5. Open Channel Design

5.1 General

Open channel systems are an integral part of stormwater drainage design. In addition to natural channels, dry and wet swales, drainage ditches, riprap channels, concrete lined channels, and grass channels, encompass open channels. This section provides an overview of open channel design criteria and methods.

5.1.1 Considerations for Use of Open Channels

Open channels for use in the major drainage system have significant impact to stormwater drainage design in the aspects of cost, capacity, and aesthetic purposes. Disadvantages of open channels include right-of-way needs and maintenance costs.

Open channels may be used in lieu of storm sewers to convey storm runoff where:

- Sufficient right-of-way is available.
- Sufficient cover for the storm sewers is not available.
- It is important to maintain compatibility with existing or proposed developments.
- Economy of construction can be shown without long-term public maintenance expenditures.

Intermittent alternating reaches of opened and closed systems should be avoided.

The ideal channel is a natural one carved by nature over a long period of time and protected through comprehensive storm water management techniques. The benefits of a natural channel include:

- Lower velocities and increased stability in channel bottom and banks.
- Channel storage tends to decrease peak flows.
- Decrease in maintenance associated with stability.
- Increase in ecological habitat.
- Channel provides desirable green belt.

In general, the man-made channel that most nearly conforms to the character of the natural channel is the most efficient and the most desirable.

In many areas undergoing development, the runoff has been so minimal that natural channels do not exist. However, a small trickle path nearly always exists which provides an excellent basis for location and construction of channels. Utilization of these trickle paths reduces development costs and minimize drainage problems by following grade and working with gravity.

Channel stability is a well-recognized problem in urban settings because of the significant increase in low flows and peak storm discharges.

Sufficient right-of-way or permanent easements should be provided adjacent to open channels to allow entry of city maintenance vehicles.

5.1.2 Open Channel Types

The three main classifications of open channel types according to channel linings are vegetated, flexible, and rigid. Vegetated linings include natural, grass-lined, grass with mulch, sod and lapped sod, and wetland channels. Riprap and gabions are examples of flexible linings, while rigid linings are generally concrete or rigid block.

Vegetative Linings – Vegetation, where practical, is the preferred lining for man-made channels. It stabilizes the channel body and bed, reduces erosion on the channel surface, and provides habitat and water quality benefits.

Conditions under which vegetation may not be acceptable include but are not limited to:

- High velocities.
- Lack of maintenance required to prevent growth of taller or woody vegetation and invasive species.
- Lack of nutrients and inadequate topsoil.
- Severe lack of access for maintenance.

Proper seeding, mulching and soil preparation are required during construction to assure establishment of healthy vegetation. Also, erosion control matting or other geofabrics may be required to be placed along the base and / or side slopes of these channels to allow establishment of vegetation. Post construction care of vegetation is critical to successful establishment.

Flexible Linings – Rock riprap, including rubble, is the most common type of flexible lining for channels. It presents a rough surface that can dissipate energy. These linings are usually less expensive than rigid linings. However, they may require the use of a filter fabric depending on the erosive characteristics of the underlying soils, and the growth of grass and weeds may present maintenance problems. Silty sand or silty loam soils typically require the use of a filter fabric. The US Army Corps of Engineers provides detailed design approach for riprap in Engineer Manual No. 1110-2-1601, Hydraulic Design of Flood Control Channels.

Rigid Linings – Rigid linings are generally constructed of articulated block or concrete and used where high flow capacity is required. Higher velocities, however, create the potential for scour at channel lining transitions and may lead to channel head cutting.

