Standard Test Method for Indirect Measurements of Discharge by Step-Backwater Method[1]

This standard is issued under the fixed designation D 5388; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the computation of discharge of water in open channels or streams using representative cross-sectional characteristics, the water-surface elevation of the upstream-most cross section, and coefficients of channel roughness as input to gradually-varied flow computations.[2]

1.2 This test method produces an indirect measurement of the discharge for one flow event, usually a specific flood. The computed discharge may be used to define a point on the stage-discharge relation.

1.3 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1129 Terminology Relating to Water[3]

D 2777 Practice for Determination of Precision and Bias of Applicable Methods of Committee D19 on Water[3]

D 3858 Practice for Open-Channel Flow Measurement of Water by Velocity-Area Methods[3]

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of terms used in this test method, refer to Terminology D 1129.

3.2 *Definitions of Terms Specific to This Standard:*

NOTE—Several of the following terms are illustrated in Fig. 1.

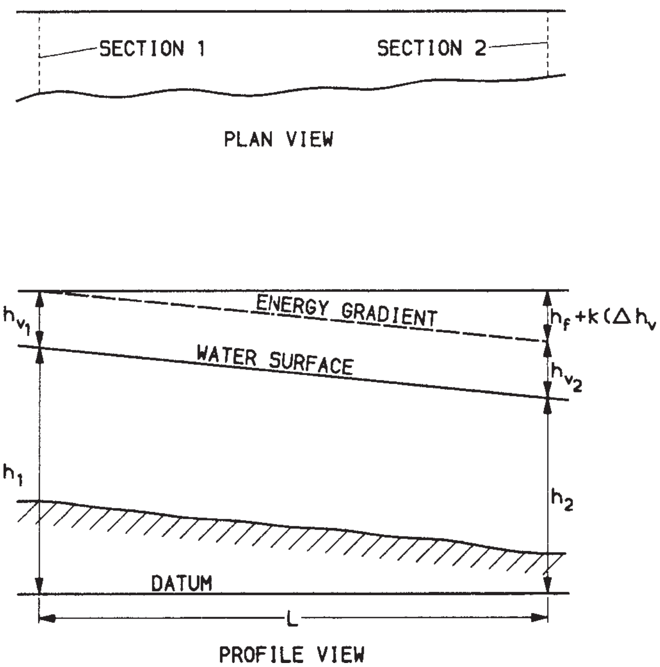

FIG. 1 Definition Sketch of Step-Backwater Reach

3.2.1 *alpha (α)*—a dimensionless velocity-head coefficient that represents the ratio of the true velocity head to the velocity head computed on the basis of the mean velocity. It is assumed equal to unity if the cross section is not subdivided. For subdivided sections, α is computed as follows:

$$\alpha = \frac{\Sigma \frac{{k_i}^3}{{a_i}^2}}{\frac{{K_T}^3}{{A_T}^2}} \quad (1)$$

where:

k and a = the conveyance and area of the subsection indicated by the subscript *i*, and

K and A = the conveyance and area of the total cross section indicated by the subscript *T*.

3.2.2 *conveyance (K)*—a measure of the carrying capacity of a channel without regard to slope and has dimensions of cubic feet per second. Conveyance is computed as follows:

[1] This test method is under the jurisdiction of ASTM Committee D19 on Water and is the direct responsibility of Subcommittee D19.07 on Sediments, Geomorphology, and Open-Channel Flow.

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[2] Barnes, H. H., Jr., "Roughness Characteristics of Natural Streams," *U.S. Geological Survey Water Supply Paper 1849*, 1967.

[3] *Annual Book of ASTM Standards*, Vol 11.01.

$$K = \frac{1.49}{n} AR^{2/3} \quad (2)$$

3.2.3 *cross-section area (A)*—the area at the water below the water-surface elevation that it computed. The area is computed as the summation of the products of mean depth multiplied by the width between stations of the cross section.

