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CHAPTER 3

Discharge Measurements and Streamflow Analysis

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I. INTRODUCTION

The most important of all the geologic processes is the force applied to land forms by running water. In the same manner, running water can have a significant effect upon the distribution of the flora and fauna in lotic ecosystems (Statzner *et al.* 1988, Gordon *et al.* 1992). The most fundamental of hydrological measurements that characterize all river and stream ecosystems is that of *discharge,* the volume of water flowing through a cross section of a stream channel per unit time. The amount of water flowing past a given point, when combined with the slope of the stream channel, yields an indication of *stream power* or the ability of the river to do work. This potential energy is dissipated as frictional heat loss on the streambed and when the stream picks up and moves material. The work performed by the stream is important to lotic ecologists because it influences the distribution of suspended sediment, bed material, particulate organic matter, and other nutrients. The distribution of these materials has substantial influence on the distribution of riverine biota (Vannote *et al.* 1980, Vannote and Minshall 1984, Statzner *et al.* 1988). In addition, discharge and stream power combine with other basin conditions to influence meander pattern and floodplain dynamics (Leopold *et al.* 1964).

Traditionally, discharge has been measured in the United States in terms of cubic feet per seconds (cfs), but, with a greater emphasis on employing SI units, most ecologists prefer to express discharge as cubic meters per second (m^3/s) (sometimes called "cumecs"). Because so much of the hydrological information in the United States is maintained by the United States Geological Survey (USGS), stream ecologists and hydrologists must be familiar with translating gaging records. This conversion can be expressed as 1 cfs = 0.0038 m^3/s (cumecs) and 1 m^3/s = 35.315 cfs.

At most gaging stations, flow is measured by recording the *stage,* or height, of the surface of the water above an arbitrary datum (or benchmark). Discharge can be calculated for different cross sections or at the same cross section at different velocities and water surface elevations (or stages). A graphical relationship (Fig. 3.1) between stage and discharge produces a rating curve so that discharges can be predicted at stages other than those measured. Often a simple *staff gage,* a piece of metal rod with measured increments representing measures of stage heights, is used at each sampling site so that stream ecologists can quickly note discharge at any observation time. Note that hydrologists often refer to "the stage at zero flow." This is not the period when the channel is dry, but rather it is the stage or water surface elevation at which the effective discharge measured across a given transect is 0.

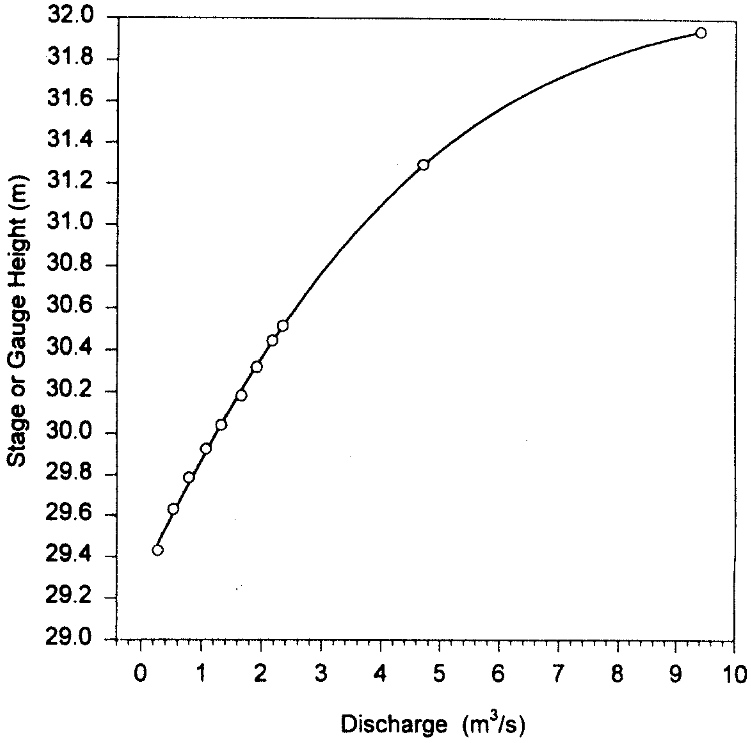

FIGURE 3.1 Stage–discharge relationship for the Olifants River (near Hexrivier Farm, Eastern Cape Province, Republic of South Africa). Based upon surveyed water surface elevations (gage height) and discharge calculated using a current meter.

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An analysis of the manner in which discharge varies over time, or the *hydrograph,* allows a lotic scientist to examine the characteristics of the watershed that influence such conditions as runoff and storage. A hydrograph (Fig. 3.2) can be plotted from gaging records to display yearly, monthly, daily, or instantaneous discharges. Ecologists usually obtain gaging records from Water Supply papers published annually by the Water Resources Division of the USGS. These data can provide information on total flow (monthly and daily), mean monthly discharge, base (often groundwater maintained) flow, stage height, and periods of high and low flow.