5.2 Design Criteria

Open channels shall be designed to the following criteria:

- In all cases for open channels, the design engineer shall calculate the 100-year flow and show the 100-year flow boundary and water surface elevation in the Plans and Specifications.
- Channel or adjacent public drainage/floodplain easement, floodway, etc., shall be capable of containing the fully developed 100-year storm with a minimum one-foot freeboard. Public drainage easements bordering adjacent areas should encompass the width of the flow channel, floodway, floodplain, etc., with an additional 15 feet on each side of the specified design. For example, if the channel, floodway, or floodplain width is 50 feet wide, the drainage easement width at the same point will be 80 feet.
- Trapezoidal or parabolic cross sections are preferred.
- Channel side slopes shall be designed to have a maximum slope of 3:1 unless otherwise justified. Roadside ditches should have a maximum side slope of 3:1.
- Channel design shall consider effects of channel lining.
- If a stream channel must be relocated, the cross-sectional shape, meander, pattern, roughness, sediment transport capacity, and slope should conform to the existing conditions to the extent practicable. Some means of energy dissipation may be necessary when existing conditions cannot be duplicated.
- Streambank stabilization should be provided as a result of any stream disturbance such as encroachment and should include both upstream and downstream banks as well as the local site.

5.2.1 Velocity Limitations

The final design of engineered open channels should be consistent with the velocity limitations for the selected channel lining. Maximum velocity values for earthen materials categories are presented in Table 5.1. Seeding and mulch should only be used when the design value does not exceed the allowable value for bare soil. Velocity limitations for vegetative linings are reported in Table 5.1. Erosion Control Matting may be used if designed and constructed in accordance with manufacturer's specifications subject to the limitations provided in this manual.

Table 5.1 Maximum velocities for comparing lining materials.

Material	Maximum Velocity (ft/s)
Sand	2.0
Silt	3.5
Firm Loam	3.5
Fine Gravel	5.0
Stiff Clay	5.0
Graded Loam or Silt to Cobbles	5.0
Coarse Gravel	6.0
Shales and Hard Pans	6.0
Erosion control matting	*

Source: AASHTO Model Drainage Manual, 1991.

* Based on manufacturer specifications and subject to approval by City Design Review Engineer.

Table 5.2 Maximum velocities for vegetative channel linings.

Vegetation Type	Slope Range (%)[1]	Maximum Velocity[2] (ft/s)
Bermuda grass	0-10	5
Bahia		4
Tall fescue grass mixtures[3]	0-10	4
Kentucky bluegrass	0-5	6
Buffalo grass	0-10	5
	>10	4
Grass mixture	0-5[1]	4
	5-10	3
Annuals[4]	0-5	3
Sod		4
Staked sod		5

1. Do not use on slopes steeper than 10% except for side-slope in combination channel.
2. Use velocities exceeding 5 ft/s only where good stands can be maintained.
3. Mixtures of Tall Fescue, Bahia, and/or Bermuda.
4. Annuals - use on mild slopes or as temporary protection until permanent covers are established.
5. Source: Manual for Erosion and Sediment Control in Georgia, 1996.

5.2.2 Channel Cross Sections

The channel shape may be almost any type suitable to the location and to the environmental conditions. The shape may be able to be designed to promote open space, recreational needs and to create additional benefits.

1. Bend Radius: 25 feet or 10 times the bottom width, whichever is larger, is the minimum bend radius required for open channels.
2. Freeboard: Freeboard to top of bank shall be based on velocities associated with the design storm and shall be a minimum of 1 foot for channel velocities up to 8 ft/s and 2 feet for velocities exceeding 8 ft/s at the design storm. For deep flows with high velocities, greater freeboard shall be required, calculated in accordance with the following formula:

$$\boldsymbol{Freeboard\ (ft) = 1.0 + 0.025\, vD^{1/3}} \quad \textbf{Eq. 5.1}$$

   Where: v = velocity of flow (ft/s)

   D = depth of flow (ft)

   For freeboard of a channel on a sharp curve less than the minimum bend radius, additional freeboard, to account for superelevation of the water surface, shall be computed as:

$$\boldsymbol{H = v^2\,((T + b)/2gR_c)} \quad \textbf{Eq. 5.2}$$

   Where: H = additional height on the outside edge of channel (ft)

   v = velocity of flow (ft/s)

   T = top width of water surface (ft)

   b = bottom width of channel (ft)

   g = acceleration of gravity (32.2 ft/s2)

   Rc = mean radius of bend (ft)

3. Connections: Connections at the junction of two or more open channels shall be designed to minimize transition loss for both vertical and horizontal transitions. Pipe and box culverts or sewers entering an open channel shall not project into the normal channel section. Nor will they be permitted to discharge into an open channel at an angle that directs flow upstream.