3.2.4 *cross sections (numbered consecutively in downstream order)*—representative of a reach and channel and are positioned as nearly as possible at right angles to the direction of flow. They must be defined by coordinates of horizontal distance and ground elevation. Sufficient ground points must be obtained so that straight-line connection of the coordinates will adequately describe the cross-section geometry.

3.2.5 *expansion or contraction loss (ho)*—in the reach is computed by multiplying the change in velocity head through the reach by a coefficient. For an expanding reach:

$$ho = Ke(h_{v_1} - h_{v_2}) \quad (3)$$

and for a contracting reach:

$$ho = Kc(h_{v_2} - h_{v_1}) \quad (4)$$

where:
h_v = velocity head at the respective section, and
Ke and Kc = coefficients.

3.2.5.1 *Discussion*—The values of the coefficients can range from zero for ideal transitions to 1.0 for *Ke* and 0.5 for *Kc* for abrupt changes.

3.2.6 *fall (Δh)*—the drop in the water surface, in ft (m), computed as the difference in the water-surface elevation at adjacent cross sections (see Fig. 1):

$$\Delta h = h_1 - h_2 \quad (5)$$

3.2.7 *friction loss (h_f)*—the loss due to boundary friction in the reach and is computed as follows:

$$h_f = \frac{L\,Q^2}{K_1 K_2} \quad (6)$$

where:
L = length of reach, feet (metres), and
K = conveyance at the respective section.

3.2.8 *Froude number (F)*—an index to the state of flow in the channel. In a prismatic channel, the flow is tranquil or subcritical if the Froude number is less than unity and a rapid or supercritical if it is greater than unity. The Froude number is computed as follows:

$$F = \frac{V}{\sqrt{gdm}} \quad (7)$$

where:
V = the mean velocity, ft/s (m/s),
dm = the mean depth in the cross section, feet, and
g = the acceleration of gravity, ft/s/s (m/s/s).

3.2.9 *hydraulic radius (R)*—defined as the area of a cross section or subsection divided by the corresponding wetted perimeter. The wetted perimeter is the distance along the ground surface of a cross section or subsection.

3.2.10 *Manning's equation*—Manning's equation for computing discharge for gradually-varied flow is:

$$Q = \frac{1.49}{n} A\,R^{2/3} S_f^{1/2} \quad (8)$$

where:
Q = discharge, ft^3/s (m^3/s),
n = Manning's roughness coefficient,
A = cross-section area, ft^2(m^2),
R = hydraulic radius, ft, (m), and
S_f = friction slope, ft/ft (m/m).

3.2.11 *roughness coefficient (n)*—or Manning's *n* is used in the Manning equation. Roughness coefficient or Manning's *n* is a measure of the resistance to flow in a channel. The factors that influence the magnitude of the resistance to flow include the character of the bed material, cross-section irregularities, depth of flow, vegetation, and channel alignment. A reasonable evaluation of the resistance to flow in a channel depends on the experience of the person selecting the coefficient and reference to texts and reports that contain values for similar stream and flow conditions (see 10.3).

3.2.12 *velocity head (h_v)*—in ft(m), compute velocity head as follows:

$$h_v = \frac{\alpha V^2}{2g} \quad (9)$$

where:
α = velocity-head coefficient,
V = the mean velocity in the cross section, ft/s (m/s), and
g = the acceleration of gravity, ft/s/s (m/s/s).

4. Summary of Test Method

4.1 The step-backwater test method is used to indirectly determine the discharge through a reach of channel. The step-backwater test method needs only one high-water elevation and that being at the upstream most cross section. A field survey is made to define cross sections of the stream and determine distances between them. These data are used to compute selected properties of the section. The information is used along with Manning's *n* to compute the change in water-surface elevation between cross sections. For one-dimensional and steady flow the following equation is written for the sketch shown in Fig. 1:

$$h_1 = h_2 + h_{v_2} + hf + ho - h_{v_1} \quad (10)$$

where:
h = elevation of the water surface above a common datum at the respective sections,
hf = the loss due to boundary friction in the reach, and
ho = the energy loss due to deceleration or acceleration of the flow (in the downstream direction) in an expanding or contracting reach.