Examination of the shape of a daily hydrograph during a storm event

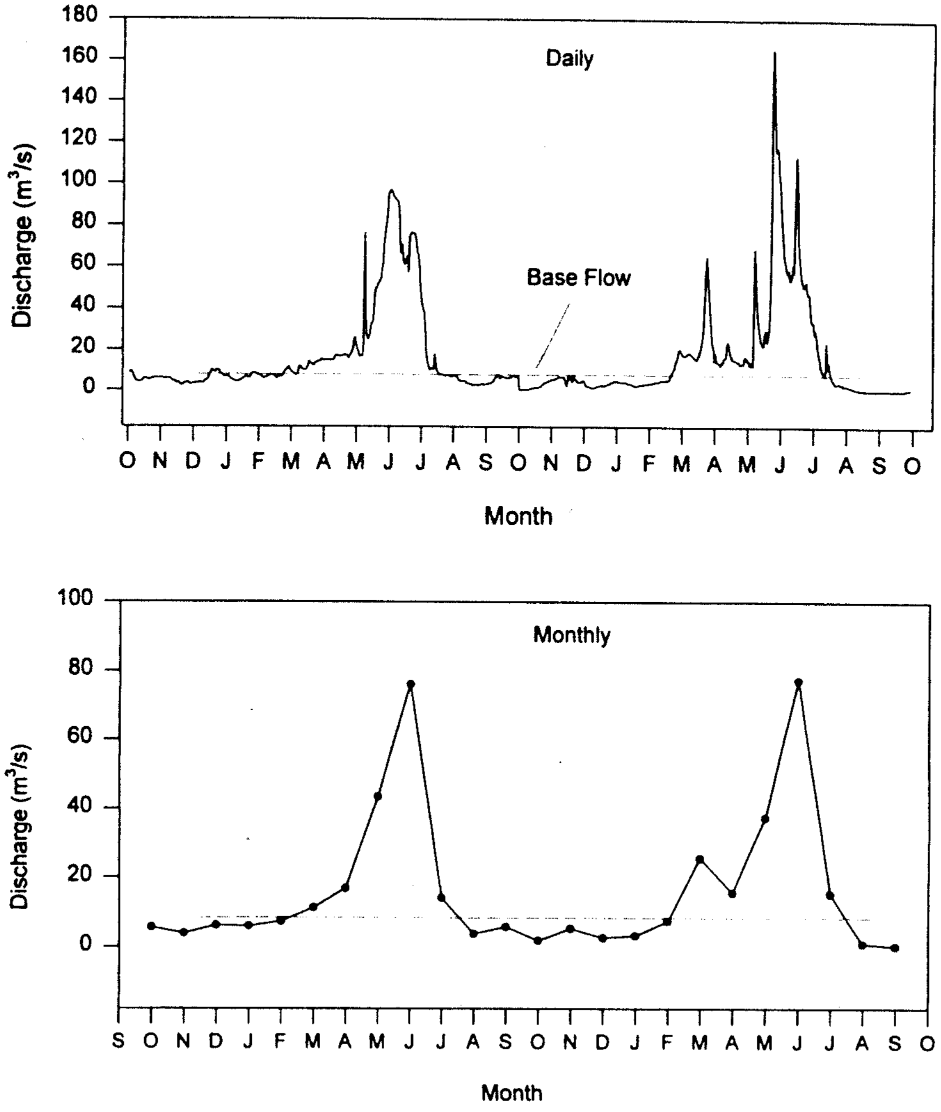

FIGURE 3.2 Hydrographs of the Tongue River (near Miles City, Montana) for water years 1965 and 1966.

can indicate the condition of the stream and its basin. The rising limb of the curve is usually concave and is an index of infiltration capacity of the catchment. In a small basin, the time from the onset of precipitation to the rise in the ascending limb of the hydrograph curve represents the time to reach soil saturation. A catchment with a large storage capacity, absorptive surface, or large channel will have a lower stage-height peak than a similar size basin with little storage (e.g., small channel, lower vegetation density, more clay in soils, greater human development, etc.). Agricultural land, for example, produces a more rapid response in the hydrograph than woodlands (Gregory and Walling 1973) because densely wooded areas restrict surface flow and enhance infiltration. The shape of the hydrograph also reflects the longitudinal profile and basin shape. A steep basin gradient is reflected in a rapid response curve, whereas a low basin gradient will produce a hydrograph with a slow and prolonged response curve. A catchment with many headwater streams but few tributaries in lower reaches will produce a hydrograph with a sharp flood peak. However, the peak is delayed from the onset of the precipitation event. An elongated catchment with many tributaries has a hydrograph that rises rapidly and falls over a longer period of time. A catchment with many subbasins often produces a hydrograph with several flood peaks depending upon distribution of rainfall in the area.

The discharge of a stream or river is also affected by conditions within the channel and the channel geometry. The location of the deepest part of the channel, the *thalweg,* is influenced by the shape of the banks, the width of the stream, the bed material, and the rate of deposition of sediment. In general, the highest stream velocities occur at or near the thalweg (see Chapter 4) and are a function of resistance to flow, usually as a result of the streambed material (i.e., *bed roughness*). The *wetted perimeter* is the cross-sectional distance along the streambed and banks where they contact water. Wetted perimeter can be the same for a deep, high-banked, narrow mountain stream and a broad, shallow lowland river, yet the same discharge through those channels will yield very different flow conditions (Lane 1937, Chow 1959). The *hydraulic radius* of the stream is the ratio of cross-sectional area to the wetted perimeter. The *hydraulic depth* is the ratio of cross-sectional area to the width of the river at the surface. In streams which are very wide in relation to their depth (e.g., greater than 20:1, width:depth), hydraulic radius and hydraulic depth are nearly equal and are approximated by the average depth of the stream. Most hydrologists and stream ecologists thus use the terms mean depth, hydraulic depth, and sometimes hydraulic radius interchangeably.

Streamflow data can also be used to produce flow-duration graphs and flood-frequency predictions. A *flow-duration curve* is a semilogarithmic plot

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of discharge versus the percentage of the time that a given discharge is equaled or exceeded. If the curve has an overall steep slope, the catchment has a large amount of direct runoff. If the curve is relatively flat, there is substantial storage within the catchment, either as surface or groundwater (Morisawa 1968). A frequent application of discharge records is to predict the magnitude and frequency of flood events. The *flood-frequency curve* allows hydrologists to assess the probability of a certain size of flood or greater occurring in any year. By convention, maximum discharges for each year of gaging record are ranked and plotted as a cumulative frequency curve (Fig. 3.3). A recurrence interval (the number of years within which a flood of a given magnitude or greater is likely to occur) may be calculated as an alternative way of expressing the flood frequency.

