PDHonline Course H138 (2 PDH)

Open Channel Hydraulics I – Uniform Flow

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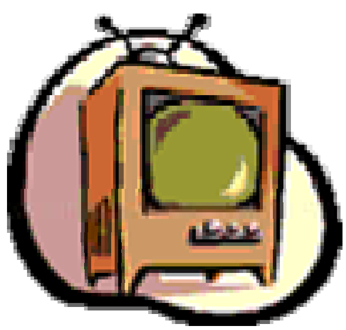
COURSE CONTENT

1. Introduction

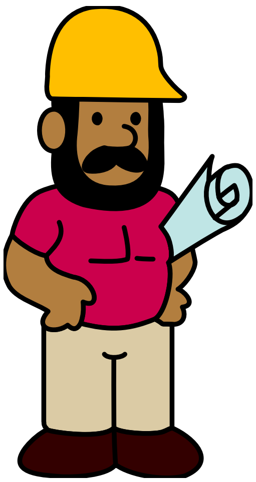
Open channel flow occurs whenever the flowing liquid has a free surface at atmospheric pressure. For example, this may be in a natural river channel, in a manmade concrete channel for transporting wastewater, or in a closed conduit, such as a storm sewer, which is flowing partially full. The driving force for open channel flow must be gravity, since the flow, which is open to the atmosphere, cannot be pressurized. In contrast, the primary driving force for flow in pressurized, closed conduit flow is usually pressure. There may be a gravity component in pressurized, closed conduit flow as well, but, in fact, the flow is often against gravity, as when the fluid is being pumped upward. In this course several aspects of open channel flow will be presented, discussed and illustrated with examples. The major topics included in this introductory course are: i) classifications of open channel flow and ii) uniform flow in open channels.



Uncle Hector can't find any programs on channel 55.

I wonder if it's an OPEN CHANNEL.

2. Classifications of Open Channel Flow



There are several way of classifying open channel flow. It may be i) laminar or turbulent, ii) steady state or unsteady state, iii) uniform or non-uniform, and iv) critical, subcritical, or supercritical. Each of these classifications will be presented and discussed briefly in this section. Uniform flow will be covered extensively in the rest of this course. Critical and non-uniform flow will be covered in a follow-up course, "Open Channel Hydraulics II - Critical and Non-uniform Flow."

i) Laminar or Turbulent Flow: As with pipe flow, the criterion for whether open channel flow is laminar or turbulent, is a value for Reynold's number (Re). Laminar open channel flow occurs for Re less than about 500 and turbulent flow for Re greater than about 2000 to 3000. Flows with Re value of 500 to 3000 are in the transition region, where the flow may be either laminar or turbulent depending upon other factors such as the smoothness of the walls and upstream conditions. With great care, laminar flow can be maintained to Re as high as 12,500, and some sources use this as the Re value above which flow will be turbulent. Under normal conditions, however, Re > 3000 is a good criterion for turbulent flow. The definition of the Reynold's number for open channel flow and examples of its use will be covered in Section 3, and are not included here. Most practical cases of open channel flow in a natural or manmade channel have Re greater than 3000, and thus are turbulent flow. The main exception is flow in a thin layer on a large flat surface, such as rainfall runoff from a highway, parking lot or airport runway. This is sometimes called sheet flow. Special equations are used to make calculations for sheet flow.

NOTE: Laminar flow, also called streamline flow is characterized by low velocity and/or high viscosity for the flowing fluid. The liquid flows in streamlines, not mixing with adjacent fluid. Turbulent flow, on the other hand, is characterized by high velocity and/or low viscosity for the flowing fluid. In turbulent flow, the average velocity of the fluid is in the direction of flow, but there are eddy currents in all directions, which cause mixing among adjacent layers of fluid. The classic experiment of Osborne Reynolds involved injection of a dye into a transparent pipe containing a fluid flowing in laminar flow conditions and observing that the dye flowed in a streamline and did not mix with the rest of the fluid. When dye was injected into a fluid flowing at higher velocity, such that the flow was turbulent, it mixed into the fluid, so that the entire mass of fluid became colored. This is illustrated for open channel flow in Figure 1, below.

