Appendix A - Design Charts and Nomographs

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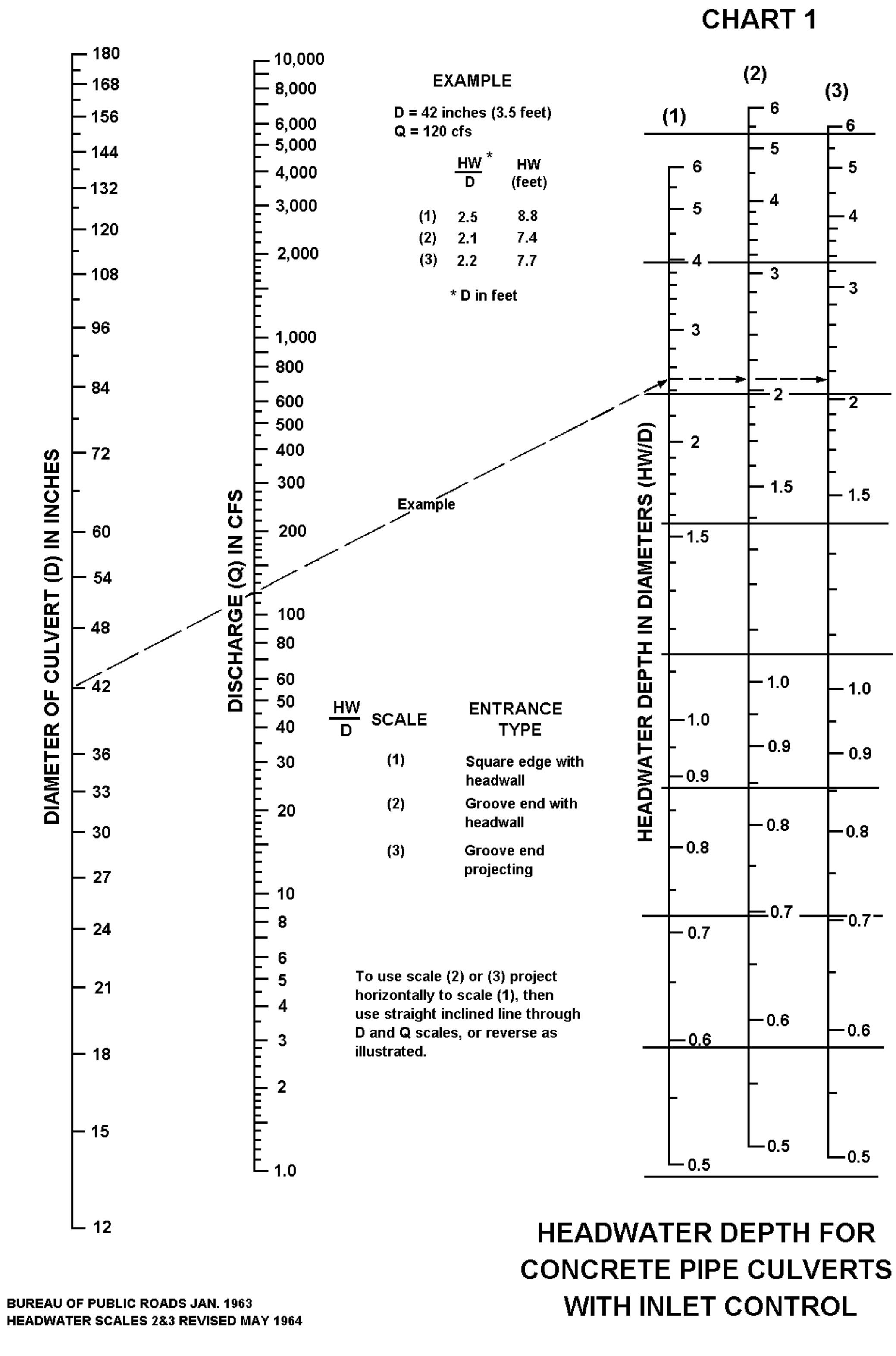
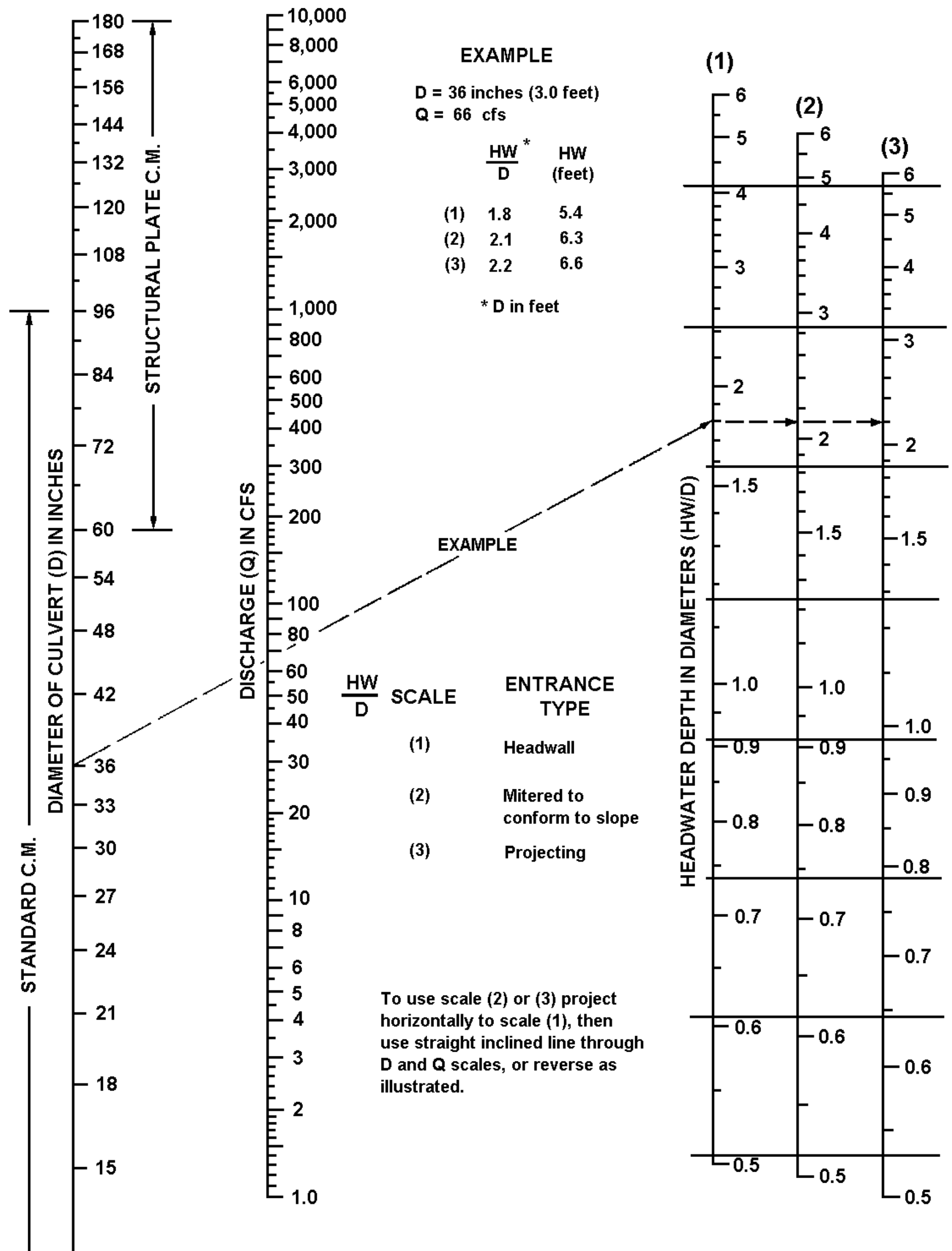


CHART 1
EXAMPLE
D = 42 inches (3.5 feet)
Q = 120 cfs
HW/D * HW (feet)
(1) 2.5 8.8
(2) 2.1 7.4
(3) 2.2 7.7
* D in feet
DIAMETER OF CULVERT (D) IN INCHES
DISCHARGE (Q) IN CFS
HEADWATER DEPTH IN DIAMETERS (HW/D)
Example
HW/D SCALE
ENTRANCE TYPE
(1) Square edge with headwall
(2) Groove end with headwall
(3) Groove end projecting
To use scale (2) or (3) project horizontally to scale (1), then use straight inclined line through D and Q scales, or reverse as illustrated.
HEADWATER DEPTH FOR CONCRETE PIPE CULVERTS WITH INLET CONTROL
BUREAU OF PUBLIC ROADS JAN. 1963
HEADWATER SCALES 2&3 REVISED MAY 1964

CHART 2

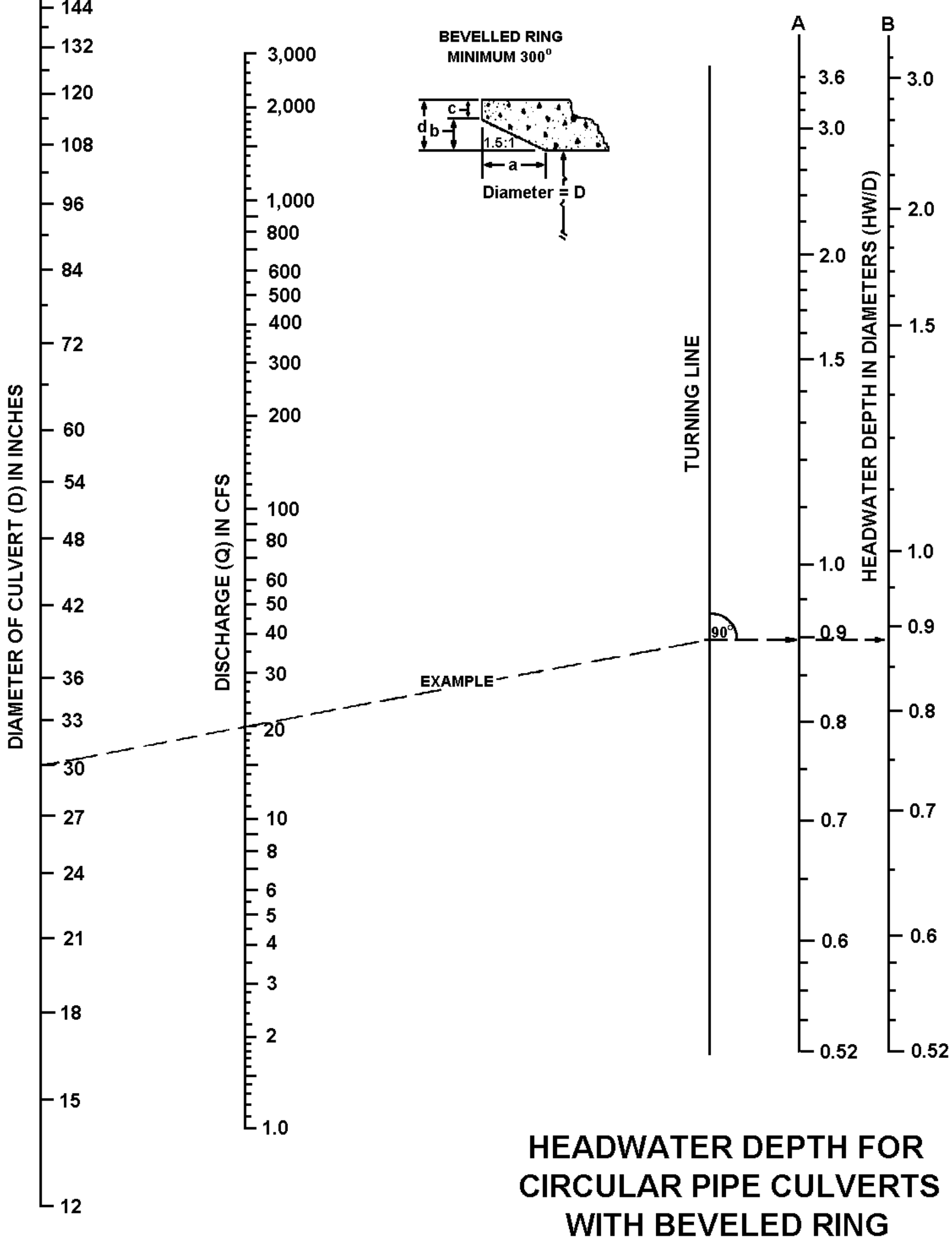


HEADWATER DEPTH FOR C.M. PIPE CULVERTS WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 3

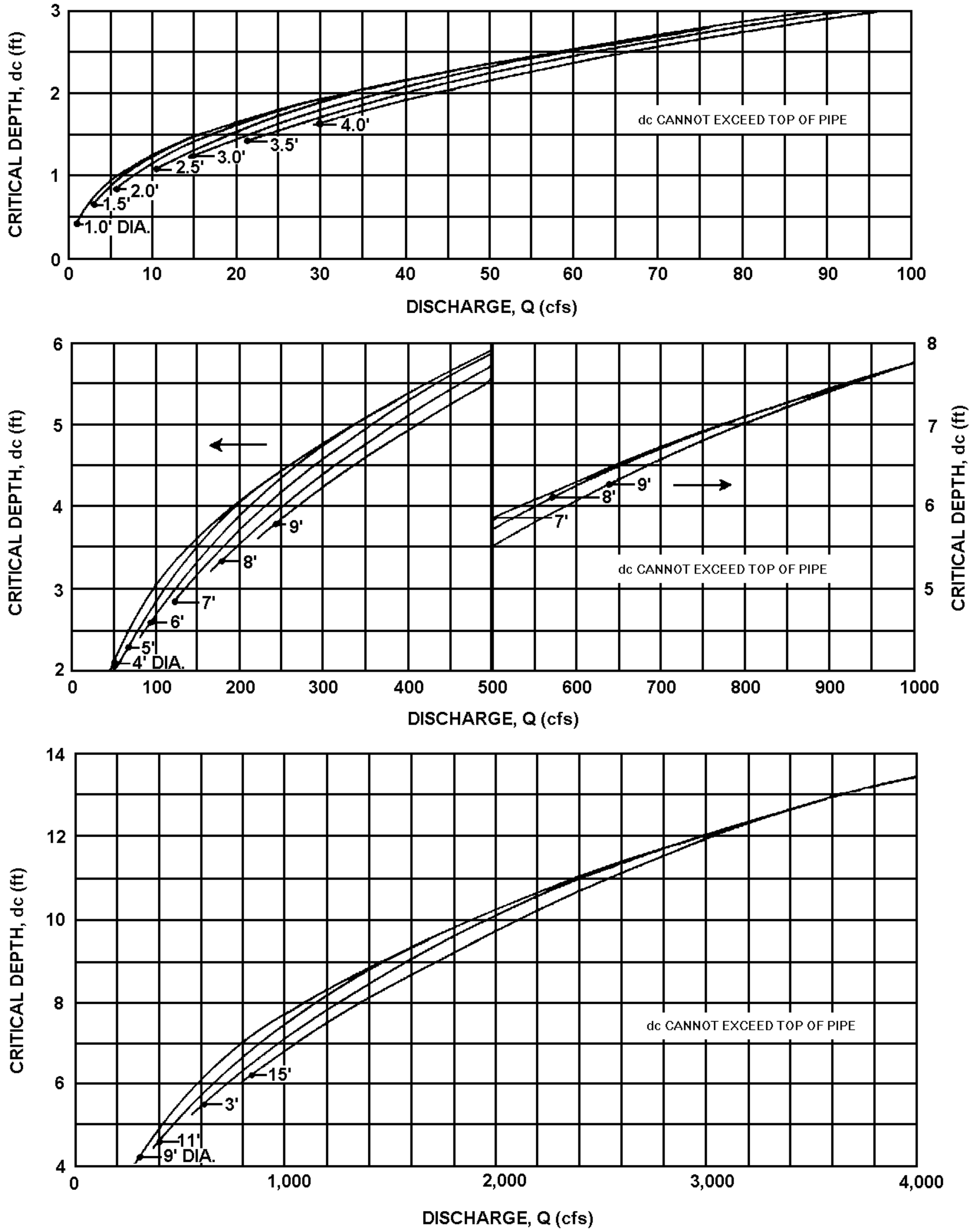
b/D	a/D	c/D	d/D	Entrance Type
0.042	0.063	0.042	0.083	A
0.083	0.125	0.042	0.125	B