Another useful representation of flows may be obtained by plotting the cumulative discharge versus time. This allows the actual sequence and persistence of flows from month to month or year to year to be assessed.

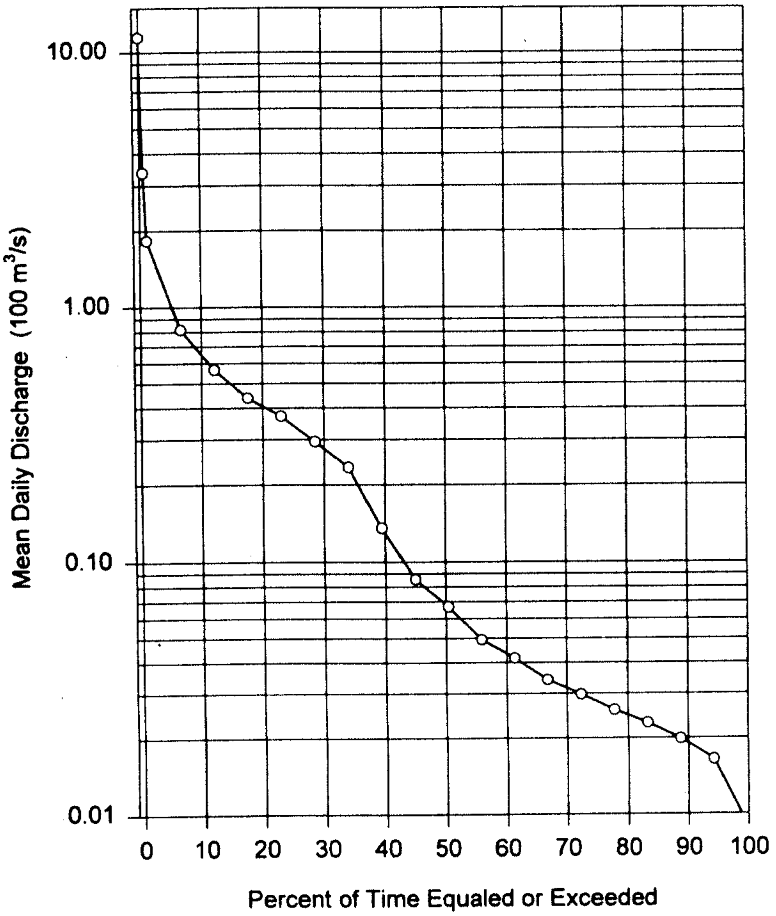

FIGURE 3.3 Flow duration curve for the Locust Fork River, at the USGS gaging station near Trafford, Alabama, for water year 1951.

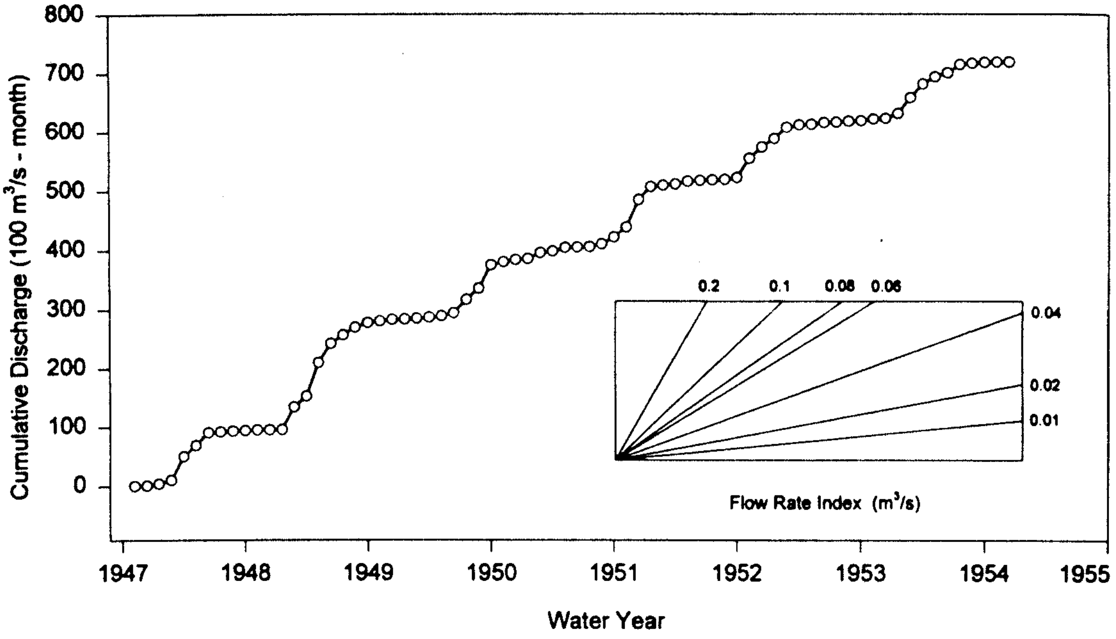

FIGURE 3.4 Discharge mass curve for the Locust Fork River, at the USGS gaging station near Trafford, Alabama, for water years 1947 through 1954.

The shape of the flow line in this form of plot (a mass curve) is equal to a rate of flow (Fig. 3.4).