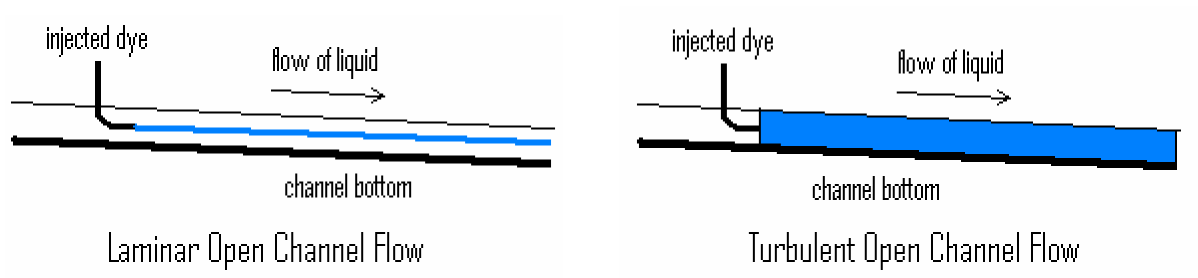


Figure 1. Dye injection into laminar & turbulent open channel flow

ii) Steady State or Unsteady State Flow: The definitions of steady state and unsteady state are the same for open channel flow as for pipe flow and for numerous other applications. Steady state flow is characterized by no changes in velocity patterns and magnitude with time at a given channel cross section. Unsteady state flow does have changing velocity with time at a given cross section. Steady state open channel flow will take place when a constant flow rate of liquid is passing through the channel. Unsteady state open channel flow will occur due to changing flow rate, as in a river following a rain storm. Many practical applications of open channel flow are steady state or nearly steady state. The equations and calculations in this course will be for steady state flow.

iii) Uniform or Non-Uniform Flow: Uniform flow will occur in a stretch of open channel (called a ‘reach’ of channel) which has a constant flow rate of liquid passing through it, constant bottom slope, and constant cross-section shape & size. For these conditions, the depth of flow and average velocity of the flowing liquid will remain constant in that reach of channel. Non-uniform flow occurs in reaches of channel, where the bottom slope, cross-section shape, and/or cross-section size change. If a new set of condition remains constant in a downstream reach of channel, then new uniform flow conditions will occur there. This is illustrated in Figure 2.

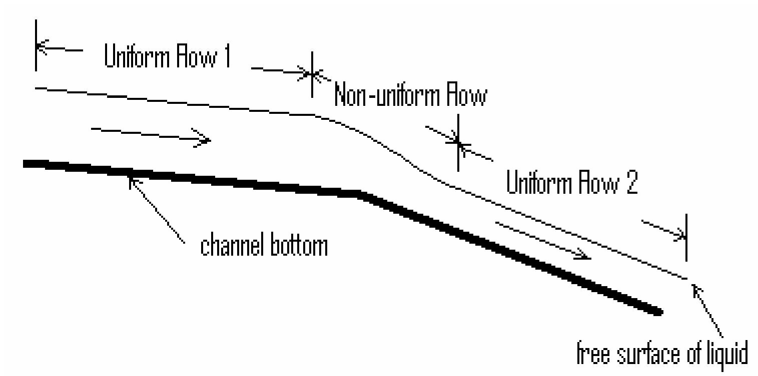


Figure 2. Uniform and Non-uniform Open Channel Flow

iv) Critical, Subcitical, or Supercritical Flow:

The first three classifications of open channel flow (laminar or turbulent, steady or unsteady state, & uniform or non-uniform flow) all make sense and can be understood intuitively. Your intuition, however, will probably not expect some of the behaviors for subcritical and supercritical flows and the transitions between them. Subcritical flow is characterized by low liquid velocity and deep flow. It occurs when the Froude number ($Fr = V/(gl)^{1/2}$) is less than one. Critical flow occurs when Fr = 1, and supercritical flow, which is characterized by high velocity, shallow flow, occurs when Fr > 1. The Froude number and critical, subcritical, and supercritical flow will be discussed in more detail in a follow-up course, "Open Channel Hydraulics II - Critical and non-uniform flow."