HEADWATER DEPTH FOR CIRCULAR PIPE CULVERTS WITH BEVELED RING INLET CONTROL

FEDERAL HIGHWAY ADMINISTRATION MAY 1973

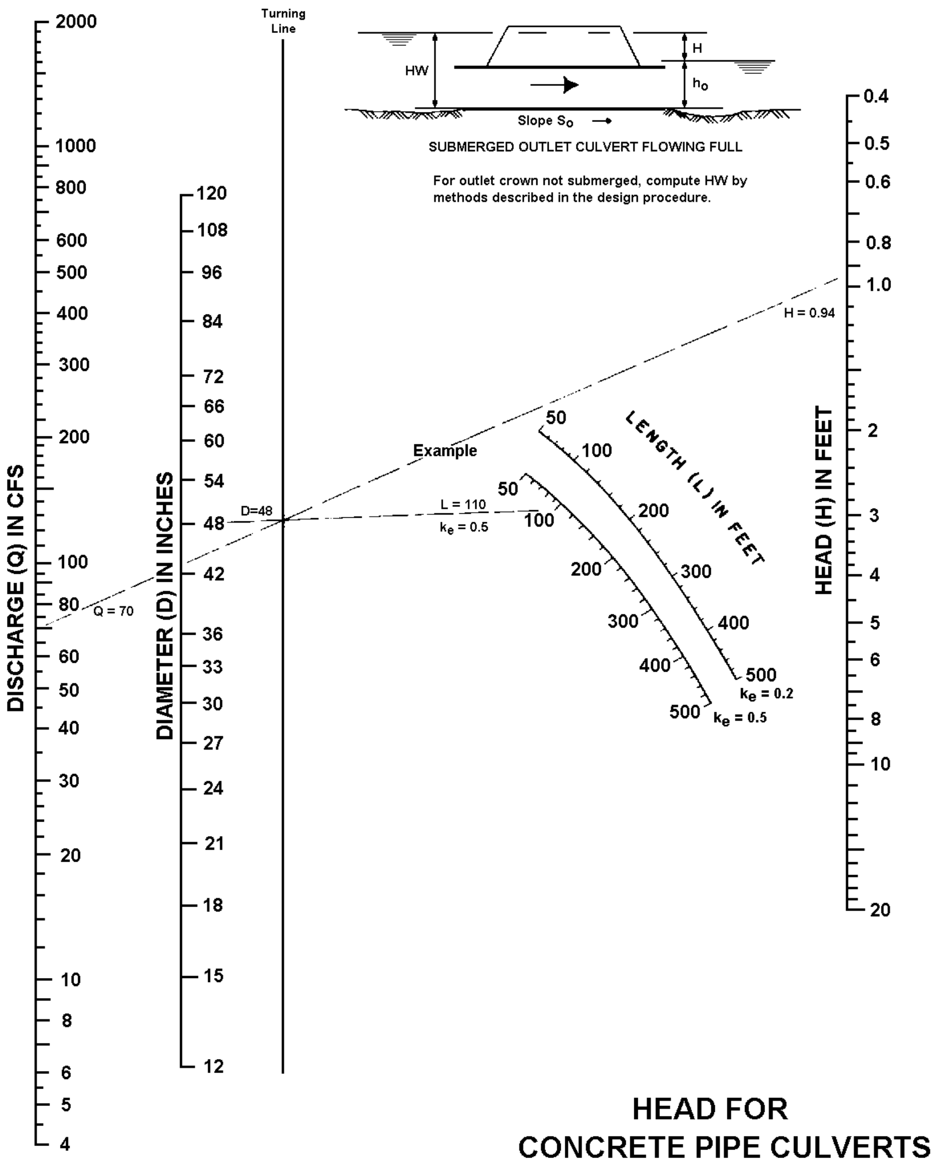
CHART 4



BUREAU OF PUBLIC ROADS JAN. 1964

**CRITICAL DEPTH
CIRCULAR PIPE**

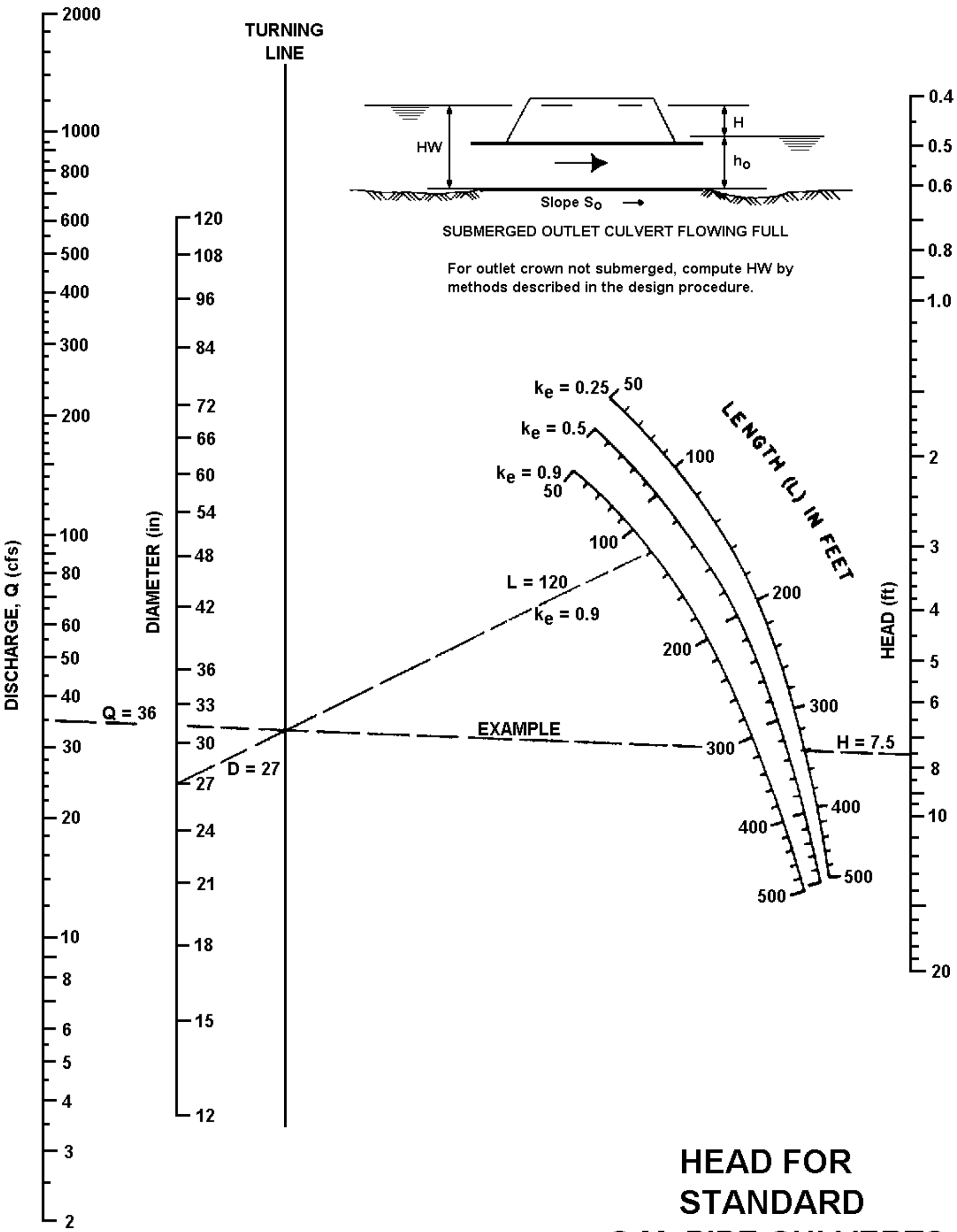
CHART 5



HEAD FOR CONCRETE PIPE CULVERTS FLOWING FULL
n = 0.012

BUREAU OF PUBLIC ROADS JAN. 1963

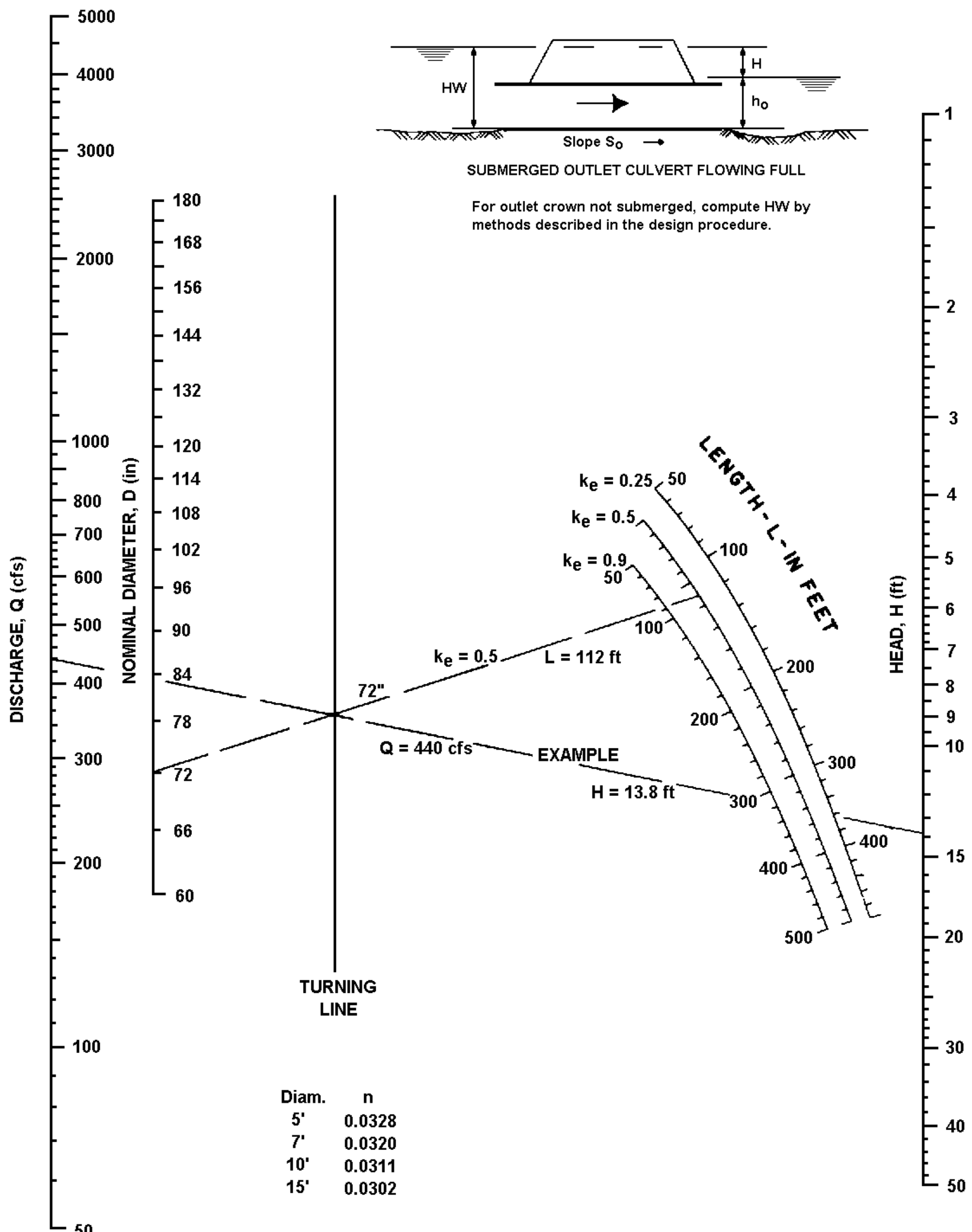
CHART 6



HEAD FOR STANDARD C.M. PIPE CULVERTS FLOWING FULL
n = 0.024

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 7

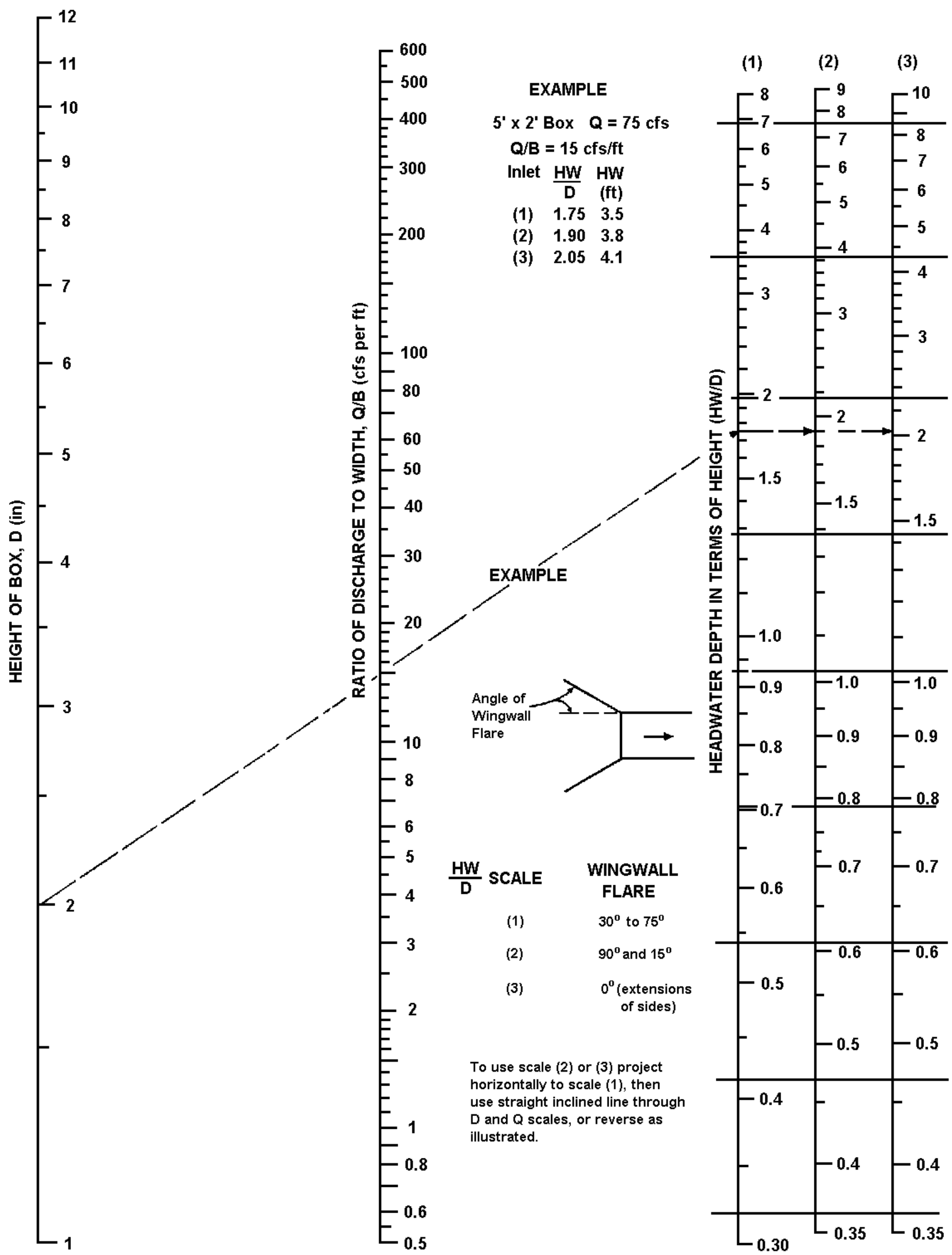


Diam.	n
5'	0.0328
7'	0.0320
10'	0.0311
15'	0.0302

BUREAU OF PUBLIC ROADS JAN. 1963

HEAD FOR STRUCTURAL PLATE CORR. METAL PIPE CULVERTS FLOWING FULL
n = 0.0328 TO 0.0302

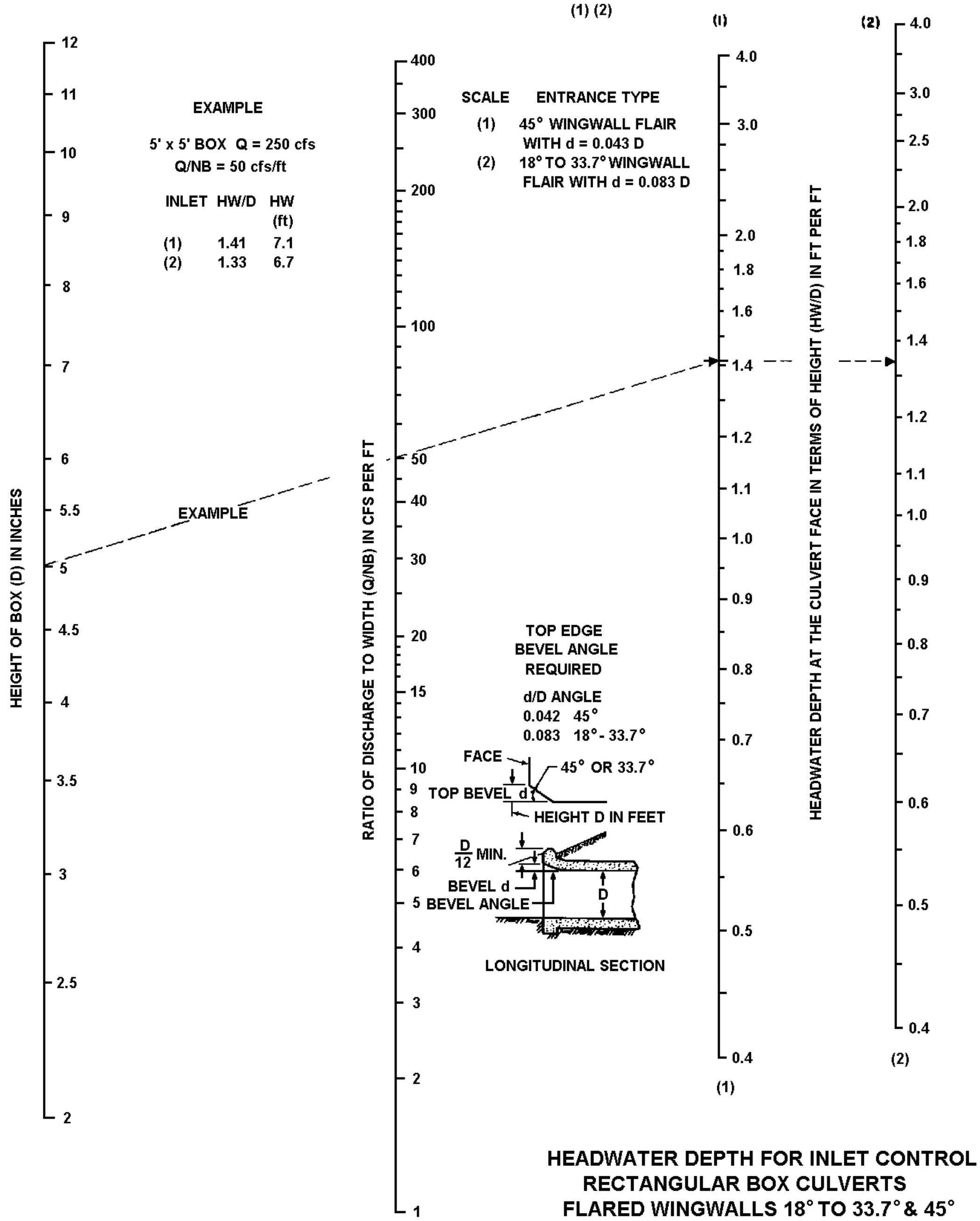
CHART 8



BUREAU OF PUBLIC ROADS JAN. 1963

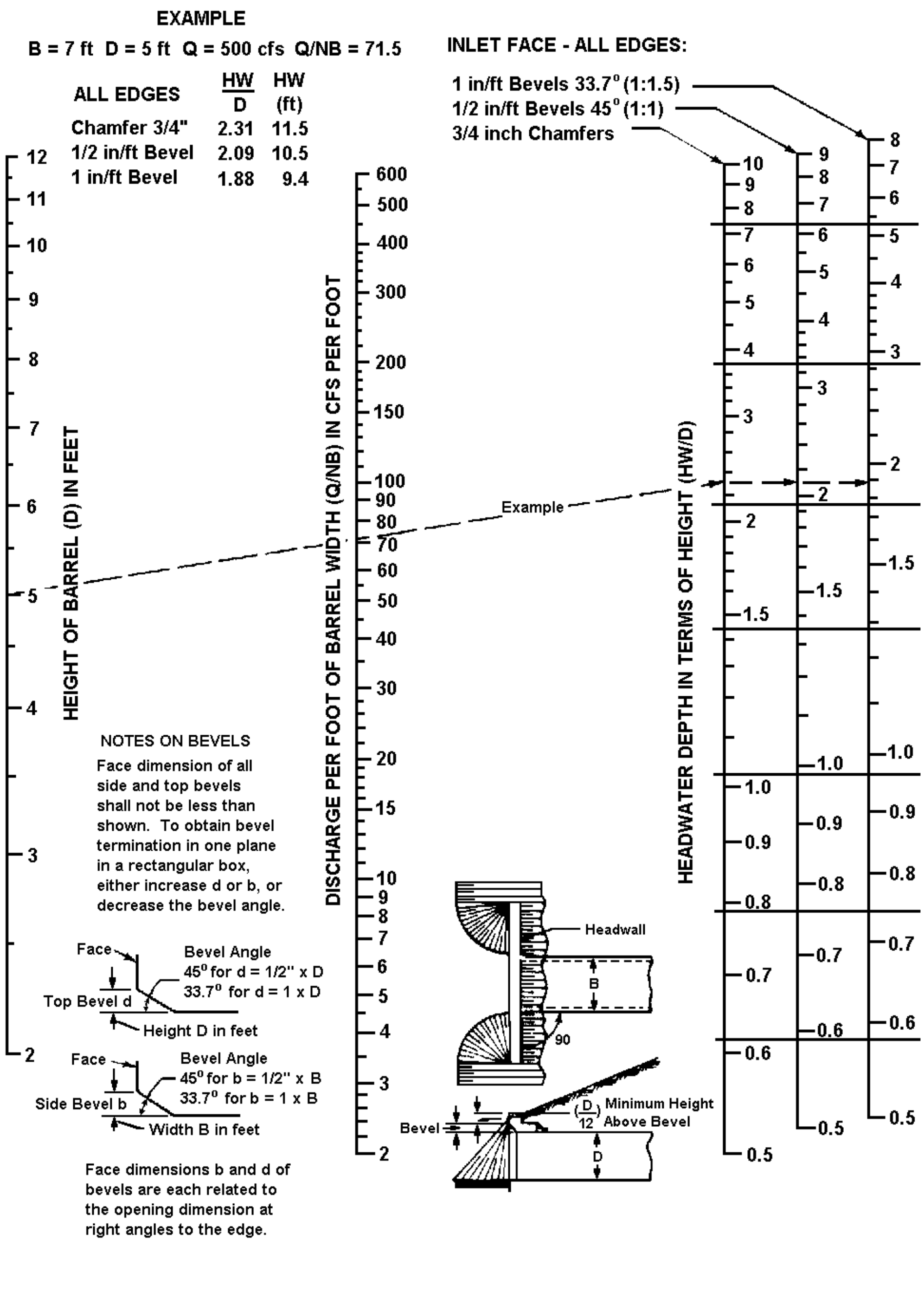
HEADWATER DEPTH FOR BOX CULVERTS WITH INLET CONTROL

CHART 9



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS 18° TO 33.7° & 45°
WITH BEVELED EDGE AT TOP OF INLET

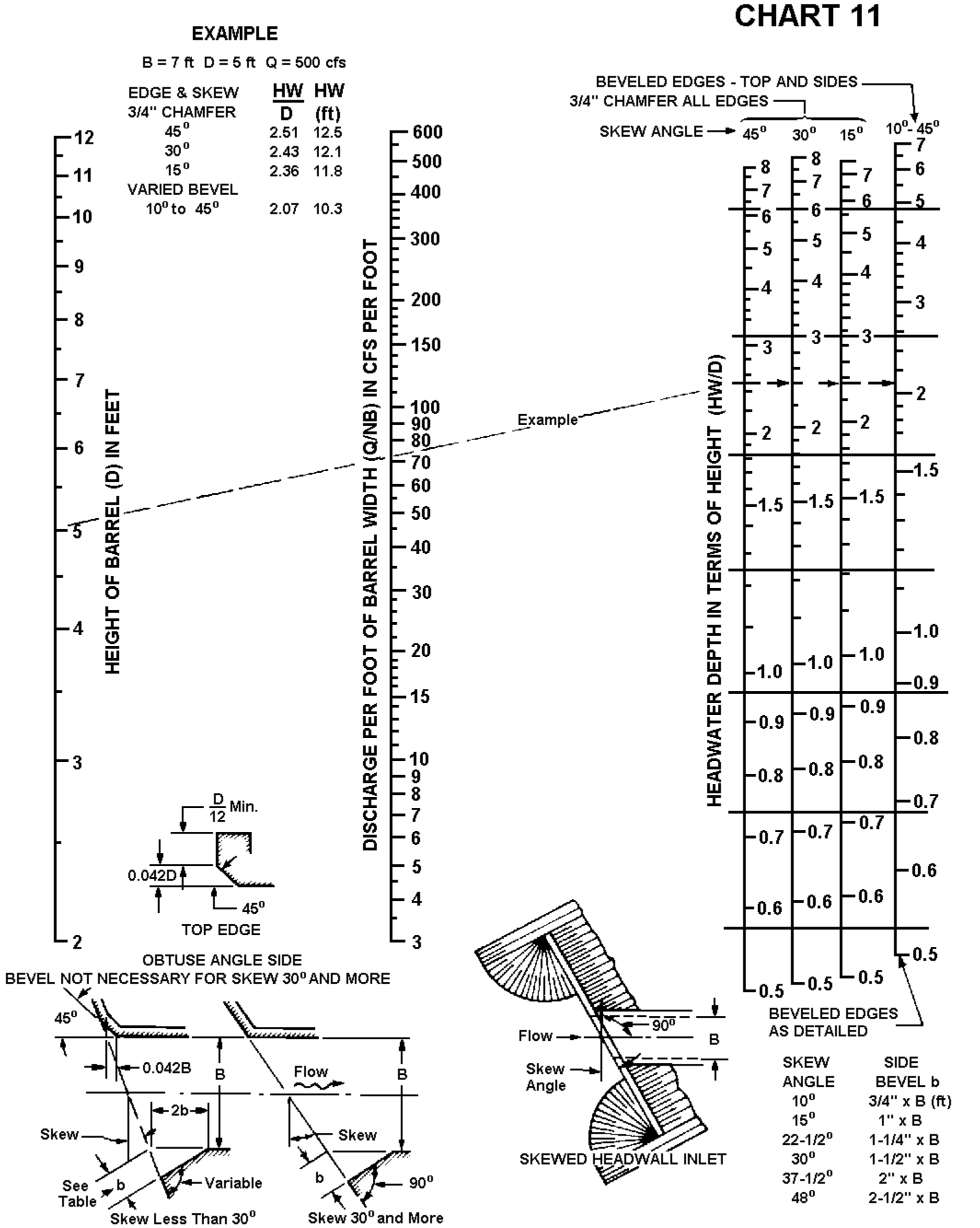
CHART 10



FEDERAL HIGHWAY ADMINISTRATION MAY 1973

HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
90° HEADWALL
CHAMFERED OR BEVELED INLET EDGES

CHART 11

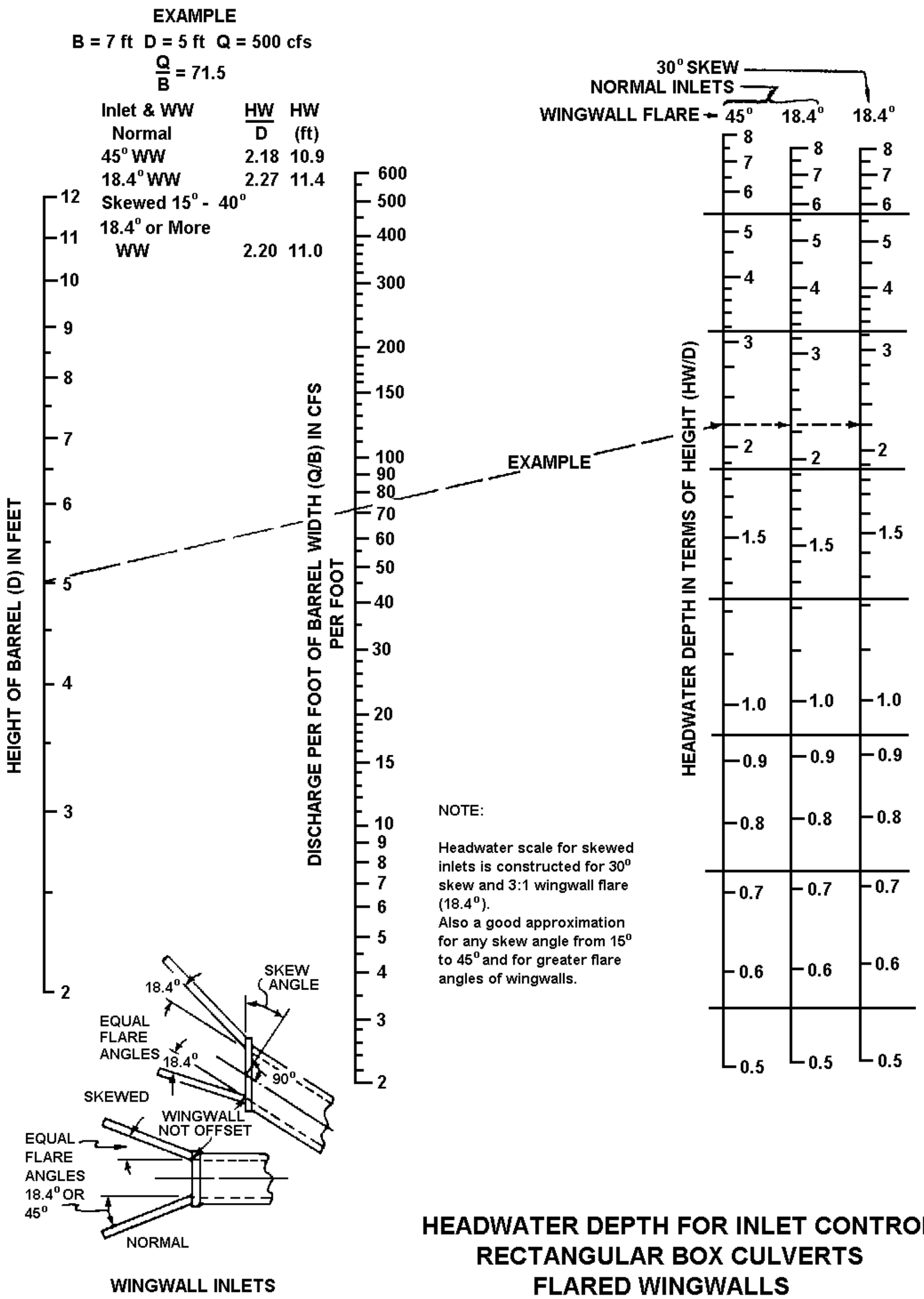


ACUTE ANGLE SIDE
BEVELED INLET EDGES
DESIGNED FOR SAME CAPACITY AT ANY SKEW

HEADWATER DEPTH FOR INLET CONTROL
SINGLE BARREL BOX CULVERTS
SKEWED HEADWALLS
CHAMFERED OR BEVELED INLET EDGES

FEDERAL HIGHWAY ADMINISTRATION MAY 1973

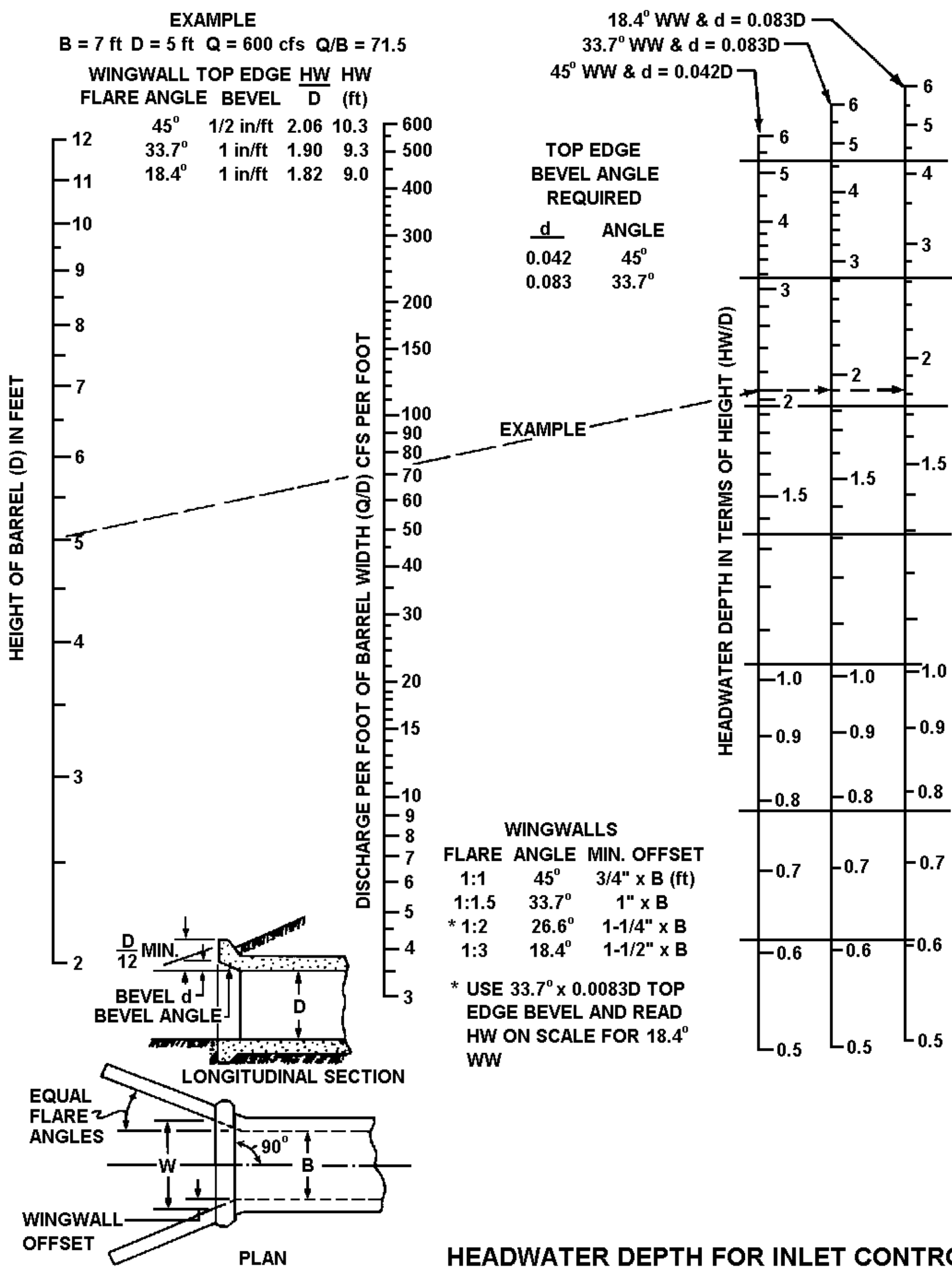
CHART 12



HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
FLARED WINGWALLS
NORMAL AND SKEWED INLETS
3/4" CHAMFER AT TOP OF OPENING

BUREAU OF PUBLIC ROADS
OFFICE OF R&D AUGUST 1968

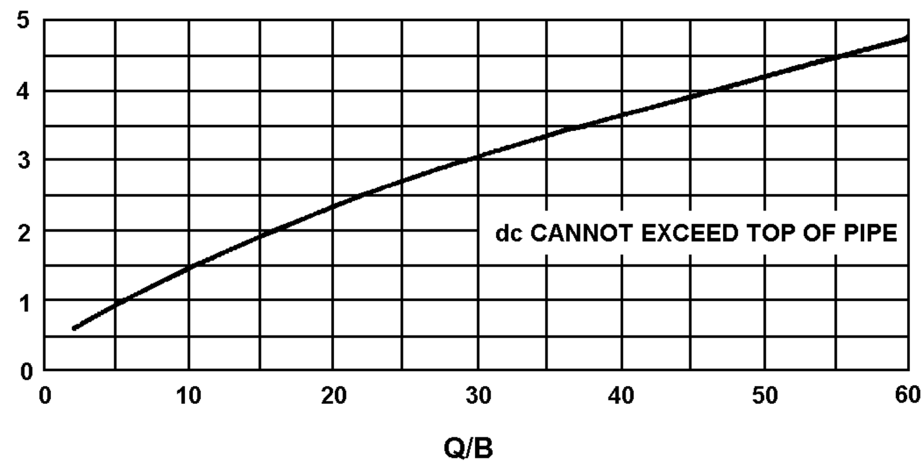
CHART 13

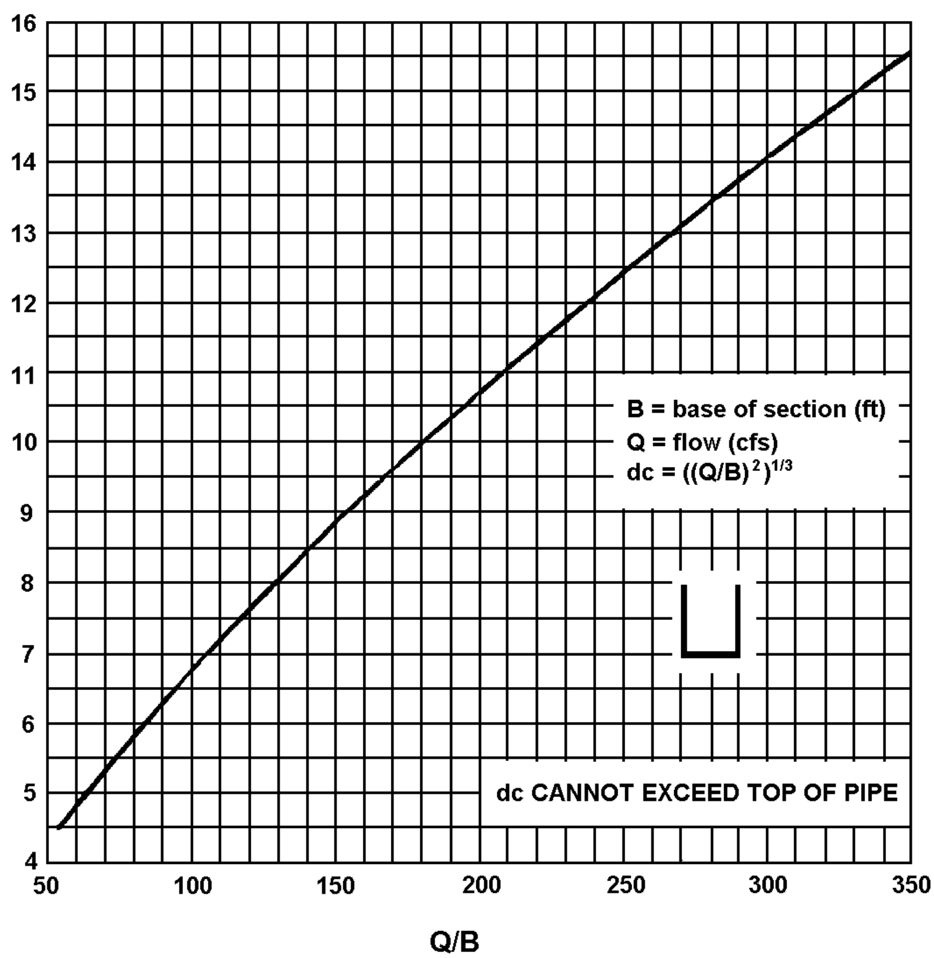


HEADWATER DEPTH FOR INLET CONTROL
RECTANGULAR BOX CULVERTS
OFFSET FLARED WINGWALLS
AND BEVELED EDGE AT TOP OF INLET

BUREAU OF PUBLIC ROADS
OFFICE OF R&D AUGUST 1968

CHART 14

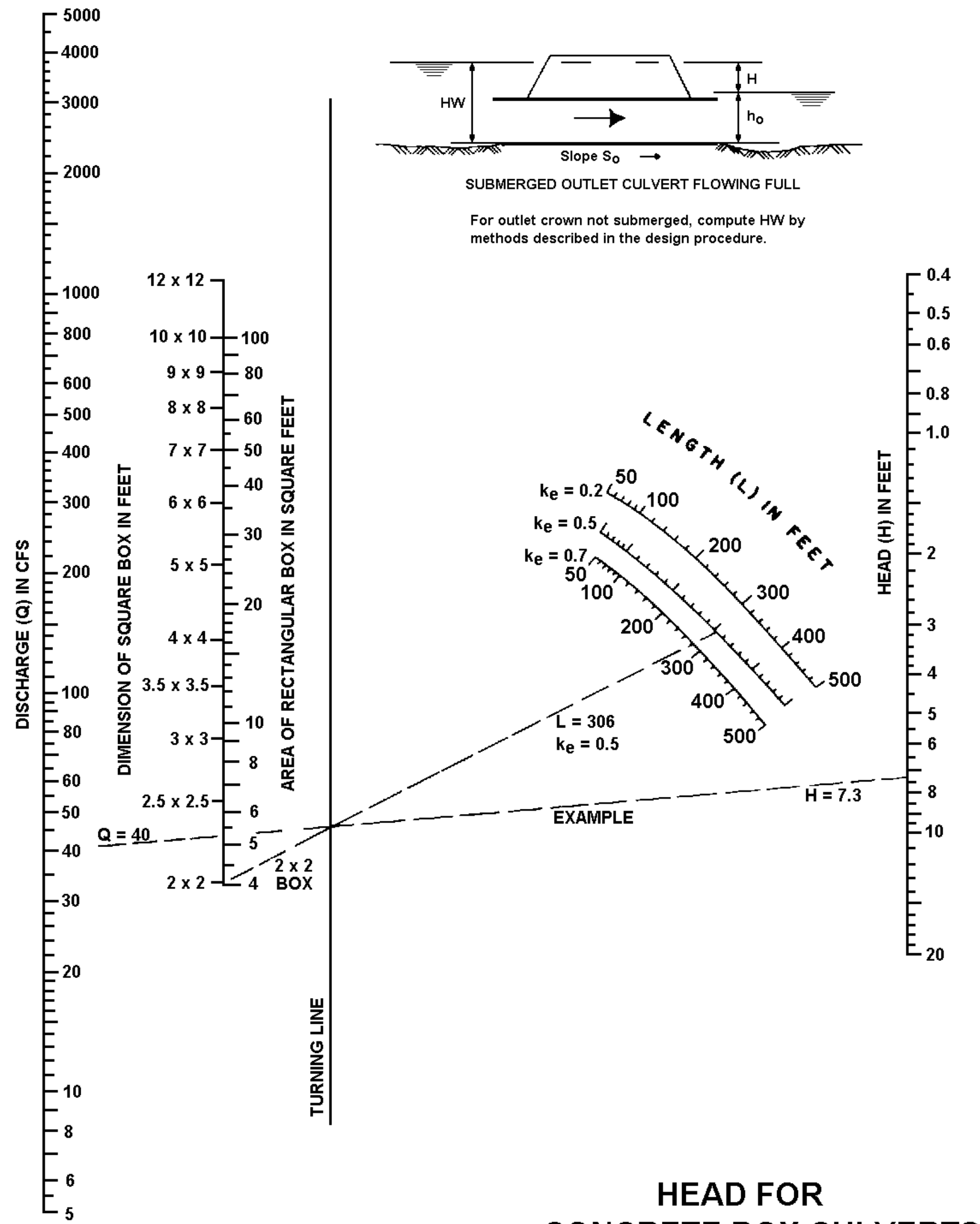




BUREAU OF PUBLIC ROADS JAN. 1963

CRITICAL DEPTH
RECTANGULAR SECTION

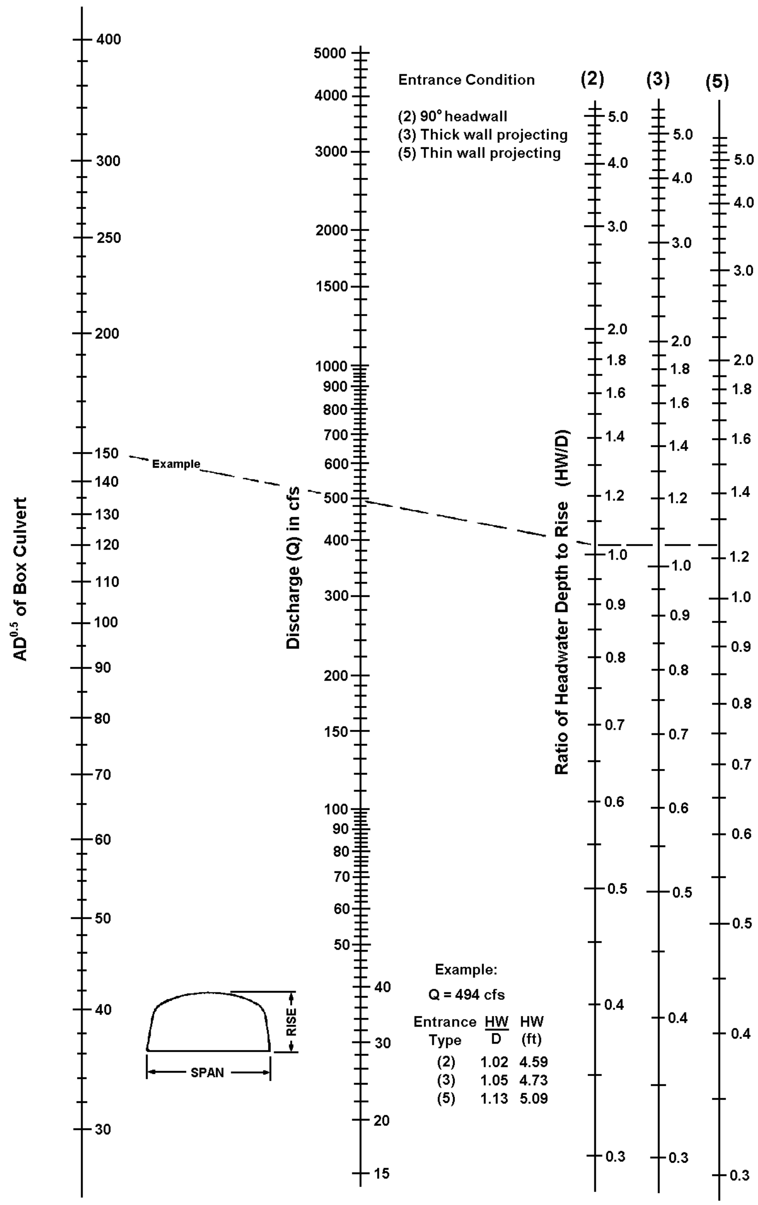
CHART 15



HEAD FOR CONCRETE BOX CULVERTS FLOWING FULL
n = 0.012

BUREAU OF PUBLIC ROADS JAN. 1963

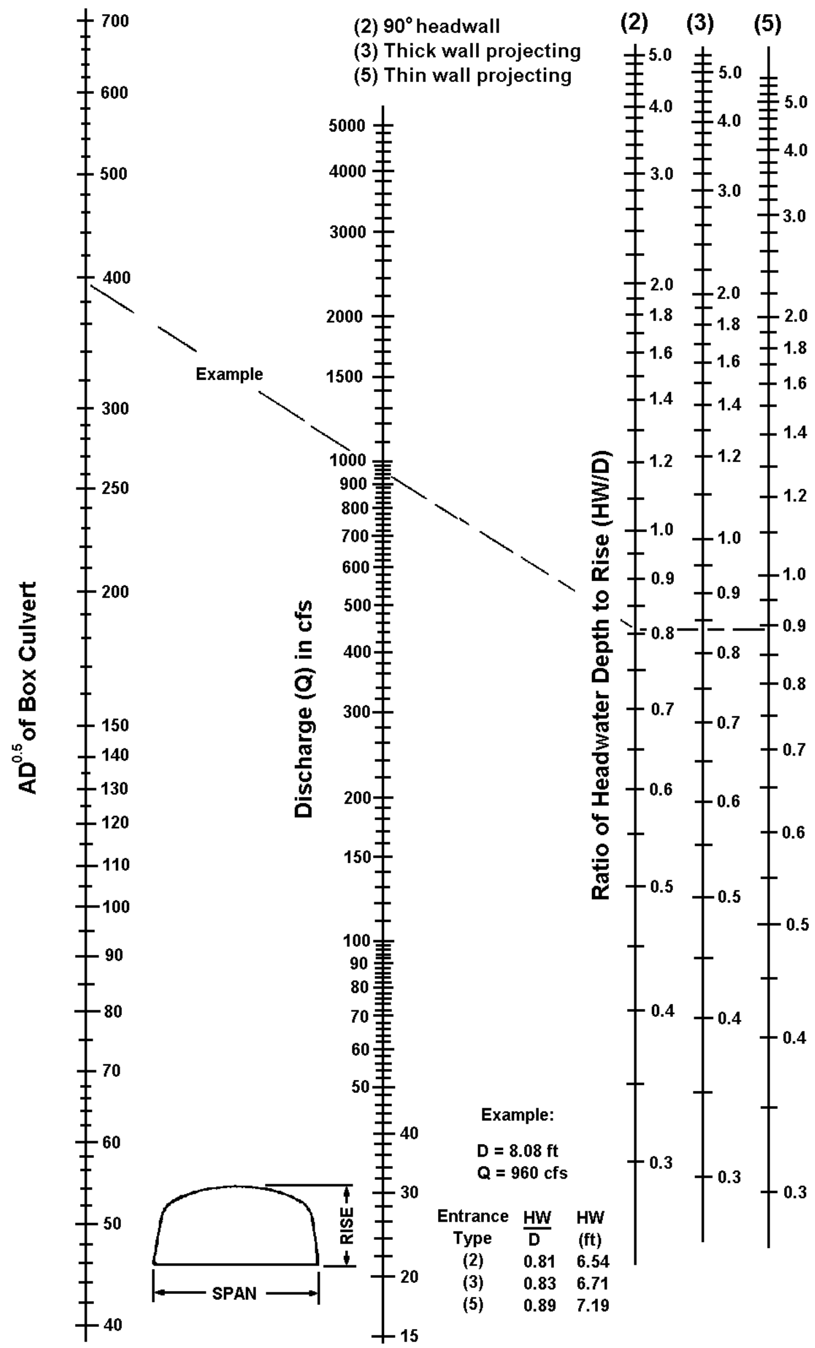
CHART 16



HEADWATER DEPTH
FOR C.M. BOX CULVERTS
RISE/SPAN < 0.3
WITH INLET CONTROL

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation.