5.2.3 Channel Drops

Sloped drops shall have roughened faces and shall be no steeper than 2:1. They shall be adequately protected from scour and shall not cause an upstream water surface drop that will result in high velocities upstream. Downcutting and lateral cutting just downstream from the drops is a common problem which must be protected against. FHWA's HEC-14 manual and programs like HY-8 can be used to calculate scour potential and design energy dissipators.

5.2.4 Baffle Chutes

Baffle chutes are used to dissipate the energy in the flow at a larger drop. They require no tailwater to be effective. They are partially useful where the water surface upstream is held at a higher elevation to provide head for filling a side storage pond during peak flows.

Baffle chutes may be used in channels where water is to be lowered from one level to another. The baffle piers prevent undue acceleration of the flow as it passes down the chute. The baffled apron shall be designed for the full discharge design flow and shall be protected from scouring at the lower end. A stilling basin shall be added where appropriate based on velocities.

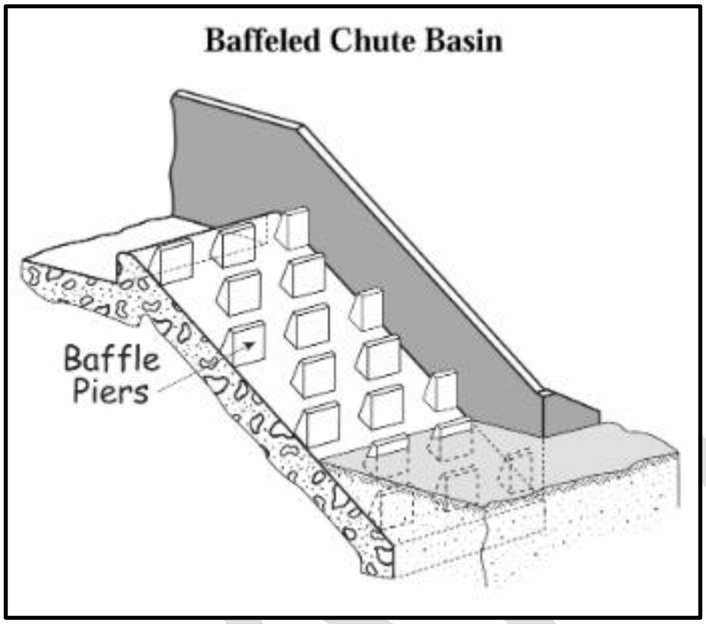


Figure 5.1 Example of Baffle Chute Basin

5.35.3 Computation and Software

Computer programs that utilize the Manning's equation shall be used for open channel design. Computer programs such as Hydraflow Express or the FHWA Hydraulic Toolbox may be used for Uniform Flow conditions; however, for more complex reaches or streams with higher flows, a backwater model such as HEC-RAS should be used. The general information to be provided in an open channel design is:

- Plan View - Existing and proposed topography.
- Profile - Left and right top of bank, 100-yr HGL, slope, invert flowlines.
- Cross-section - Dimensions, 100-yr hydraulic parameters.

Design flow and applicable design standards, design geometry required based on operational characteristics – freeboard, velocity, minimum standard capacity and site requirements, and flow regime – subcritical or supercritical – shall be reported and taken into consideration as part of design. Table 5.3 is a sample output file using Hydraflow Express computer software; FHWA Hydraulic Toolbox software provides a similar output report.

Table 5.3 Channel report output file.