No, No, No, SUPERCRITICAL FLOW is not finding fault with anything !

3. Uniform Open Channel Flow Calculations

As stated above and illustrated in Figure 2, uniform open channel flow occurs for a constant volumetric flow rate of liquid through a section of channel which has a constant bottom slope, size & shape of the channel cross-section, and roughness of the channel surface. For these conditions, the liquid will flow at a constant depth, which is called the normal depth for the given channel and volumetric flow rate.

i) The Manning Equation

The most commonly used equation for relating parameters of interest in uniform open channel flow of water, is the Manning Equation, which was proposed by the Irish engineer, Robert Manning in 1889. The Manning Equation with U.S. units is:

$$\mathbf{Q = (1.49/n)A(R_h^{2/3})S^{1/2}} \qquad (1)$$

Where: Q = volumetric flow rate passing through the stretch of channel, ft^3/sec

A = cross-sectional area of flow normal to the flow direction, ft^2

S = the constant bottom slope of the channel*, ft/ft (dimensionless)

n = Manning Roughness coefficient (empirical constant), dimensionless

R_h = hydraulic radius = A/P

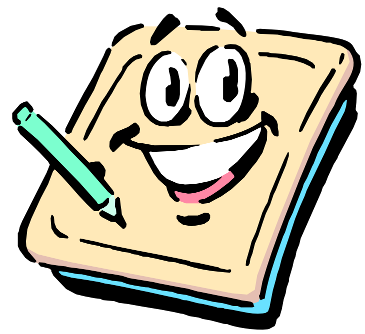
Where: A = cross-sectional area as defined above, ft^2

P = wetted perimeter of the cross-sectional area of flow, ft

*Theoretically, S is the slope of the liquid surface, but with constant depth of flow, the slope of the liquid surface will be the same as the channel bottom slope, so the latter is typically used for S in this equation.

NOTE: The Manning equation is an empirical, dimensional equation. With the constant having a value of 1.49, the units on each variable must be as shown above.

The Manning Roughness coefficient, n, is an empirical constant, dependent upon the nature of the channel and its surface(s). Tables are available in many handbooks and textbooks giving values of n for for different channel types and surfaces. Table 2, on the next page, is an example with values of n for a variety of man-made open channel surfaces.



What is a HYDRAULIC RADIUS ?

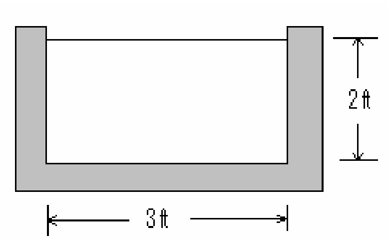
Does it need to be round ?

The **Reynolds number** for open channel flow is defined as Re = $\rho V R_h/\mu$, where ρ and μ are the density and viscosity respectively of the flowing fluid, V is the average velocity defined as Q/A, and the hydraulic radius, R_h, was defined above. Note that the Reynold's number is dimensionless, so any dimensionally consistent set of units can be used. The Manning Equation applies only to turbulent flow. As mentioned above, however, almost all practical situations of water being transported through an open channel have Re greater than 3000, and are thus turbulent flow. The exception, mentioned above, is sheet flow, in a thin layer, on a large flat surface. Tables with values of density, ρ, and viscosity, μ, for water over a range of temperatures are available in many handbooks and fluid mechanics or thermodynamics textbooks, as for example, in reference #1 for this course. Table 1 shows density and viscosity for water at temperatures from 32^o F to 70^o F.