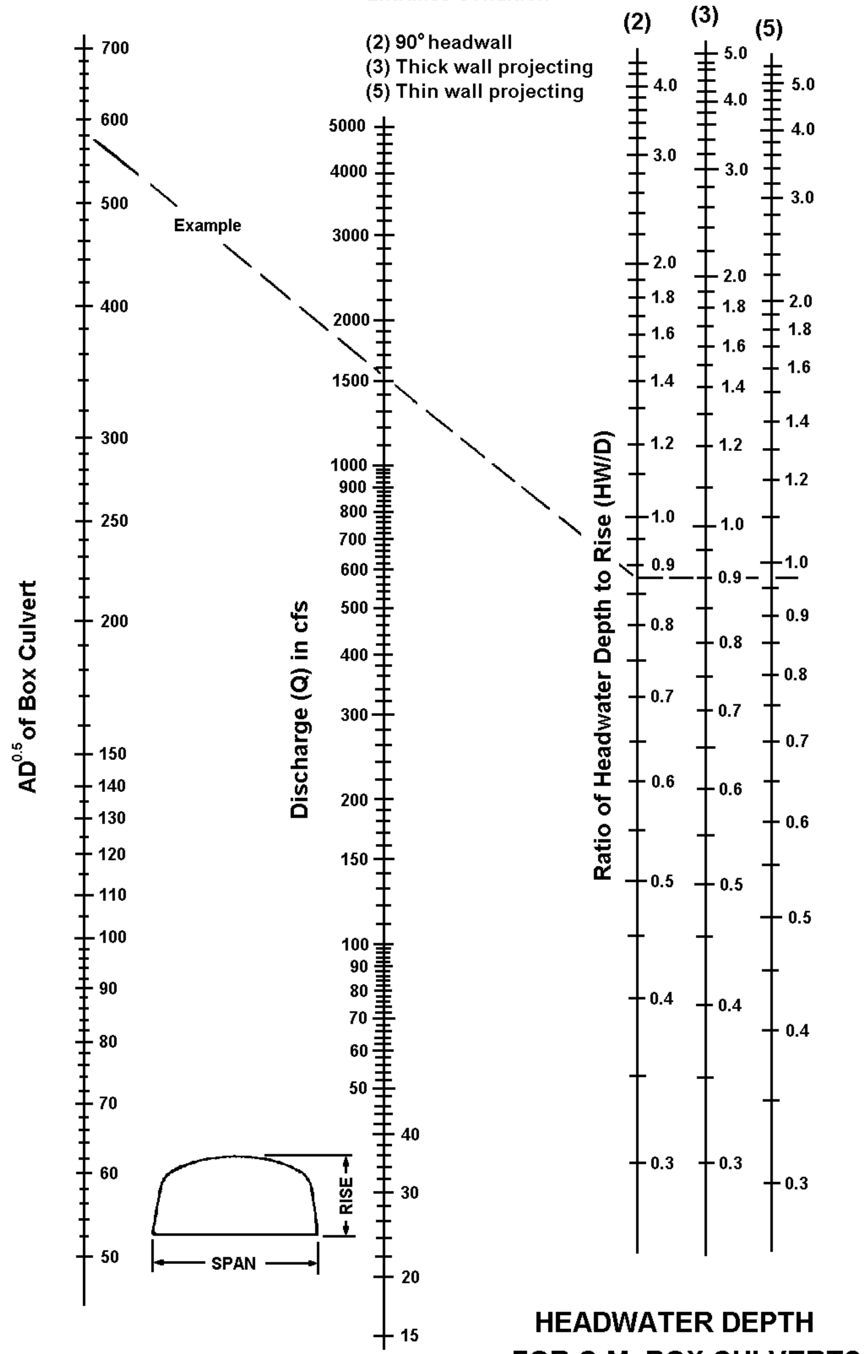
CHART 17



HEADWATER DEPTH FOR C.M. BOX CULVERTS 0.3≤ RISE/SPAN < 0.4 WITH INLET CONTROL

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

CHART 18



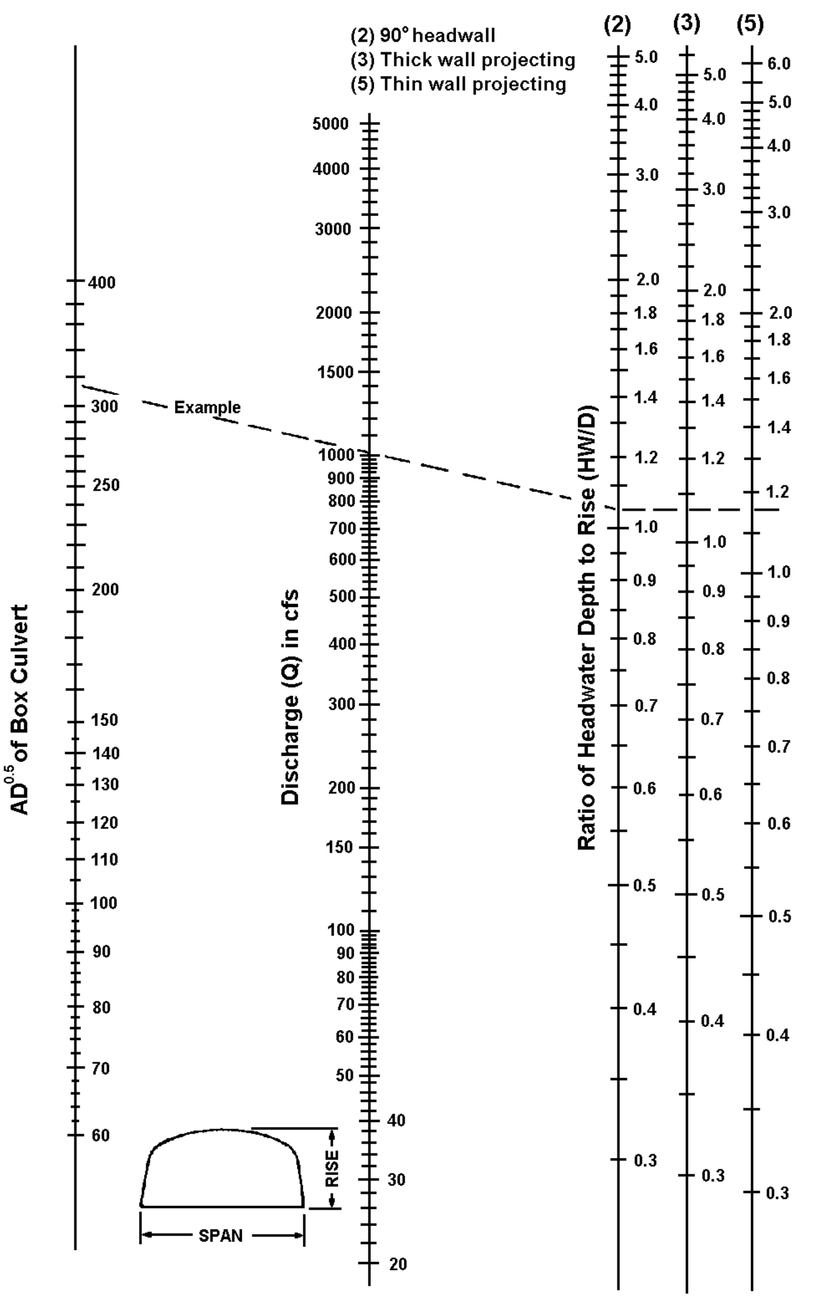
Example:
D = 9.67 ft
Q = 1520 cfs

Entrance Type	HW/D	HW (ft)
(2)	0.88	8.51
(3)	0.90	9.38
(5)	0.97	9.38

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

HEADWATER DEPTH FOR C.M. BOX CULVERTS $0.4 \le$ RISE/SPAN < 0.5 WITH INLET CONTROL

CHART 19



Example:

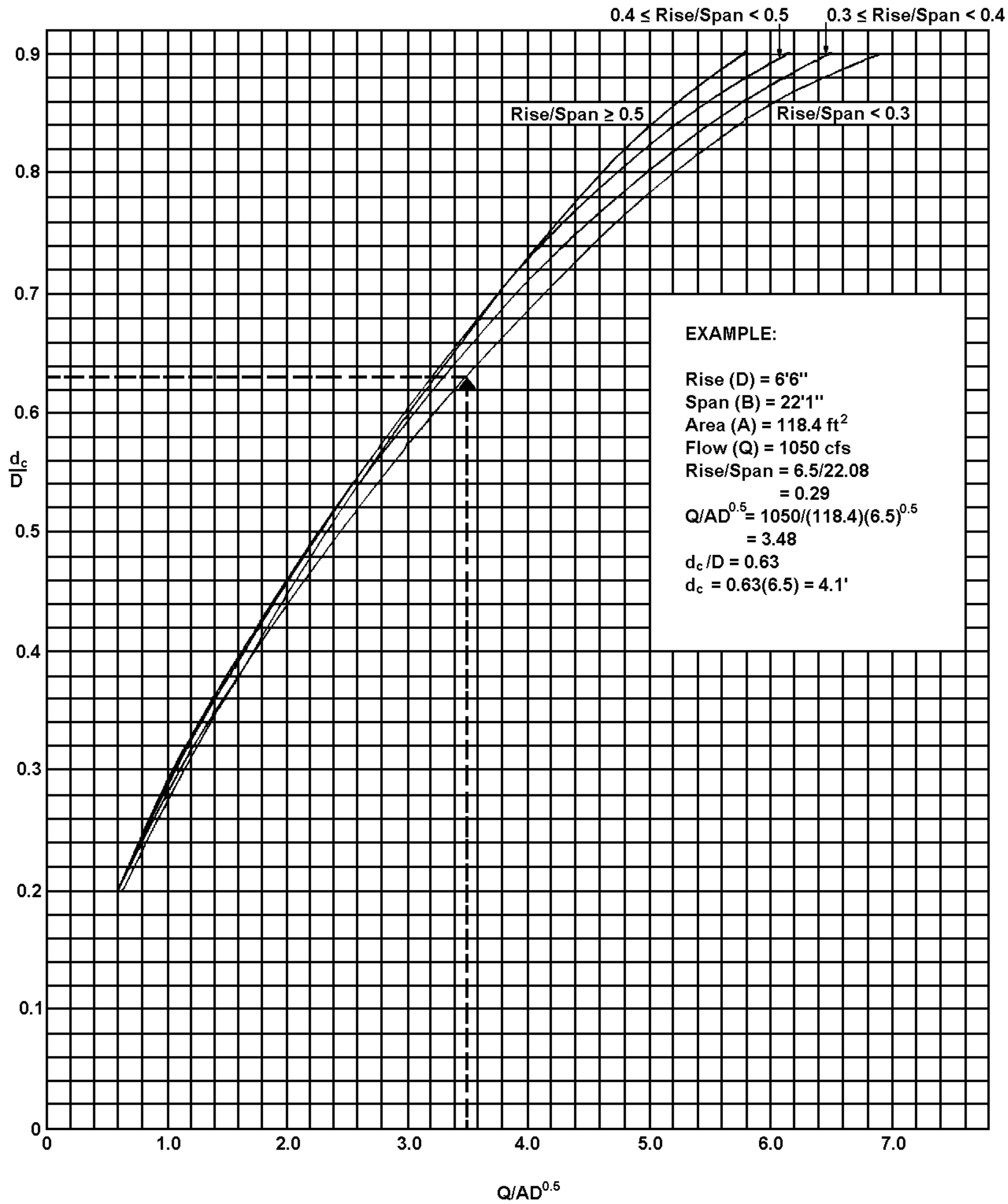
D = 8.0 ft
Q = 1004 cfs

Entrance Type	HW/D	HW (ft)
(2)	1.04	8.32
(3)	1.07	8.58
(5)	1.15	9.20

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation.

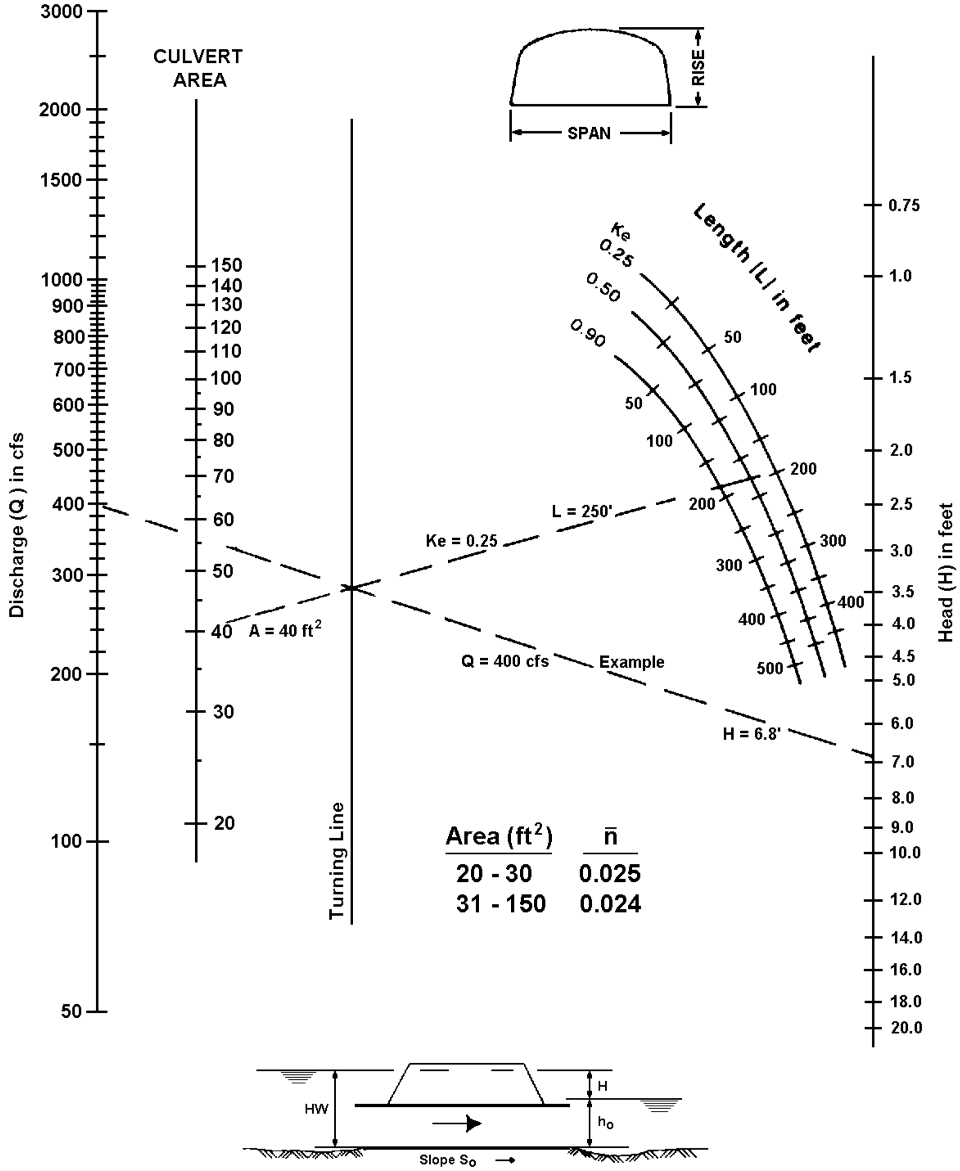
HEADWATER DEPTH FOR C.M. BOX CULVERTS $0.5 \leq$ RISE/SPAN WITH INLET CONTROL

CHART 20



0.4 ≤ Rise/Span < 0.5
0.3 ≤ Rise/Span < 0.4
Rise/Span ≥ 0.5
Rise/Span < 0.3
EXAMPLE:
Rise (D) = 6'6"
Span (B) = 22'1"
Area (A) = 118.4 ft^2
Flow (Q) = 1050 cfs
Rise/Span = 6.5/22.08
= 0.29
Q/AD$^{0.5}$= 1050/(118.4)(6.5)$^{0.5}$
= 3.48
d_c/D = 0.63
d_c = 0.63(6.5) = 4.1'
$\frac{d_c}{D}$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Q/AD$^{0.5}$

CHART 21



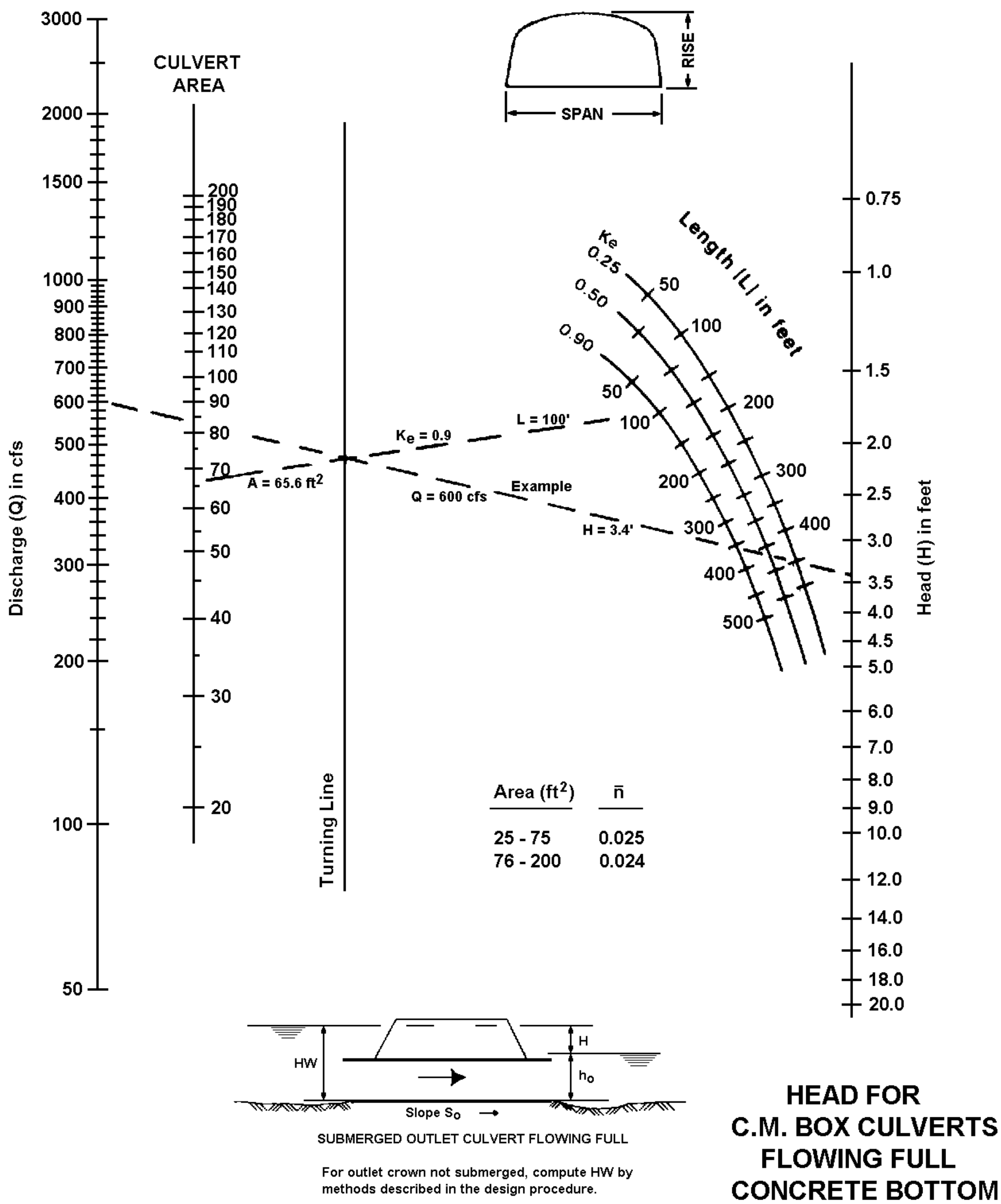
SUBMERGED OUTLET CULVERT FLOWING FULL

For outlet crown not submerged, compute HW by methods described in the design procedure.

HEAD FOR C.M. BOX CULVERTS FLOWING FULL CONCRETE BOTTOM RISE/SPAN < 0.3

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

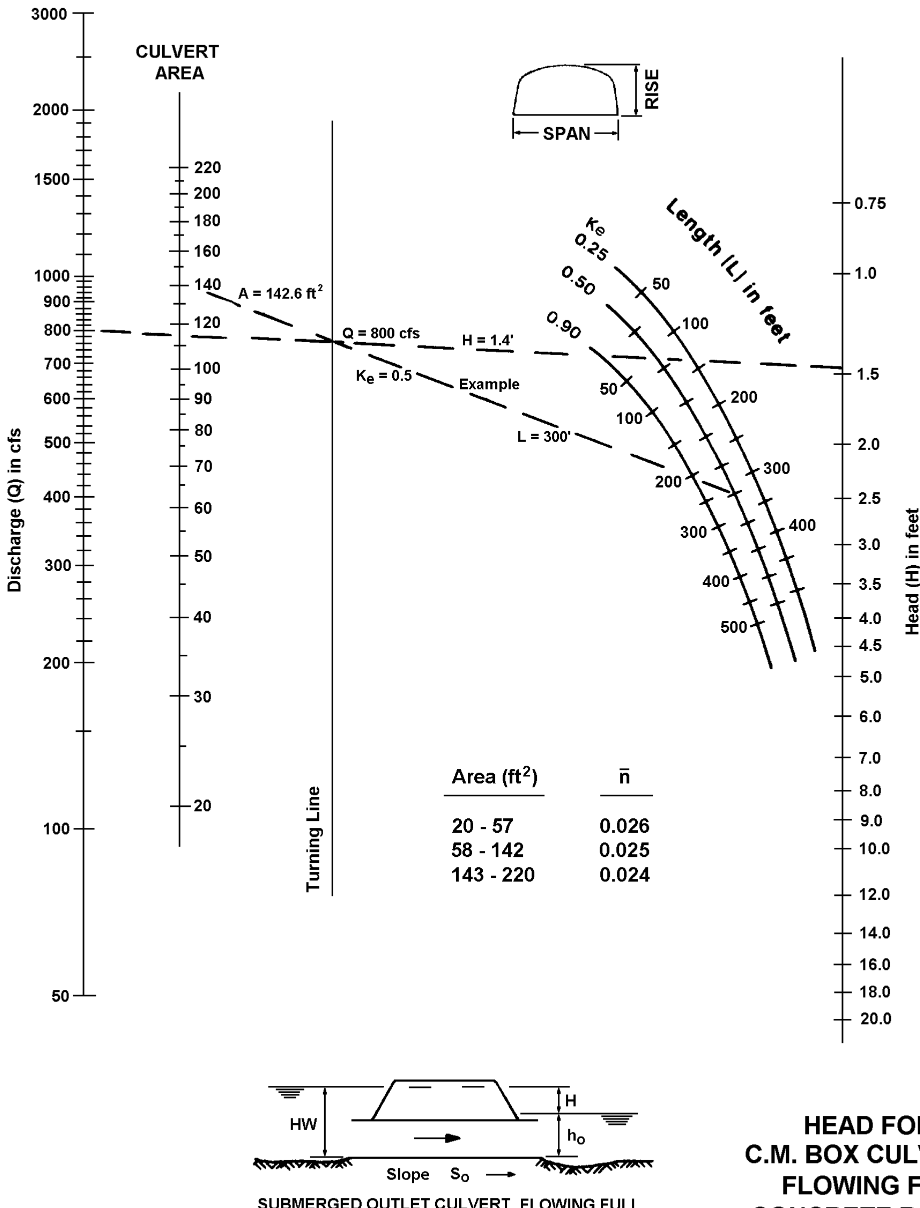
CHART 22



**HEAD FOR
C.M. BOX CULVERTS
FLOWING FULL
CONCRETE BOTTOM
$0.3 \leq$ RISE/SPAN < 0.4**

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

CHART 23

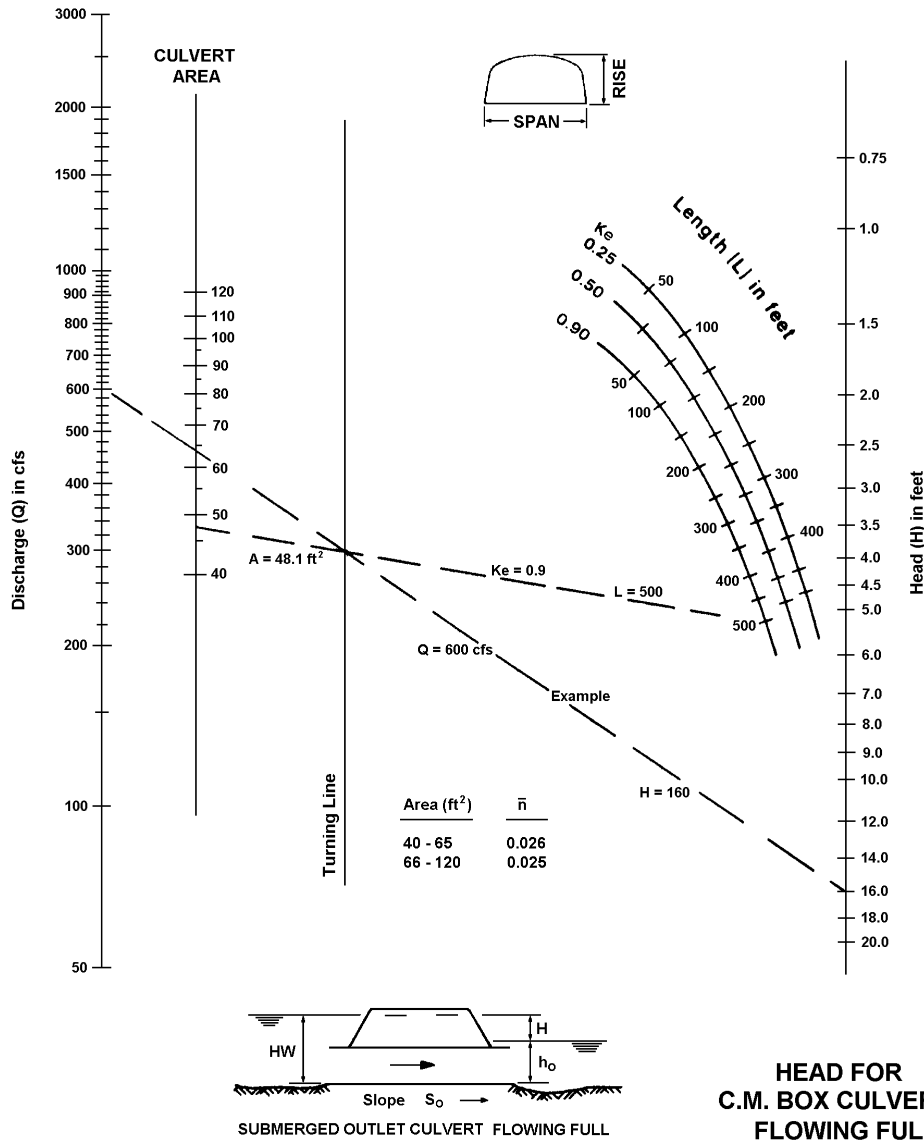


Area (ft²)	n̄
20 - 57	0.026
58 - 142	0.025
143 - 220	0.024

HEAD FOR C.M. BOX CULVERTS FLOWING FULL CONCRETE BOTTOM $0.4 \leq$ RISE/SPAN < 0.5

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

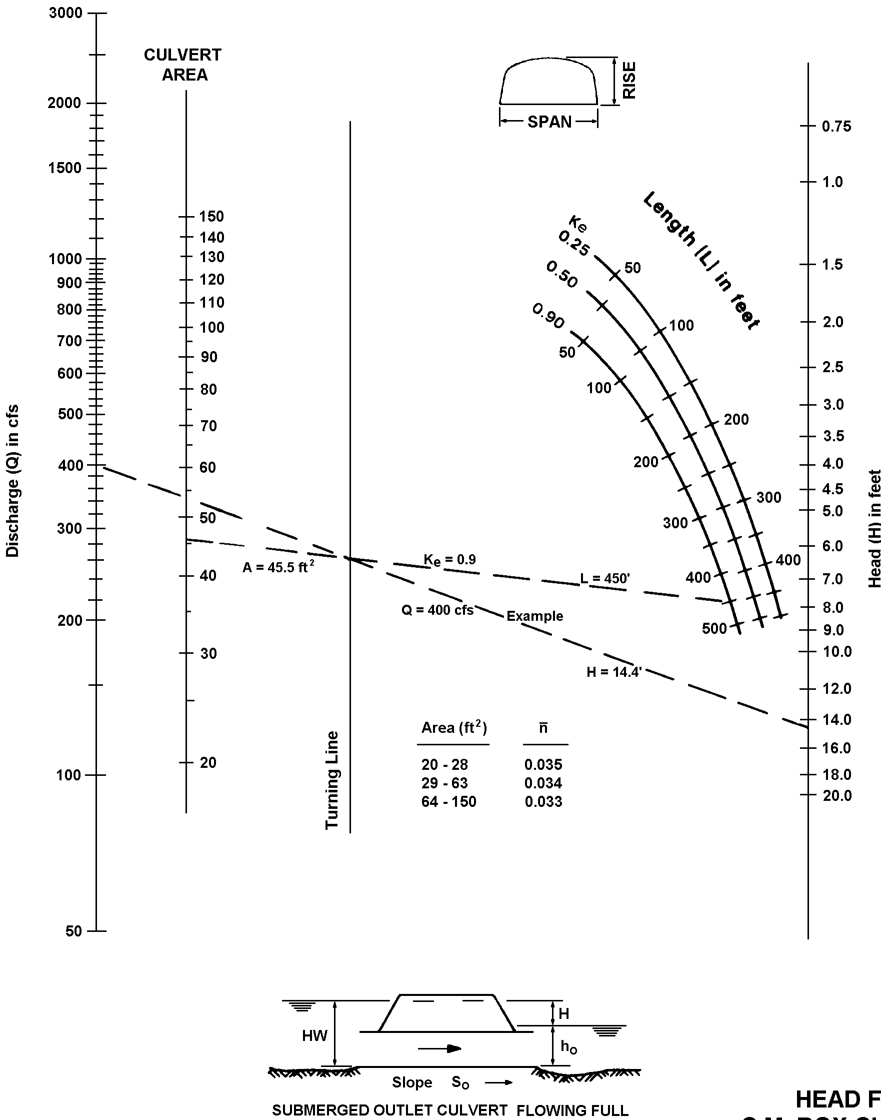
CHART 24



HEAD FOR
C.M. BOX CULVERTS
FLOWING FULL
CONCRETE BOTTOM
0.5 ≤ RISE/SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