In this chapter, several field methods to measure discharge are presented along with analytical techniques to produce and examine hydrographs. Some methods are appropriate only for low-order streams, but most can be adapted for larger order systems. The specific objectives are to: (1) understand methods used to pick a specific site for discharge measurement, (2) familiarize lotic researchers with the proper techniques for using current meters, calculating velocities and discharges, and producing and analyzing hydrographs, and (3) provide a better understanding of the use of discharge analysis to interpret channel form, basin shape, land-use patterns, flood conditions, and the distribution of biota in the river system.

II. GENERAL DESIGN

Discharge is usually determined by multiplying the mean velocity by the cross-sectional area of the flow. The cross-sectional area can be measured directly by stretching a measuring tape across the stream or river[1] and taking several measurements of depth with a meter stick or surveyor's stadia rod or staff. Several measurements of mean velocity must be taken

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[1] This is modified in large rivers by using premeasured cables or surveying techniques.

across the stream, because flow is unevenly distributed across the stream channel. However, if the flow is very irregular, say on a meander bend or where undercut banks and boulders obstruct or alter flow, the entire velocity distribution must be measured and plotted to determine a mean. In general, stream ecologists and hydrologists try to avoid these situations because of the relative difficulty in obtaining accurate measures at these sites. Between entering tributaries, discharge should be fairly constant, but may vary with gains or losses to the stream channel.[2] Likewise, measures of true discharge may vary according to the sensitivities of the equipment and abilities of the researchers. A useful tactic is to measure the discharge across several transects in a stream reach and compare calculated flows.

A. Site Selection

The selection of the site for measurement of discharge is a critical consideration. In general, the best sites are those in which the flow appears to be relatively uniform across the width of the channel and the surface is not broken by protruding objects, which tend to alter local velocity and depth measurements. The selected section should then have uniform flow that is parallel to the banks. In small streams or those streams with very low discharge (usually with nonparallel or sinuous flow patterns), a small straight section of channel (essentially, a small weir) can be built up using large stones between which the majority of flow passes. This system can be used to measure discharge, but cannot be used to describe the pattern of flow; that is, measurements from this artificial section should not be reported as typical mean depths and velocities.

In general, volumetric analysis (Exercise 1) is most appropriate for low-order streams (first- and second-order). The velocity–area method (Exercise 2) is appropriate for any stream order, but works best on third-order and higher systems. Under unusual flow conditions (extremely shallow, low flows or bankfull or over-bank floods), the slope–area method (Exercise 3) is most useful in estimating discharge. Analysis of discharge patterns over a long period of time is best accomplished in the field by establishing a stage–discharge relationship (Exercise 4) and through graphical and mathematical analysis of published gaging records (Exercise 5).

B. Discharge, Cross-Sectional Area, and Velocity

The simplest form of discharge measurement is

$$Q = A \cdot v, \qquad (3.1)$$

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[2] Particularly in alluvial, gravel-bed streams, a significant amount of water may be lost to or gained from the hyporheic zone along an unconfined stream reach (see Chapters 6 and 30).

where Q represents discharge (in cfs or cumecs); A, cross-sectional area of the channel at a certain transect; and v, the mean water-column velocity at a designated transect.

To measure discharge (Q), stretch a measuring tape across the stream and then divide the transect into convenient increments, or *cells*. If the flow is relatively uniform, the transect should be divided up into at least five cells of equal width. As a general rule, however, cell widths should not exceed 3 m. A stream of 30 m width, then, should have at least 10 cells to be measured. It is not necessary to make uniform width cells. If there are any hydraulic irregularities (a protruding boulder, a cascade, a pool, etc.) across the transect, a new cell should be designated at the point where the irregularity begins and a new cell designated where more uniform conditions resume. If flow is uniform, the mean velocity is measured in the middle of each cell at a height of 0.4 times the depth at that location (see Chapter 4 for the reasoning behind this choice). At a cell where the depth exceeds 60 cm, the mean velocity should be calculated as an average between velocities measured at 0.2 and 0.8 times the depth at that point.

There are a variety of velocity meters available and all are acceptable. Each requires its own special technique for use. In general, most hydrologists prefer either the (Gurley) pygmy or (Price AA) regular horizontal bucket impeller types. However, horizontal screw (Ott) or electromagnetic (Marsh–McBurney) meters are equally useful but usually require more frequent calibration and servicing.

The current meter is attached to a wading rod made of stainless steel that is marked in increments of 0.1 m or 0.1 ft. Depending upon construction, some will automatically set the current meter at the appropriate depth, using a Vernier scale, or quick field calculations must be made. In large rivers, a winch and cable in conjunction with a sonde replaces the wading rod. The winch is attached to a boat which is tethered to a cable stretched across the river at the site of the transect or attached to a "bridge board" that is suspended on a bridge over the river. The current meter is attached to the end of the cable. The winch, which usually has a depth meter attached, is calibrated to a zero point when the current meter is at the surface of the river. When using the cable and sonde, a finned weight (up to 50 kg) is attached below the current meter to maintain orientation in the current and to keep the cable vertical in each cell.

When using a mechanical current meter, a set of earphones is employed to "count clicks" produced by each revolution of the current meter. The count should last for at least 30 s and the exact number of revolutions and the time counted should be recorded for each cell. Many newer instruments have automatic timing devices and internal calculators that will provide a direct readout of the velocity. Usually some sort of rating curve is provided with each instrument to yield a velocity measured by each revolution.

The product of the width of the cell, the depth at the midpoint of the cell, and the mean velocity is calculated as the cell discharge. The sum of the cell discharges, then, is the discharge for the stream on that date at that stage height.