Table 1. Density and Viscosity of Water

Temperature, °F	Density, slugs/ft^3	Dynamic Viscosity, lb-s/ft^2
32	1.940	3.732×10^{-5}
40	1.940	3.228×10^{-5}
50	1.940	2.730×10^{-5}
60	1.938	2.334×10^{-5}
70	1.936	2.037×10^{-5}

Example #1: Water is flowing 2 feet deep in a 3 foot wide, open channel of rectangular cross section, as shown in the diagram below. The channel is made of concrete (made with wood forms), with a constant bottom slope of 0.004.
a) Estimate the flow rate of water in the channel. b) Was the assumption of turbulent flow correct ?



Solution: a) Based on the description, this will be uniform flow. Assume that the flow is turbulent in order to be able to use equation (1), the Manning equation. All of the parameters on the right side of equation (1) are known or can be calculated: From Table 2, n = 0.015. The bottom slope is given as: S = 0.004. From the diagram, it can be seen that the cross-sectional area perpendicular to flow is 2 ft times 3 ft = 6 ft^2. Also from the figure, it can be seen that the wetted perimeter is 2 + 2 + 3 ft = 7 ft. The hydraulic radius can now be calculated:

R_h = A/P = 6 ft^2/7 ft = 0.8571 ft

Substituting values for all of the parameters into Equation 1:

$Q = (1.49/0.015)(6)(0.8571^{2/3})(0.004^{1/2})$ = **34.0 ft^3/sec**

(see part (b) of the solution after Table 2.)

Table 2. Manning Roughness Coefficient, n, for Selected Surfaces

Channel Surface	Manning Roughness Coefficient, n
Asbestos cement	0.011
Brass	0.011
Brick	0.015
Cast-iron, new	0.012
Concrete, steel forms	0.011
Concrete, wooden forms	0.015
Concrete, centrifugally spun	0.013
Copper	0.011
Corrugated metal	0.022
Galvanized Iron	0.016
Lead	0.011
Plastic	0.009
Steel - Coal-tar enamel	0.01
Steel - New unlined	0.011
Steel - Riveted	0.019
Wood stave	0.012

b) Since no temperature was specified, assume a midrange temperature of 50° F. From Table 1, ρ = 1.94 slugs/ft^3, and $\mu = 2.730 \times 10^{-5}$ lb-s/ft^2. Calculate average velocity, V:

$$V = Q/A = 34.0/6 \text{ ft/sec} = 5.667 \text{ ft/sec}$$

Reynold's number ($Re = \rho V R_h/\mu$) can now be calculated:

$$Re = \rho V R_h/\mu = (1.94)(5.667)(0.8571)/(2.730 \times 10^{-5}) = 3.45 \times 10^5$$

Since Re > 3000, this is turbulent flow

ii) Hydraulic Radius for Various Common Shapes

It is helpful to develop equations for hydraulic radius for common cross-sectional shapes for open channels. The shapes to be considered here are: **trapezoid**, **circular**, **semicircular**, and **triangular**. The rectangular cross-section was already introduced in **Example #1.**

Many natural channels can be approximated as a **trapezoid**. Figure 3 below, shows a trapezoidal open channel cross-section with the parameters typically used to describe it. B is the width of the liquid surface; b is the bottom width; y is the depth of flow; ℓ, is the wetted length on each sloped side, measured along the sloped side; and the side slope is often specified as: horiz : vert = z : 1. The side slope also may be specified as the angle from vertical, α.