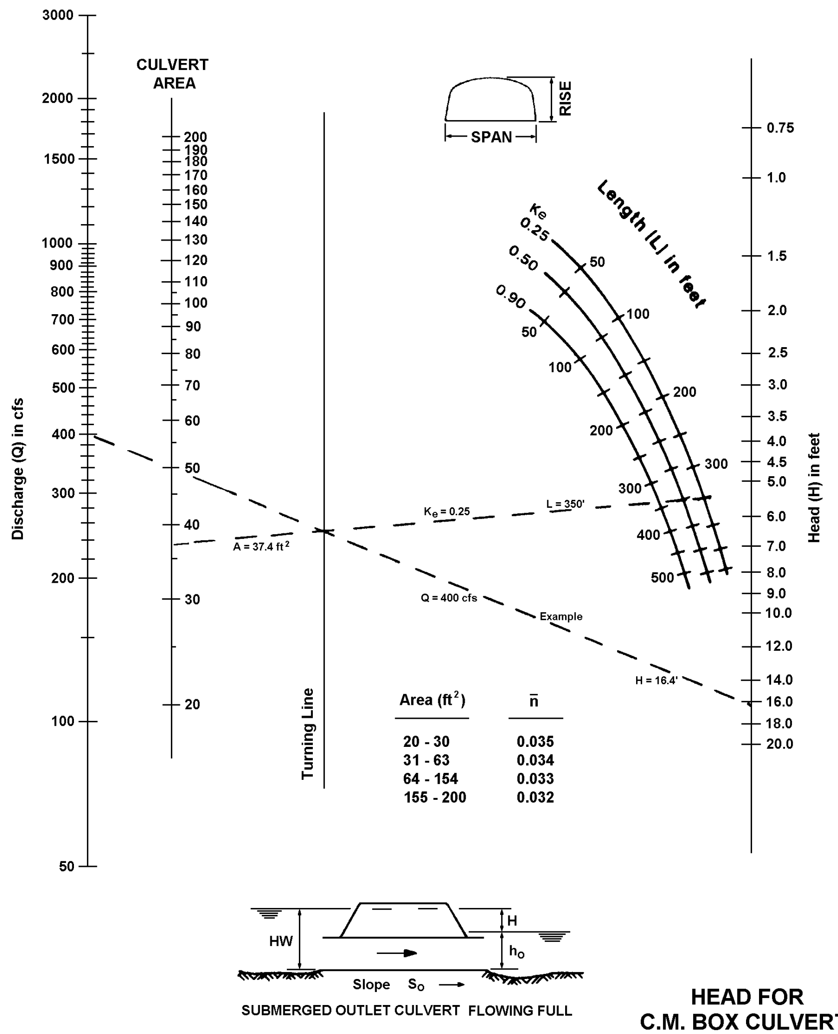
CHART 25



Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

HEAD FOR C.M. BOX CULVERTS FLOWING FULL CORRUGATED METAL BOTTOM 0.3< RISE/SPAN

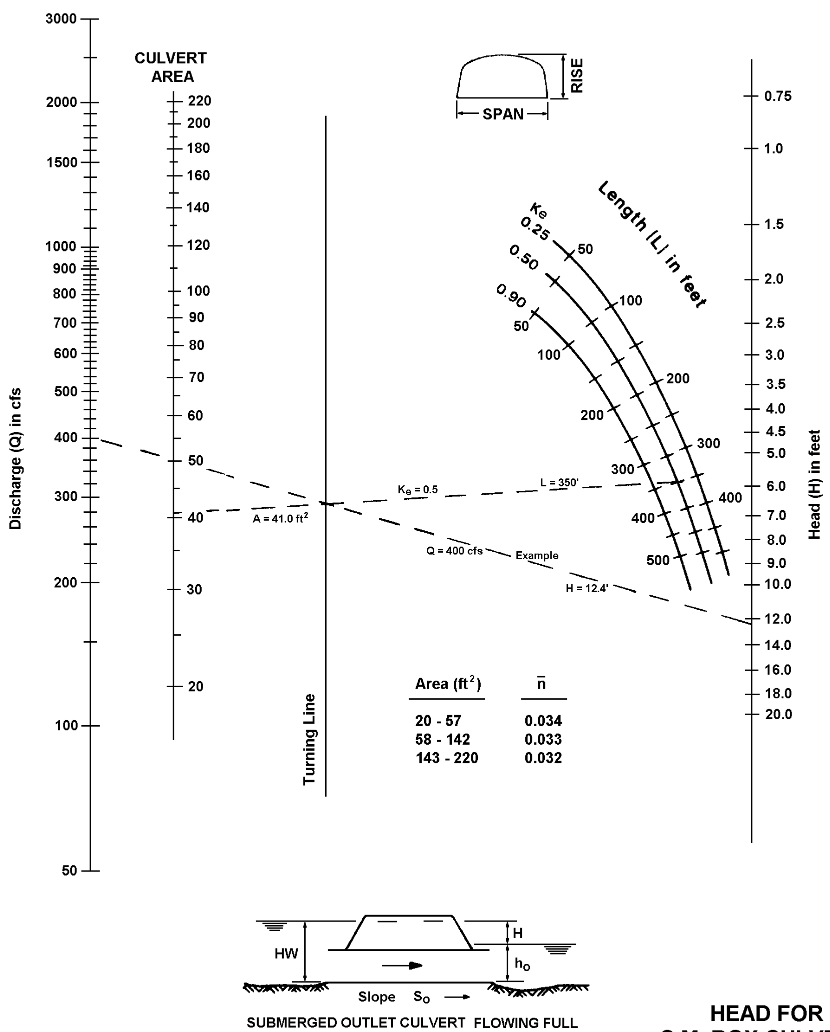
CHART 26



HEAD FOR
C.M. BOX CULVERTS
FLOWING FULL
CORRUGATED METAL BOTTOM
0.4 ≤ RISE/SPAN < 0.5

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

CHART 27

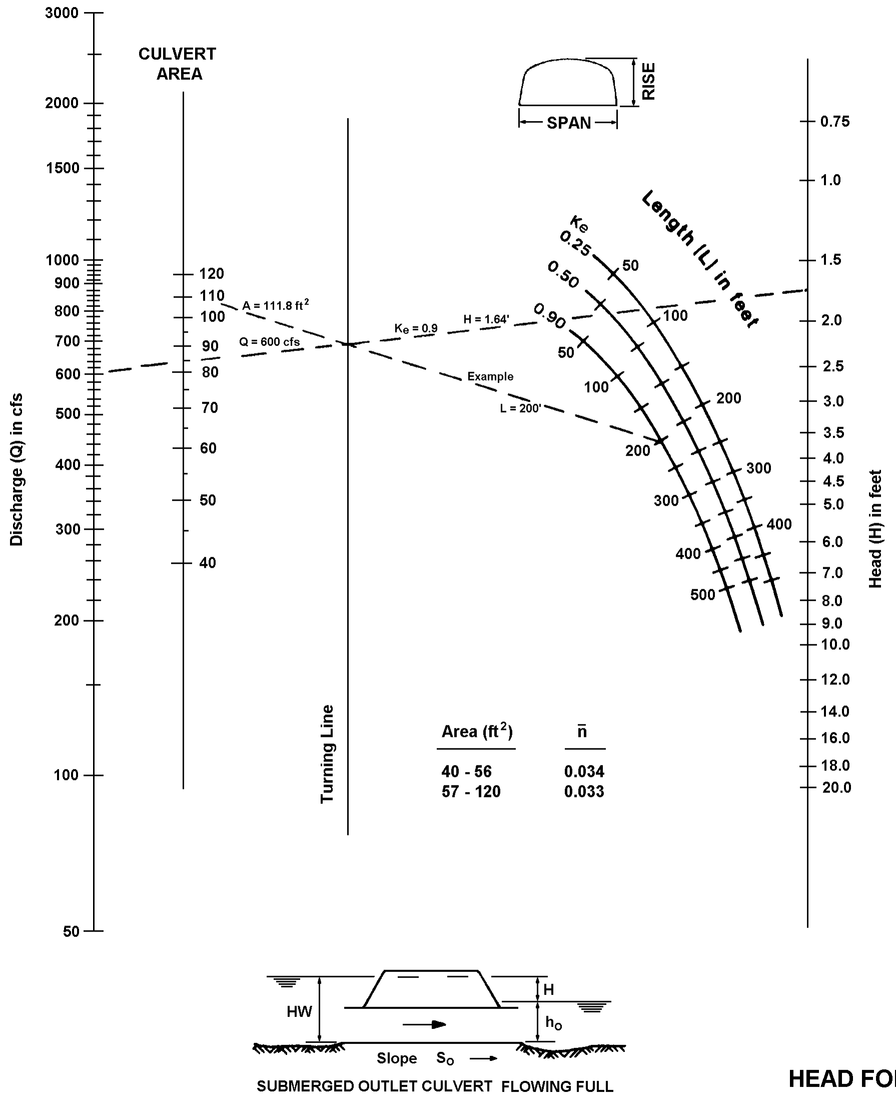


Area (ft^2)	$\bar{n}$
20 - 57	0.034
58 - 142	0.033
143 - 220	0.032

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

HEAD FOR C.M. BOX CULVERTS FLOWING FULL CORRUGATED METAL BOTTOM $0.4 \le$ RISE/SPAN < 0.5

CHART 28

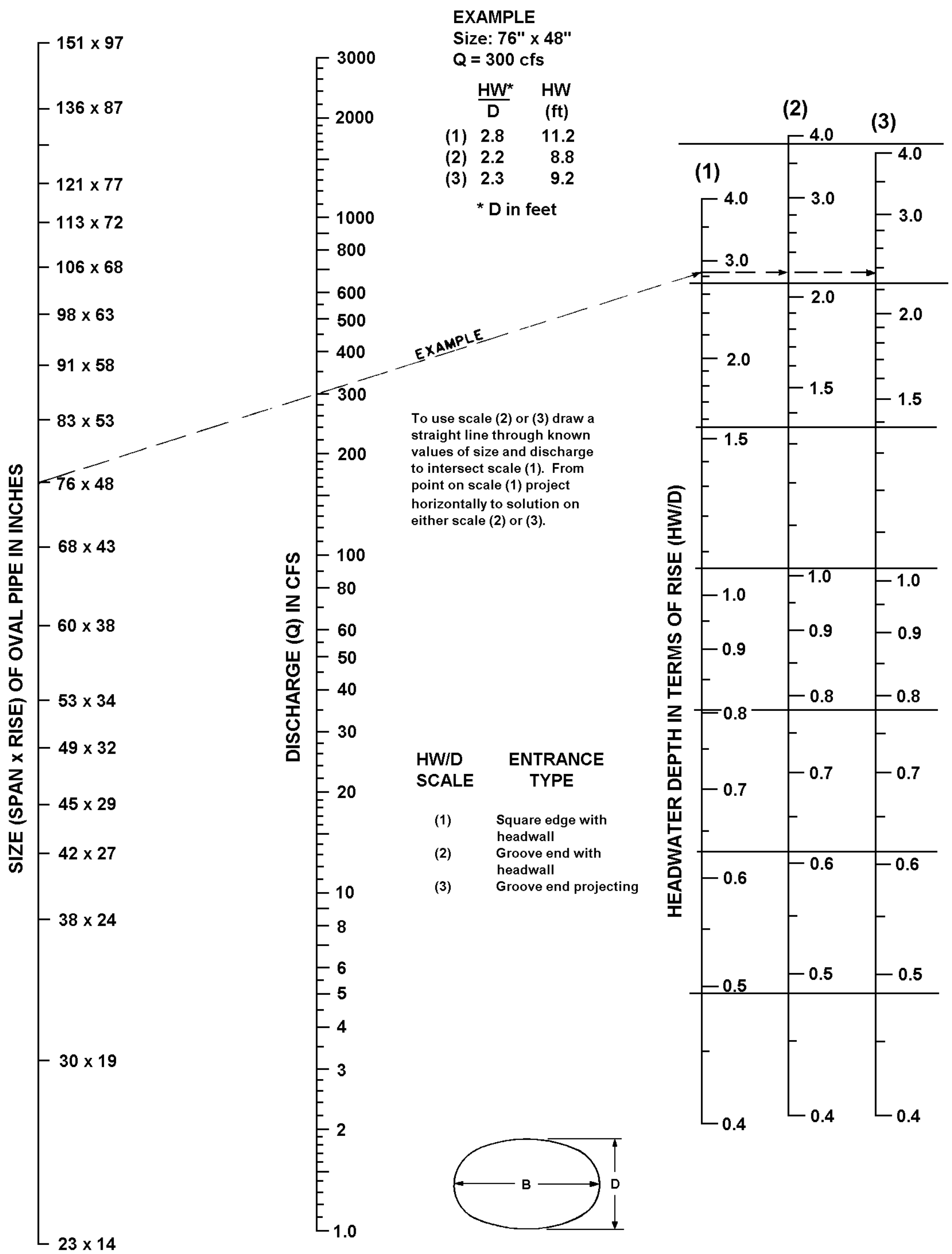


Area (ft^2)	$\bar{n}$
40 - 56	0.034
57 - 120	0.033

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

HEAD FOR C.M. BOX CULVERTS FLOWING FULL CORRUGATED METAL BOTTOM $0.5 \leq$ RISE/SPAN

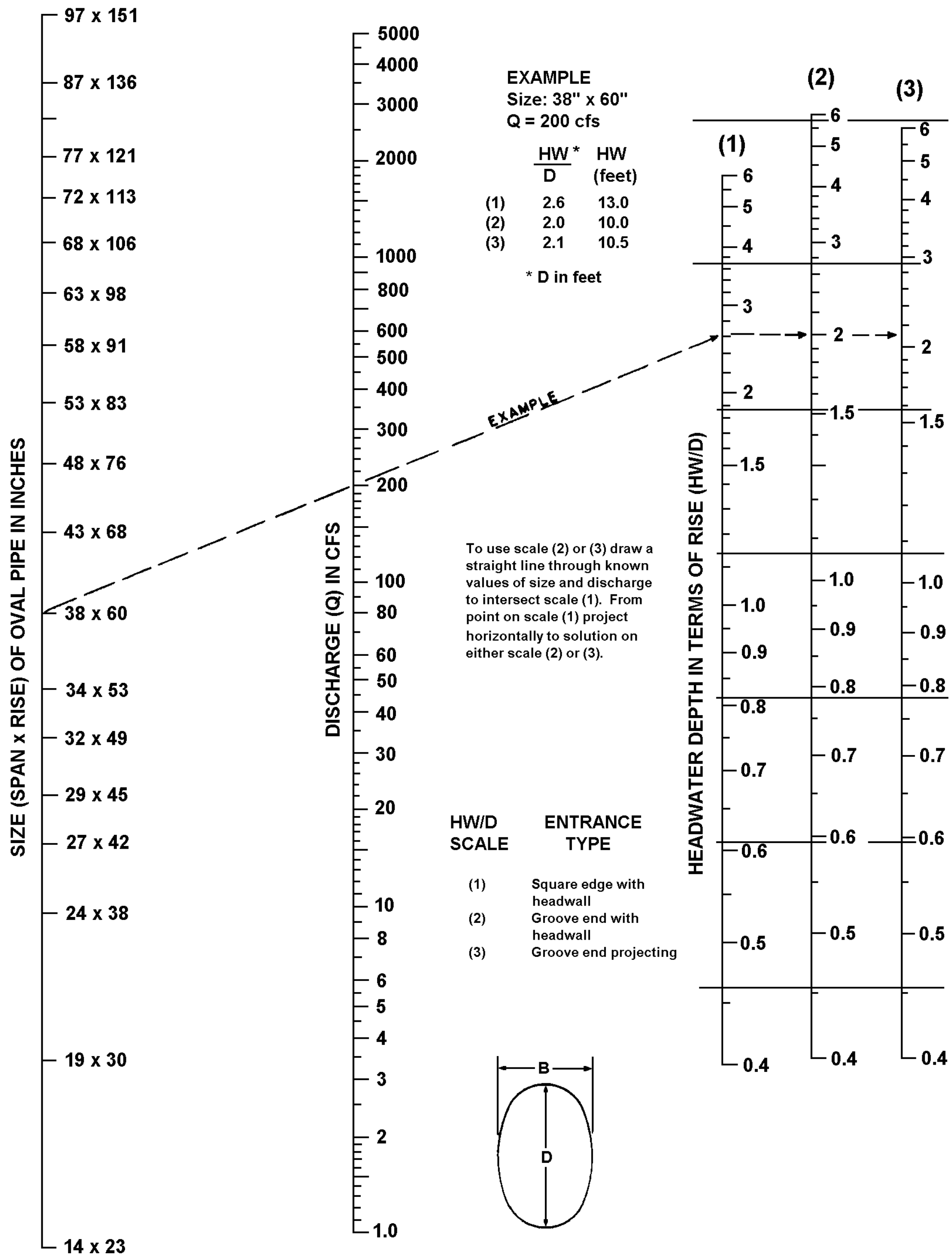
CHART 29



HEADWATER DEPTH FOR OVAL CONCRETE PIPE CULVERTS LONG AXIS HORIZONTAL WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

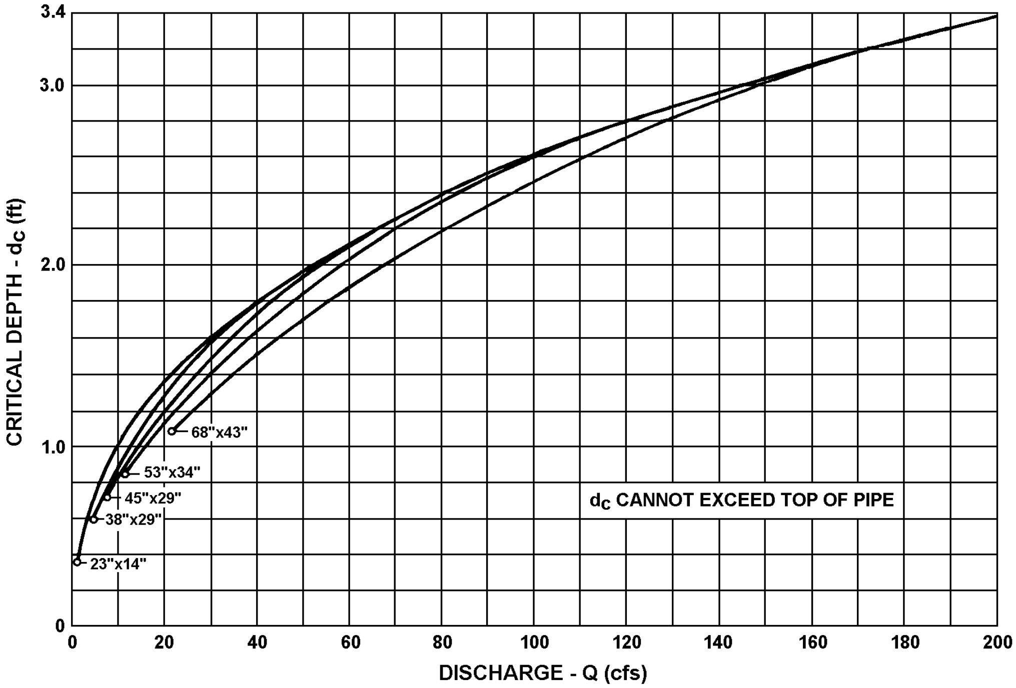
CHART 30

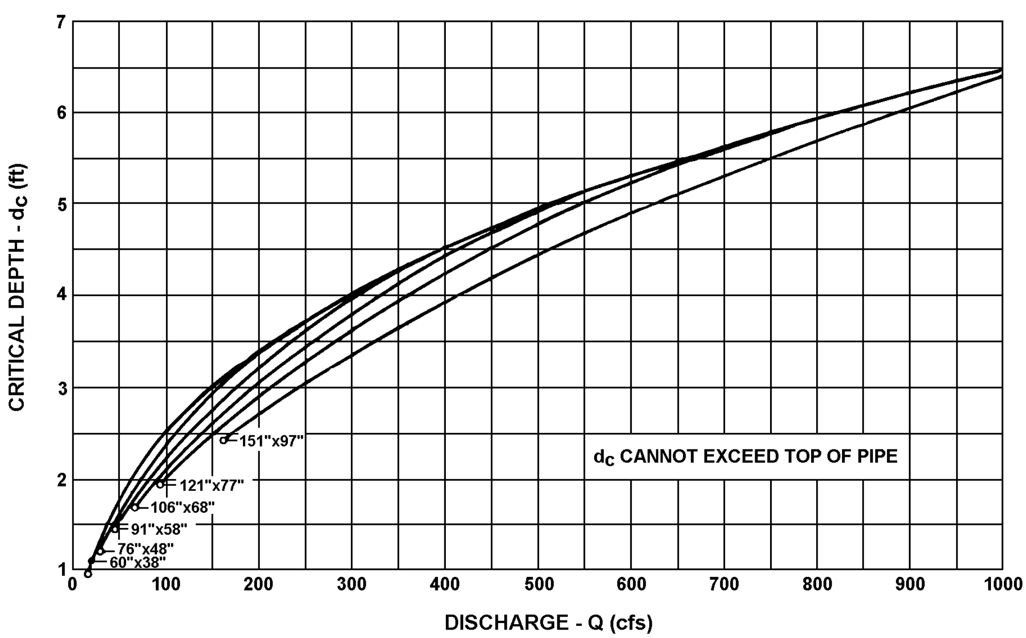


HEADWATER DEPTH FOR
OVAL CONCRETE PIPE CULVERTS
LONG AXIS VERTICAL
WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 31

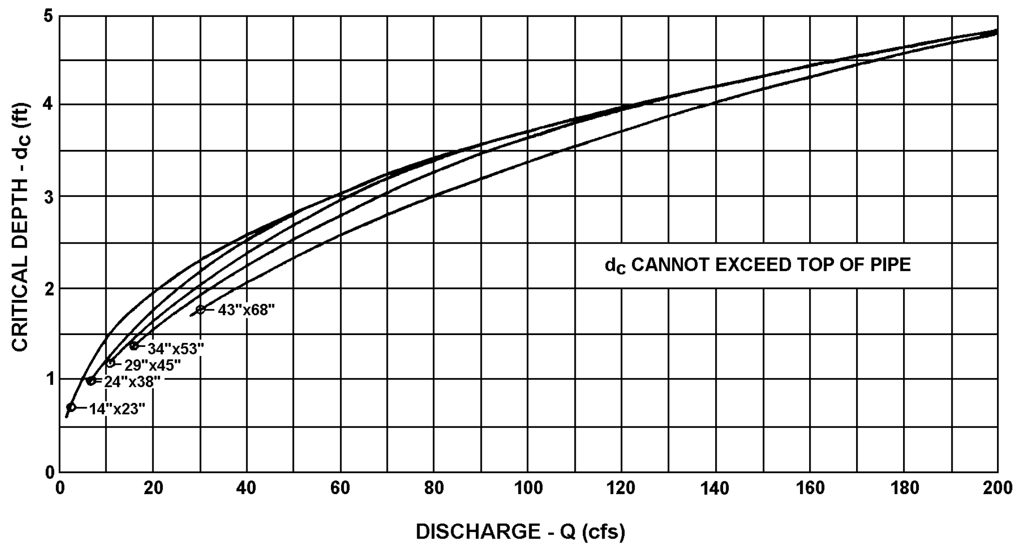


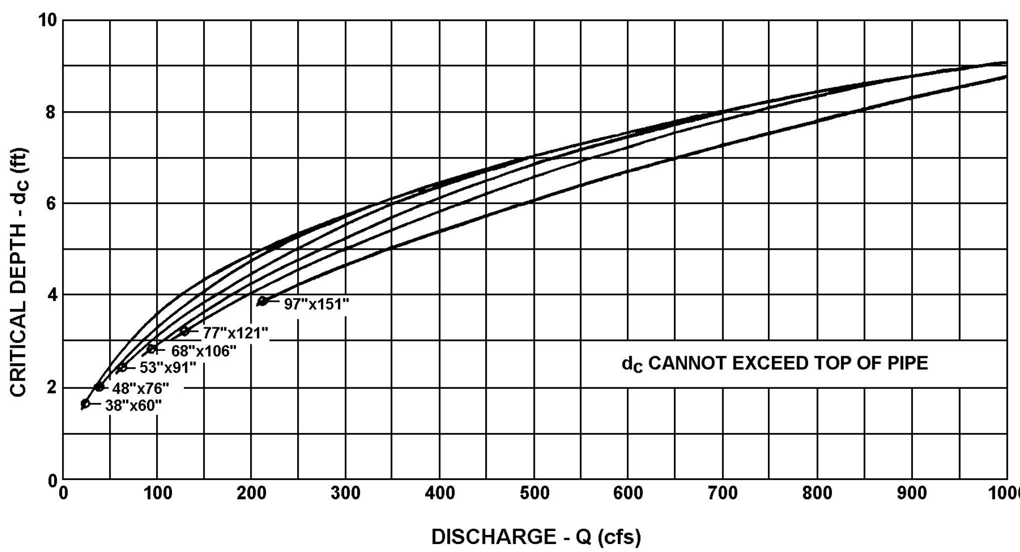


BUREAU OF PUBLIC ROADS JAN. 1964

CRITICAL DEPTH
OVAL CONCRETE PIPE
LONG AXIS HORIZONTAL

CHART 32

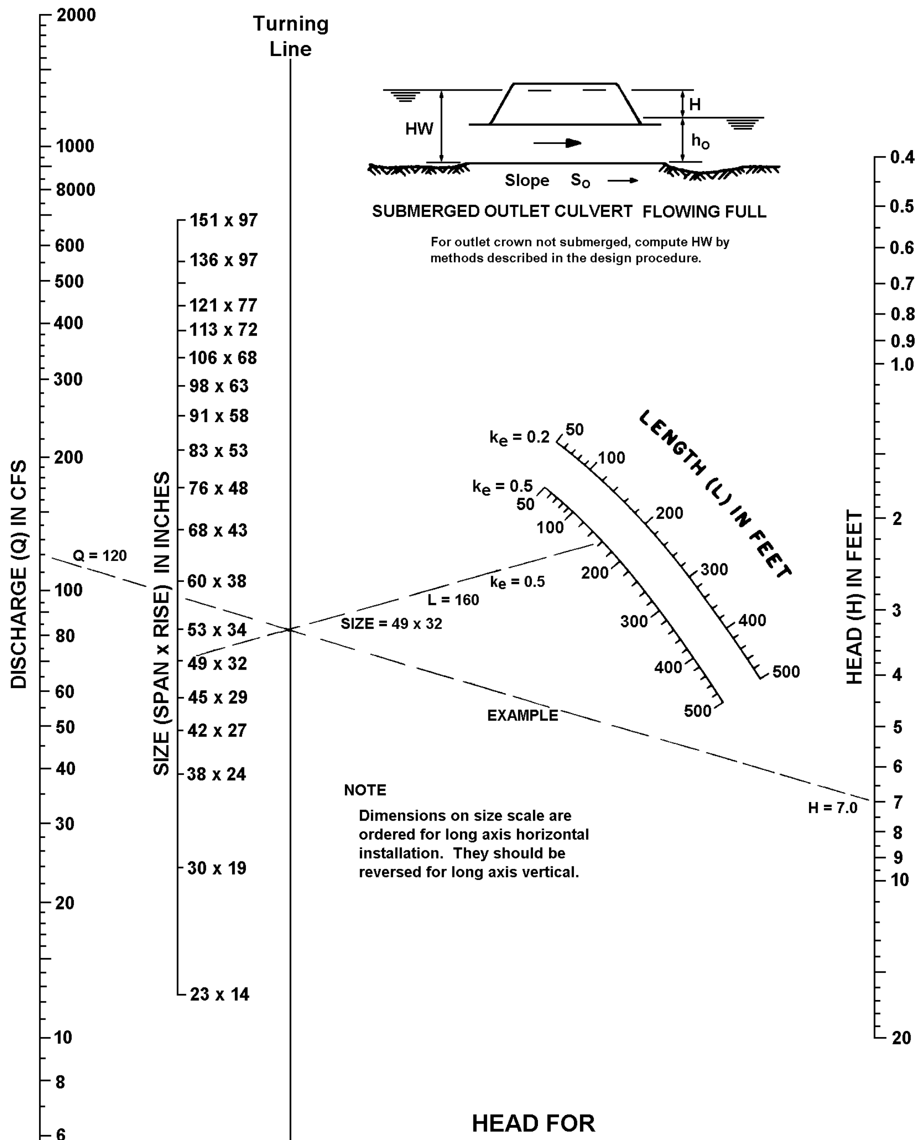




BUREAU OF PUBLIC ROADS JAN. 1964

CRITICAL DEPTH
OVAL CONCRETE PIPE
LONG AXIS VERTICAL

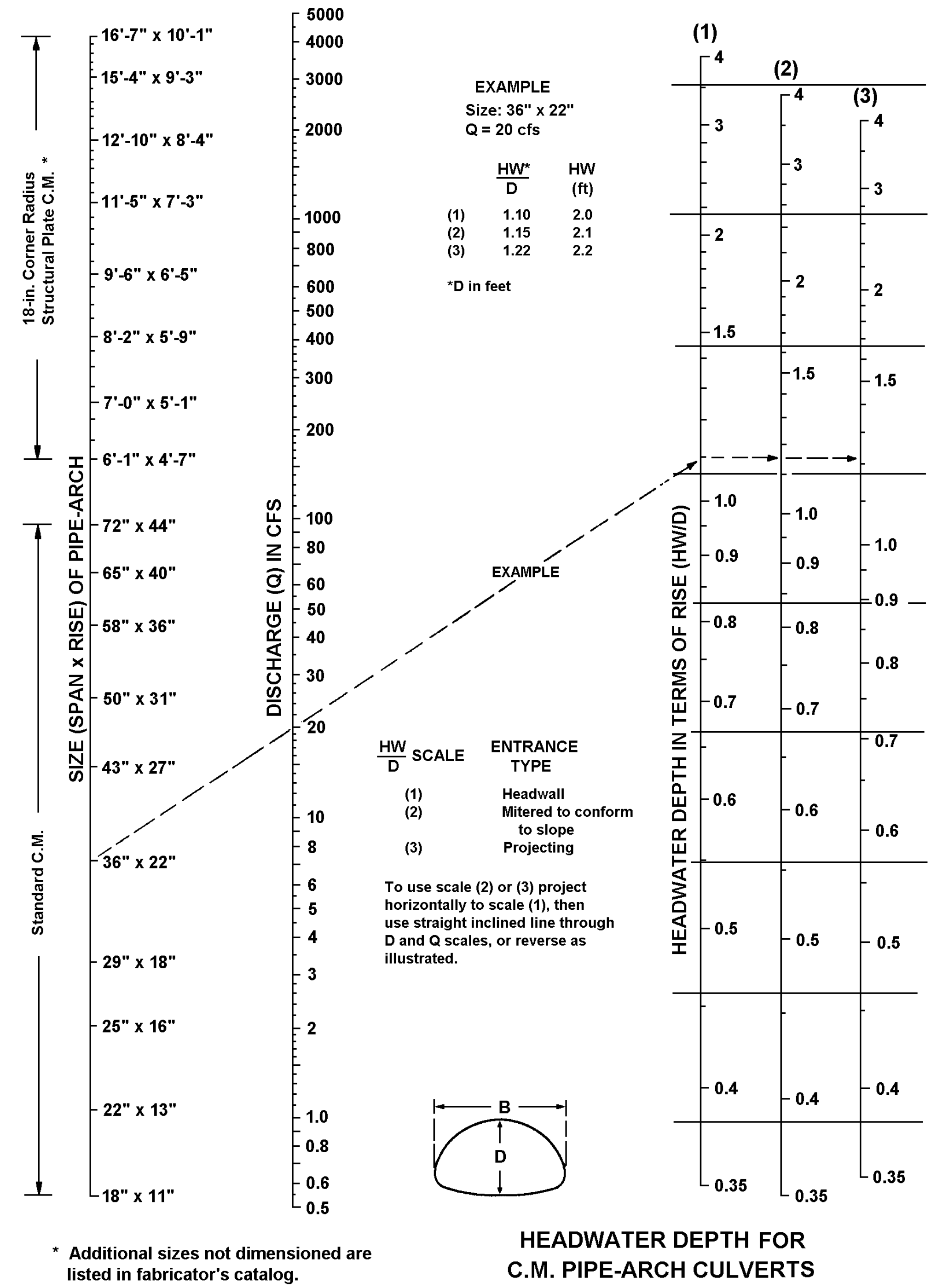
CHART 33



HEAD FOR
OVAL CONCRETE PIPE CULVERTS
LONG AXIS HORIZONTAL OR VERTICAL
FLOWING FULL
n = 0.012

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 34

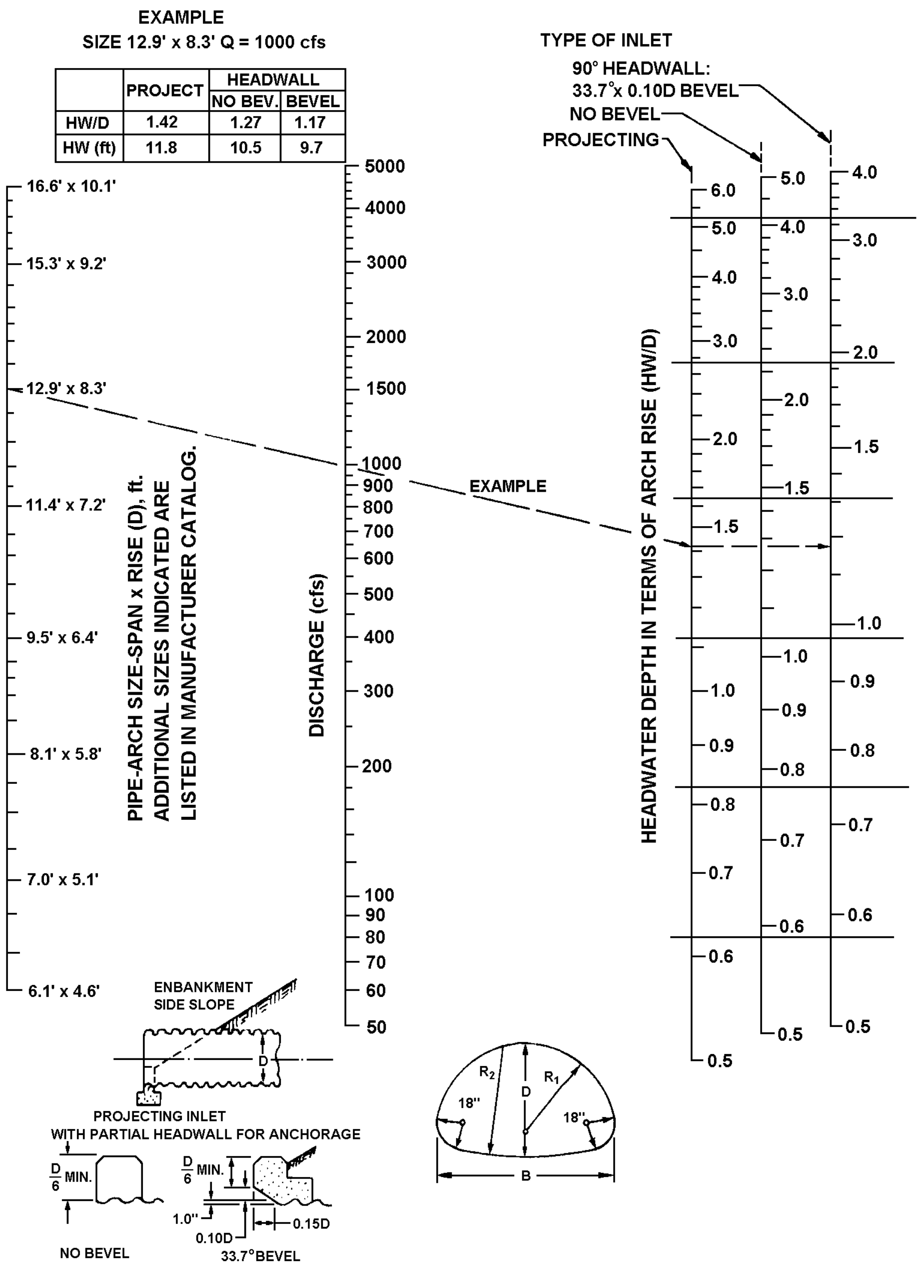


* Additional sizes not dimensioned are listed in fabricator's catalog.

