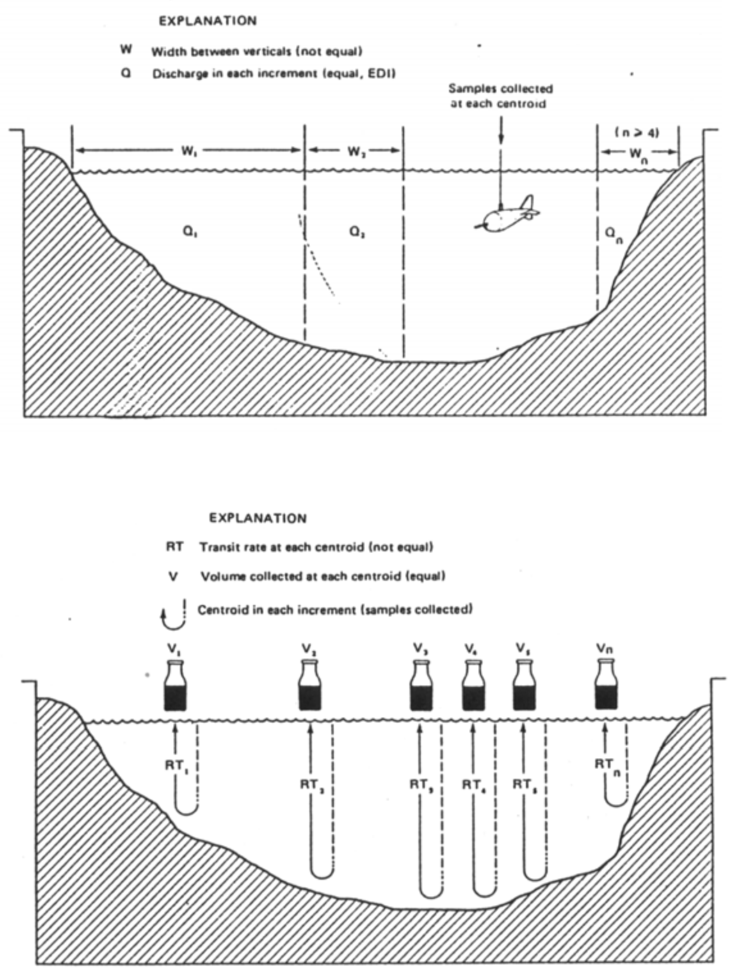


Figure 41.—EDI Method

Proper Suspended-Sediment Sampling in a Vertical

In each vertical, the purpose of sampling is to determine the instantaneous mean discharge-weighted suspended-sediment concentration of the vertical at the time of the sampling. The methods used to do this depends on the flow conditions and particle size of the suspended sediment being transported. Each of these cases are listed below (Edwards and Glysson, 1988, pp49-53).

CASE 1—low velocity (<2 ft/sec) and no sand being transported (no sediments >0.062mm)

- Because no sand is present, the distribution of suspended sediment in the water column from bed to water surface is relatively uniform. Therefore the sampling error is reduced. Therefore, it is not as important to collect the sample isokinetically.
- In shallow streams, the sample at the vertical may be collected by submerging an open mouthed bottle into the stream by hand. The mouth should be pointed upstream and the bottle held at a 45 degree angle from the streambed. The bottle should be filled by moving it from the surface to the streambed and back. A 3 inch unsampled zone should be maintained to match the unsampled zone of the regular suspended sampler (figure 33).

CASE 2—velocities between 2 ft/sec and 12 ft/sec and depths less than 15 feet

- Depth integrating (or point-integrating) samplers must be used. Depth integration is accomplished by traversing the entire depth of the stream from surface to the bed and back to the surface.
- Use the proper transit rate for the sampler. The transit rate is dependent on bottle size, nozzle size, and stream velocity. Determination of the transit rate will be discussed below.

CASE 3—velocities between 2 ft/sec and 12 ft/sec and depths greater than 15 feet

- Point samplers must be used. Depth samplers should not be used because by using the proper transit rate at depths greater than 15 feet, the bottles will overfill before the sampler can traverse the entire depth of the vertical.
- For depths of 15 to 30 feet, using the point sampler, take a depth integrated sample from the surface down to the bed. The sampler valve should be shut off. The sampler should be brought to the surface and the bottle changed. The sampler should then be lowered to the bed (with the valve closed), then opening the valve, an integrated sample should be collected from the bed to the surface.
- For depths greater than 30 feet, split the vertical into 2 segments and use 4 bottles to sample the vertical, 2 bottles for descending and 2 bottles for the ascending.
- Use the proper transit rate for the sampler.

CASE 4—velocities greater than 12 ft/sec

- In velocities this large, it is often impossible to sample the entire depth (unless it is shallow) and often there is a great amount of debris. Sample the top 2/10 depth only. As soon as it is possible to sample the entire depth, collect another sample of the top 2/10 depth followed immediately by a sample of the entire depth at the same vertical. This will allow a correction factor to be determined and applied to the Case 4 sample.

An isokinetic sample is a must to properly sample suspended-sediment. If a sample is not isokinetically sampled, then it will be biased high or low, depending on if the velocity in the nozzle is too fast or too slow compared to the ambient stream velocity near the sampler. Ensuring isokinetic conditions requires selecting the proper transit rate for the sampler to travel through the water. If the proper transit rate is exceeded, the pressure in the bottle does not equilibrate with external water fast enough, thus causing a slower velocity in the nozzle than in the stream. On the other hand, if too slow a transit rate is used, the bottle would be overfilled.