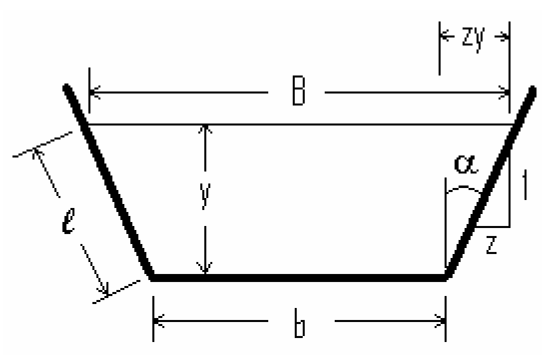


Figure 3. Trapezoidal Open Channel Cross-section

The hydraulic radius for the trapezoidal cross-section can be expressed in terms of bottom width, depth of flow, & side slope (b, y & z) as follows:

$$\text{The area of the trapezoid} = A = y(b + B)/2 = (y/2)(b + B)$$

By using similar triangles, we note that B is greater than b by the length, zy at each end of the liquid surface, as shown in Figure 3. Thus:

$$\mathbf{B = b + 2zy}$$

Substituting into the equation for A:

$$A = (y/2)(b + b + 2zy) = (y/2)(2b + 2zy)$$

Simplifying: $A = by + zy^2$

As seen in Figure 3, the wetted perimeter for the trapezoidal cross-section is:

$$P = b + 2\ell$$

By Pythagoras' Theorem: $\ell^2 = y^2 + (yz)^2$ or $\ell = (y^2 + (yz)^2)^{1/2}$

Substituting into the above equation for P and simplifying:

$$\mathbf{P = b + 2y(1 + z^2)^{1/2}}$$

Thus for a trapezoidal cross-section the hydraulic radius is found by substituting equations (2) & (3) into $R_h = A/P$, yielding the following equation:

For a **trapezoid**: $\mathbf{R_h = (by + zy^2)/(b + 2y(1 + z^2)^{1/2})}$ (2)

Open channel gravity flow takes place in **circular** conduits such as storm sewers and sanitary sewers. Storm and sanitary sewers usually flow only partially full, however hydraulic design calculations are usually made for full flow, which is a "worst case" scenario. For a circular conduit flowing full, the cross-sectional area and perimeter can be expressed in terms of the diameter of the conduit, D, and then used to calculate the hydraulic radius as follows:

For a circular conduit of diameter D (radius R) flowing full:

The x-sect. area of flow is: $A = \pi R^2 = \pi(D/2)^2 = \pi D^2/4$

The wetted perimeter is: $P = 2\pi R = \pi D$

Hydraulic radius $= R_h = A/P = (\pi D^2/4)/(\pi D)$, simplifying:

For a **circular** conduit flowing full: $\mathbf{R_h = D/4}$ (3)

For a circular conduit flowing half full, which results in a semicircular cross-sectional area of flow, the area and perimeter are each half of the value for a circle, so the ratio remains the same, D/4. Thus:

For a **semicircular** x-section: $\mathbf{R_h = D/4}$ (4)

Figure 4 shows a **triangular** open channel cross-section with both sides sloped at the same angle from vertical. The parameters shown in the diagram are as follows. B is the width of the liquid surface; y is the depth of flow; ℓ, is the wetted length on each sloped side, measured along the sloped side; and the side slope is specified as: horiz : vert = z : 1.

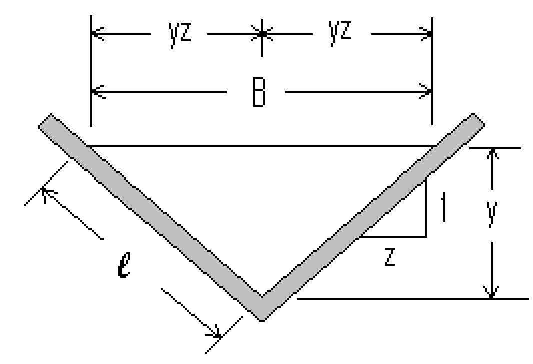


Figure 4. Triangular Open Channel Cross-section

The cross-sectional area of flow and wetted perimeter for flow through a triangular channel of the configuration shown in Figure 4, can be expressed in terms of the depth of flow, y, and the side slope, z, as follows:

The area of the triangular area of flow is: $A = ½ By$, but as shown in Figure 4:

$B = 2yz$, Thus: $A = ½ (2yz)y$ or simply: $\mathbf{A = y^2z}$

The wetted perimeter is: $P = 2\ell$ and $\ell^2 = y^2 + (yz)^2$, solving for ℓ and substituting:

$$\mathbf{P = 2[y^2(1 + z^2)]^{1/2}}$$

Hydraulic radius: $R_h = A/P$

For a **trianglular** x-section: $\mathbf{R_h = y^2z/(2[y^2(1 + z^2)]^{1/2}}$) (5)

Example #2: A triangular flume has 12 ft^3/sec of water flowing at a depth of 1.5 ft above the vertex of the triangle. The side slopes of the flume are: horiz : vert = 1 : 1. The bottom slope of the flume is 0.003. What is the Manning roughness coefficient, n, for this flume?

Solution: From the problem statement: y = 1.2 ft and z = 1, substituting into Equation (5):

$$R_h = 1.5^2(1)/(2[1.5^2(1 + 1^2)]^{1/2}) = 0.5303 \text{ ft}$$

The cross-sectional area of flow is: $A = y^2z = (1.5^2)(1) = 2.25 \text{ ft}^2$

Substituting these values for R_h and A along with given values for Q and S into equation (1) gives:

$$12 = (1.49/n)(2.25)(0.5303^{2/3})(0.003^{1/2})$$

Solving for n: **n = 0.010**

iii) Alternate Forms for the Manning Equation

The Manning Equation is sometimes given as an equation for the average velocity of the flow through the open channel (in ft/sec) instead of for the volumetric flow rate. It then becomes:

$$V = (1.49/n)(R_h^{2/3})S^{1/2} \quad (6)$$

Where the definition of average velocity, V, is the volumetric flow rate divided by the cross-sectional area of flow:

$$V = Q/A \qquad (7)$$

The Manning Equation is also sometimes expressed in SI units instead of in U.S. units. It then becomes:

$$Q = (1.00/n)A(R_h^{2/3})S^{1/2} \qquad (8)$$

Where: Q = volumetric flow rate passing through the stretch of channel, m^3/sec

A = cross-sectional area of flow normal to the flow direction, m^2

S = the constant bottom slope of the channel, m/m (dimensionless)

n = Manning Roughness coefficient (empirical constant), dimensionless

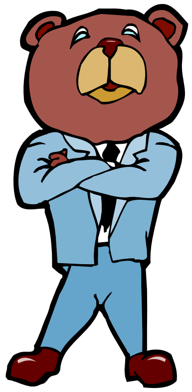
R_h = hydraulic radius = A/P

Where: A = cross-sectional area as defined above, m^2

P = wetted perimeter of the cross-sectional area of flow, m

iv) Determination of Normal Depth

The depth of flow for a given flow rate, bottom slope, and channel size and material is called the **normal depth,** usually represented by the symbol, y_o. Determination of y_o is more difficult than determination of the parameters calculated in the first two examples. **Example #1** illustrated the determination of flow rate for given depth of flow, bottom slope, and channel shape, size and



NORMAL DEPTH, Hah ! What's so normal about it ?

material. **Example #2** illustrated determination of Manning roughness coefficient for given flow rate, depth of flow and channel shape and size. In both of these cases, the Manning Equation could be solved for the unknown parameter and the unknown parameter could be calculated by substituting values into the equation. If the rest of the parameters are specified, the required channel bottom slope can be calculated in the same manner. For determination of normal depth, however, this is typically not the case. It is possible to get an equation with y_o as the only unknown, but usually the equation cannot be solved explicitly for y_o. An iterative or "trial & error" solution is necessary. This is illustrated in the next example for a rectangular channel.

Example #3: Determine the normal depth for a water flow rate of 10 ft^3/sec, through a rectangular channel with a bottom slope of 0.0005, bottom width of 2 ft, and Manning roughness coefficient of 0.015.