HEADWATER DEPTH FOR C.M. PIPE-ARCH CULVERTS WITH INLET CONTROL

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 35



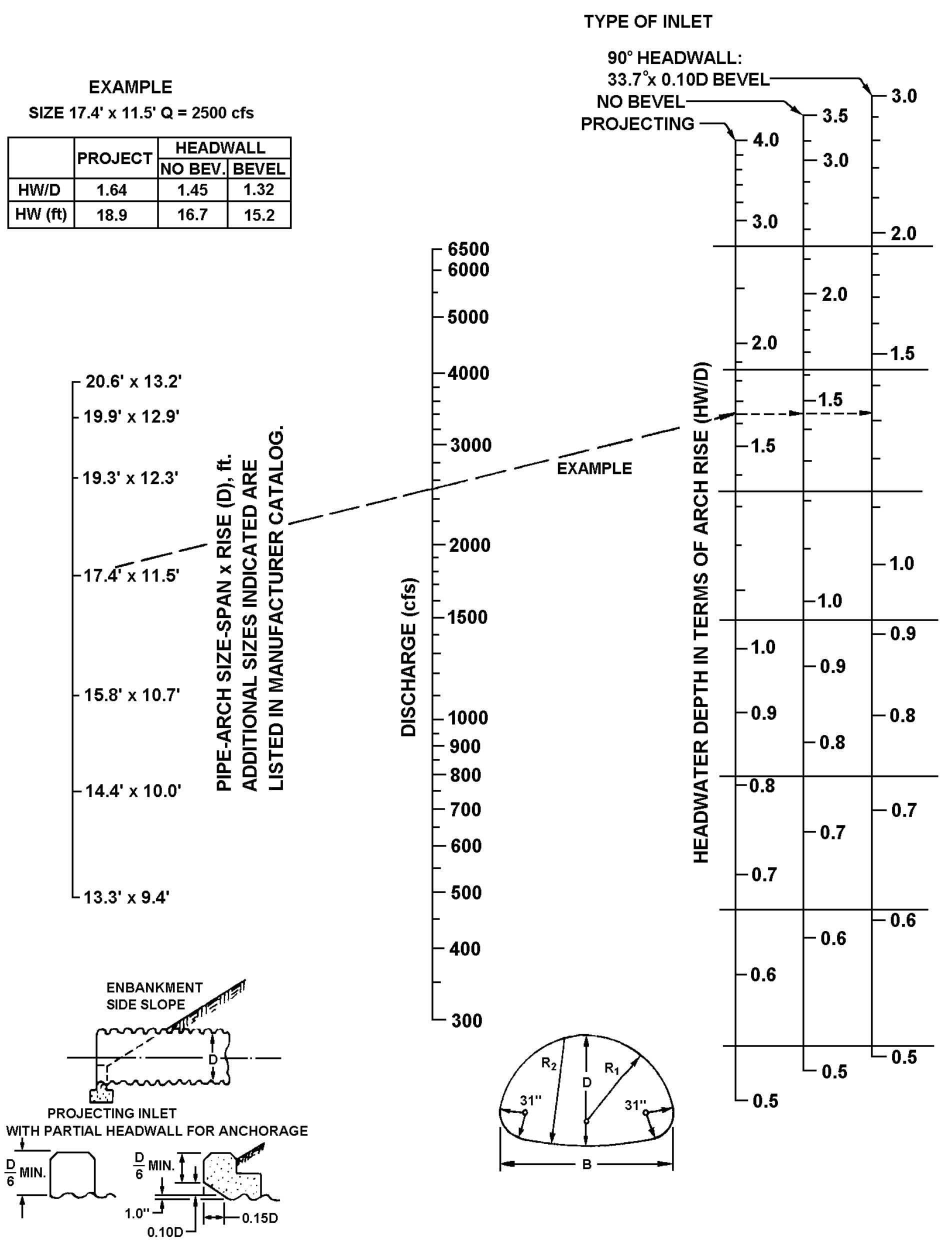
BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1968

HEADWATER DEPTH FOR INLET CONTROLS
STRUCTURAL PLATE PIPE-ARCH CULVERTS
18 in. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

CHART 36

EXAMPLE
SIZE 17.4' x 11.5' Q = 2500 cfs

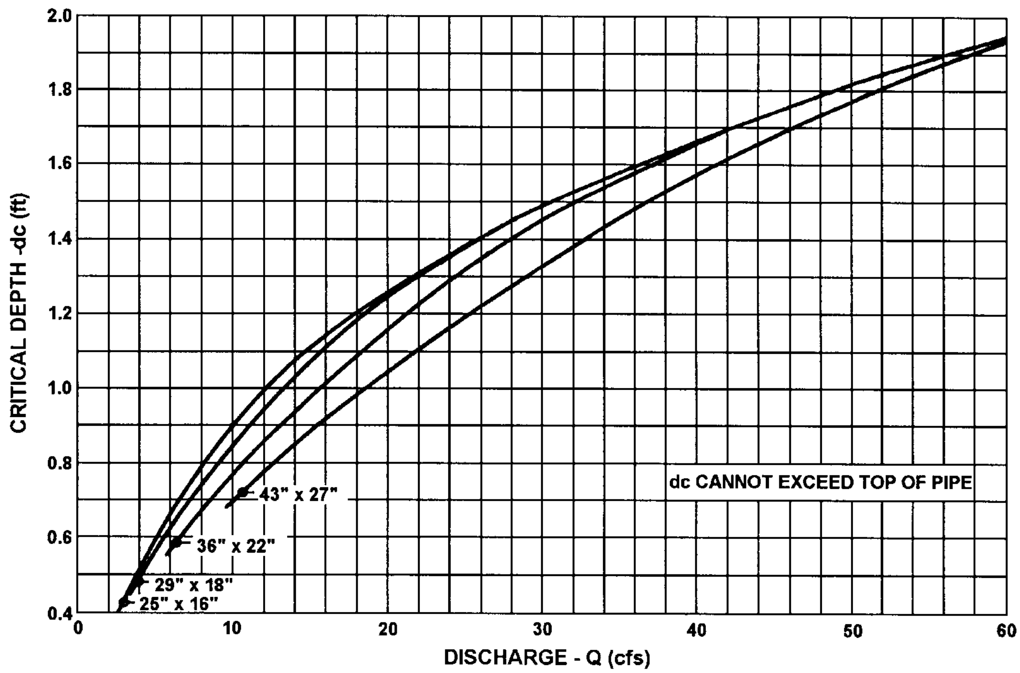
	PROJECT	HEADWALL	
		NO BEV.	BEVEL
HW/D	1.64	1.45	1.32
HW (ft)	18.9	16.7	15.2

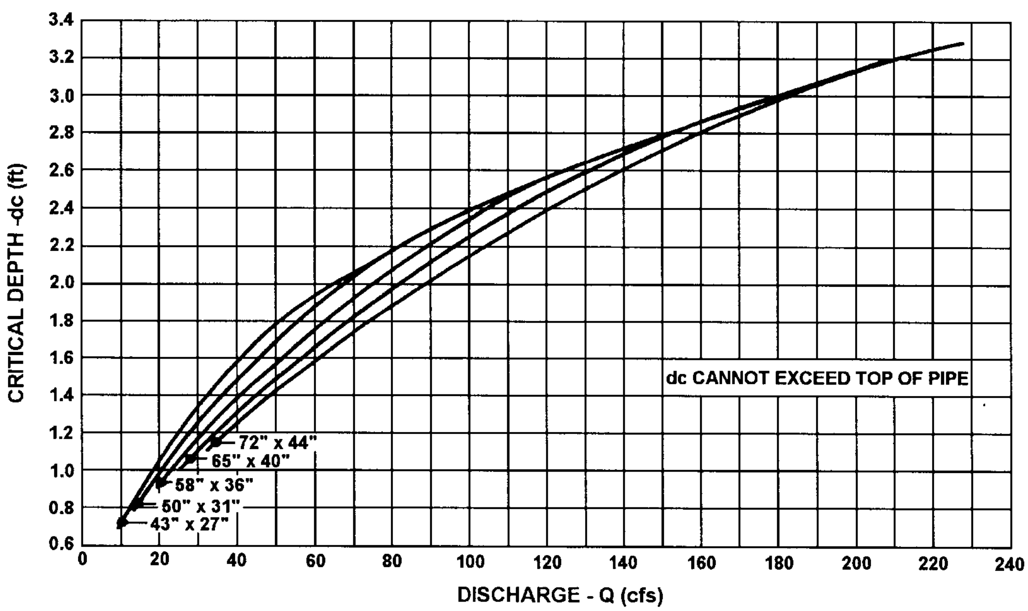


BUREAU OF PUBLIC ROADS
OFFICE OF R&D JULY 1966

HEADWATER DEPTH FOR INLET CONTROL
STRUCTURAL PLATE PIPE-ARCH CULVERTS
31 in. RADIUS CORNER PLATE
PROJECTING OR HEADWALL INLET
HEADWALL WITH OR WITHOUT EDGE BEVEL

CHART 37

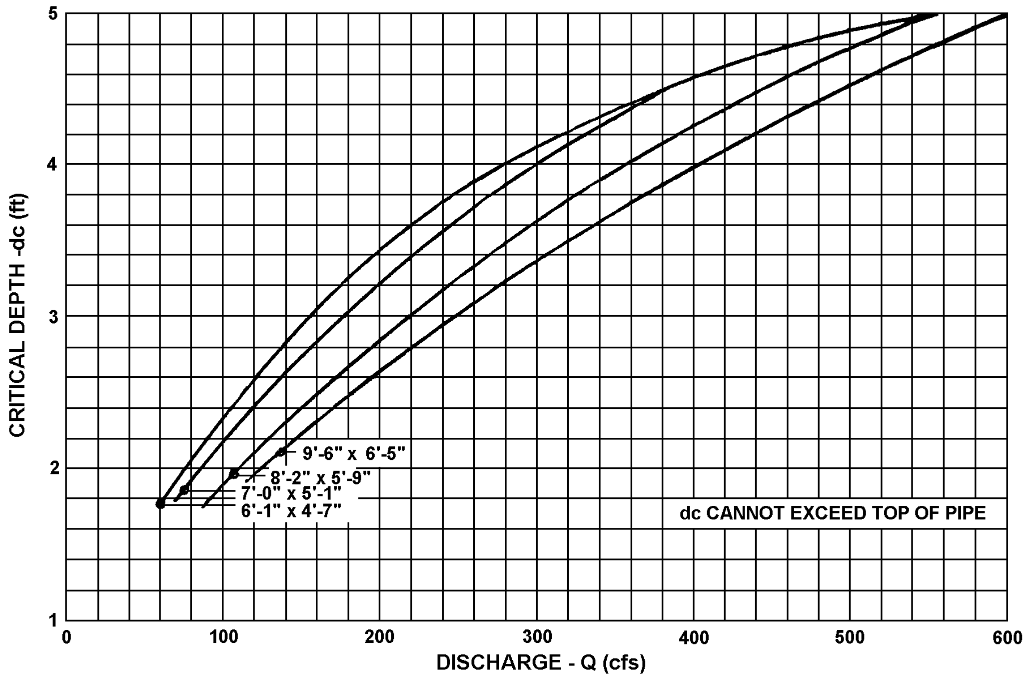


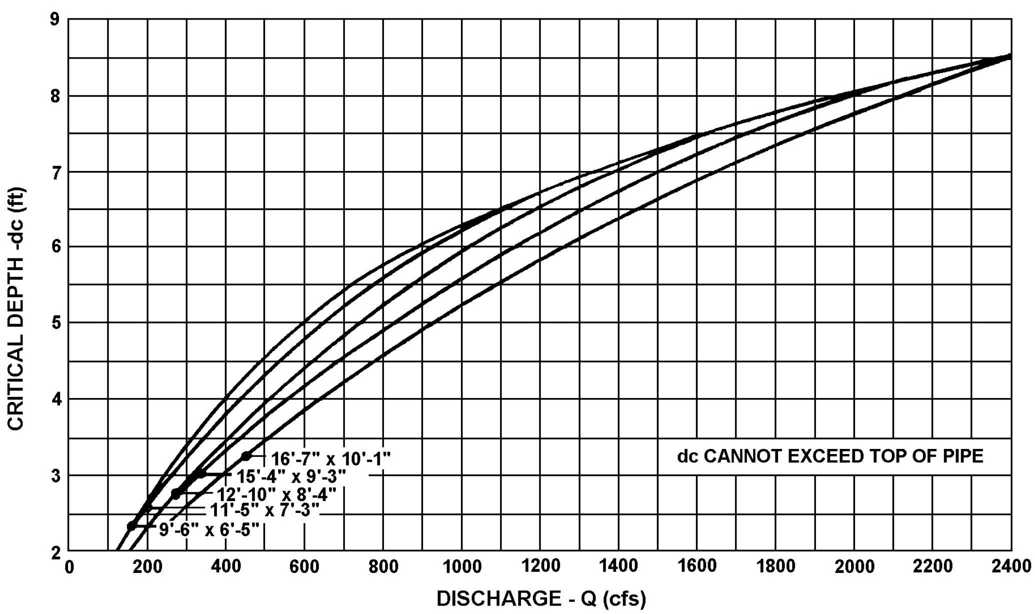


CRITICAL DEPTH
STANDARD C.M. PIPE ARCH

BUREAU OF PUBLIC ROADS
JAN. 1964

CHART 38

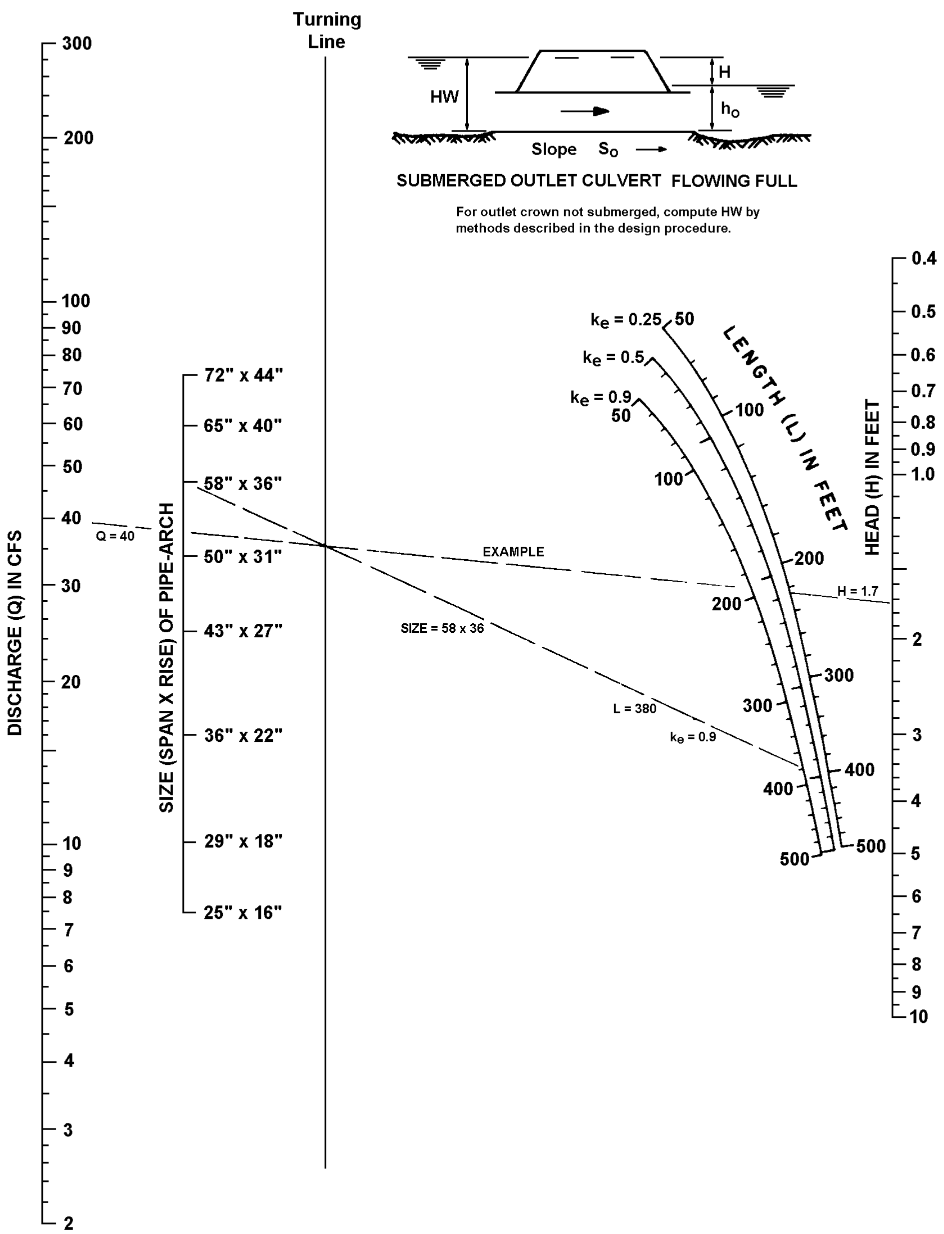




BUREAU OF PUBLIC ROADS
JAN. 1964

**CRITICAL DEPTH
STRUCTURAL PLATE
C.M. PIPE ARCH
18 in. CORNER RADIUS**

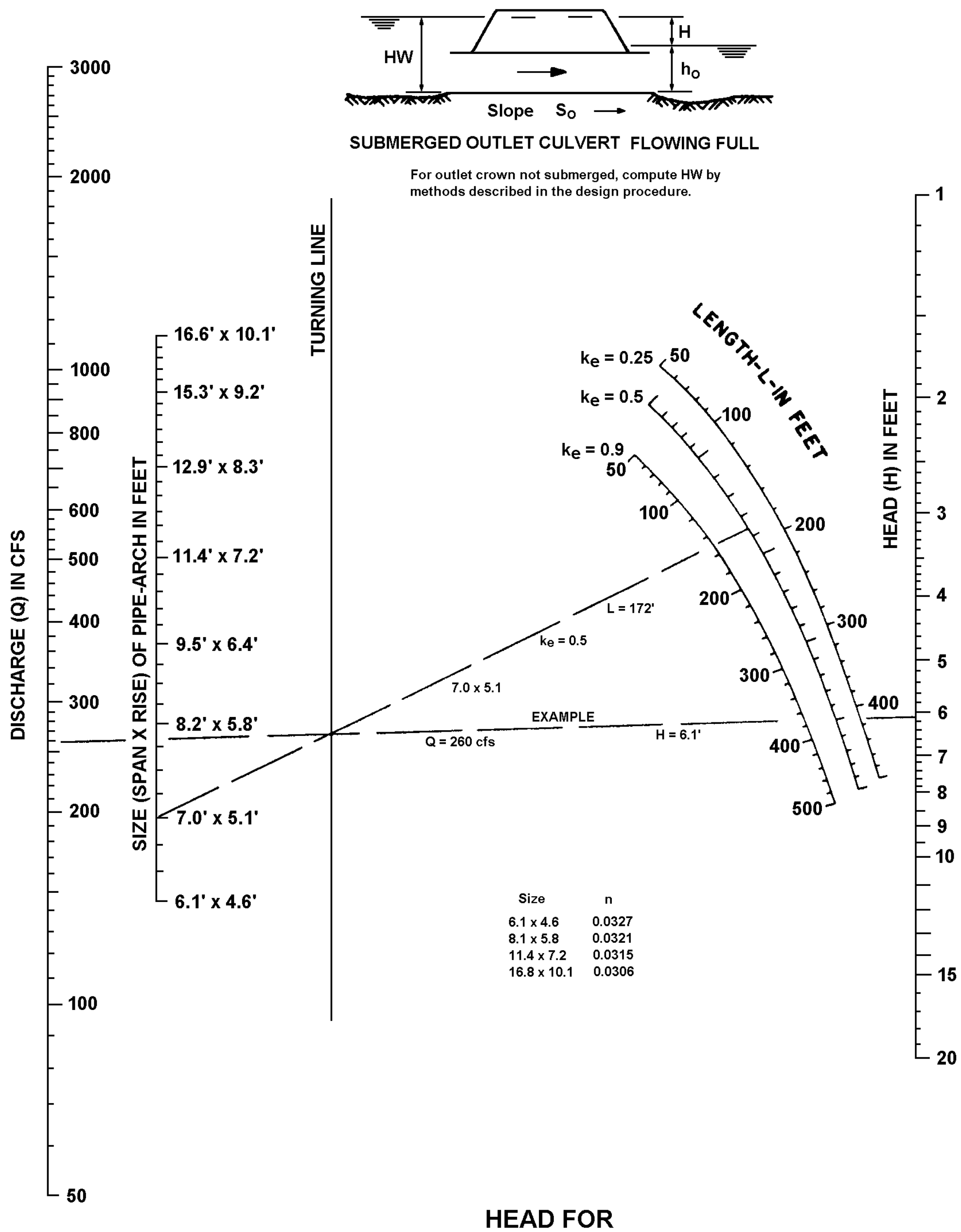
CHART 39



HEAD FOR
STANDARD C.M. PIPE-ARCH CULVERTS
FLOWING FULL
n = 0.024

BUREAU OF PUBLIC ROADS JAN. 1963

CHART 40



Size	n
6.1 x 4.6	0.0327
8.1 x 5.8	0.0321
11.4 x 7.2	0.0315
16.8 x 10.1	0.0306

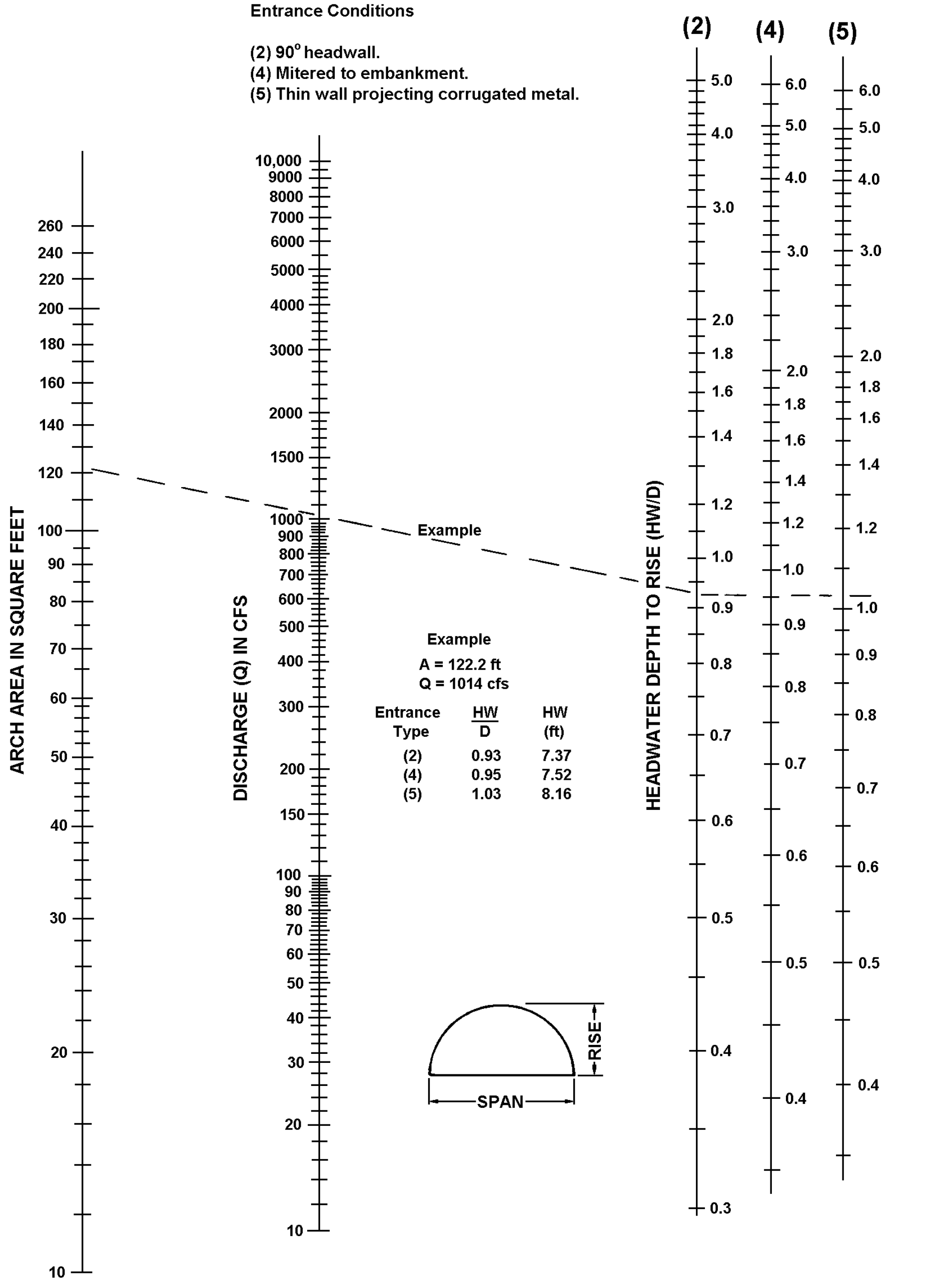
BUREAU OF PUBLIC ROADS JAN. 1963

**HEAD FOR
STRUCTURAL PLATE
C.M. PIPE ARCH CULVERTS
18 in. CORNER RADIUS
FLOWING FULL
n = 0.0327 TO 0.0306**

CHART 41

Entrance Conditions

(2) 90° headwall.
(4) Mitered to embankment.
(5) Thin wall projecting corrugated metal.



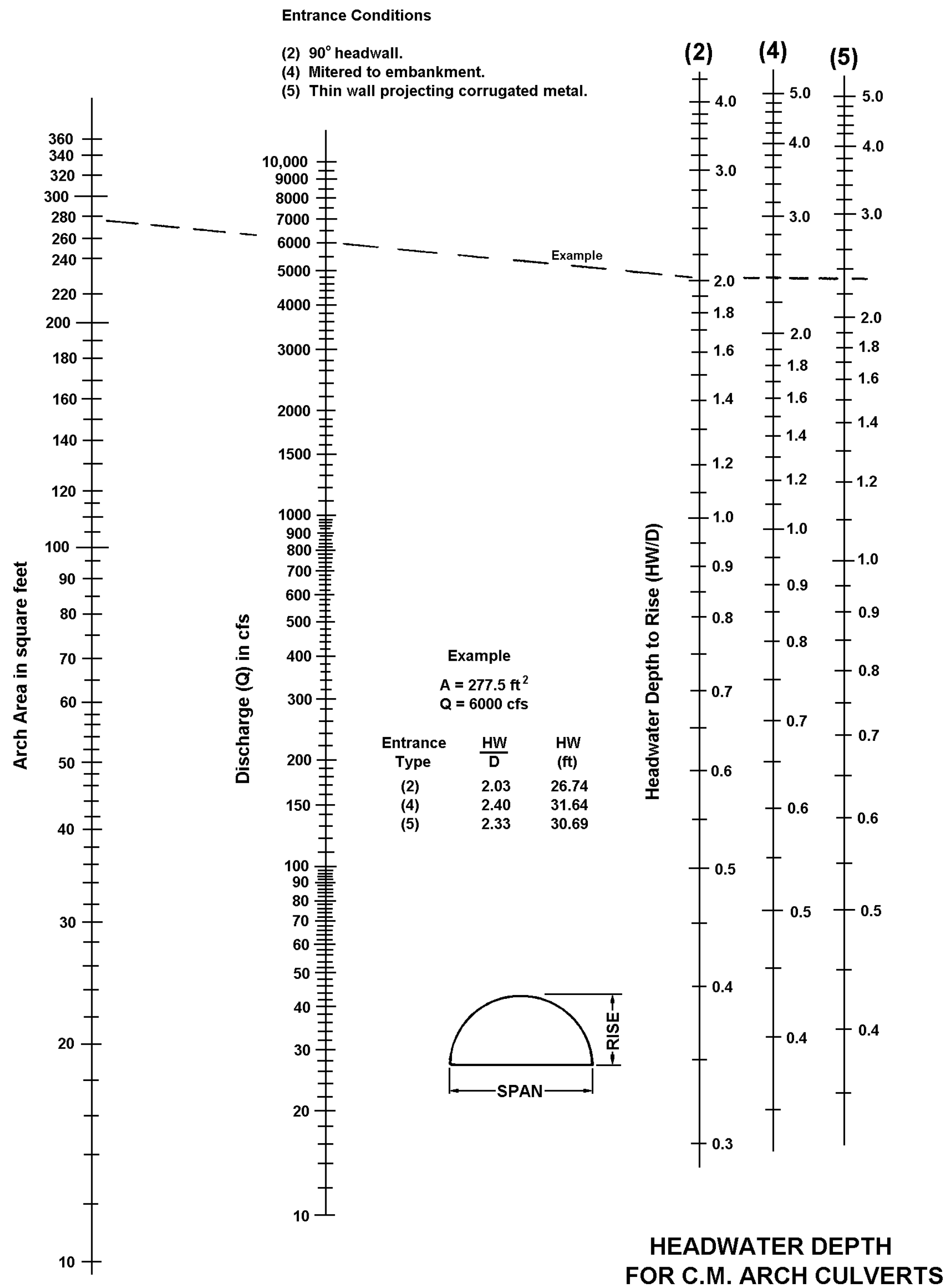
Example
A = 122.2 ft
Q = 1014 cfs

Entrance Type	HW/D	HW (ft)
(2)	0.93	7.37
(4)	0.95	7.52
(5)	1.03	8.16

HEADWATER DEPTH
FOR C.M. ARCH CULVERTS
0.3 ≤ RISE/SPAN < 0.4
WITH INLET CONTROL

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

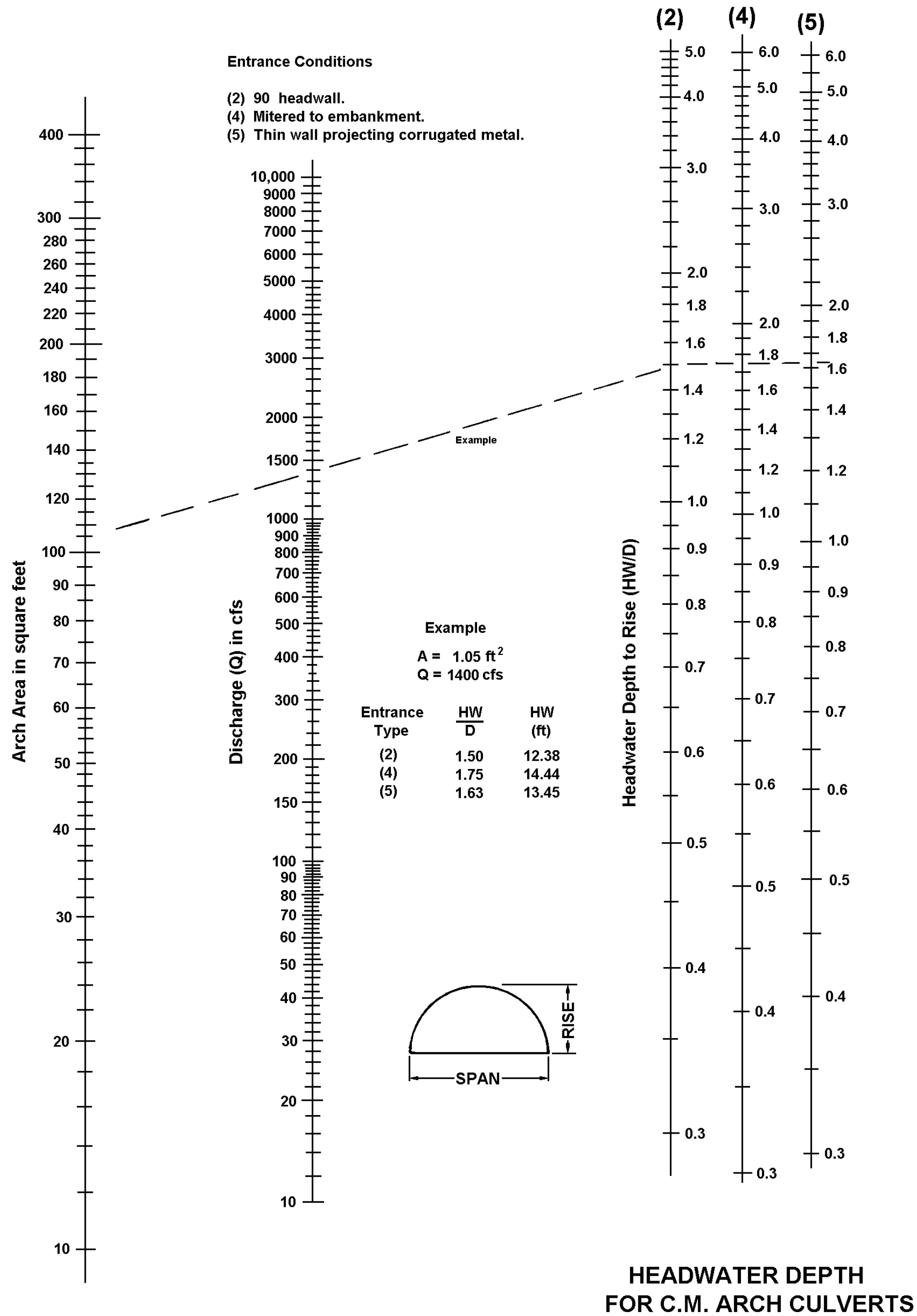
CHART 42



Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation.
Duplication of this nomograph may distort scale.