The proper transit rate is dependent on nozzle size, bottle size, depth, and water velocity. Figures 42-47 are graphs that are used to select the proper transit rate. Figure 42 is for a 1/8 inch nozzle and pint bottle. If the stream depth was 10 feet, the optimal transit rate divided by the mean velocity is around 0.11. If the stream velocity was 5 ft/sec, the optimal transit rate would be 0.11 multiplied by 5 ft/sec. This would result in an optimal transit rate of 0.55 ft/sec. If transit rate tables are not available, then the general rule of thumb is that the absolute maximum transit rate is 0.4 times the stream velocity (note: the majority of the time the transit rate will be much less than 0.4 times the stream velocity).

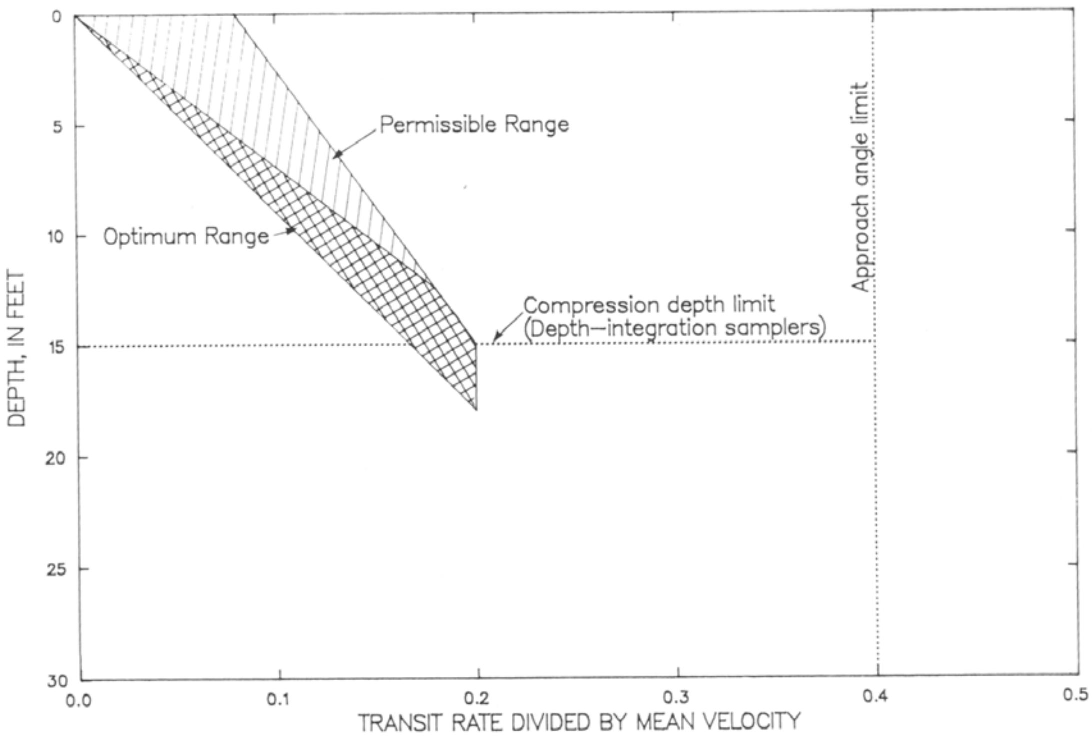


Figure 42.—Transit rate determination for 1/8-inch nozzle and pint bottle

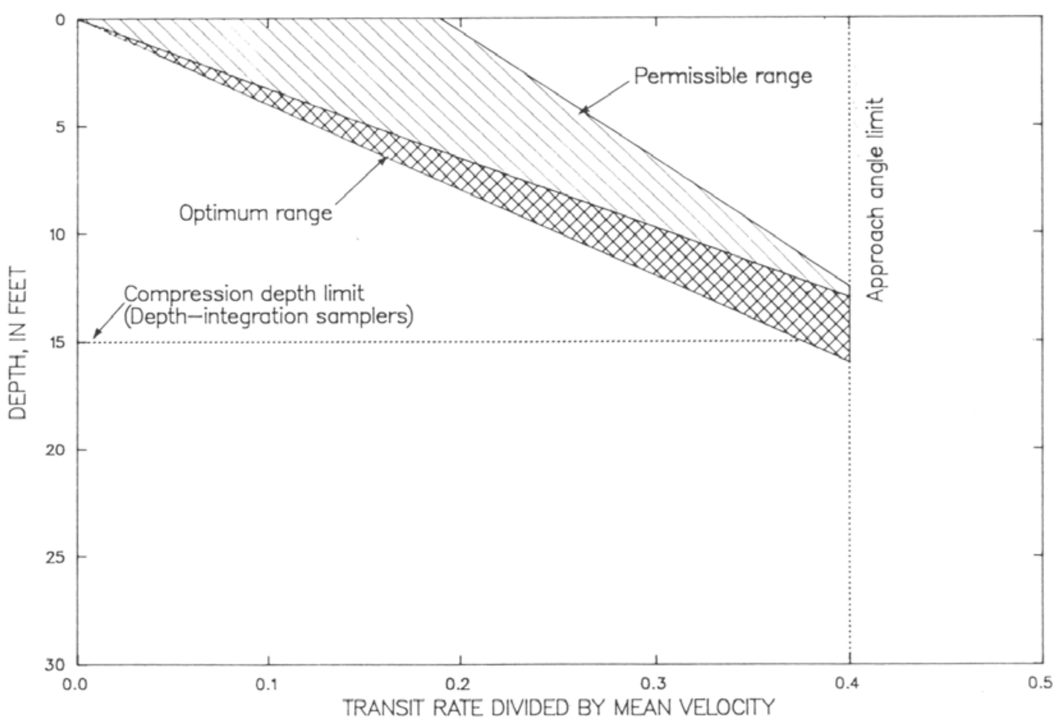


Figure 43.—Transit rate determination for 3/16-inch nozzle and pint bottle

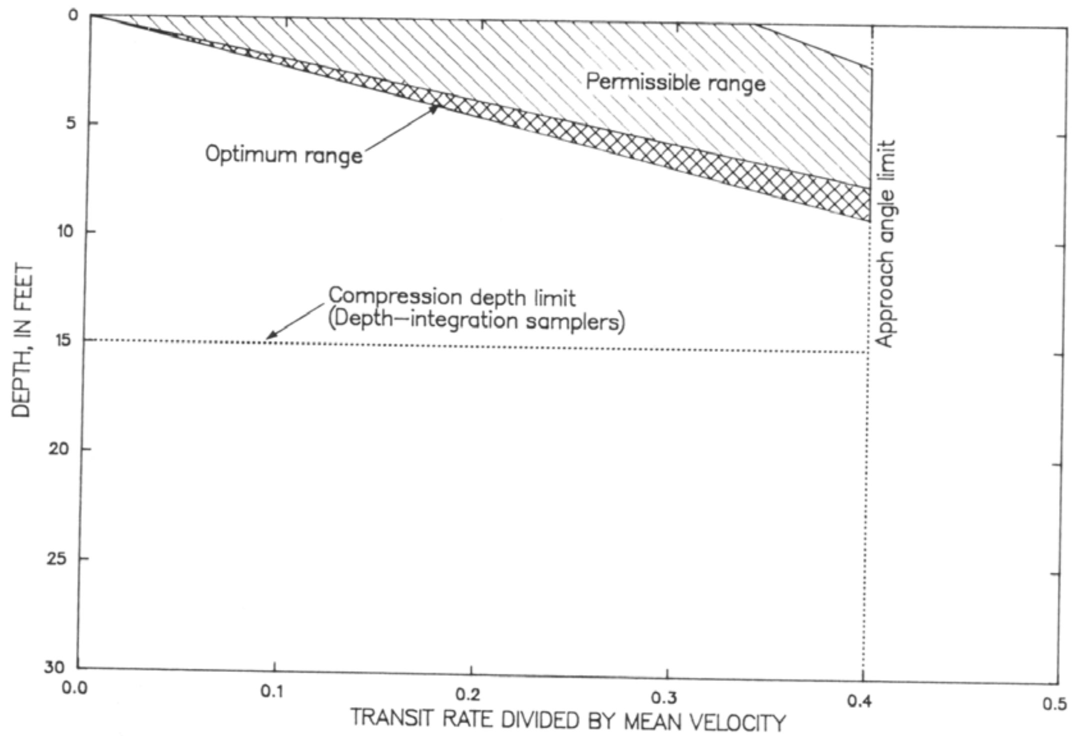


Figure 44.—Transit rate determination for ¼-inch nozzle and pint bottle

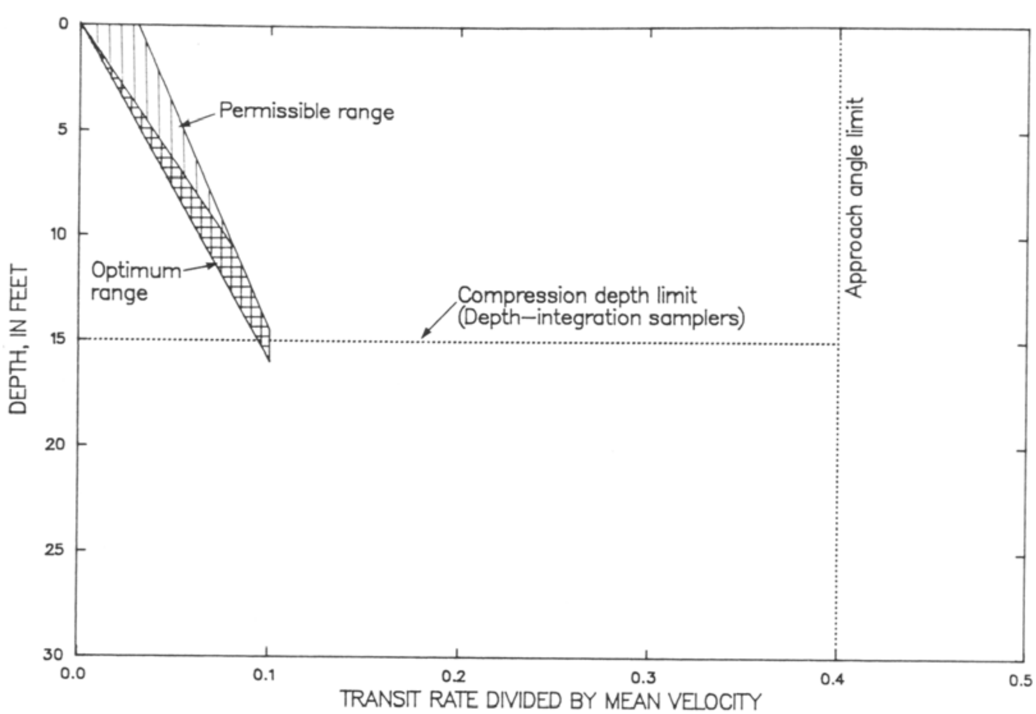


Figure 45.—Transit rate determination for 1/8-inch nozzle and quart bottle

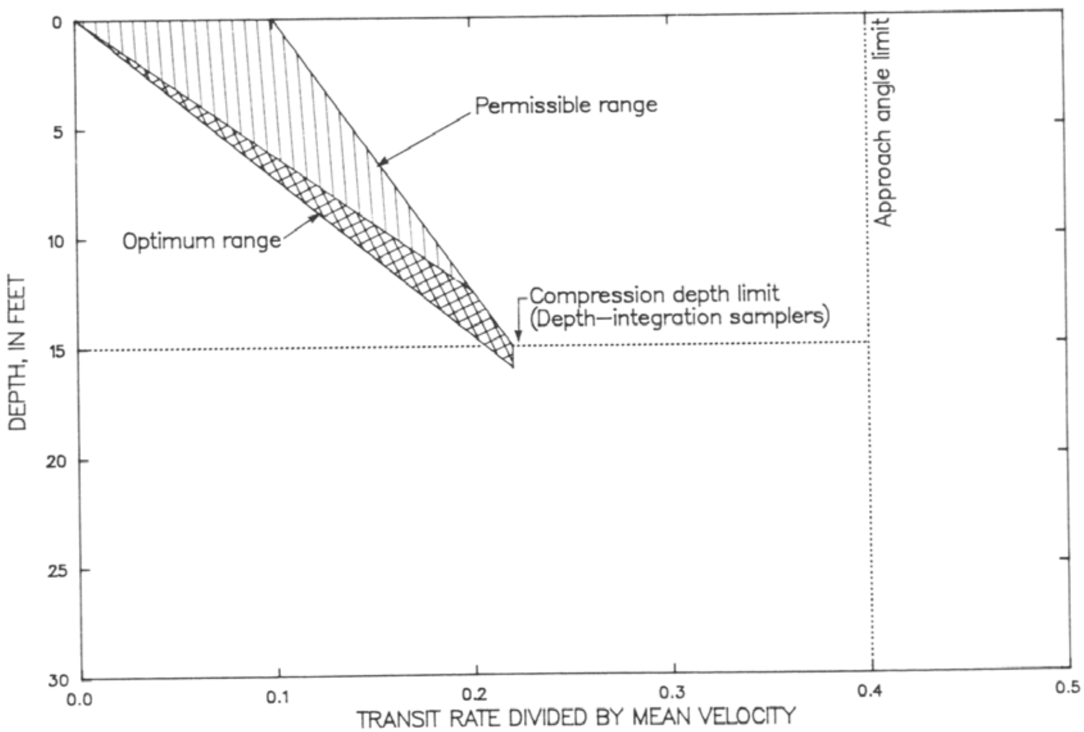


Figure 46.—Transit rate determination for 3/16-inch nozzle and quart bottle

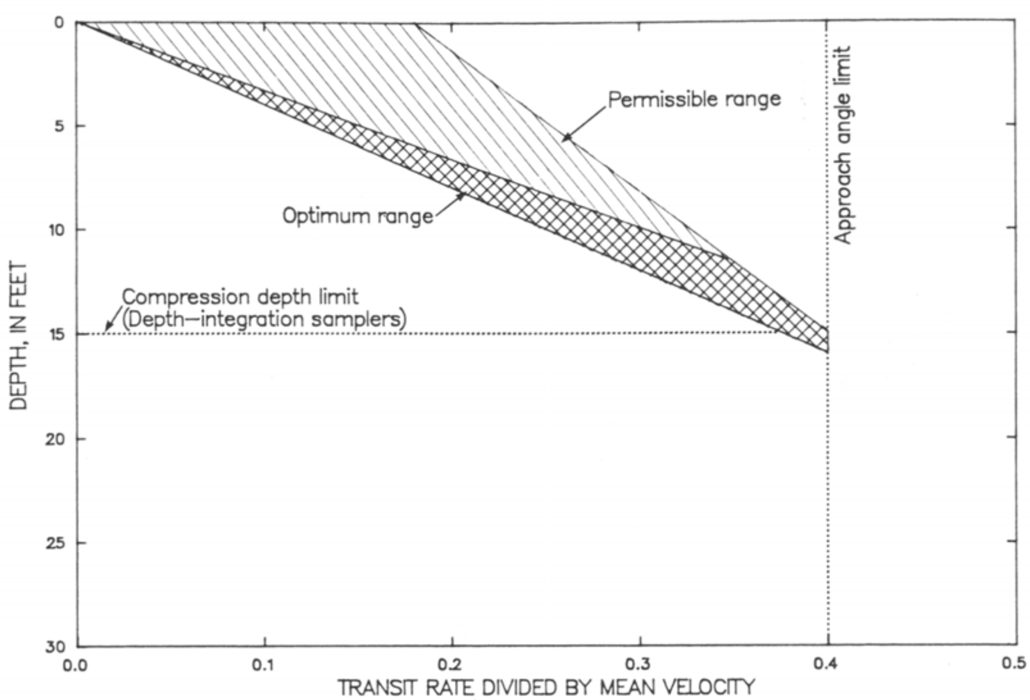


Figure 47.—Transit rate determination for ¼-inch nozzle and quart bottle

Bed Material Sampling Methods

Bed-material samples are collected and a variety of data can be extracted from the samples. Among these types of data are: particle-size distribution, bulk density of a sample volume, particle lithology and mineralogy, particle density, particle dimensions (form, roundness, sphericity), sediment chemistry, etc. The types of bed-material samples collected are:

- Surface sample
- Sub-surface sample
- Bulk sample

The type of bed–material sample to be collected depends on the type of data to be extracted (as listed above), the field conditions (samples collected under water, above the water line, etc), particles sizes in the bed, and the resources of the project (funds, personnel, and equipment).