5. Significance and Use

5.1 This test method is particularly useful for determining the discharge when it cannot be measured directly (such as during high flow conditions) by some type of current meter to obtain velocities and with sounding weights to determine the cross section (refer to Test Method D 3858). This test method requires only one high-water elevation, unlike the slope-area test method that requires numerous high-water marks to define the fall in the reach. It can be used to determine a stage-discharge relation without needing data from several high-water events.

5.1.1 The user is encouraged to verify the theoretical stage-discharge relation with direct current-meter measurements when possible.

5.1.2 To develop a rating curve, plot stage versus discharge for several discharges and their computed stages on a rating curve together with direct current-meter measurements.

6. Interferences

6.1 The cross sections selected should be typical and representative of the reach half way to each adjacent cross section. If there are abrupt changes between adjacent cross sections, the results could be suspect. The ratio of the conveyance to the conveyance at an adjacent cross section should stay within 0.7 and 1.4.

6.2 Care must be taken in selecting the water-surface elevation for the downstream cross section. It should not be so high that it would reflect backwater at the upstream cross section or so low that it would be in super-critical flow. A good rule of thumb is to select a stage so that the conveyance of the downstream cross section is approximately equal to the conveyance of the upstream-most cross section.

6.3 The only way to be certain that the water-surface elevation is not too high or too low or that the reach is sufficiently long enough or that enough cross sections are used, or all of the above, is to use the converging profile method. In this method, several profiles are developed using a range of starting water-surface elevations. The slope of the profiles from the higher starting elevations should increase as you move in an upstream direction. The slope of the profiles from the lower starting elevations should decrease as you move in an upstream direction. At some distance upstream, the profiles will converge.

6.4 A minimum of about ten cross sections are needed to develop a smooth backwater curve.

7. Apparatus

7.1 The equipment generally used for a "transit-stadia" survey is recommended. An engineer's transit, a self-leveling level with azimuth circle, newer equipment using electronic circuitry, or other advanced surveying instruments may be used. Standard level rods, a telescoping 25-ft (7.62-m) level rod, rod levels, head levels, steel and metallic tapes, tag lines (small wires with markers fixed at known spacings), vividly colored flagging, survey stakes, a camera (preferably stereo) with built-in light meter with color film, and ample note paper are necessary items.

7.2 Additional equipment that may expedite a survey includes axes, machetes, a boat with oars and motor, hip boots, waders, rain gear, sounding equipment, and two-way radios.

7.3 Safety equipment should include life jackets, first aid kit, drinking water, and pocket knives.

8. Sampling

8.1 Sampling as defined in Terminology D 1129 is not applicable in this test method.

9. Calibration

9.1 Check the surveying instruments, levels, transits, etc. adjustments before each use, and possibly daily when in continuous use, or after some occurrence that may have affected the adjustment.

9.2 The standard check is the *two-peg* or *double-peg* test. If the error is over 0.03 ft in 100 ft (0.009 m in 30.4 m), adjust instrument. The two-peg test and how to adjust the instrument are described in many surveying textbooks and in instructions provided by the manufacturer. Refer to manufacturer's manual for the electronic instruments.

9.3 If the *reciprocal leveling* technique is used in the survey, it is the equivalent of the two-peg test between each of the two successive hubs.

9.4 Check sectional and telescoping level rods visually at frequent intervals to be sure sections are not separated. A proper fit at each joint can be quickly checked by measurements across the joint with a steel tape.

9.5 Check all field notes of the transit-stadia survey before proceeding with the computations.

10. Procedure

10.1 Selection of a reach of channel is the first and probably the most important step to obtain reliable results. Ideal reaches rarely exist; thus the various elements in a reach must be evaluated and compromises made so that the best reach available is selected. This test method requires that the reach be much longer than a reach using the slope-area test method.

10.2 The reach of the channel should be as uniform as possible. Changes in channel conveyance should be fairly uniform from section to section. Avoid abrupt changes in channel shape because of uncertainties regarding the value of the expansion/contraction loss coefficient and the friction losses in the reach.