HEADWATER DEPTH FOR C.M. ARCH CULVERTS 0.4 ≤ RISE/SPAN < 0.5 WITH INLET CONTROL

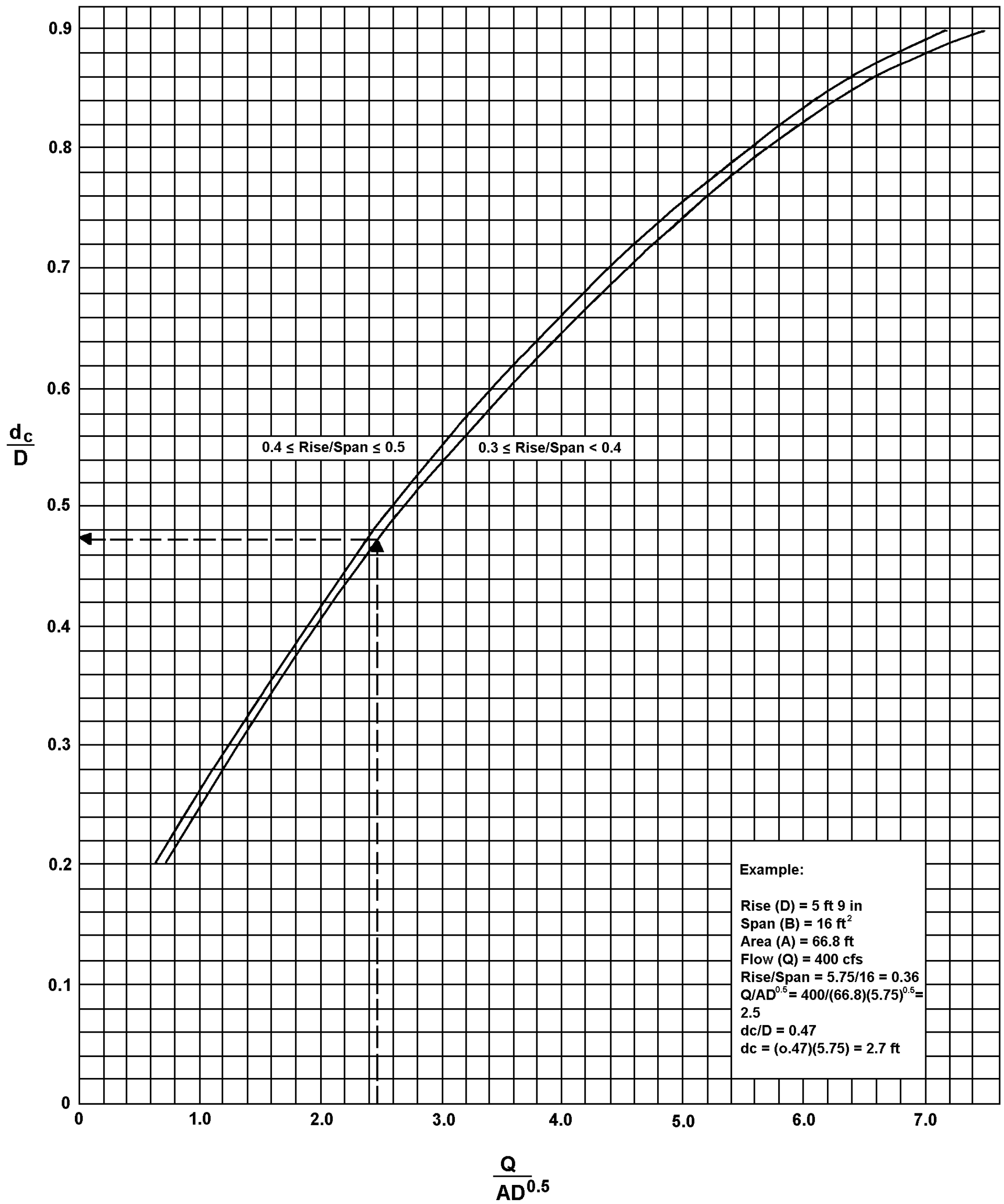
CHART 43



HEADWATER DEPTH
FOR C.M. ARCH CULVERTS
0.5 ≤ RISE/SPAN
WITH INLET CONTROL

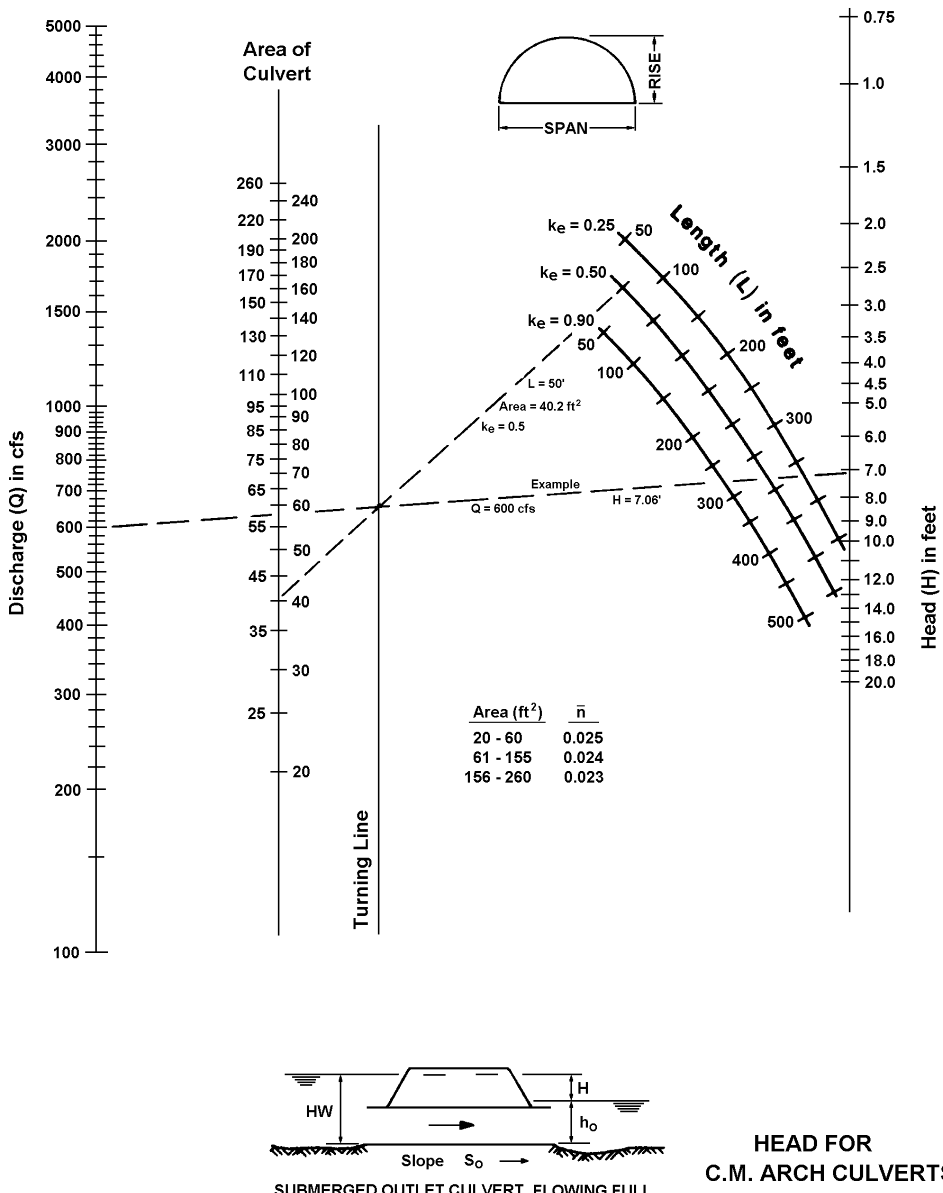
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation.
Duplication of this nomograph may distort scale.

CHART 44



DIMENSIONLESS CRITICAL DEPTH CHART FOR C.M. ARCH CULVERTS

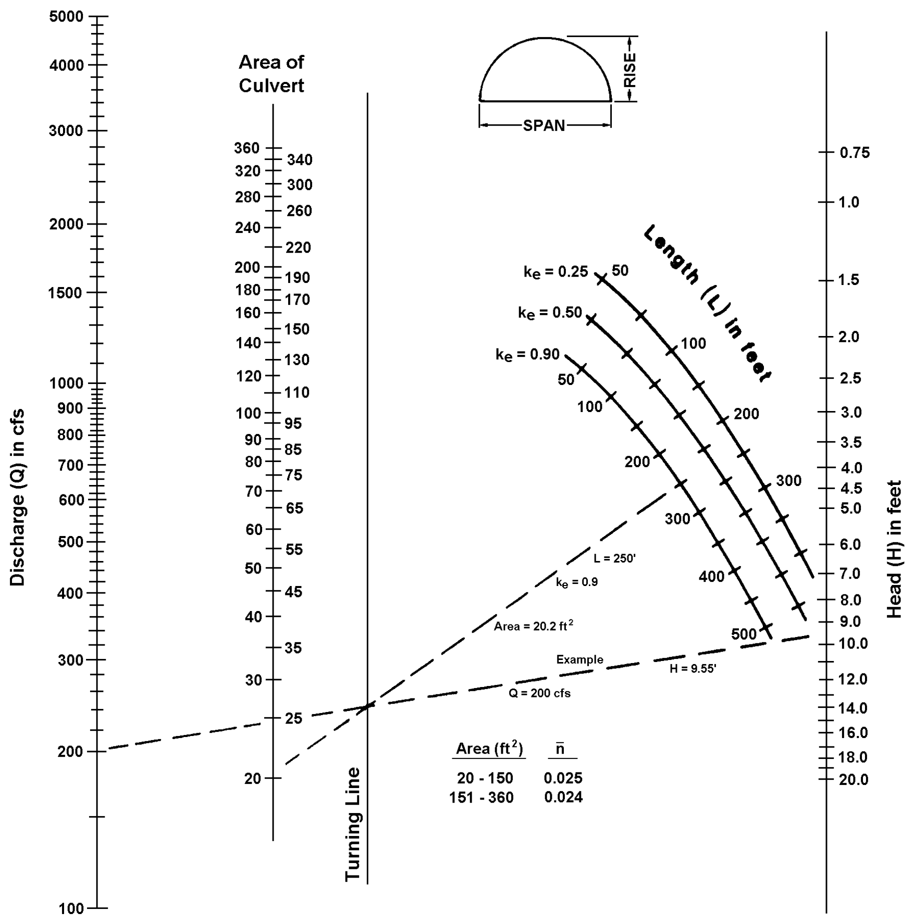
CHART 45

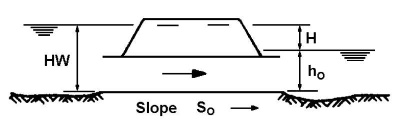


HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
CONCRETE BOTTOM
0.3 ≤ RISE/SPAN < 0.4

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

CHART 46



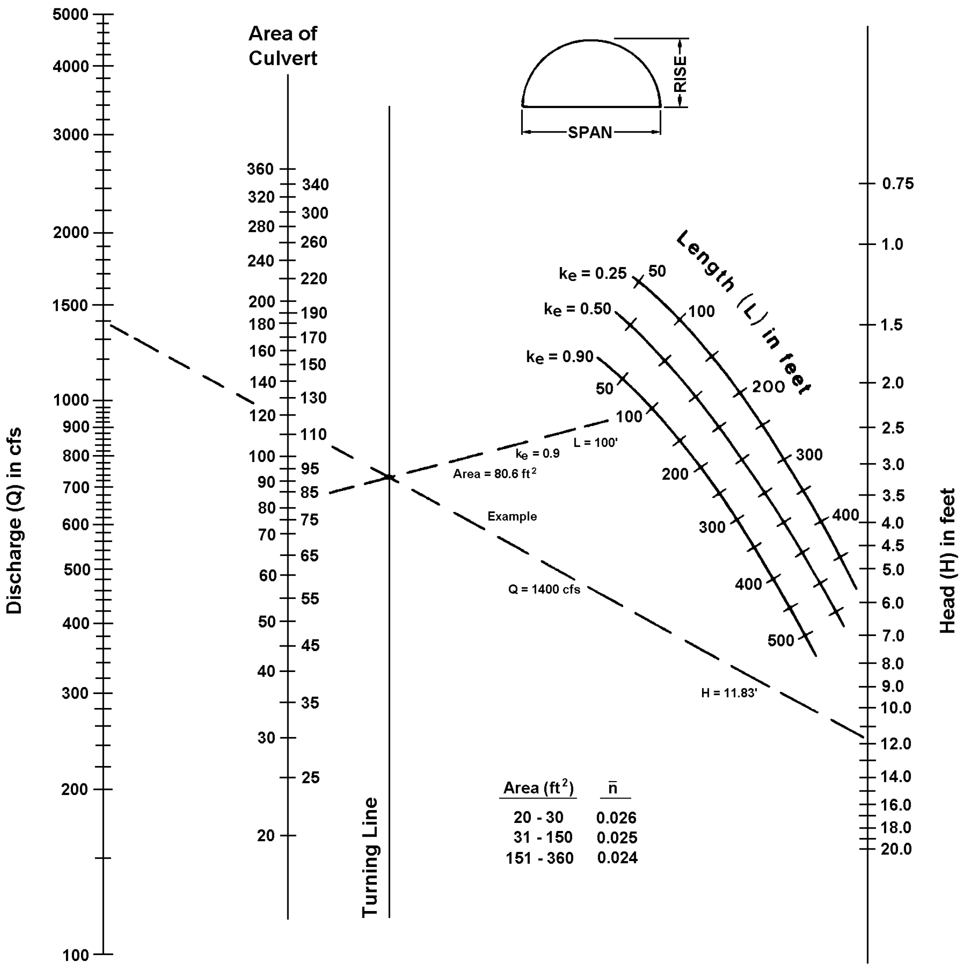


SUBMERGED OUTLET CULVERT FLOWING FULL

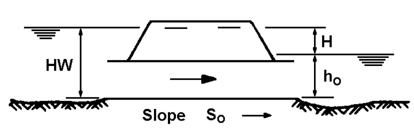
HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
CONCRETE BOTTOM
0.4 ≤ RISE/SPAN < 0.5

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

CHART 47



Area (ft²)	$\bar{n}$
20 - 30	0.026
31 - 150	0.025
151 - 360	0.024

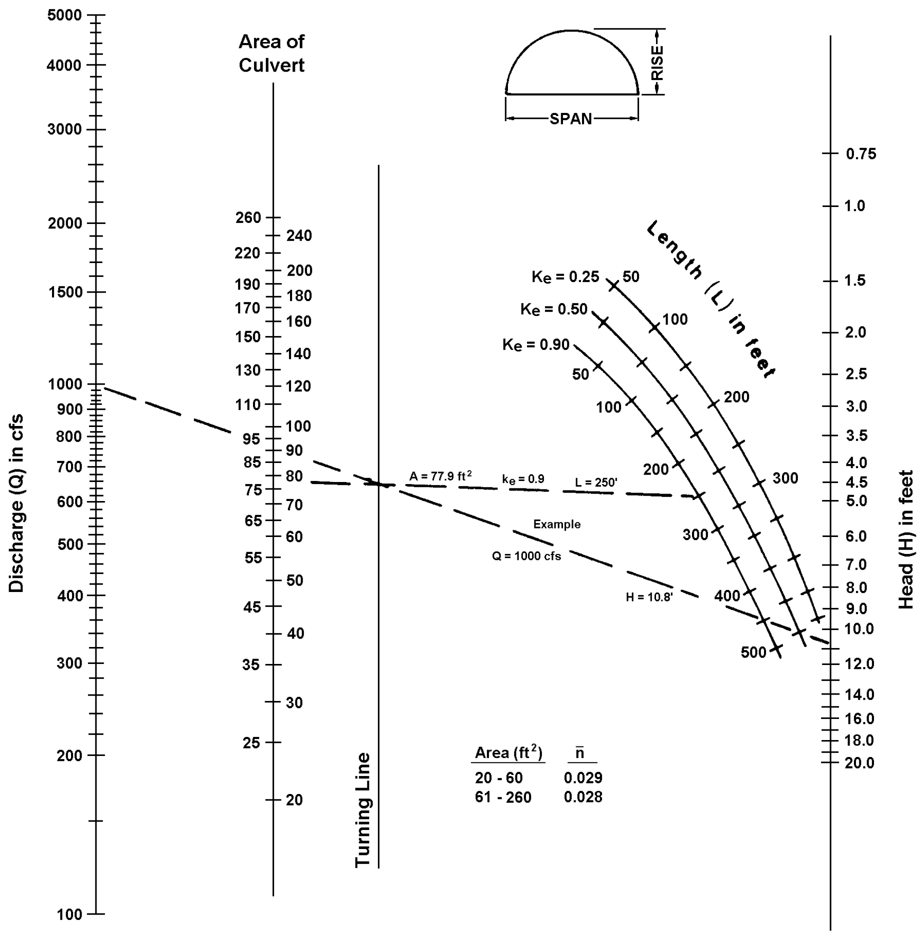


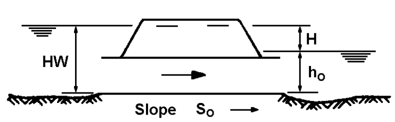
SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR C.M. ARCH CULVERTS FLOWING FULL CONCRETE BOTTOM $0.5 \leq$ RISE/SPAN

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

CHART 48



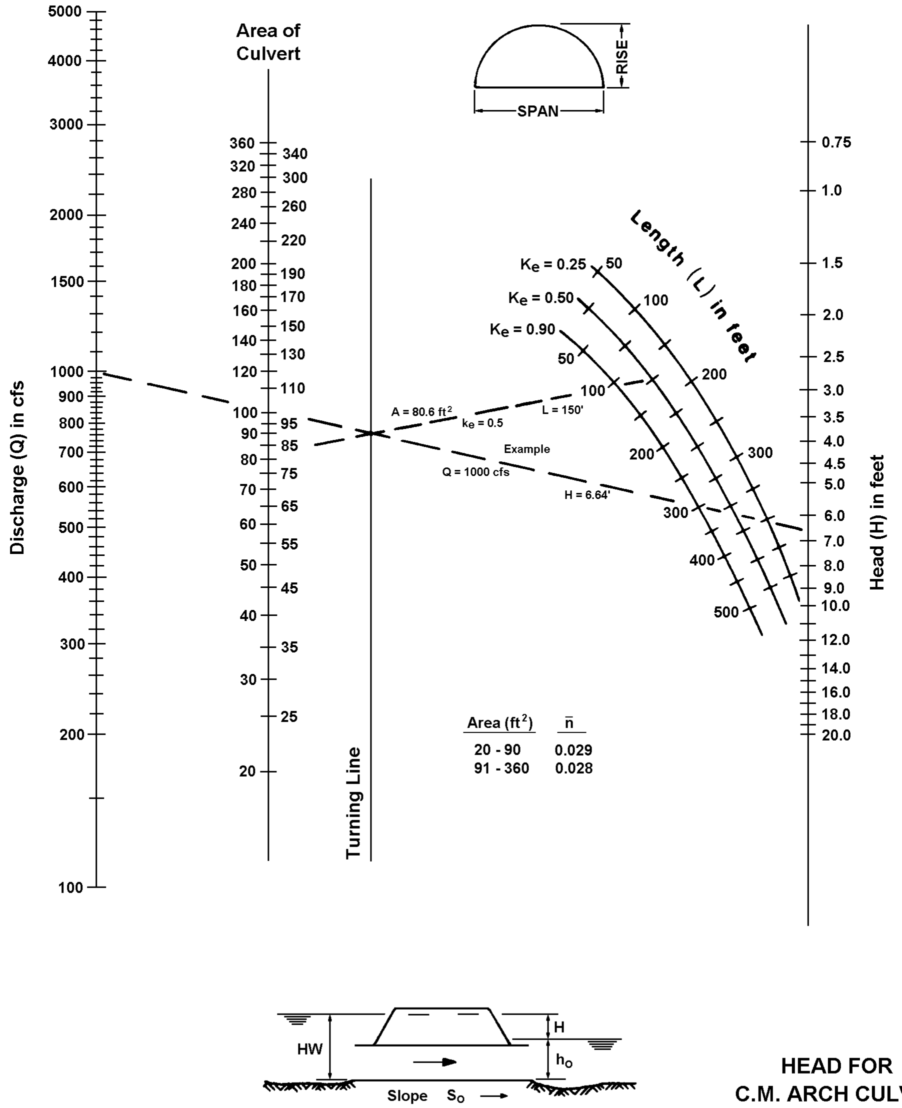


SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
EARTH BOTTOM (n_b = 0.022)
0.3 ≤ RISE/SPAN < 0.4

Nomographs adapted from material furnished by
Kaiser Aluminum and Chemical Corporation.
Duplication of this nomograph may distort scale.

CHART 49

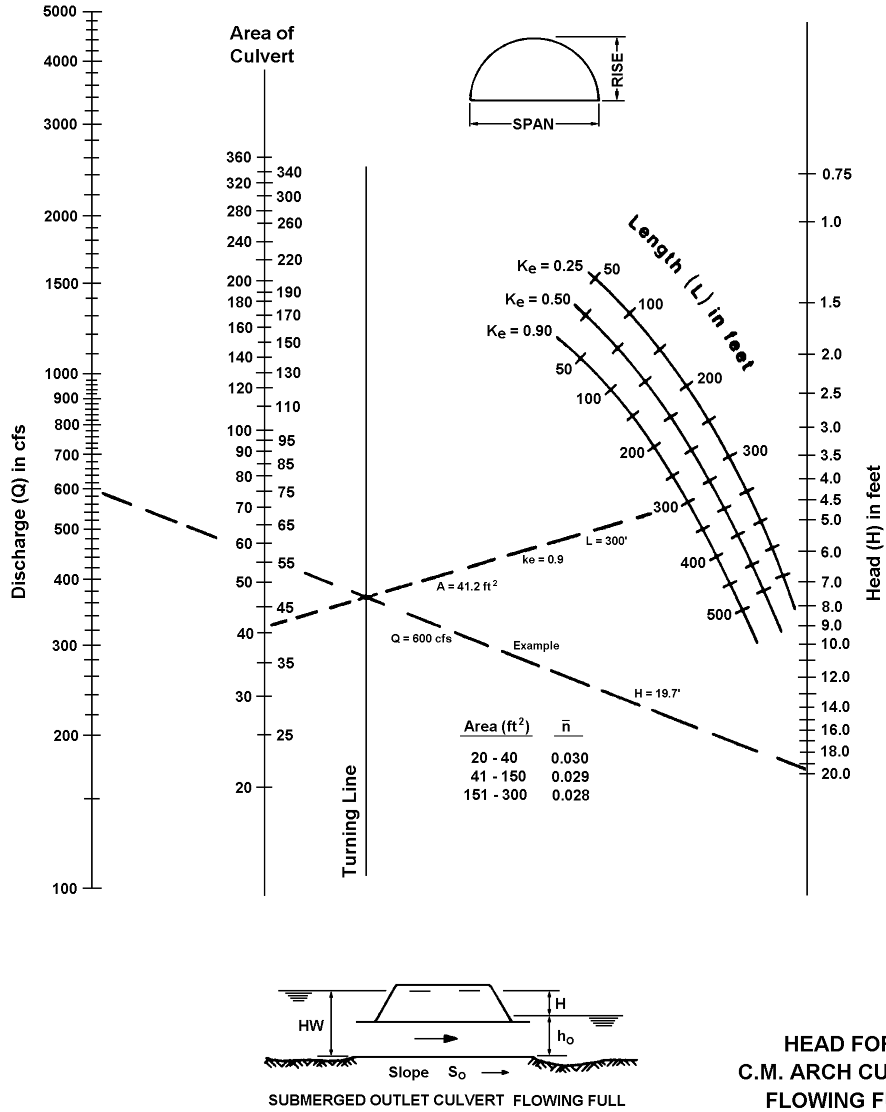


SUBMERGED OUTLET CULVERT FLOWING FULL

HEAD FOR
C.M. ARCH CULVERTS
FLOWING FULL
EARTH BOTTOM (n_b = 0.022)
0.4 ≤ RISE/SPAN < 0.5

Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

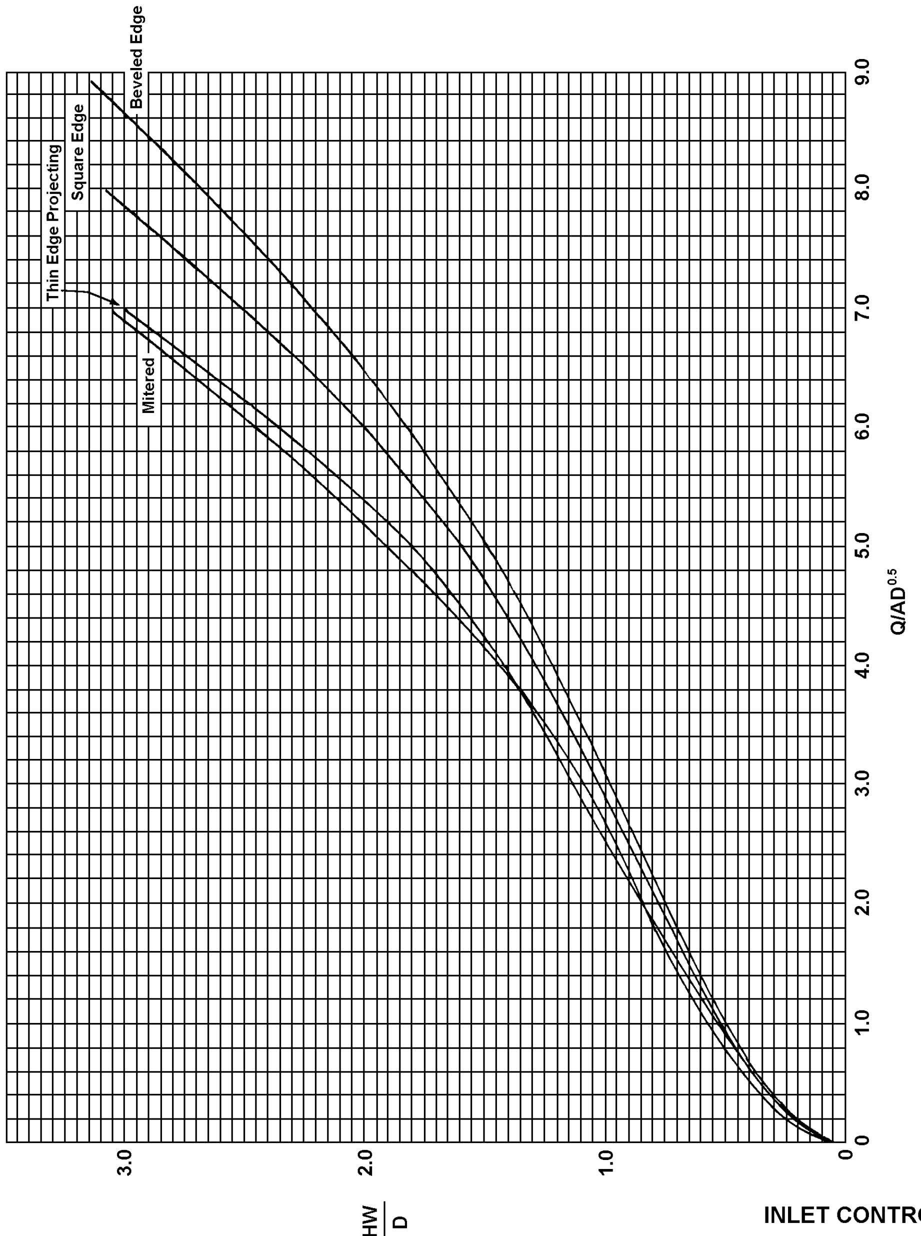
CHART 50



HEAD FOR C.M. ARCH CULVERTS FLOWING FULL EARTH BOTTOM (n_b = 0.022) 0.5 ≤ RISE/SPAN

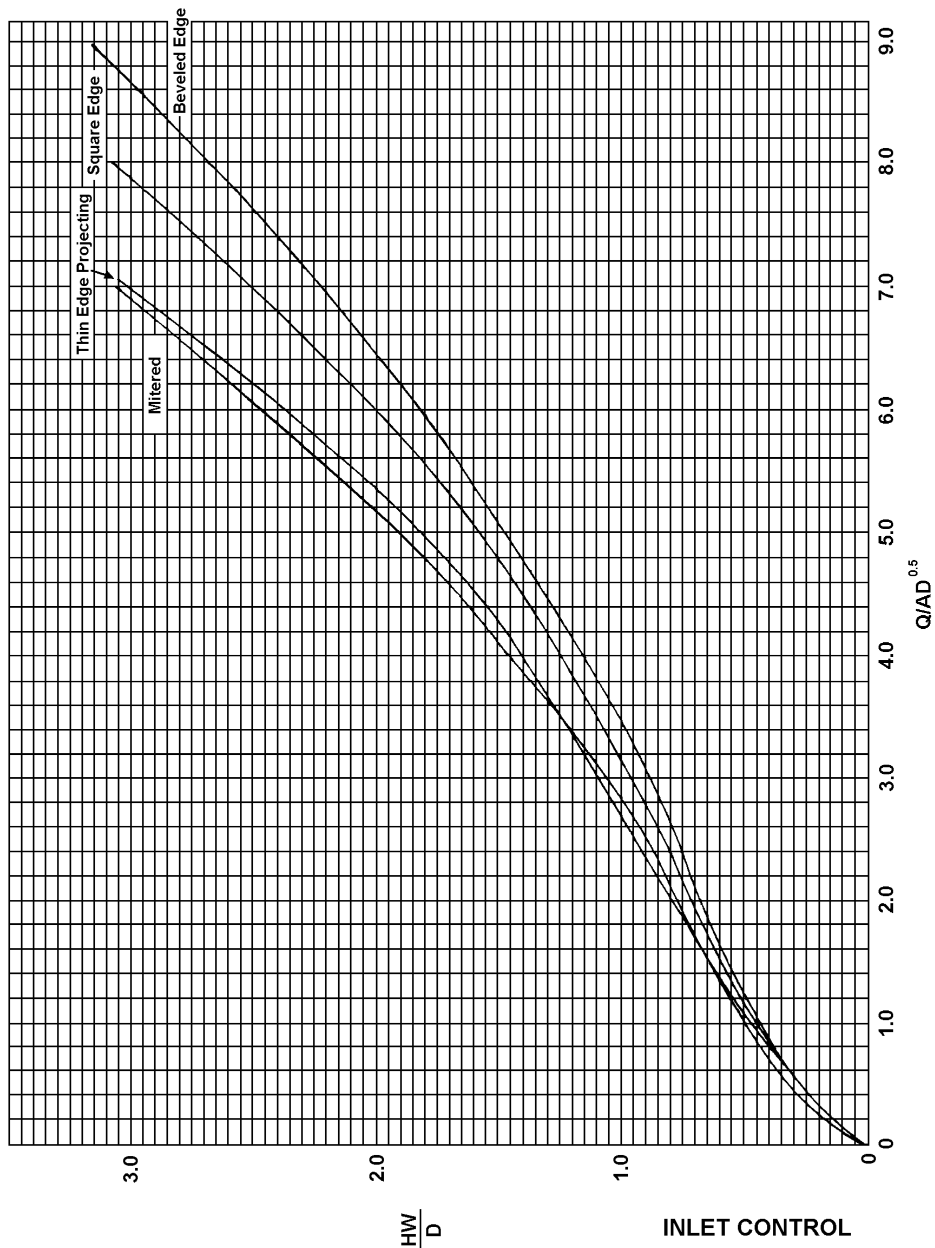
Nomographs adapted from material furnished by Kaiser Aluminum and Chemical Corporation. Duplication of this nomograph may distort scale.