When using a mechanical sampler, bed-material samples are collected at verticals selected in the same way as suspended-sediment samples, EWI or EDI methods. These methods are explained in Suspended-Sediment Sampling Methods section. At the present time, no mechanical bed-material sampler is adequate to obtain a representative sample of coarse gravel-sized material in water that is too deep to wade.

If particle size is of interest, for those sites above the water line, particle counts can be conducted. A template of some type has be used to guide selection of various particles at 100 sites within the sample area. A tape measure is used to determine the secondary axis size. When all 100 particles have been measured, a particle size distribution can be determined.

To collect subsurface samples, the most common method of collection is using a shovel at locations above the water line. Other methods require specialized equipment such as a drill rig (split spoon samples) or pipe coring rig.

Bedload Sampling Methods

There are many different opinions on how to properly sample for bedload, as this subject has been debated for many years. Edwards and Glysson (1988, pp91-107) discuss some of the methods that have been used over the years. The Single Equal Width Increment (SEWI) method is outlined as an example as follows:

1. Divide the cross section by 20 which equals b
2. The first sample is taken at b/2 from the streambank, the second sample is collected at b/2+b, etc.
3. At each vertical, lower the sampler to the bottom and allow the sampler to stay on the bottom for a set length of time
4. Each vertical should have the sampler on the bottom for the same length of time.
5. The sample collected at each vertical should be weighed

To calculate the bedload transport rate at a vertical, the following process should be used:

$$R_i = \frac{KM_i}{t_i}$$

Where R_i = bedload transport rate, as measured by the bedload sampler at vertical i, in tons per day per foot;

M_i = mass of sample collected at vertical i, in grams;

t_i = time the sampler was on the bottom at vertical i, in seconds;and

K = a conversion factor used to convert both the sampler width and the metric units into a unit of tons per day per foot. It is computed as:

$$K = \left(86{,}400\,\frac{\sec}{day}\right)\left(\frac{tons}{907{,}200\,grams}\right)\left(\frac{12\,inches}{NozzleWidth}\right)$$

For a 3-inch nozzle width, K = 0.381.

Bedload transport for the total cross section could be made using one of three methods: total cross-section, midsection, or the mean-section method. These methods are explained in Edwards and Glysson (1988, pp 103-106). The total cross-section method assumes that (1) sample times at each vertical are equal, (2) verticals were evenly spaced across the cross section, and (3) the first sample was collected at one-half the sample width. The total cross-section method is given below:

$$Q_b = K \frac{W_T}{T} M_T$$

Where Q_b = bedload discharge, as measured by the bedload sampler, in tons per day;

W_T = total width of the stream, in feet;

T = total time the sampler was on the bed, in seconds;

M_T = total mass of sample collected from all verticals; and

K = conversion factor as defined in preceeding discussion, for nozzle 3-inch width, K = 0.381.

Sediment Records Computation

Daily Estimates of Suspended-Sediment Transport

By sampling for suspended-sediment often enough to determine a continuous sediment-concentration hydrograph (figure 48), a daily record of suspended-sediment load calculated. In addition, the continuous water-discharge hydrograph must also be known. For each time interval, the time series data from both of these concurrent data sets are multiplied together and then by the time interval (a units conversion coefficient of 0.0027 is also used to have the units of tons per day). The daily suspended-sediment load is then estimated as the sum of all the incremental loads throughout the 24 hour period.