Solution: Substituting specified values into the Manning equation [$Q = (1.49/n)A(R_h^{2/3})S^{1/2}$] gives:

$$10 = (1.49/0.015)(2y_o)((2y_o/(2 + 2y_o))^{2/3})(0.0005^{1/2})$$

Rearranging this equation gives: $2\,y_o(2y_o/(2 + 2y_o))^{2/3} = 4.50215$

Although this equation cannot be solved explicitly for y_o, there is a unique value of y_o which satisfies the equation. An iterative solution to find that value for y_o, using an Excel spreadsheet, is shown in the table below. By trying values of 1, 2, & 3 for y_o, it can be seen that the correct value for y_o lies between 2 and 3. The next two trials show that it is between 2.7 and 2.8. The next four entries show that the right hand column is closest to 4.50215 for y_o = 2.77, thus **y_o = 2.77 to three significant figures**. If greater precision is needed, additional trials would show that **y_o = 2.765 to four significant figures**.

Determination of normal depth in a trapezoidal or triangular channel would be very similar. The equations for R_h are slightly more complicated, and the side slope, z, must also be specified for these two cases, but the overall procedure would be just as in the example above.

y_o	$2\, y_o(2y_o/(2 + 2y_o))^{2/3}$
1	1.2599
2	3.0526
3	4.9529
2.8	4.5685
2.7	4.3769
2.75	4.4726
2.78	4.5301
2.77	4.5110
2.76	4.4918

v) Uniform Open Channel Flow in Natural Channels

The main difference between application of the Manning Equation to natural channels rather than manmade channels is the greater diversity in the type and description of the channel, as needed to determine a value for the Manning roughness coefficient, n. One approach is experimental measurements to determine n. If the depth of flow, channel shape, size, & bottom slope, and volumetric flow rate are measured or estimated for a given reach of open channel at a time when it is flowing at a reasonably constant depth, those parameters can be used in the Manning equation to calculate an empirical value for the Manning roughness coefficient, n, for that reach of channel.

There are also many tables available with n values for natural channels. An example is given by the two-page table, presented on the next two pages. It came from the Indiana Department of Transportation Design Manual, available on the internet at: http://www.in.gov/dot/div/contracts/standards/dm/index.html. Minimum, normal and maximum values for the Manning roughness coefficient, n, are given for a wide range of natural channel descriptions.

Type of Channel and Description	Minimum	Normal	Maximum
EXCAVATED OR DREDGED			
1. Earth, Straight and Uniform	0.016	0.018	0.020
a. Clean, recently completed	0.018	0.022	0.025
b. Clean, after weathering	0.022	0.025	0.030
c. Gravel, uniform section, clean	0.022	0.027	0.033
2. Earth, Winding and Sluggish			
a. No vegetation	0.023	0.025	0.030
b. Grass, some weeds	0.025	0.030	0.033
c. Dense weeds or aquatic plants in deep channel	0.030	0.035	0.040
d. Earth bottom and rubble sides	0.025	0.030	0.035
e. Stony bottom and weedy sides	0.025	0.035	0.045
f. Cobble bottom and clean sides	0.030	0.040	0.050
3. Dragline, Excavated or Dredged			
a. No vegetation	0.025	0.028	0.033
b. Light brush on banks	0.035	0.050	0.060
4. Rock Cut			
a. Smooth and uniform	0.025	0.035	0.040
b. Jagged and irregular	0.035	0.040	0.050
5. Channel Not Maintained, Weeds and Brush Uncut			
a. Dense weeds, high as flow depth	0.050	0.080	0.120
b. Clean bottom, brush on sides	0.040	0.050	0.080
c. Clean bottom, highest stage of flow	0.045	0.070	0.110
d. Dense brush, high stage	0.080	0.100	0.140
NATURAL STREAM			
1. Minor Stream (top width at flood stage < 100 ft)			
a. Stream on plain			
(1) Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
(2) Same as above, but more stones or weeds	0.030	0.035	0.040
(3) Clean, winding, some pools or shoals	0.033	0.040	0.045
(4) Same as above, but some weeds or stones	0.035	0.045	0.050
(5) Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
(6) Same as (4), but more stones	0.045	0.050	0.060
(7) Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
(8) Very weedy reaches, deep pools, or floodway with heavy stand of timber and underbrush	0.075	0.100	0.150