C. Incorporating Channel Resistance and Slope

For a variety of purposes, such as more sophisticated hydrological and ecological modeling, it may be necessary to incorporate changes in streambed roughness or changes in gradient as they affect discharge over the length of the stream. These conditions, especially roughness, can alter velocity significantly (see Chapter 4). As a result, equations that incorporate resistance to flow (*shear stress*) have been developed to get a more accurate picture of velocity along channel boundaries. Roughness is evaluated in a number of different ways, as described below. Energy slope (S) is calculated as the change in elevation over a given distance. In a stream with uniform flow, this can be taken as either the change in elevation of the water surface or the channel bottom. If the reach can be located on a topographical map, slope can be estimated in this manner. A far better, but more time consuming method is to take measures 30 m upstream and 30 m downstream of the transect using a stadia rod and a surveyor's level to estimate change in elevation over that short distance.

Chezy's Equation was developed in the 1700s and incorporates channel roughness (C) to estimate stream discharge. The equation is

$$V = C(RS)^{1/2}, \tag{3.2}$$

where R is the hydraulic radius (m) and S the energy slope (Henderson 1966). Chezy's C varies from approximately 30 for small, cobble-bottomed streams up to 90 for large, smooth sand-bottomed rivers (White 1986). Discharge is calculated as the product of cross-sectional area (A) and the calculated velocity (V) value (see Eq. (3.1)). The Chezy equation is used primarily in Europe. The details for calculating C are discussed by Chow (1959).

Manning's Equation is more commonly used for calculations of discharge where bed roughness is of great concern. It is expressed as

$$V = 1/n\,(R^{2/3}S^{1/2}) \tag{3.3}$$

or

$$Q = 1/n\,(AR^{2/3}S^{1/2}), \tag{3.4}$$

where n is an index of channel roughness known as "*Manning's n.*" The standard technique for approximating Manning's n is presented in Table 3.1. It should be noted that calculating discharge according to Manning's

TABLE 3.1
Calculation of *Manning's* "*n*" from Field Observation

Channel condition	Value
$n = (n_0 + n_1 + n_2 + n_3 + n_4)$ m	
Additive factors	
Material involved	n_0
Earth	0.020
Rock Cut	0.025
Fine Gravel	0.024
Coarse Gravel	0.028
Cobble	0.030–0.050
Boulder	0.040–0.070
Degree of irregularity	n_1
Smooth	0.000
Minor (slight scour)	0.015
Moderate (slumping)	0.010
Severe (eroded banks)	0.020
Variation in channel cross section (location of thalweg)	n_2
Gradual	0.000
Alternating occasionally	0.005
Alternating frequently	0.010–0.015
Effect of obstructions	n_3
Negligible	0.000
Minor (15% of area)	0.010–0.015
Appreciable (up to 50%)	0.020–0.030
Severe (>50% is turbulent)	0.040–0.060
Vegetation	n_4
None	0.000
Low (grass/weeds)	0.005–0.010
Medium (brush, none in streambed)	0.010–0.025
High (young trees)	0.025–0.050
Very high (brush in streams, full grown trees)	0.050–0.100
Multiplicative factors	
Degree of Meandering	m
Minor	1.000
Appreciable	1.150
Severe	1.300

Note. Adapted from Cowan (1956).

equation does not require direct measurement of average velocities, but instead depends upon reliable and consistent evaluations of the channel condition and an accurate measurement of the cross-sectional area, hydraulic radius, and slope.

D. Flow-Duration Curve

These curves can be prepared only if gaging records for a single location on a stream are available for a substantial period of time, usually several years. In the United States, gaging records can be obtained through local offices of the USGS. Otherwise, a gaging station or a staff gage that has been calibrated and read at regular intervals must be installed to generate the flow data.

To prepare the flow-duration curve, all flows during the given period (i.e., daily, monthly, or yearly, depending upon the analysis needed) are listed according to their magnitude. The percentage of time that each was equalled or exceeded is then calculated and plotted on a semilogarithmic plot (percentages on an arithmetic scale on the x-axis and the log of the discharge on the y-axis). Analysis of the shape of the curve provides an idea of basin or catchment characteristics. A manual of duration curve interpretations has been published by Searcy (1959).

Several duration indices have been used to compare various stream systems. For these purposes, the same period of record must be used for production of all flow duration curves. The discharge at which flows are exceeded 50% of the time is the median value, or Q_{50}. The Q_{90} is often used as a low-flow (or minimum flow) index. The ratio Q_{90}/Q_{50} is often used as an index of baseflow contribution (Gordon *et al.* 1992), whereas Q_{10}/Q_{50} may be used as an index of flood peaks. At the upper range of discharges, the values between Q_{30} and Q_{10} have been used to analyze the value and importance of the floodplain by the amount of time it is under water.

E. Flood-Frequency Analysis

The Weibull plotting method is the most commonly applied technique for analyzing flood conditions (Dalrymple 1967). To construct a recurrence curve, the average daily flows are most often examined. When producing a flood-frequency curve, the maximum discharge in a stream or river each year, or all discharges greater than a certain level (e.g., one that will flood a certain area, like a lowland pasture or structure, like a levee) irrespective of year, are used. Most commonly, the annual maximum discharge is used. The best flood-frequency analyses are produced by gaging records of long duration. In most cases, at least 20 years of record should be used to obtain reasonable predictions. Peak discharges are listed according to magnitude with the highest discharge first. Probability of exceedance, P, is calculated as

$$P = \left[\frac{m^*}{(n^* + 1)}\right] 100\%. \tag{3.5}$$

The recurrence interval, T (usually in years), is calculated as

$$T = \frac{n^* + 1}{m^*}, \qquad (3.6)$$

where n^* is the number of years of record and m^* the magnitude of the flood by its rank value ($m^* = 1$ at the highest discharge on record). Each flood discharge (y-axis) is plotted against its probability of exceedance or recurrence interval on probability paper. The points are joined to form a flood-frequency curve or exceedance curves (see Figs. 3.3 and 3.4). Even without having extremely long-term records, these sorts of curves are used to calculate the discharge for a 100-year event. In turn, that 100-year event discharge can then be compared to a rating curve for the stage–discharge relationship and an estimated height required for a levee or building to withstand that event can be estimated.