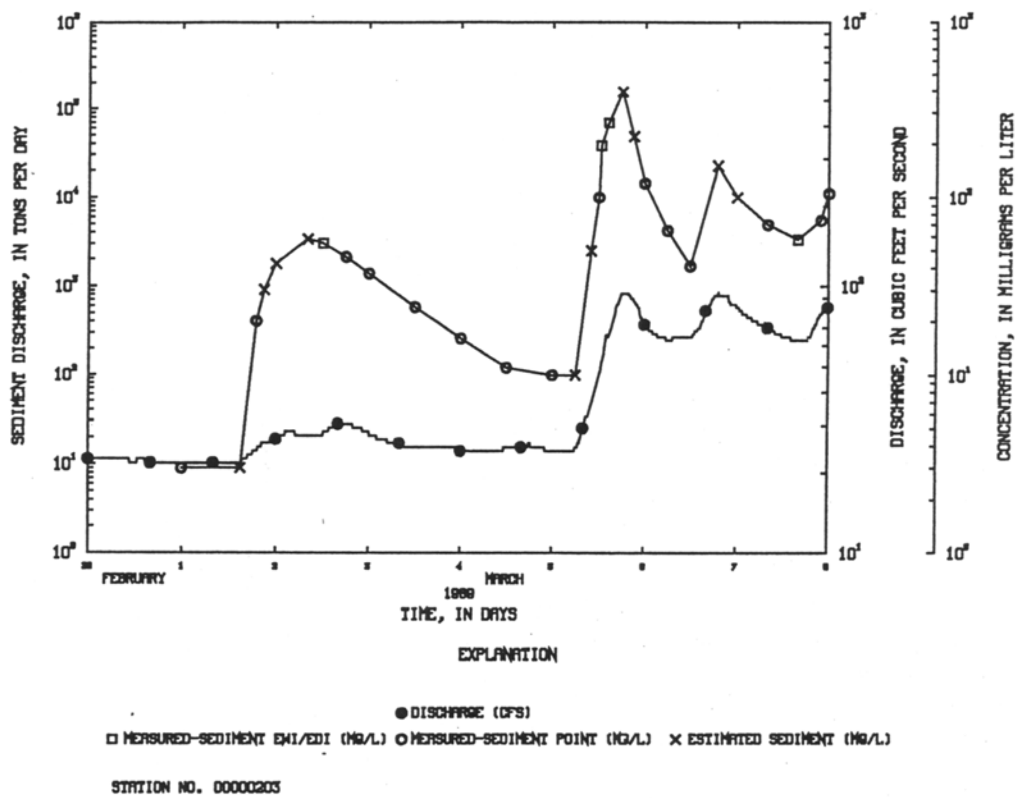


Figure 48.—Sample time series plot of sediment concentration and water discharge

Bedload Transport Computation

Bedload is usually not computed on a daily basis, but rather estimated for periods longer than a day. This is because of the necessity to use a bedload transport relation based either on bedload samples collected over various hydraulic conditions or theoretical equations to compute the bedload based on other hydraulic and geometric parameters. Figure 49 shows as the relations of bedload and discharge for various theoretical estimates of bedload for various locations on the Mississippi and Missouri Rivers

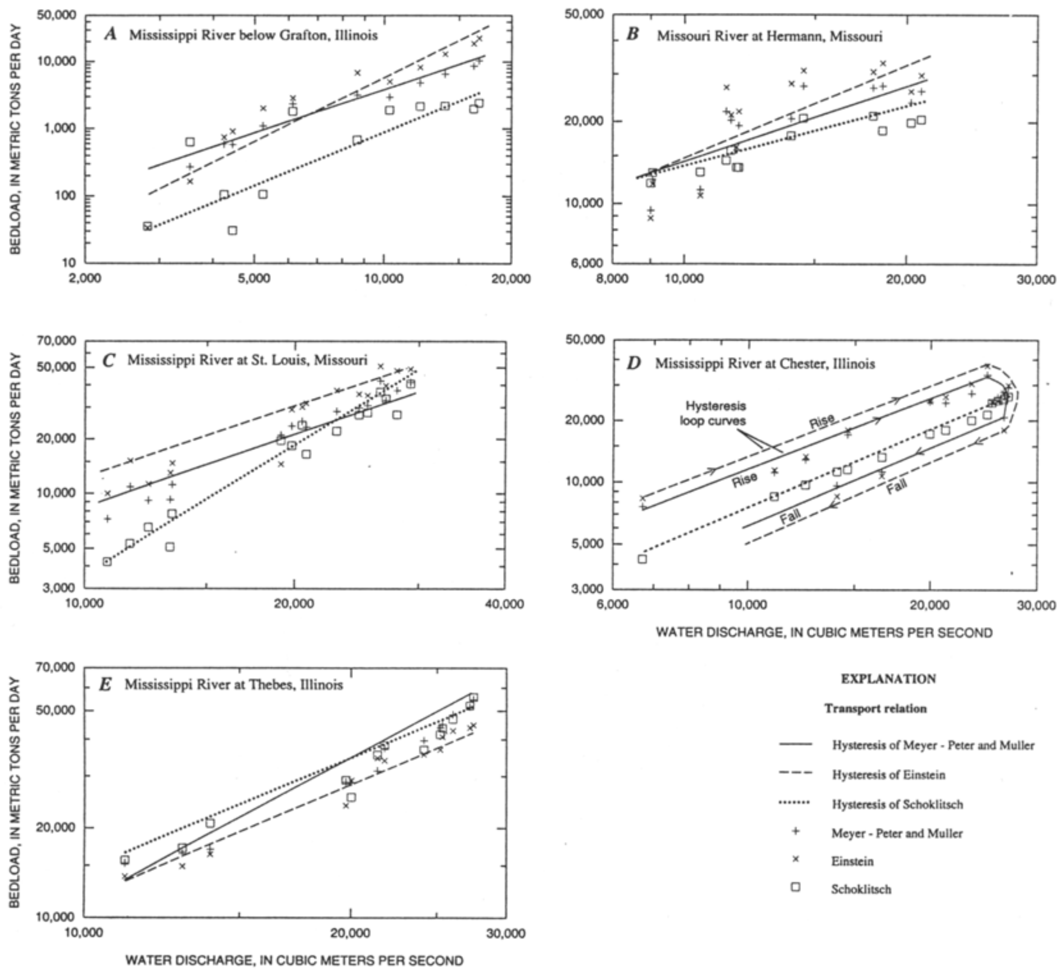


Figure 49.—Theoretical bedload transport relations computed for the 1993 flood at various locations on the Mississippi and Missouri Rivers (Holmes, 1996)

Periodic Estimates of Suspended-Sediment Transport

When a continuous hydrograph of sediment concentration is not known, but enough samples of suspended-sediment have been taken at enough variation of hydraulic conditions, an estimate of sediment load for periods larger than a day can be made. This is accomplished by constructing a suspended-sediment transport curve. (Figure 50-52) When the water discharge is known, an estimate of suspended-sediment transport can be made for that time period. The estimates from this method increases in accuracy the longer the period of estimation. For example, a monthly estimate of suspended-sediment load is more accurate than a weekly estimate and a yearly estimate is more accurate than a monthly estimate. This is because the errors tend to average out.