Channel Section			
Channel Section Data:		**Highlighted:**	
Bottom Width (ft)	2.00	Depth (ft)	0.80
Side Slopes (z:1)	3.00, 3.00	Q (cfs)	13.00
Total Depth (ft)	2.00	Area (sq ft)	3.52
Invert Elevation (ft)	100.00	Velocity (ft/s)	3.69
Slope (%)	1.00	Wetted Perimeter (ft)	7.06
N-Value	0.025	Critical Depth, Yc (ft)	0.77
		Top Width (ft)	6.80
Calculations:		EGL (ft)	1.01
Compute by:	Known Q		
Known Q (cfs)	13.00		

5.3.1 Manning's n Values

Recommended Manning's n values for artificial channel linings are given in Table 5.4. The Values in Table 5.4 are based off the flow depth of the channel. For natural channels, earthen channels, and various types of vegetation, Manning's n values should be estimated using experienced judgment and based on the information in Table 5.5. Additional details are provided in the *Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains*, FHWA-TS 84-204, 1984.

Table 5.4 Manning's roughness coefficients (n) for artificial lined channels.

Category	Lining Type	Depth Ranges		
		0-0.5 ft	0.5-2.0 ft	>2.0 ft
Rigid	Concrete	0.015	0.013	0.013
	Grouted Riprap	0.040	0.030	0.028
	Stone Masonry	0.042	0.032	0.030
	Soil Cement	0.025	0.022	0.020
	Asphalt	0.018	0.016	0.016
Unlined	Bare Soil	0.023	0.020	0.020
	Rock Cut	0.045	0.035	0.025
Temporary*	Woven Paper Net	0.016	0.015	0.015
	Jute Net	0.028	0.022	0.019
	Fiberglass Roving	0.028	0.022	0.019
	Straw with Net	0.065	0.033	0.025
	Curled Wood Mat	0.066	0.035	0.028
	Synthetic Mat	0.036	0.025	0.021
Gravel Riprap	1-inch D50	0.044	0.033	0.03
	2-inch D50	0.066	0.041	0.034
Rock Riprap	6-inch D50	0.104	0.069	0.035
	12-inch D50	----	0.078	0.040

Note: Values listed are representative values for the respective depth ranges. Manning's roughness coefficients, n, vary with the flow depth.

*Some "temporary" linings become permanent when buried.
Source: HEC-15, 1988.

Table 5.5 Uniform flow values of roughness coefficient (n) for natural channels.

Type of Channel and Description	Minimum	Normal	Maximum
Natural Streams **-** Minor streams (top width at flood stage < 100 ft)			
1. Main Channels			
a. Clean, straight, full stage	0.025	0.030	0.033
b. Same as above, but some stones and weeds	0.030	0.035	0.040
c. Clean, winding, some pools and shoals	0.033	0.040	0.045
d. Clean, winding, but some weeds and some stones	0.035	0.045	0.050
e. Same as 4, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. Same as 4, but more stones	0.045	0.050	0.060
g. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
a. Bottom: gravels, cobbles, few boulders	0.030	0.040	0.050
b. Bottom: cobbles with large boulders	0.040	0.050	0.070
3. Floodplains			
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, summer, straight	0.110	0.150	0.200
2. Cleared land, 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 down 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

Table 5.5 Uniform flow values of roughness coefficient n for natural channels.

Type of Channel and Description	Minimum	Normal	Maximum
5. EXCAVATED OR DREDGED			
a. Earth, straight and uniform			
1. Clean, recently completed	0.016	0.018	0.020
2. Clean, after weathering	0.018	0.022	0.025
3. Gravel, uniform section, clean	0.022	0.025	0.030
4. With short grass, few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish			
1. No vegetation	0.023	0.025	0.030
2. Grass, some weeds	0.025	0.030	0.033
3. Dense weeds/plants in deep channels	0.030	0.035	0.040
4. Earth bottom and rubble sides	0.025	0.030	0.035
5. Stony bottom and weedy sides	0.025	0.035	0.045
6. Cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline-excavated or dredged			
1. No vegetation	0.025	0.028	0.033
2. Light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. Smooth and uniform	0.025	0.035	0.040
2. Jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. Dense weeds, high as flow depth	0.050	0.080	0.120
2. Clean bottom, brush on sides	0.040	0.050	0.080
3. Same, highest stage of flow	0.045	0.070	0.110
4. Dense brush, high stage	0.080	0.100	0.140