III. SPECIFIC EXERCISES

A. Exercise 1: Volummetric Analysis[3]

This exercise works well for only the lowest discharge conditions or for low-order streams.

1. Choose a container of known volume or graduated with known volumes. It should be of at least 4 liters capacity (for stream orders greater than 2 or 3, a larger volume may be required).
2. Place the container under the outflow and begin recording the time it takes to fill the container to the known volume mark.[4] A stopwatch is best for the timing and should be started at the exact time the container is placed into the flow. Be sure that the volume is sufficient that it takes at least 3 s or longer to fill the container. A more accurate measurement would be to start the timing as the level passes a certain graduation and stop it when the level passes yet another.
3. Discharge is calculated as

$$Q = \forall / t, \qquad (3.7)$$

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[3] This is the most accurate technique but can be used only in places where the flow is concentrated, e.g., the notch of a permanent weir or the outflow of a pipe or a culvert under a bridge or highway.

[4] Another handy method is to use a heavy-gage plastic garbage bag that can be held down and open on the stream bed. The rate of fill is timed and the contents of the bag are poured into a measuring container.

where Q is the discharge in m^3/s (or liters/s); $\forall$, volume in m^3 (or liters); and t, time (s).

4. Several readings should be taken to obtain a mean and variance in the measure.

B. Exercise 2: Velocity–Area Method

1. Stretch a measuring tape across the stream and divide it into at least 10 intervals or cells. In any case no individual interval or cell should exceed 3 m. Record the width (m) of each cell.
2. At the center point of each cell, measure the depth (m) and record.

Option a: Float Method

3. Measure a length of stream equal to at least 20 m to assure a travel time of at least 20 s. This is the designated reach length, L. This section should overlap one of the sections being measured for cross-sectional area. Mark the upper and lower ends of this interval with a stake or a string across the stream.
4. Choose a float that is only slightly buoyant. This will allow the object to flow with the velocity and minimize influence from air currents. An orange (peeled oranges float lower in the water), a chunk of ice, a half-filled fishing float or bobber, or water-logged branch are ideal.
5. Introduce the float a slight distance upstream of the upstream mark so that the float can reach the speed of the water before it passes the first mark. In large rivers (>10 m width), divide the stream into thirds and make several passes with the float in each third to obtain an average velocity.
6. Use a stopwatch to measure the time (t) of travel of the float between the upstream and downstream marks. Record several measurements through each section to obtain an average. Surface velocity (V_s) is calculated as

$$V_s = L/t. \tag{3.8}$$

A correction factor, k, for the roughness of the bed that affects the slope of the velocity profile must be applied to get an estimate of the mean velocity, V:

$$V = kV_s. \tag{3.9}$$

The correction factor varies between 0.8 for rough beds to 0.9 for smooth beds, but 0.85 is most commonly used unless a singularly rough or smooth bed is being measured. Go to step 7 below.

Option b: Current Meter Method

1. At each section midpoint, place the current meter into the stream, with the meter facing into the current and the researcher standing downstream of the measuring device. Make sure that eddies around legs do not disturb the activity of the current meter.

2. If depth (D) is less than 60 cm, read the velocity at $0.4 \times D$, measured upward from the streambed. If depth is greater than 60 cm, read and record velocities for $0.2 \times D$ and $0.8 \times D$. The mean velocity is the average of the two readings.

3. If the water column for the cell being measured contains large submerged objects (logs, boulders, etc.) or is disturbed by overhanging vegetation, read and record velocities at $0.2D$, $0.4D$, and $0.8D$. Calculate mean velocity as

$$V = 0.25(V_{0.2} + V_{0.8} + 2V_{0.4}). \tag{3.10}$$

4. If velocities are extremely high or flood flows exist and it is difficult to place the current meter and wading rod (or sounding cable) into the water and maintain a vertical position, measure and record the velocity at the surface. Calculate mean velocity using Eq. (3.9), where k is usually 0.85.

5. Calculate and record the discharge for each cell (n) as

$$Q_n = w_n D_n V_n, \tag{3.11}$$

where w_n is the width of cell (m); D_n, depth of the cell at the midpoint (m); and V_n, mean velocity of the cell at the midpoint (m/s).

6. Discharge for the transect is calculated as

$$Q = \Sigma Q_n = w_1 D_1 V_1 + w_2 D_2 V_2 + \cdots + w_n D_n V_n. \tag{3.12}$$

C. Exercise 3: Slope–Area Method

This is an indirect method for estimating discharge when no gaging information is available. Most often this is used to estimate discharges at high flows such as bankfull flows or recent flood events. It can also be used when a current meter or float is not practical (e.g., low flows that barely cover the stream bed). However, it should be noted that the prediction of *Manning's* "n" is more difficult.

1. Choose a straight reach of stream where flows are uniform. The water slope and channel bed slope should be relatively parallel. The length of the study reach should be at least six times the mean channel width (the

average recurrence interval of pools and riffles). The important factor is that a pool and riffle pair be included for the best estimate of average slope.

2. Stretch a measuring tape across the stream and divide it into at least five cells. In any case, no cell should be wider than 3 m. Measure and record the width (m) of each cell.