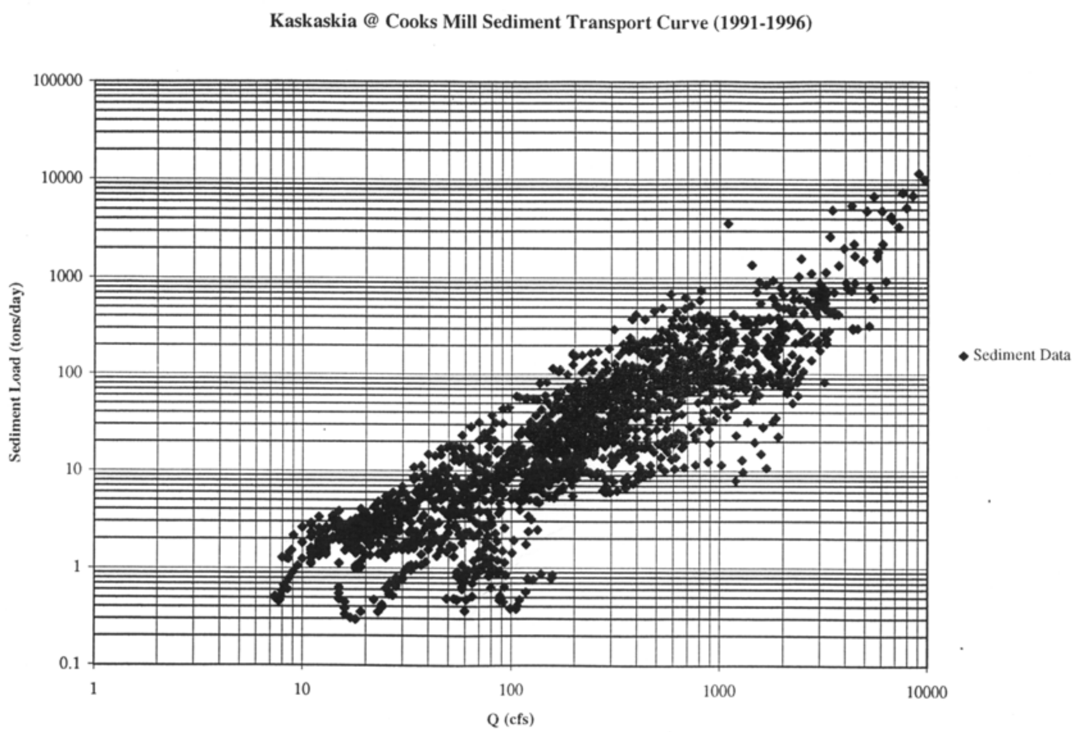


Figure 50.—Plot of sediment load versus water discharge for the Kaskaskia River at Cooks Mills, Illinois

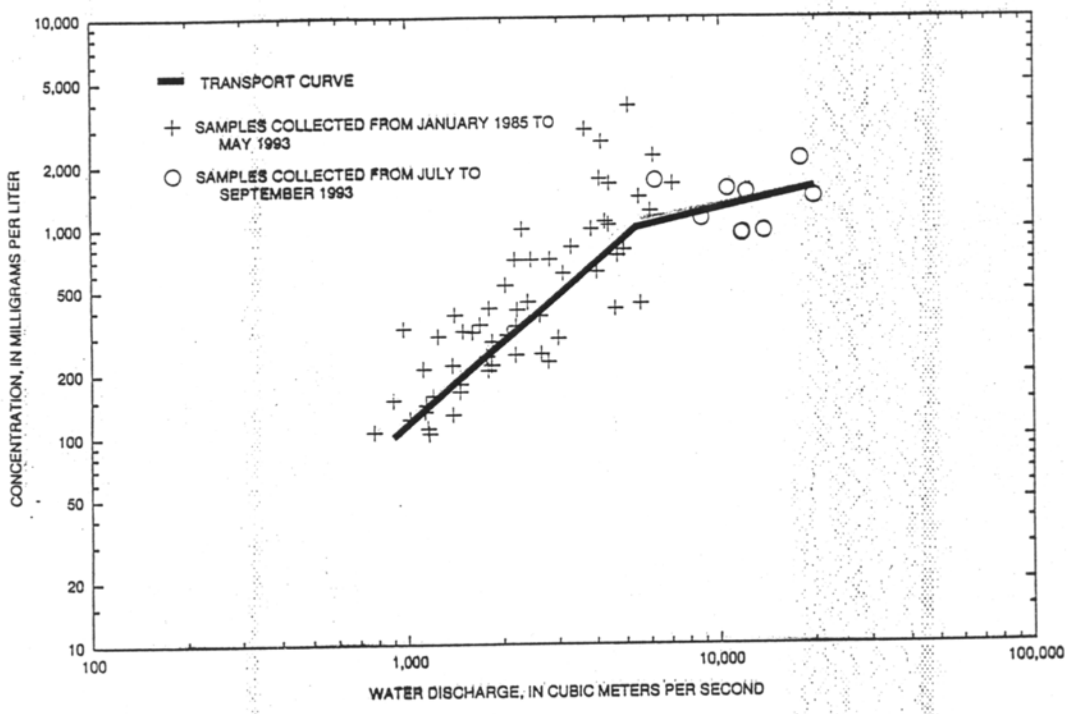


Figure 51.—Discontinuous sediment transport relation used for the Missouri River at Hermann, Missouri for the 1993 flood (Holmes, 1996)

Bibliography

Benson, M.A., and Dalrymple, Tate, 1967, General field and office procedures for indirect discharge measurements: USGS—TWRI Book 3, Chapter A1, 30 p.