5.3.2 Channel Discharge - Manning's Equation

Manning's equation, presented in three forms below, shall be used for evaluating uniform flow conditions in open channels:

$$\boldsymbol{V} = (1.49/\boldsymbol{n})\ \boldsymbol{R}^{2/3}\ \boldsymbol{S}^{1/2} \qquad \textbf{Eq. 5.3}$$

$$\boldsymbol{Q} = (1.49/\boldsymbol{n})\ \boldsymbol{A}\boldsymbol{R}^{2/3}\ \boldsymbol{S}^{1/2} \qquad \textbf{Eq. 5.4}$$

$$\boldsymbol{S} = \left[\boldsymbol{Q}\boldsymbol{n}\ /\ (1.49\ \boldsymbol{A}\boldsymbol{R}^{2/3})\right]^2 \qquad \textbf{Eq. 5.5}$$

Where: V = average channel velocity (ft/s)

Q = discharge rate for design conditions (cfs)

n = Manning's roughness coefficient

A = cross-sectional area (ft2)

R = hydraulic radius A/P (ft)

P = wetted perimeter (ft)

S = slope of the energy grade line (ft/ft)

If the channel is uniform in resistance and gravity forces are in exact balance, the water surface will be parallel to the bottom of the channel. This is the condition of uniform flow.

Open channel flow in urban drainage systems is complicated by bridge openings, curbs, and structures. Typically backwater computations will be required for channel design work; however, a check should also be performed for velocity based on headwater-controlled conditions.

A water surface profile shall be computed for all channels and shown on all final drawings. Computation of the water surface profile should utilize standard backwater methods or acceptable calculation procedures, taking into consideration all losses due to the changes in velocity, drops, bridge openings, and other obstructions.

Where practical, unlined channels should have sufficient gradient, depending upon the type of soil, to provide velocities that will be self-cleaning but will not cause erosion. Lined channels, drop structures, check dams, or concrete spillways may be required to control erosion that results from the high velocities of large volumes of water. Unless approved otherwise by the Director of Planning and Development or the Public Works Director, channel velocities in man-made channels shall not exceed those specified in Tables 5.1 and 5.2. Where velocities exceed specified velocities, riprap, pavement, or other approved erosion protection measures shall be required. As minimum protection to reduce erosion, all open channel slopes shall be seeded or sodded expeditiously after grading has been completed.

5.4 Channel Lining Design

5.4.1 Vegetative Design

For channels with vegetative and temporary lining, design stability shall be determined using Manning's n based upon poor vegetation conditions and for design capacity better conditions should be used. Channel velocities shall not exceed the maximum permissible velocities given in Tables 5.1 and 5.2. For more details on vegetative design refer to HEC-15.

5.4.2 Riprap Design

Where the use of riprap is allowed by the City Design Review Engineer, riprap sizing shall be determined based on maximum anticipated channel velocities. Adequate erosion protection shall be provided for the design configurations. For example, if riprap will extend into a stream with higher water surface elevations and/or velocities, i.e., at a pipe outfall going into a creek, then the riprap must be sized to resist the forces of the higher flow in the creek. When rock riprap is used, the need for an underlying filter material must be evaluated. The filter material may be either a granular blanket or plastic filter cloth.