3. At the center point of each cell, measure and record the depth (m).

4. Identify the water level of interest. This does not necessarily have to be the present water surface elevation. Levels such as bankfull or high-water marks (i.e., indicating the last flood) can be flagged with surveyor's tape or markers.

5. Surveys should be made for three or more typical cross sections in the reach. At each survey point, set up a surveyor's level able to swivel to see points at least 20 m upstream and downstream of the transect. In some instances this may be a clear position along the bank or a position on a mid-channel bar. Using a surveyor's level and rod, measure and record bed elevations and water surface elevations at points 20 m upstream and downstream of the transect (without moving the level). For bed elevations, the rod should be placed at or near a point equal to the average depth and close to the thalweg. For water surface elevations, the rod holder should just touch the water surface several times while elevations are recorded. The average of three or four of these readings will be acceptable as water surface elevations.

6. During a walking survey of the stream reach, estimate *Manning's "n"* according to values printed in Table 3.1 or Table 3.2. Strickler's (1923) estimate for deeper channels where depth of flow is at least three times greater than the median diameter (D_{50}) of streambed material projecting into the flow is calculated as

$$n = 0.04D_{50}^{1/6}. \qquad (3.13)$$

7. Calculate the cross-sectional area of each cell (A_n) as the product of cell width (w_n) and cell depth (D_n).

8. Total cross-sectional area (A) is calculated as

$$A = \Sigma A_n = A_1 + A_2 + \cdots + A_n. \qquad (3.14)$$

9. Calculate the mean depth as an average of the cell depths. For a wide shallow stream this approximate value may be used for the hydraulic radius (R); however, at bankfull and flood stages the calculated hydraulic radius should be used.

TABLE 3.2
Typical *Manning's* "*n*" Values for Low-Order, Natural Streams (bankfull stage <30 m)

Channel	Typical "*n*"
Lowland and Foothill Streams	
Clean, straight, no deep pools	0.030
Clean, straight, some cobble and weeds	0.035
Clean, winding, some pools and riffles	0.040
Clean, winding, pools, riffles, some cobble and weeds	0.045
Clean, winding, pools, riffles, many cobbles	0.050
Sluggish, deep, weedy pools	0.070
Weedy reach, deep pools, riparian with stands of timber and brush	0.100
Mountain Streams	
Streambed of gravel, cobble and a few boulders	0.040
Bed of medium and large cobble and boulders	0.050

Note. Adapted from Chow (1959).

10. The energy slope[5] of the stream (S) is calculated as the difference in water surface elevations (E, in meters) between the upstream point (E_{upstream}) and the downstream point ($E_{\text{downstream}}$) divided by the distance between the points (L, in meters):

$$S = \frac{(E_{\text{upstream}} - E_{\text{downstream}})}{L}. \tag{3.15}$$

11. Calculate discharge for that transect and water surface elevation as using Eq. (3.4).

D. Exercise 4: Stage–Discharge Method

This method requires many discharge measurements at a number of different water surface elevations. It is used to construct a gaging system (i.e., rating curve) for a particular sampling site that will be visited frequently and a rapid measure of discharge is required for each sampling visit.

1. Discharge measurements must be made for at least three different water surface elevations: low flow, median flow, and high flow.
2. The section that is measured should be accessible at all water surface

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[5] Except for purposes of examining local hydraulic conditions, bed slope is not appropriate as a substitution for power slope.

elevations and flows to be measured. Choose a straight reach of stream where flows are uniform. The water slope and channel bed slope should be relatively parallel.

3. At each flow, measure the discharge by the current meter method listed in Exercise 2, Option b.

4. Plot the dependent variable (i.e., discharge) on the x-axis and the independent variable (i.e., water surface elevation or stage) on the y-axis. The points are plotted on log–log graph paper. In most cases, this will plot the points as a straight line.

5. For most ecological studies, an approximation of the rating curve can be made by visually constructing a straight line through the points that were measured and plotted. In most instances, the line can be safely extended to a discharge 2.5 times higher than the highest discharge measured and to 0.4 times the lowest discharge measured (Bovee and Milhous 1978).

6. For a more accurate rating curve, the three flows can be fit to the equation

$$Q = a(h - z)^b, \tag{3.16}$$

where h represents gage height or water surface elevation; z, gage height at "zero flow"; and a and b are regression coefficients. The equation is fitted through simple regression techniques (see Haan 1977 or any other standard text on statistics). The regression equation is fitted with $(h - z)$ as the independent variable and Q as the dependent variable, despite the fact that the rating curve was plotted with the axes reversed. The value of z must be derived by trial and error. The true value of z is assumed to be that point at which the rating curve plots a straight line on the log–log paper. Thus, it is possible to visually estimate z by graphical extrapolation and "test" this value into the regression equation. If the z value is too small, the plotted equation will be concave downward. If the z value is too large, the plotted equation will be concave upward.

7. At the sampling site, place a staff gage into the stream. The staff gage consists of a rod[6] that has been painted a bright color for visibility and marked at appropriate intervals to match the rating curve. For example, markings can be every 0.1 m and a meter stick used to measure exact distances between major marks to get exact water surface elevation. The staff gage[7] should be placed well enough away from the bank so that the water surface will still wet the gage at the lowest flows. The staff rod should

[6] Reinforcing bar ("rebar") of 2.5 cm diameter works well.

[7] Commercial staff gages, already marked with appropriate intervals are also available (e.g., Ben Meadows Company, Forestry Suppliers).

extend 1 m or more below the marked section. Pound the rod into the substratum until the water surface covers the mark at the appropriate elevation for the discharge on the day the gage is installed.

8. During subsequent sampling trips, read the water surface elevation from the staff gage, compare to the derived rating curve, and record the corresponding discharge for the activities undertaken on that day.