CHART 51



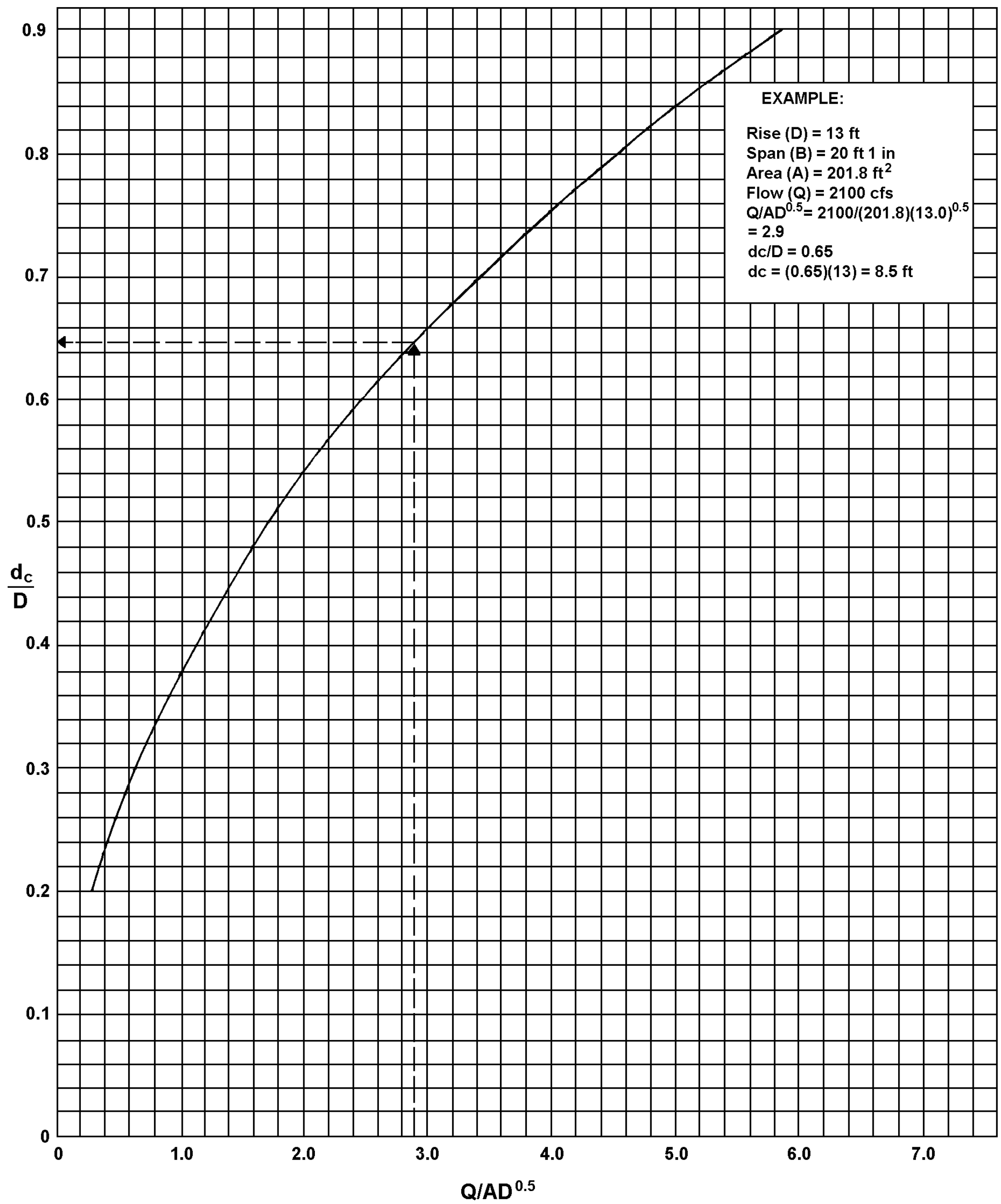
**INLET CONTROL
HEADWATER DEPTH FOR
CIRCULAR OR ELLIPTICAL
STRUCTURAL PLATE
C.M. CONDUITS**

CHART 52



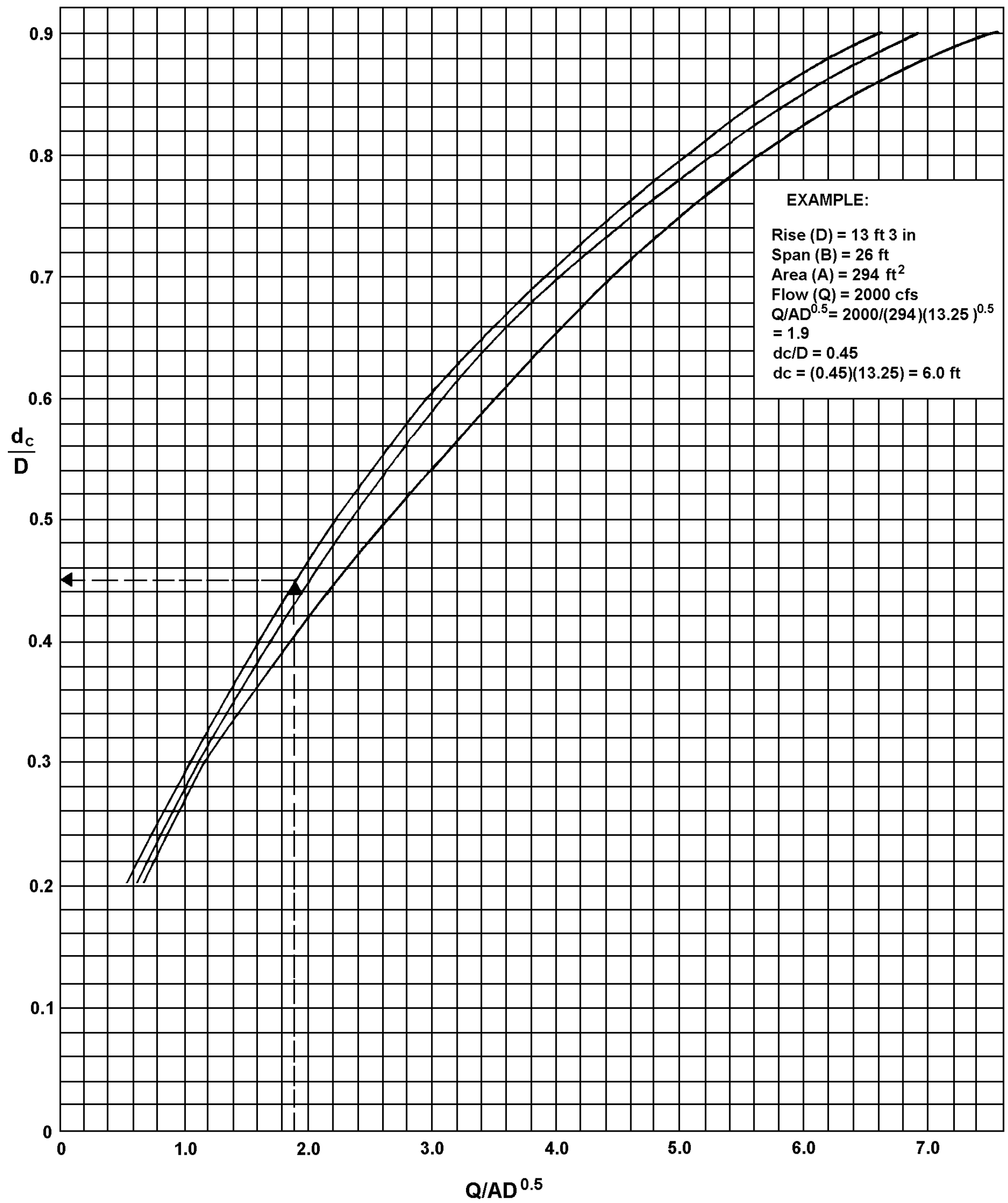
INLET CONTROL HEADWATER DEPTH FOR HIGH AND LOW PROFILE STRUCTURAL PLATE C.M. ARCH

CHART 53



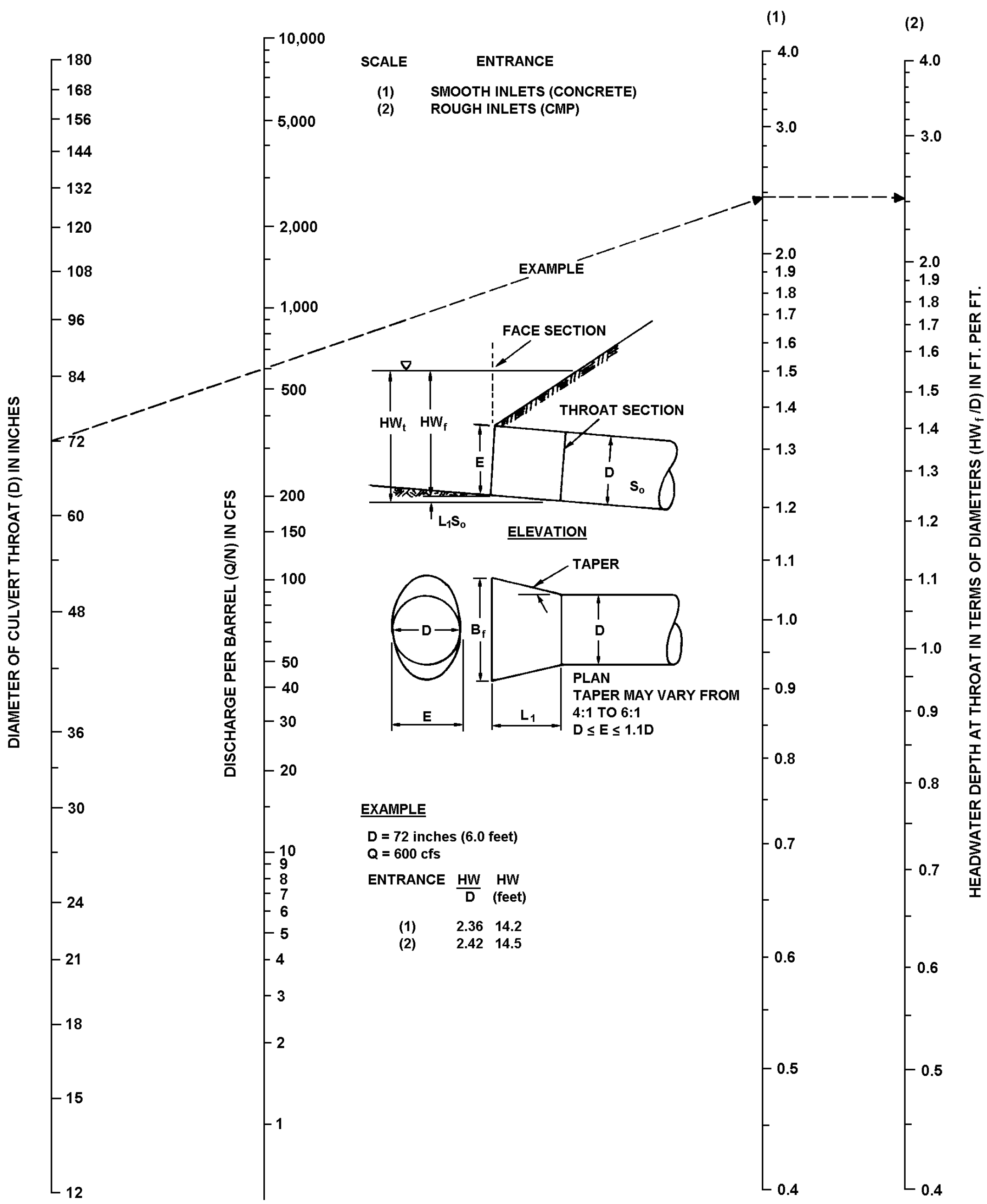
DIMENSIONLESS CRITICAL DEPTH CHART
FOR STRUCTURAL PLATE
ELLIPSE LONG AXIS HORIZONTAL

CHART 54



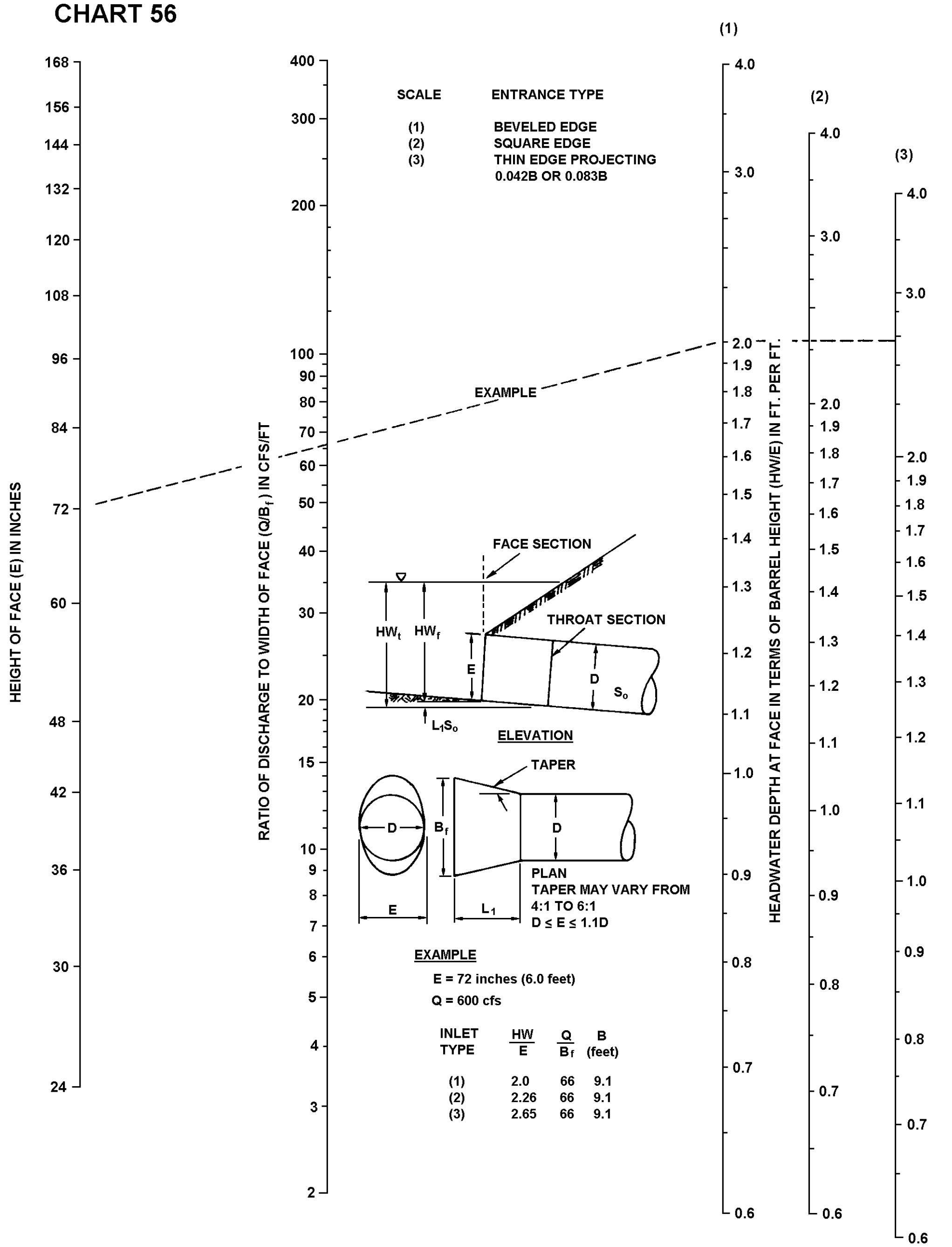
DIMENSIONLESS CRITICAL DEPTH CHART FOR STRUCTURAL PLATE LOW- AND HIGH-PROFILE ARCHES

CHART 55



THROAT CONTROL
FOR SIDE-TAPERED INLETS
TO PIPE CULVERT
(CIRCULAR SECTION ONLY)

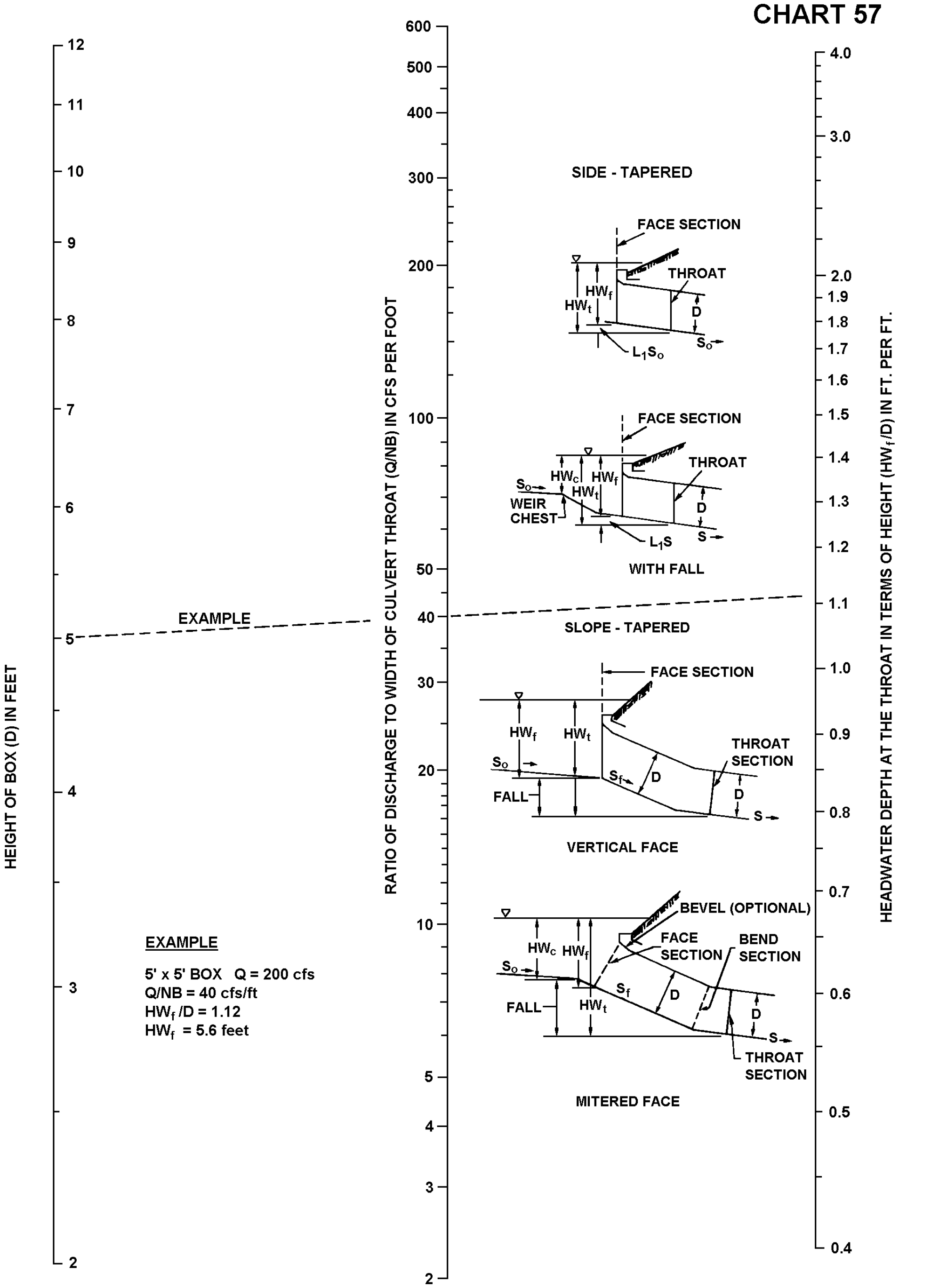
CHART 56



INLET TYPE	$\frac{HW}{E}$	$\frac{Q}{B_f}$	B (feet)
(1)	2.0	66	9.1
(2)	2.26	66	9.1
(3)	2.65	66	9.1

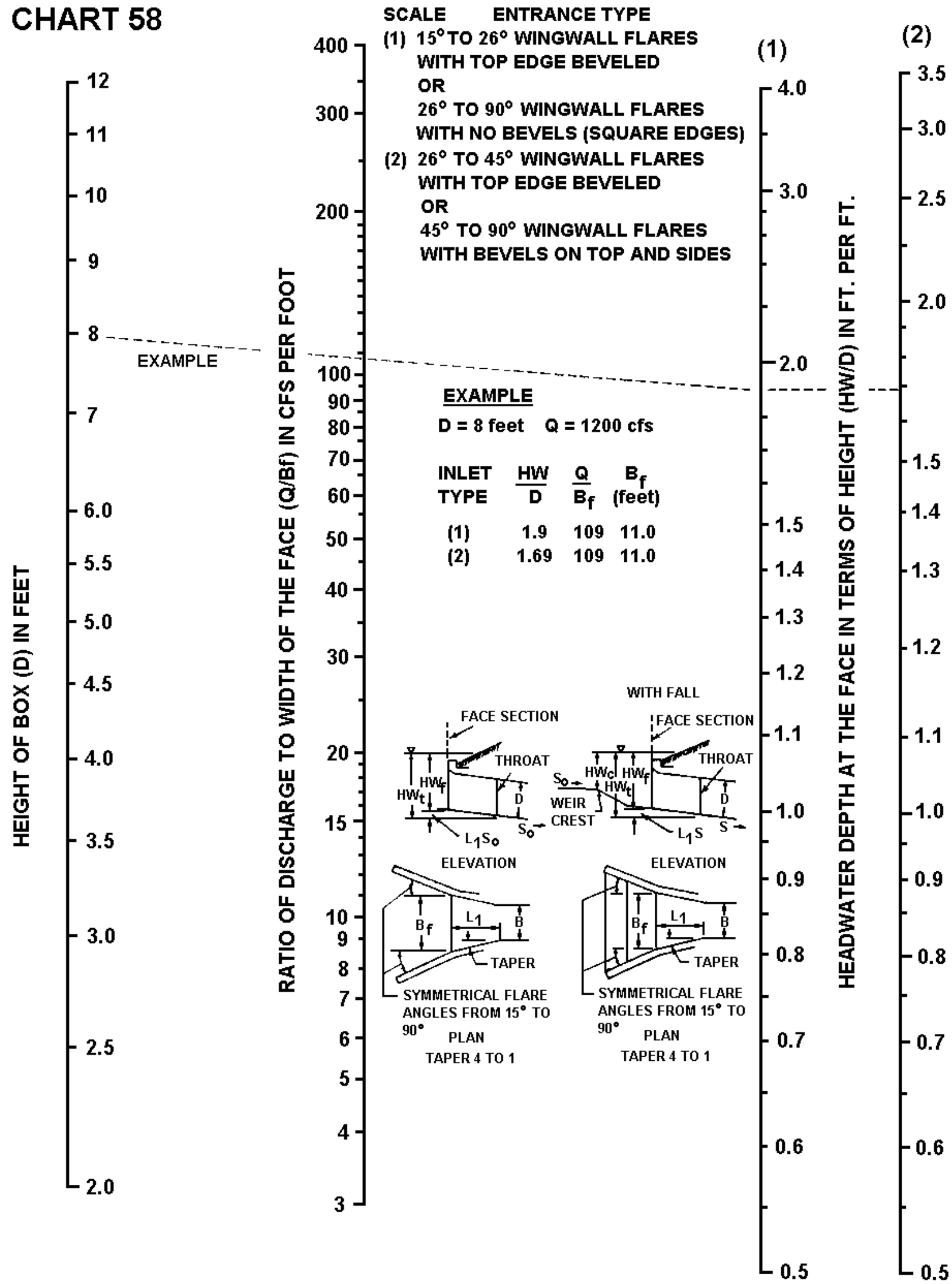
FACE CONTROL FOR SIDE-TAPERED
INLETS TO PIPE CULVERTS
(NON-RECTANGULAR SECTIONS ONLY)

CHART 57



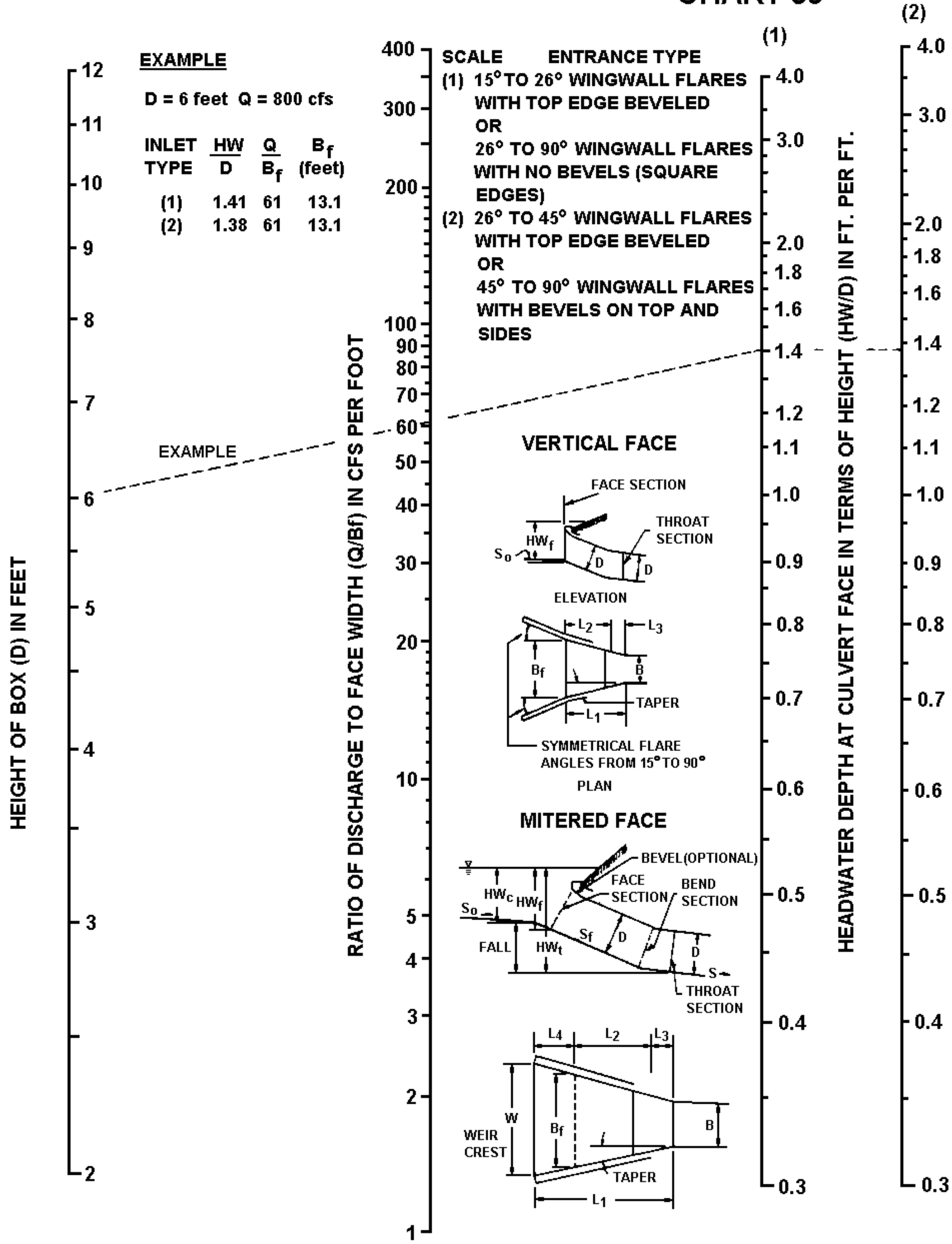
THROAT CONTROL FOR BOX CULVERTS WITH TAPERED INLETS

CHART 58



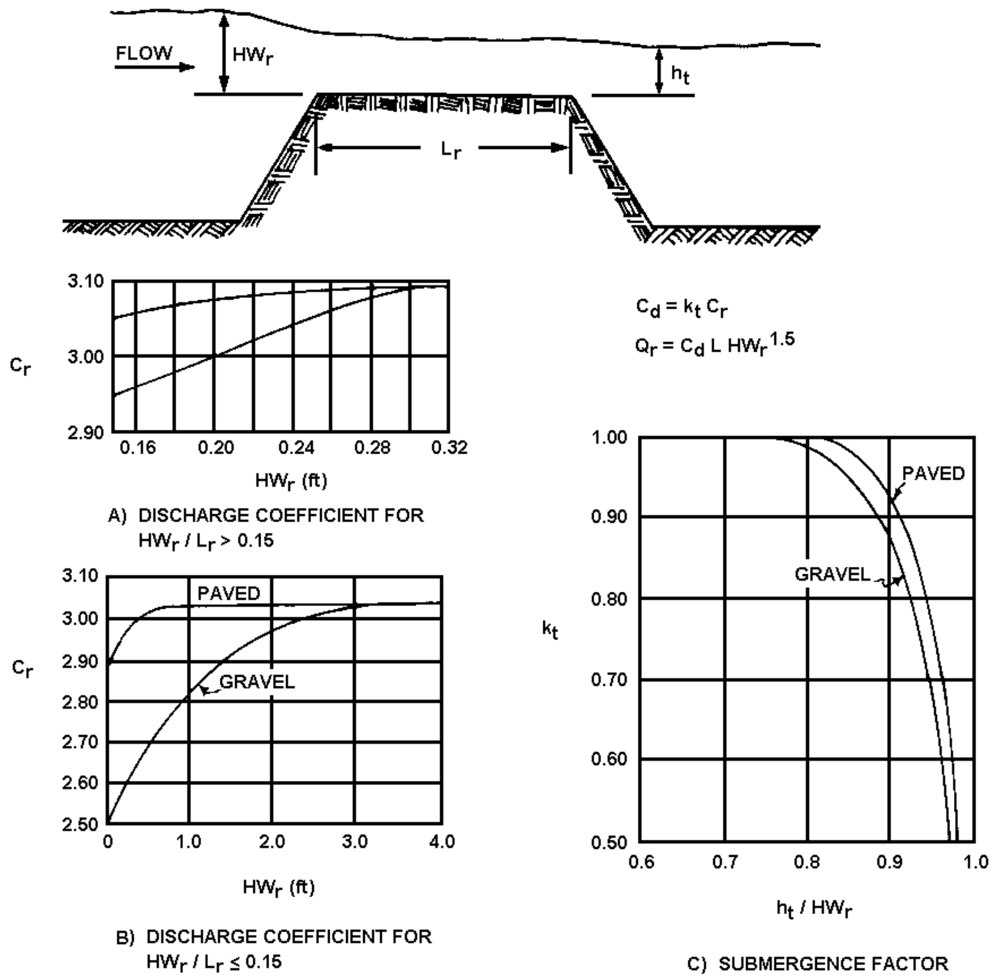
FACE CONTROL FOR BOX CULVERTS WITH SIDE-TAPERED INLETS

CHART 59



FACE CONTROL FOR BOX CULVERTS
WITH SLOPE TAPERED INLETS

CHART 60



DISCHARGE COEFFICIENTS FOR ROADWAY OVERTOPPING

CHAPTER

OPEN CHANNEL DESIGN 5

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Appendix C Grassed Channel Design Figures **5-77**

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To provide consistency within this chapter as well as throughout this manual the following symbols will be used. These symbols were selected because of their wide use in open channel publications.

Table 5-1 Symbols and Definitions

Symbol	Definition	Units
α	Energy coefficient	-
A	Cross-sectional area	ft^2
b	Bottom width	ft
C_g	Specific weight correction factor	-
D or d	Depth of flow	ft
d	Stone diameter	ft
d_c	Critical depth	ft
d_x	Diameter of stone for which x percent, by weight, of the gradation is finer	ft
E	Specific energy	ft
Fr	Froude Number	-
g	Acceleration of gravity	32.2 ft/s^2
h_{loss}	Head loss	ft
K	Channel conveyance	-
k_e	Eddy head loss coefficient	ft
K_T	Trapezoidal open channel conveyance factor	-
L	Length of channel	ft
L_p	Length of downstream protection	ft
n	Manning's roughness coefficient	-
P	Wetted perimeter	ft
Q	Discharge rate	cfs
R	Hydraulic radius of flow	ft
R_c	Mean radius of the bend	ft
S	Slope	ft/ft
SW_s	Specific weight of stone	lbs/ft^3
T	Top width of water surface	ft
V or v	Velocity of flow	ft/s
v_m	Maximum velocity	ft/s
W	Stone weight	lbs
y_n	Normal depth	ft
z	Side slopes of a channel (horizontal to vertical)	-
Z	Critical flow section factor	-

5.2 Design Criteria

5.2.1 General Criteria

In general, the following criteria should be used for open channel design:

1. Channels with bottom widths greater than 10 feet shall be designed with a minimum bottom cross slope of 12 to 1.

2. Channel side slopes shall be stable throughout the entire length and side slope shall depend on the channel material. A normal maximum for open channels should be 2:1 and a maximum of 3:1 on roadside ditches.

3. Trapezoidal or parabolic cross sections are preferred over triangular shapes.

4. For vegetative channels, design stability should be determined using low vegetative retardance conditions (Class D) and for design capacity higher vegetative retardance conditions (Class C) should be used.

5. For vegetative channels, flow velocities within the channel should not exceed the maximum permissible velocities given in Tables 5-2 and 5-3.

6. If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport, and slope should conform to the existing conditions insofar as practicable. Some means of energy dissipation may be necessary when existing conditions cannot be duplicated.

7. Streambank stabilization should be provided, when appropriate, as a result of any stream disturbance such as encroachment and should include both upstream and downstream banks as well as the local site.

8. Open channel drainage systems are sized to handle a 25-year design storm. The 100-year design storm should be routed through the channel system to determine if the 100-year plus applicable building elevation restrictions are exceeded, structures are flooded, or flood damages increased.

5.2.2 Velocity Limitations

The final design of artificial open channels should be consistent with the velocity limitations for the selected channel lining. Maximum velocity values for selected lining categories are presented in Table 5-2. 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 5-3. Vegetative lining calculations are presented in Section 5.6 and riprap procedures are presented in Section 5.7.

Table 5-2 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

Table 5-3 Maximum Velocities for Vegetative Channel Linings

Vegetation Type	Slope Range (%)[1]	Maximum Velocity[2] (ft/s)
Bermuda Grass	0 - 5	6
	5 - 10	5
Bahia		4
Tall Fescue Grass Mixtures[3]	0 - 10	4
Kentucky Bluegrass	0 - 5	5
Buffalo Grass	5 - 10	4
	>10	3
Grass Mixture	0 - 5[1]	4
	5 - 10	3
Sericea Lespedeza, Weeping Lovegrass, Alfalfa	0 - 5[4]	2.5
Annuals[5]	0 - 5	2.5
Sod		4
Lapped Sod		5.5

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

5.3 Manning's n Values

The Manning's n value is an important variable in open channel flow computations. Variation in this variable can significantly affect discharge, depth, and velocity estimates. Since Manning's n values depend on many different physical characteristics of natural and man-made channels, care and good engineering judgment must be exercised in the selection process.

Recommended Manning's n values for artificial channels with rigid, unlined, temporary, and riprap linings are given in Table 5-4. Recommended values for vegetative linings should be determined using Figure 5-1, which provides a graphical relationship between Manning's n values and the product of velocity and hydraulic radius for several vegetative retardance classifications (see Table 5-6). Figure 5-1 is used iteratively as described in Section 5.6.

Recommended Manning's values for natural channels which are either excavated or dredged and natural are given in Table 5-5. For natural channels, Manning's n values should be estimated using the procedures presented in the publication Guide For Selecting Manning's Roughness Coefficients For Natural Channels And Flood Plains, FHWA-TS-84-204, 1984.

5.4 Uniform Flow Calculations

5.4.1 Design Charts

Following is a discussion of the equations that can be used for the design and analysis of open channel flow. The Federal Highway Administration has prepared numerous design charts to aid in the design of rectangular, triangular, and trapezoidal open channel cross sections. In addition, design charts for grass lined channels have been developed. These charts and instructions for their use are given in Section 5.10 of this chapter.

5.4.2 Manning's Equation

Manning's Equation, presented in three forms below, is recommended for evaluating uniform flow conditions in open channels:

$$v = (1.49\ R^{2/3}\ S^{1/2})/n \quad (5.1)$$

$$Q = (1.49\ A\ R^{2/3}\ S^{1/2})/n \quad (5.2)$$

$$S = [Qn/(1.49\ A\ R^{2/3})]^2 \quad (5.3)$$

Where: v = average channel velocity (ft/s)
Q = discharge rate for design conditions (cfs)
n = Manning's roughness coefficient
A = cross-sectional area (ft^2)
R = hydraulic radius A/P (ft)
P = wetted perimeter (ft)
S = slope of the energy grade line (ft/ft)

For prismatic channels, in the absence of backwater conditions, the slope of the energy grade line, water surface and channel bottom are equal.

5.4.3 Geometric Relationships

Area, wetted perimeter, hydraulic radius, and channel top width for standard channel cross-sections can be calculated from geometric dimensions. Irregular channel cross sections (i.e., those with a narrow deep main channel and a wide shallow overbank channel) must be subdivided into segments so that the flow can be computed separately for the main channel and overbank portions. This same process of subdivision may be used when different parts of the channel cross section have different roughness coefficients. When computing the hydraulic radius of the subsections, the water depth common to the two adjacent subsections is not counted as wetted perimeter.

5.4.4 Direct Solutions

When the hydraulic radius, cross-sectional area, and roughness coefficient and slope are known, discharge can be calculated directly from equation 5.2. The slope can be calculated using equation 5.3 when the discharge, roughness coefficient, area, and hydraulic radius are known.

Nomographs for obtaining direct solutions to Manning's Equation are presented in Figures 5-2 and 5-3. Figure 5-2 provides a general solution for the velocity form of Manning's Equation, while Figure 5-3 provides a solution of Manning's Equation for trapezoidal channels.

Table 5-4 Manning's Roughness Coefficients For Artificial Channels - n

		n at various flow depths		
Lining Category	**Lining Type**	**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	1-inch D_{50}	0.044	0.033	0.030
	2-inch D_{50}	0.066	0.041	0.034
Rock Riprap	6-inch D_{50}	0.104	0.069	0.035
	12-inch D_{50}	----	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.