10.3 A reach with flow confined to a roughly trapezoidal channel is desirable because roughness coefficients have been determined for such shapes. However, compound channels, those with overbank flow, for example, can be used if they are properly subdivided into sub-areas that are approximately trapezoidal.

10.4 The reach should be long enough to develop a fall that is approximately equal to half of the average depth.

10.5 Cross sections represent the geometry of a reach of channel. For example, a section should be typical of the reach from halfway to the next section upstream to halfway to the next section downstream. A minimum of about ten cross sections is recommended.

10.6 The roughness coefficient, n, is assigned to a cross section or to subdivisions of a section, but the n selected should represent conditions in the reach for which the section is typical. Most texts on hydraulics give techniques of determining values of *n*. One particularly helpful reference uses photographs and descriptive stream-channel data to describe values of *n*[3]. Cowan developed a procedure for estimating the effects of these factors to determine the value of *n* for a channel.[4]

11. Interpretation of Results

11.1 Compute the discharge by trial and error. The discharge and a water-surface elevation at the downstream most cross section are assumed. A good water-surface elevation for the downstream most cross section is the given water-surface elevation at the upstream most cross section and to adjust it for the natural slope of the stream. Compute a backwater profile by starting at the downstream-most cross section and progressing upstream to the upstream-most cross section.[5] Compute a water-surface elevation for each cross section.

11.2 Compute the water-surface elevation for the first cross section upstream from the downstream-most cross section. Compute this water-surface elevation using the equations in 4.1. This computation is done by trial and error. A water-surface elevation is first assumed for this section. With the assumed elevation, compute the area, conveyance, and other section properties. Use these values in the equations in 4.1 to compute the change in water-surface elevation between this section and the downstream-most cross section. Using this change in water-surface elevation, compute an elevation for this cross section. The computed elevation should be the same as the assumed elevation for the section properties to be correct. When the water-surface elevation at this section has been determined, use it to compute the water-surface elevation at the next cross section upstream. Report the computed change in water-surface elevations between cross sections progressing in an upstream direction until a profile has been computed for the entire reach.

[4] Cowan, W. L., "Estimating Hydraulic Roughness Coefficients," *Agricultural Engineering*, July 1956, pp. 473–475.

[5] Shearman, J. O., Kirby, W. H., Schneider, V. R., and Flippo, H. N.," Bridge Waterways Analysis Model"; Research Report: *U.S. Federal Highway Administration Report No. FHWA/RD-86/108*, 1986.

11.3 If the computed water-surface elevation at the upstream cross section is lower than the given water-surface elevation, then increase the discharge and recompute backwater profile. If the recomputed water-surface elevation at the upstream cross section is higher than the given water-surface elevation, then decrease the discharge and compute another backwater profile. Repeat the procedure until the computed water-surface elevation at the upstream cross section is equal to the given water-surface elevation. A quick way to assist in selecting the final discharge is to plot a stage-discharge relation for the upstream cross section based on the results of each computed profile. Select the discharge corresponding to the given water-surface elevation from this curve and use in the next computation.

12. Precision and Bias

12.1 Determination of the precision and bias for this test method is not possible, both at the multiple and single operator level, due to the high degree of variability of open-channel flow. Both temporal and spatial variability of the boundary and flow conditions preclude the use of a consent standard for representative sampling. A minimum bias, measured under ideal conditions, is directly related to the bias of the equipment used and is listed in the following sections. A maximum precision and bias cannot be estimated due to the variability of the sources of potential errors listed in Section 11 and the temporal and spatial variability of open-channel flow. Any estimate of these errors could be very misleading to the user.

12.2 In accordance with 1.6 of Practice D 2777, an exemption to the precision and bias statement required by Practice D 2777 was recommended by the results advisor and concurred with by the Technical Operations Section of Executive Subcommittee on June 24, 1992.

12.3 The bias in selecting roughness coefficients is very important in obtaining a good value for discharge. The error in discharge is inversely proportional to errors in roughness coefficients.

13. Keywords

13.1 flood; open channel flow; water discharge