Bodhaine, G.L., 1968, Measurement of peak discharge at culverts by indirect methods: USGS—TWRI Book 3, Chapter A3, 60 p.

Buchanan, T.J., and Somers, W.P., 1968, Stage measurement at gaging stations: USGS—TWRI Book 3, Chapter A7, 28 p.

Buchanan, T.J., and Somers, W.P., 1969, Discharge measurements at gaging stations: USGS—TWRI Book 3, Chapter A8, 65 p.

Carter, R.W., and Davidian, Jacob, 1968, General procedure for gaging streams: USGS—TWRI Book 3, Chapter A6, 13 p.

Chow, V.T., 1959, Open channel hydraulics, 680 p.

Dalrymple, Tate, and Benson, M.A., 1967, Measurement of peak discharge by the slope-area method: USGS—TWRI Book 3, Chapter A2, 12 p.

Davidian, Jacob, 1984, Computation of water-surface profiles in open channels: USGS—TWRI Book 3, Chapter A15, 48 p.

Graf, W.H., 1971, Hydraulics of sediment transport: McGraw-Hill, New York, 513 p.

Guy, H.P., 1970, Fluvial sediment concepts: USGS—TWRI Book 3, Chapter C1, 55 p.

Guy, H.P., and Norman, V.W., 1970, Field methods for measurement of fluvial sediment: USGS—TWRI Book 3, Chapter C2, 59 p.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: USGS—TWRI Book 5, Chapter C1, 58 p.

Henderson, F.M., 1966, Open channel flow, 522 p.

Holmes, Jr., R.R., 1996, Sediment transport in the lower Missouri and the central Mississippi River: USGS—Circular 1120-I, 23 p.

Hulsing, Harry, 1967, Measurement of peak discharge at dams by indirect methods: USGS—TWRI Book 3, Chapter A5, 29 p.

Jobson, H.F., and Froehlich, D.C., 1988, Basic hydraulic principles of open-channel flow: USGS—Open File Report 88-707, 150 p.

Kennedy, E.J., 1984, Discharge ratings at gaging stations: USGS—TWRI Book 3, Chapter A10, 59 p.

Kennedy, E.J., 1983, Computation of continuous records of streamflow: USGS—TWRI Book 3, Chapter A13, 53 p.

Kennedy, E.J., 1990, Levels at streamflow gaging stations: USGS—TWRI Book 3, Chapter A19, 31 p.

Kilpatrick, F.A., and Wilson, J.F., Jr., 1989, Measurement of time of travel in streams by dye tracing: USGS—TWRI Book 3, Chapter A9, 27 p.

Kilpatrick, F.A., and Schneider, V.R., 1983, Use of flumes in measuring discharge: USGS—TWRI Book 3, Chapter A14, 46 p.

Kilpatrick, F.A., and Cobb, E.D., 1985, Measurement of discharge using tracers: USGS—TWRI Book 3, Chapter A16, 52 p.

Koltun, G.F., Gray, J.R., and McElhone, T.J., 1994, User's manual for SEDCALC, a computer program for computation of suspended-sediment discharge: USGS Open File Report 94-459, 46 p.

Laenen, Antonius, 1985, Acoustic velocity meter systems: USGS—TWRI Book 3, Chapter A17, 38 p.

Latkovich, V.J. and Leavesley, G.H., 1993, Automated Data Acquisition and Transmission, Chapter 25, in Handbook of Hydrology, 1993, D.R. Maidment, Editor, McGraw Hill

Maidment, D.F., 1993, Handbook of hydrology: McGraw Hill, New York

Matthai, H.F., 1967, Measurement of peak discharge at width contractions by indirect methods: USGS—TWRI Book 3, Chapter A4, 44 p.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: USGS—TWRI Book 3, Chapter C3, 66 p.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: USGS—Water Supply Paper 2175, V. 1, 2

Riggs, H.C., 1973, Regional analyses of streamflow characteristics: USGS—TWRI Book 4, Chapter B3, 15 p.

Smoot, G.F., and Novak, C.E., 1969, Measurement of discharge by the moving-boat method: USGS—TWRI Book 3, Chapter A11, 22 p.

Smoot, G.F., and Novak, C.E., Calibration and maintenance of vertical-axis type current meters: USGS—TWRI Book 8, Chapter B2, 15 p.

Vanoni, V.A., 1975, Sedimentation Engineering: ASCE Manual and Report on Engineering Practice Number 54, New York, 745 p.

Wagner, C. Russel, 1995, Stream-gaging cableways: USGS—TWRI Book 3, Chapter A21, 56 p.

Wilson, J.F., Jr., Cobb, E.D., and Kilpatrick, F.A., 1986, Fluorometric procedures for dye tracing: USGS—TWRI Book 3, Chapter A12, 34 p.