E. Exercise 5: Hydrographs—Flood-Frequency, Flow-Duration, and Discharge-Mass

Option a: Flood-Frequency

1. Obtain a gaging record for the stream or river to be analyzed. Under optimum conditions, at least 20 years of record should be available. For predictions of a 100-year event, at least 100 years of record will provide an estimate with reasonable accuracy. Monthly or annual data are adequate for this analysis.

2. List annual peak discharges according to magnitude with the highest discharge first.

3. The recurrence interval (T) is calculated using Eq. (3.6). As an alternative, a less biased estimate of peak floods (Cunnane 1978) can be produced by calculating the recurrence interval as

$$T = \frac{[(n^* + 1) - 0.8]}{m^* - 0.4}. \tag{3.17}$$

The probability (P) that a given discharge will be exceeded (i.e., probability of exceedance) is calculated using Eq. (3.5), or as the reciprocal of T ($P = 1/T$).

4. Each flood discharge (y-axis) is plotted against its recurrence interval or probability of exceedance on log–probability paper. In theory the largest flood should plot at $P = 0$, as it will never be exceeded and the smallest at $P = 1$, since it will always be exceeded. In all situations, all of the values obtained from the calculations will plot between these two values because the numerator or denominator has been adjusted to be greater than the number of observations.

5. The points are joined to form the flood-frequency curve. In general, a curve fitted by eye can be used if the intention is to provide information on floods with a recurrence interval of less than $n^*/5$. When eye-fitting the straight line, greater emphasis should be placed on the middle and high discharge events since the primary purpose of the plot is to estimate high flow events. For recurrence intervals greater than $n^*/5$, where greater accuracy is required, a theoretical probability distribution should be fitted to

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the data to obtain more reasonable estimates. The standard method applied by the USGS is the *log Pearson Type III* distribution (see Haan 1977 for specific techniques).

Option b: Flow-Duration

1. Obtain a gaging record for the stream or river to be analyzed. Under optimum conditions, several years of record should be available. If annual duration curves are the objective, then at least 20 years of record are advisable. However, daily, weekly, or monthly data can also be used to examine flow duration over shorter intervals.

2. All flows during the given period (daily, monthly, yearly, etc.) are listed according to their magnitude.

3. The range of discharges should be partitioned into 20 to 30 intervals. For example, if the total range of discharges for daily records ranged from 10 to 300 m^3/s, the researcher might enter the intervals as 0–10, 11–20, 21–30, . . . , 291–300.

3. The percentage of time that each was equalled or exceeded is then calculated and plotted on a semilogarithmic plot; put percentages on an arithmetic scale on the x-axis and the log of the discharge on the y-axis.

4. A manual of duration curve interpretations has been published by Searcy (1959) and can be used to analyze specific situations in which dilutions for pollution or flow durations for irrigation, hydropower, or transport of particulates or sediment are necessary.

Option c: Discharge-Mass

1. Obtain a gaging record for the stream or river to be analyzed. Under optimum conditions, several years of record should be available. If annual duration curves are the objective, then at least 20 years of record are advisable. However, daily, weekly, or monthly data can also be used to examine duration over shorter intervals. Traditionally, monthly total discharge values are used.

2. Cumulative discharge values for each month are plotted against the time intervals involved (see Fig. 3.4).

3. A flow rate index based upon critical discharge values (e.g., discharges required for incubation of eggs, spawning, instar success, or year-class strength) are compared to the slopes of the mass curve to determine the percentage of time, historically, a certain flow rate has been sustained.

4. Newbury and Gaboury (1993) have described various biological applications of mass curve analysis and Chow (1964) has provided information on the use of mass curves for setting flows in reservoir design. Newbury and Gaboury suggest that mass curves can be used to establish minimum

flows and indicate the amount of time necessary to recharge a system if those flow are not met or are exceeded. These curves can also be used to estimate flows at ungaged sites and to estimate bankfull conditions.

IV. QUESTIONS

1. Consider each of the techniques for directly measuring discharge. Where is error introduced into the calculations?
2. When choosing a sample transect for discharge calculation, what precautions must be taken in order to ensure that the best estimates of mean depth and velocity are obtained?
3. What are the difficulties that can be encountered when attempting to describe the resistance of the channel to flow, (i.e. Manning's "*n*")?
4. In what ways can environmental scientists and engineers use flood-frequency and stage–discharge relationships to design levees and dams yet continue to promote ecological integrity?
5. What is the value of flow-duration curves to the management and analysis of floodplains?
6. How might weeks or days of flow persistence during a sensitive spawning or incubation period be estimated using a mass curve?
7. For a measured discharge, how much variation was there in the mean velocity between riffle and pool transects? How does this affect discharge estimates?
8. Compare the hydraulic radius and the mean depth for the sample reach at high and low discharges. How would these two values alter discharge predictions?
9. Examine your estimate of roughness, Manning's *n*. What were the major factors that influenced it at the discharge you analyzed? What values will dominate the estimate of Manning's *n* at higher or lower flows?

V. MATERIALS AND SUPPLIES

Discharge Measurements

4-Liter or larger bucket or wide-mouthed container
Calculator
Current meter with wading rod (any of the standard meters; Pygmy, Price AA, Ott, Marsh–McBurney)
Float
Meter stick

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Reinforcing bar (2.5 cm diameter)–2 to 3 m length
Stop watch
Surveyor's level, tripod, and stadium/rod
Tape mesure (at least 50 m)

Hydrographs

Calculator
Gaging records for local streams and rivers (in the United States, these can be obtained in Government Documents section of most major university libraries or from area/regional office of the USGS)
Log–log graph paper
Log–probability graph paper
Semilogarithmic graph paper

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