Isbash Equation

The Isbash formula (Isbash 1936) was developed for the construction of dams by depositing rocks into moving water. The Isbash curve should only be used for quick estimates or for comparisons. A coefficient is provided to target high- and low-turbulence flow conditions, so this method can be a high- or low-energy application. The equation is:

$$\boldsymbol{V_c = C\left[2g\left(\frac{\gamma_S - \gamma_W}{\gamma_W}\right)\right]^{0.50}(D_{50})^{0.50}} \qquad \textbf{Eq. 5.6}$$

Where: V_C = critical velocity (ft/s)

C = 0.86 for high turbulence

C = 1.20 for low turbulence

g = 32.2 ft/s^2

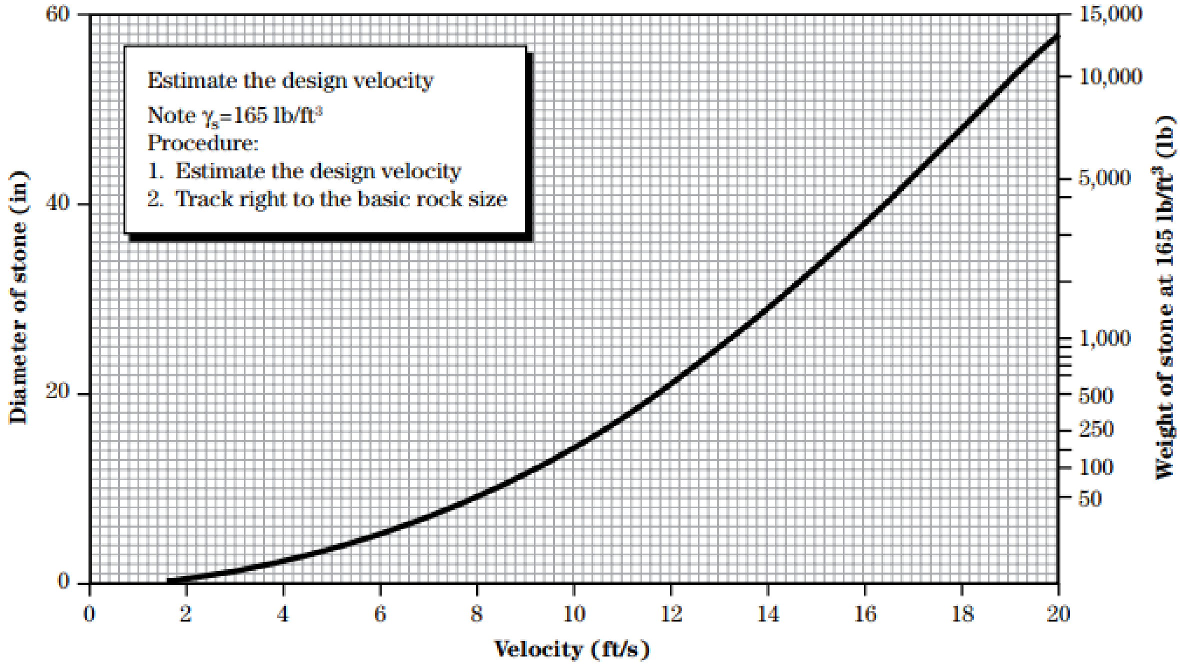
γ_S = stone density (lb/ft^3)

γ_W = water density (lb/ft^3)

D_{50} = median stone diameter (ft)

Figure 5.0 provides general riprap sizing criteria. For more detailed design, reference the US Army Corps of Engineers *Hydraulic Design of Flood Control Channels* manual. The design velocity should be based on the highest velocity of the design storm events, include velocities in receiving stream, if applicable. Extend a vertical line from the x-axis of the figure at the appropriate velocity until the curve is intersected, then extend a horizontal line to intersect the y-axis at the corresponding D_{50}, or median stone diameter for which no more than 50% of the stone by weight is smaller.

Figure TS14C–5 Rock size based on Isbash curve



(210–VI–NEH, August 2007)

Figure 5.3 Riprap sizing curve.

5.45.5 References

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