NATURAL STREAM (contd.)			
Type of Channel and Description	**Minimum**	**Normal**	**Maximum**
1. Minor Stream (contd.)			
b. Mountain stream, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
(1) Bottom: gravel, cobbles, and few boulders	0.030	0.040	0.050
(2) Bottom: cobbles with large boulders	0.040	0.050	0.07
2. Floodplain			
a. Pasture, no brush			
(1) Short grass	0.025	0.030	0.035
(2) High grass	0.030	0.035	0.050
b. Cultivated area			
(1) No crop	0.020	0.030	0.040
(2) Mature row crops	0.025	0.035	0.045
(3) Mature field crops	0.030	0.040	0.050
c. Brush			
(1) Scattered brush, heavy weeds	0.035	0.050	0.070
(2) Light brush and trees, in winter	0.035	0.050	0.060
(3) Light brush and trees, in summer	0.040	0.060	0.080
(4)Medium to dense brush, in winter	0.045	0.070	0.110
(5)Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
(1) Dense willows, in summer, straight	0.110	0.150	0.200
(2) Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
(3) Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
(4) Heavy stand of timber, a few downed trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
(5) Same as above, but with flood stage reaching branches	0.100	0.120	0.160
3. Major Stream (top width at flood stage > 100 ft). The *n* value is less than that for a minor stream of similar description, because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	n/a	0.060
b. Irregular and rough section	0.035	n/a	0.100

Example #4: A reach of channel for a stream on a plain is described as clean and winding with some pools and shoals. The bottom slope is reasonably constant at 0.0003 for a reach of this channel. Its cross-section is also reasonably constant for this reach, and can be approximated by a trapezoid with bottom width equal to 8 feet, and side slopes with horiz : vert equal to 3:1. Using the minimum and maximum values of n in the above table for this type of stream, find the range of volumetric flow rates represented by a 5 ft depth of flow.

Solution to Example #4: From the problem statement, b = 8 ft, S = 0.0003, z = 3, and y = 5 ft. From the above table, item 1. a. (3) under "Natural Stream", the minimum expected value of n is 0.033 and the maximum is 0.045. Substituting values for b, z, and y into equation (2) for a trapezoidal hydraulic radius gives:

$$R_h = [(8)(5) + 3(5^2)]/[8 + (2)(5)(1 + 3^2)^{1/2}] = 2.902 \text{ ft}$$

Also $$A = (8)(5) + 3(5^2) = 115 \text{ ft}^2$$

Substituting values into the Manning Equation $[Q = (1.49/n)A(R_h^{2/3})S^{1/2}]$ gives the following results:

Minimum n (0.033): $Q_{max} = (1.49/0.033)(115)(2.902^{2/3})(0.0003)^{1/2}$

$$\mathbf{Q_{max} = 183.0 \text{ ft}^3\text{/sec}}$$

Maximum n (0.045): $Q_{min} = (1.49/0.045)(115)(2.902^{2/3})(0.0003)^{1/2}$

$$\mathbf{Q_{min} = 134.2 \text{ ft}^3\text{/sec}}$$

4. Summary

Open channel flow, having a free surface at atmospheric pressure, occurs in a variety of natural and man-made settings. Open channel flow may be classified as i) laminar or turbulent, ii) steady state or unsteady state, iii) uniform or non-uniform, and iv) critical, subcritical, or supercritical flow. Much practical open channel flow can be treated as turbulent, steady state, uniform flow. Several parameters of interest are related through the empirical Manning Equation, for turbulent, uniform open channel flow (**$Q = (1.49/n)A(R_h^{2/3})S^{1/2}$**). Through worked examples in this course, the use of the Manning equation for uniform open channel flow calculations and the calculation of parameters in the equation, such as cross-sectional area and hydraulic radius, are illustrated.