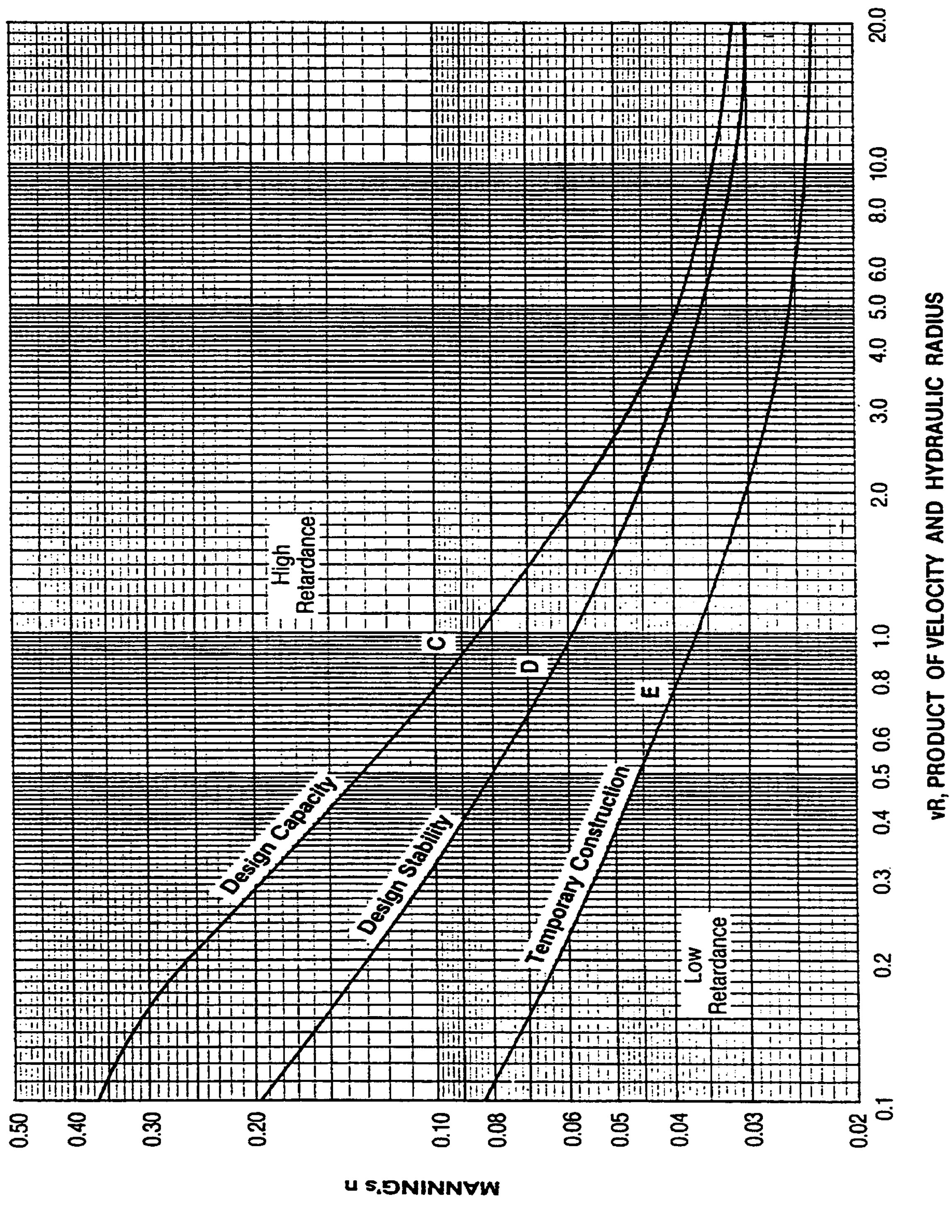


Figure 5-1 Manning's n Values For Vegetated Channels

Table 5-5 Uniform Flow Values Of Roughness Coefficient - n

Type Of Channel And Description	Minimum	Normal	Maximum
EXCAVATED OR DREDGED			
a. Earth, straight and uniform	0.016	0.018	0.020
1. Clean, recently completed	0.018	0.022	0.025
2. Clean, after weathering	0.022	0.025	0.030
3. Gravel, uniform section, clean	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
NATURAL STREAMS			
Minor streams (top width at flood stage < 100 ft)			
a. Streams 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 and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and some 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 floodways with heavy stand of timber and underbrush	0.075	0.100	0.150

Table 5-5 Uniform Flow Values Of Roughness Coefficient – n (continued)

Type Of Channel And Description	Minimum	Normal	Maximum
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: gravels, cobbles, few boulders	0.030	0.040	0.050
2. Bottom: cobbles with large boulders	0.040	0.050	0.070
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 spouts	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
Major Streams (top width at flood stage > 100 ft). The n value is less than that for minor streams of similar description, because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	.....	0.060
b. Irregular and rough section	0.035	.....	0.100

Table 5-6 Classification of Vegetal Covers as to Degrees of Retardance

Retardance	Cover	Condition
A	Weeping Lovegrass	Excellent stand, tall (average 30")
	Yellow Bluestem Ischaemum	Excellent stand, tall (average 36")
B	Kudzu	Very dense growth, uncut
	Bermuda grass	Good stand, tall (average 12")
	Native grass mixture little bluestem, bluestem, blue gamma other short and long stem midwest lovegrass	Good stand, unmowed
	Weeping lovegrass	Good stand, tall (average 24")
	Laspedeza sericea	Good stand, not woody, tall (average 19")
	Alfalfa	Good stand, uncut (average 11")
	Kudzu	Dense growth, uncut
	Weeping lovegrass	Good stand, unmowed (average 13")
	Blue gamma	Good stand, uncut (average 13")
C	Crabgrass	Fair stand, uncut (10 - 48")
	Bermuda grass	Good stand, mowed (average 6")
	Common lespedeza	Good stand, uncut (average 11")
	Grass-legume mixture: summer (orchard grass redtop, Italian ryegrass, and common lespedeza)	Good stand, uncut (6 - 8")
	Centipede grass	Very dense cover (average 6")
	Kentucky bluegrass	Good stand, headed (6 - 12")
D	Bermuda grass	Good stand, cut to 2.5"
	Common lespedeza	Excellent stand, uncut (average 4.5")
	Buffalo grass	Good stand, uncut (3 - 6")
	Grass-legume mixture: fall, spring (orchard grass, redtop, Italian ryegrass, and common lespedeza	Good stand, uncut (4 - 5")
	Lespedeza serices	After cutting to 2" (very good before cutting)
E	Bermuda grass	Good stand, cut to 1.5"
	Bermuda grass	Burned stubble

Note: Covers classified have been tested in experimental channels. Covers were green and generally uniform.

General Solution Nomograph

The following steps are used for the general solution nomograph in Figure 5-2:

1. Determine open channel data, including slope in ft/ft, hydraulic radius in ft, and Manning's n value.

2. Connect a line between the Manning's n scale and slope scale and note the point of intersection on the turning line.

3. Connect a line from the hydraulic radius to the point of intersection obtained in Step 2.

4. Extend the line from Step 3 to the velocity scale to obtain the velocity in ft/s.

<u>Trapezoidal Solution Nomograph</u>

The trapezoidal channel nomograph solution to Manning's Equation in Figure 5-3 can be used to find the depth of flow if the design discharge is known or the design discharge if the depth of flow is known.

1. Determine input data, including slope in ft/ft, Manning's n value, bottom width in ft, and side slope in ft/ft.

2. a. Given the design discharge, find the product of Q times n, connect a line from the slope scale to the Qn scale, and find the point of intersection on the turning line.

   b. Connect a line from the turning point from Step 2a to the b scale and find the intersection with the Z = 0 scale.

   c. Project horizontally from the point located in Step 2b to the appropriate Z value and find the value of d/B.

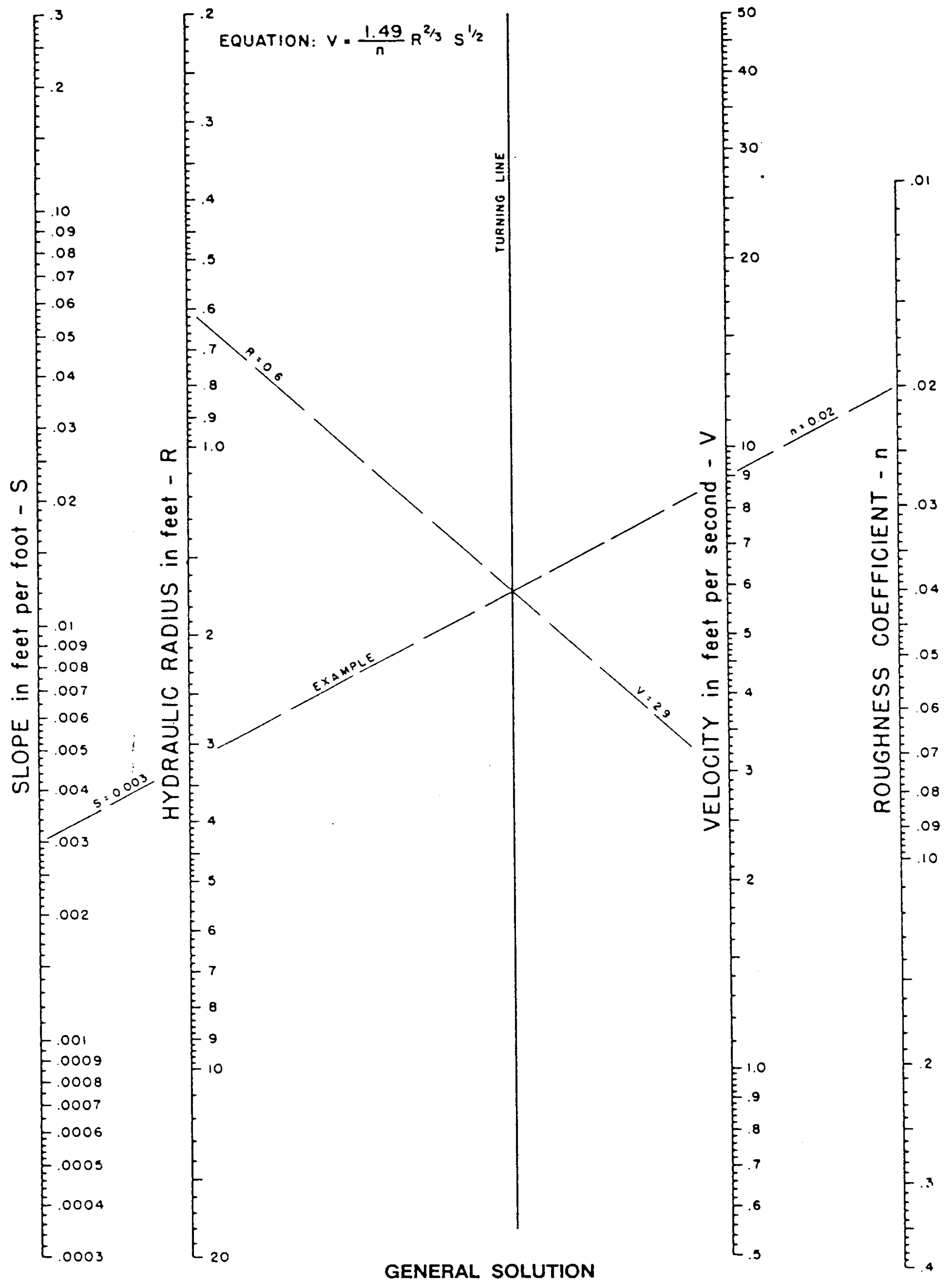
   d. Multiply the value of d/B obtained in Step 2c by the bottom width B to find the depth of uniform flow, d.

3. a. Given the depth of flow, find the ratio d divided by B and project a horizontal line from the d/B ratio at the appropriate side slope, Z, to the Z = 0 scale.

   b. Connect a line from the point located in Step 3a to the B scale and find the intersection with the turning line.

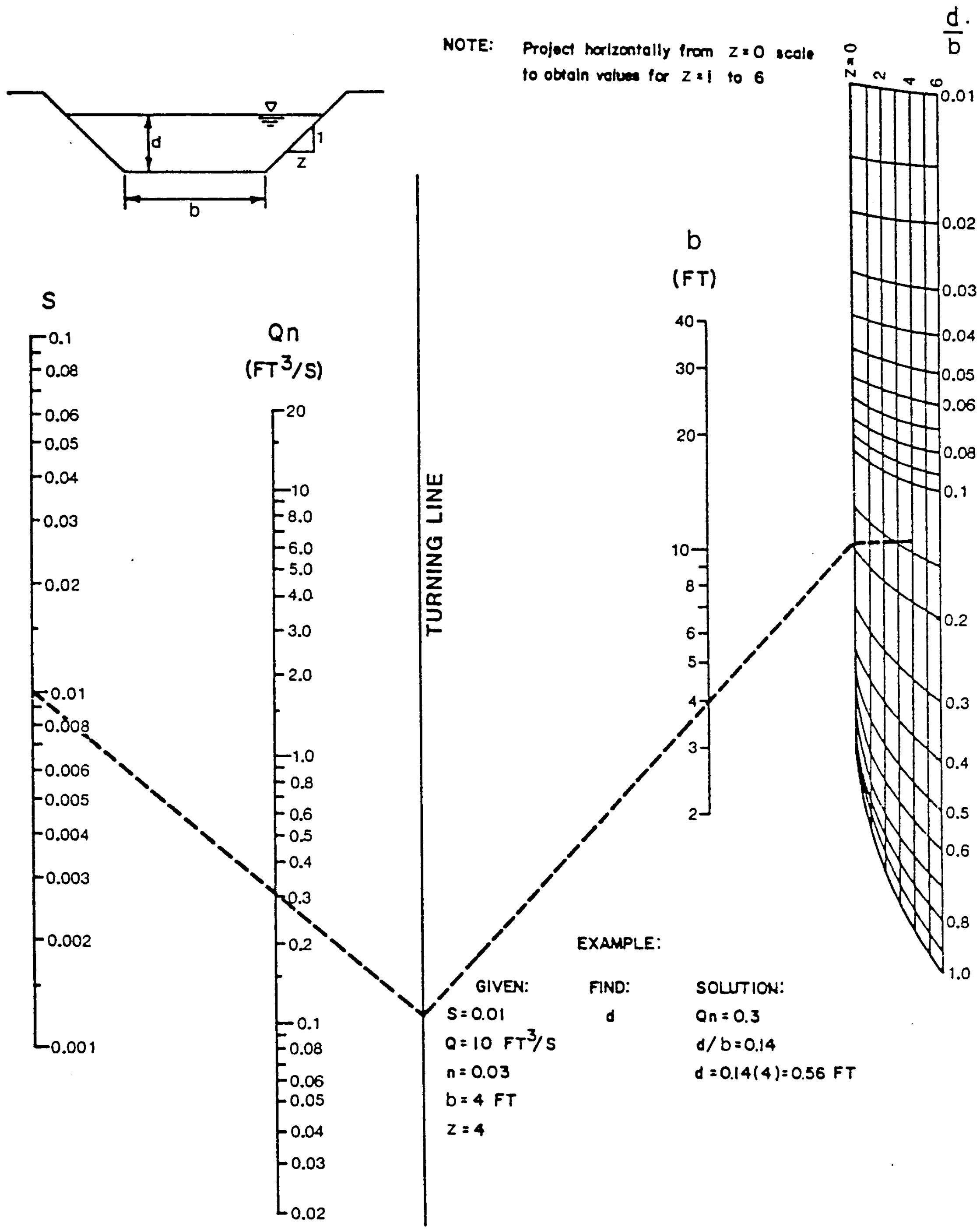
   c. Connect a line from the point located in Step 3b to the slope scale and find the intersection with the Qn scale.

   d. Divide the value of Qn obtained in Step 3c by the n value to find the design discharge, Q.



Reference: USDOT, FHWA, HDS-3 (1961).

Figure 5-2 Nomograph For The Solution Of Manning's Equation



Reference: USDOT, FHWA, HEC-15 (1986).

Figure 5-3 Solution Of Manning's Equation For Trapezoidal Channels

5.4.5 Trial And Error Solutions

A trial and error procedure for solving Manning's Equation is used to compute the normal depth of flow in a uniform channel when the channel shape, slope, roughness, and design discharge are known. For purposes of the trial and error process, Manning's Equation can be arranged as:

$$\mathbf{AR^{2/3} = (Qn)/(1.49\ S^{1/2})} \qquad \mathbf{(5.4)}$$

Where: A = cross-sectional area (ft)
R = hydraulic radius (ft)
Q = discharge rate for design conditions (cfs)
n = Manning's roughness coefficient
S = slope of the energy grade line (ft/ft)

To determine the normal depth of flow in a channel by the trial and error process, trial values of depth are used to determine A, P, and R for the given channel cross section. Trial values of $AR^{2/3}$ are computed until the equality of equation 5.4 is satisfied such that the design flow is conveyed for the slope and selected channel cross section.

Graphical procedures for simplifying trial and error solutions are presented in Figure 5-4 for trapezoidal channels, which is described below.

1. Determine input data, including design discharge, Q, Manning's n value, channel bottom width, b, channel slope, S, and channel side slope, z.

2. Calculate the trapezoidal conveyance factor using the equation:

$$\mathbf{K_T = (Qn)/(b^{8/3}S^{1/2})} \qquad \mathbf{(5.5)}$$

Where: K_T = trapezoidal open channel conveyance factor
Q = discharge rate for design conditions (cfs)
n = Manning's roughness coefficient
b = bottom width (ft)
S = slope of the energy grade line (ft/ft)

3. Enter the x-axis of Figure 5-4 with the value of K_T calculated in Step 2 and draw a line vertically to the curve corresponding to the appropriate z value from Step 1.

4. From the point of intersection obtained in Step 3, draw a horizontal line to the y-axis and read the value of the normal depth of flow over the bottom width, d/b.

5. Multiply the d/b value from Step 4 by b to obtain the normal depth of flow.

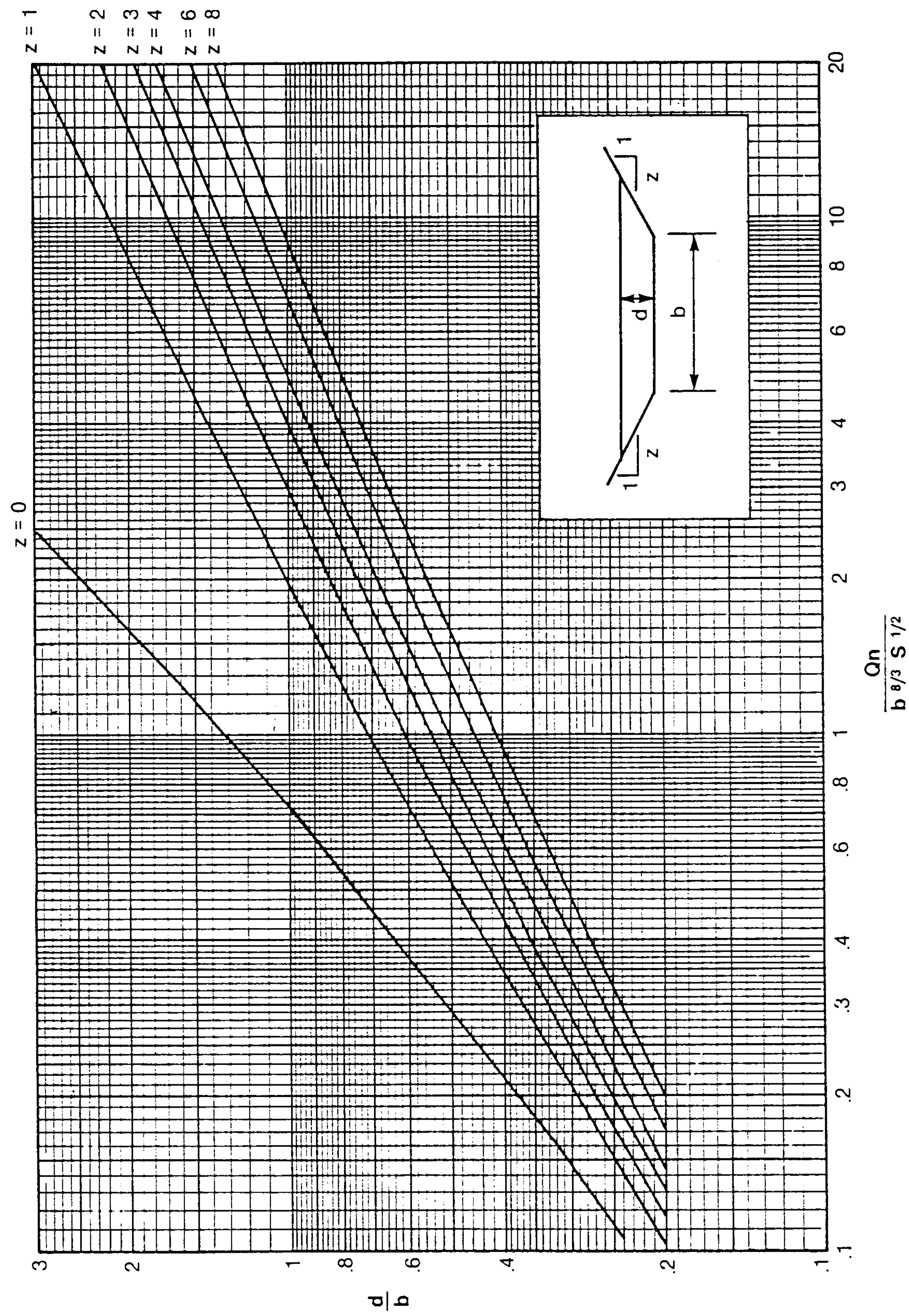


Figure 5-4 Trapezoidal Channel Capacity Chart

5.5 Critical Flow Calculations

5.5.1 Background

In the design of open channels, it is important to calculate the critical depth in order to determine if the flow in the channel will be subcritical or supercritical. If the flow is subcritical, it is relatively easy to handle the flow through channel transitions because the flows are tranquil and wave action is minimal. In subcritical flow, the depth at any point is influenced by a downstream control, which may be either the critical depth or the water surface elevation in a pond or larger downstream channel. In supercritical flow, the depth of flow at any point is influenced by a control upstream, usually critical depth. In addition, the flows have relatively shallow depths and high velocities.

Critical depth depends only on the discharge rate and channel geometry. The general equation for determining critical depth is expressed as:

$$\mathbf{Q^2/g = A^3/T} \qquad \textbf{(5.6)}$$

Where: Q = discharge rate for design conditions (cfs)
g = acceleration due to gravity (32.2 ft/s^2)
A = cross-sectional area (ft^2)
T = top width of water surface (ft)

Note: A trial and error procedure is needed to solve equation 5-6.

5.5.2 Semi-Empirical Equations

Semi-empirical equations (as presented in Table 5-7) or section factors (as presented in Figure 5-5) can be used to simplify trial and error critical depth calculations. The following equation is used to determine critical depth with the critical flow section factor, Z:

$$\mathbf{Z = Q/(g^{0.5})} \qquad \textbf{(5.7)}$$

Where: Z = critical flow section factor
Q = discharge rate for design conditions (cfs)
g = acceleration due to gravity (32.3 ft/s^2)

The following guidelines are given for evaluating critical flow conditions of open channel flow:

1. A normal depth of uniform flow within about 10 percent of critical depth is unstable and should be avoided in design, if possible.

2. If the velocity head is less than one-half the mean depth of flow, the flow is subcritical.

3. If the velocity head is equal to one-half the mean depth of flow, the flow is critical.

4. If the velocity head is greater than one-half the mean depth of flow, the flow is supercritical.

The Froude number, Fr, calculated by the following equation, is useful for evaluating the type of flow conditions in an open channel:

$$\mathbf{Fr = v/(gA/T)^{0.5}} \qquad \textbf{(5.8)}$$

Where: Fr = Froude number (dimensionless)
v = velocity of flow (ft/s)
g = acceleration of gravity (32.2 ft/s^2)
A = cross-sectional area of flow (ft^2)
T = top width of flow (ft)

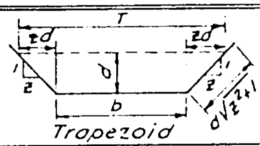
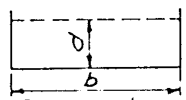
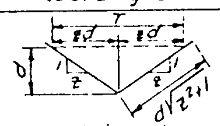
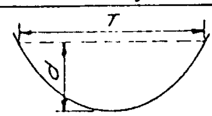
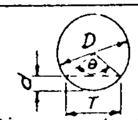
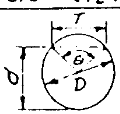
If Fr is greater than 1.0, flow is supercritical; if it is under 1.0, flow is subcritical. Fr is 1.0 for critical flow conditions.

Table 5-7
Critical Depth Equations For Uniform Flow In Selected Channel Cross Sections

Channel Type[1]	Semi-Empirical Equations[2] for Estimating Critical Depth	Range of Applicability
1. Rectangular[3]	$d_c = [Q^2/(gb^2)]^{1/3}$	N/A
2. Trapezoidal[3]	$d_c = 0.81[Q^2/(gz^{0.75}b^{1.25})]^{0.27} - b/30z$	$0.1 < 0.5522\ Q/b^{2.5} < 0.4$ For $0.5522\ Q/b^{2.5} < 0.1$, use rectangular channel equation
3. Triangular[3]	$d_c = [(2Q^2)/(gz^2)]^{1/5}$	N/A
4. Circular[4]	$d_c = 0.325(Q/D)^{2/3} + 0.083D$	$0.3 < d_c/D < 0.9$
5. General[5]	$(A^3/T) = (Q^2/g)$	N/A

Where: d_c = critical depth (ft)
Q = design discharge (cfs)
g = acceleration due to gravity (32.2 ft/s^2)
b = bottom width of channel (ft)
z = side slopes of a channel (horizontal to vertical)
D = diameter of circular conduit (ft)
A = cross-sectional area of flow (ft^2)
T = top width of water surface (ft)

[1]See Figure 5-5 for channel sketches
[2]Assumes uniform flow with the kinetic energy coefficient equal to 1.0
[3]Reference: French (1985)
[4]Reference: USDOT, FHWA, HDS-4 (1965)
[5]Reference: Brater and King (1976)

Section	Area A	Wetted Perimeter P	Hydraulic Radius R	Top Width T	Critical Depth Factor, Z
 Trapezoid	$bd+zd^2$	$b+2d\sqrt{z^2+1}$	$\frac{bd+zd^2}{b+2d\sqrt{z^2+1}}$	$b+2zd$	$\frac{[(b+zd)d]^{1.5}}{\sqrt{b+2zd}}$
 Rectangle	bd	$b+2d$	$\frac{bd}{b+2d}$	b	$bd^{1.5}$
 Triangle	zd^2	$2d\sqrt{z^2+1}$	$\frac{zd}{2\sqrt{z^2+1}}$	$2zd$	$\frac{\sqrt{2}}{2}zd^{2.5}$
 Parabola	$\frac{2}{3}dT$	$T+\frac{8d^2}{3T}$ [1]	$\frac{2dT^2}{3T^2+8d^2}$ [1]	$\frac{3a}{2d}$	$\frac{2}{9}\sqrt{6}\,Td^{1.5}$
 Circle - < ½ full [2]	$\frac{D^2}{8}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$\frac{\pi D\theta}{360}$	$\frac{45D}{\pi\theta}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$	$a\sqrt{\frac{a}{D\sin\frac{\theta}{2}}}$
 Circle - > ½ full [3]	$\frac{D^2}{8}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$\frac{\pi D(360-\theta)}{360}$	$\frac{45D}{\pi(360-\theta)}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$	$a\sqrt{\frac{a}{D\sin\frac{\theta}{2}}}$

[1] Satisfactory approximation for the interval $0 < \frac{d}{T} \leq 0.25$. When $d/T > 0.25$, use $p = \frac{1}{2}\sqrt{16d^2+T^2} + \frac{T^2}{8d}\sinh^{-1}\frac{4d}{T}$

[2] $\theta = 4\sin^{-1}\sqrt{d/D}$
[3] $\theta = 4\cos^{-1}\sqrt{d/D}$
Insert θ in degrees in above equations

Note: Small z = Side Slope Horizontal Distance
Large Z = Critical Depth Section Factor

Reference: USDA, SCS, NEH-5 (1956).

Figure 5-5 Open Channel Geometric Relationships For Various Cross Sections

5.6 Vegetative Design

5.6.1 Introduction

A two-part procedure is recommended for final design of temporary and vegetative channel linings. Part 1, the design stability component, involves determining channel dimensions for low vegetative retardance conditions, using Class D as defined in Table 5-6. Part 2, the design capacity component, involves determining the depth increase necessary to maintain capacity for higher vegetative retardance conditions, using Class C as defined in Table 5-6. If temporary lining is to be used during construction, vegetative retardance Class E should be used for the design stability calculations.

If the channel slope exceeds 10 percent, or a combination of channel linings will be used, additional procedures not presented below are required. References include HEC-15 (USDOT, FHWA, 1986) and HEC-14 (USDOT, FHWA, 1983).

5.6.2 Design Stability

The following are the steps for design stability calculations:

1. Determine appropriate design variables, including discharge, Q, bottom slope, S, cross section parameters, and vegetation type.

2. Use Table 5-3 to assign a maximum velocity, v_m based on vegetation type and slope range.

3. Assume a value of n and determine the corresponding value of vR from the n versus vR curves in Figure 5-1. Use retardance Class D for permanent vegetation and E for temporary construction.

4. Calculate the hydraulic radius using the equation:

$$\mathbf{R = (vR)/v_m} \qquad \mathbf{(5.9)}$$

Where: R = hydraulic radius of flow (ft)
vR = value obtained from Figure 5-1 in Step 3
v_m = maximum velocity from Step 2 (ft/s)

5. Use the following form of Manning's Equation to calculate the value of vR:

$$\mathbf{vR = (1.49\, R^{5/3}\, S^{1/2})/n} \qquad \mathbf{(5.10)}$$

Where: vR = calculated value of vR product
R = hydraulic radius value from Step 4 (ft)
S = channel bottom slope (ft/ft)
n = Manning's n value assumed in Step 3

6. Compare the vR product value obtained in Step 5 to the value obtained from Figure 5-1 for the assumed n value in Step 3. If the values are not reasonably close, return to Step 3 and repeat the calculations using a new assumed n value.

7. For trapezoidal channels, find the flow depth using Figures 5-3 or 5-4, as described in Section 5.4.5. The depth of flow for other channel shapes can be evaluated using the trial and error procedure described in Section 5.4.5.

8. If bends are considered, calculate the length of downstream protection, L_p, for the bend using Figure 5-6. Provide additional protection, such as gravel or riprap in the bend and extending downstream for length, L_p.

5.6.3 Design Capacity

The following are the steps for design capacity calculations:

1. Assume a depth of flow greater than the value from Step 7 above and compute the waterway area and hydraulic radius (see Figure 5-5 for equations).

2. Divide the design flow rate, obtained using appropriate procedures from Chapter 2 - Hydrology, by the waterway area from Step 1 to find the velocity.

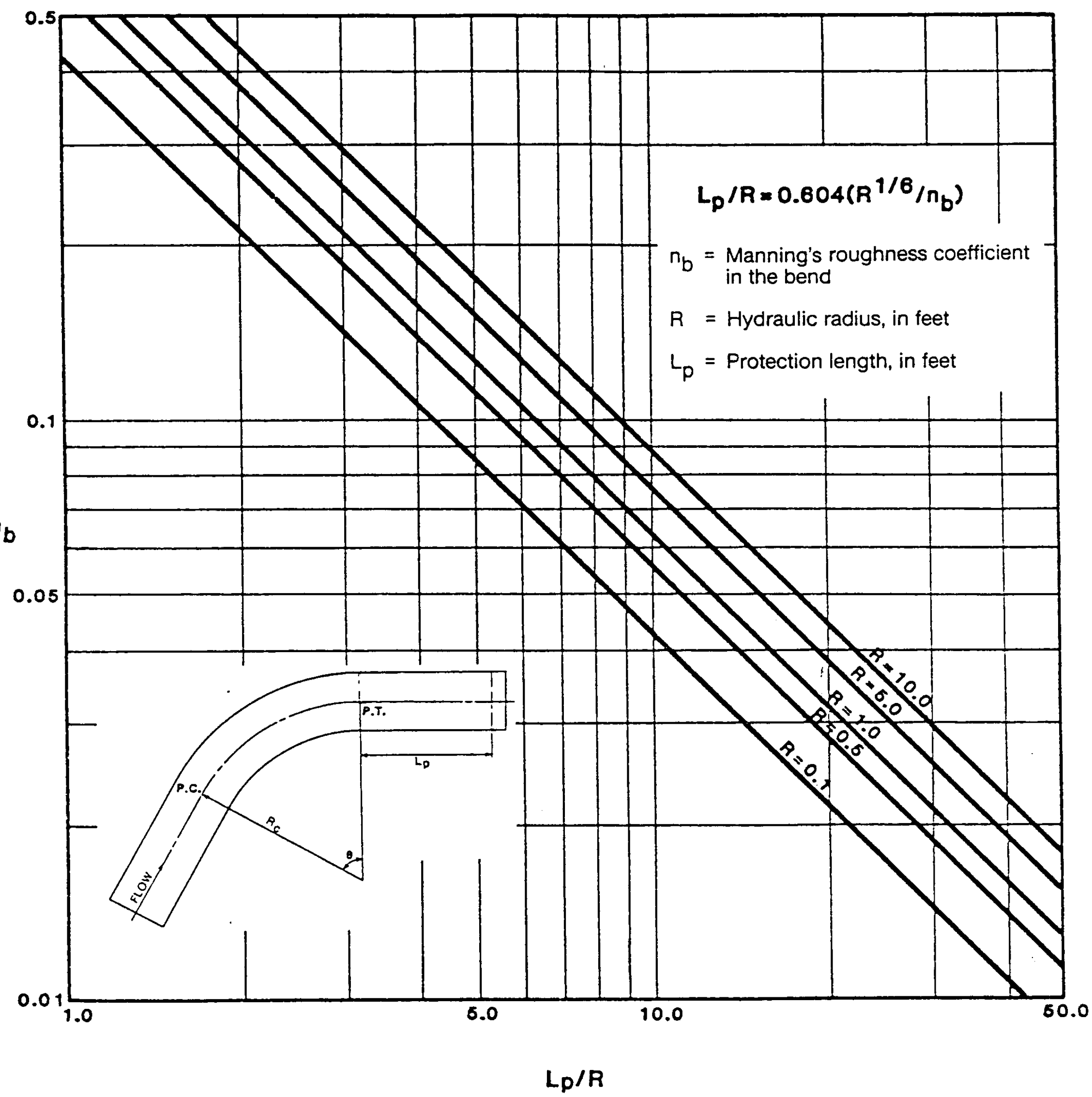
3. Multiply the velocity from Step 2 by the hydraulic radius from Step 1 to find the value of vR.

4. Use Figure 5-1 to find a Manning's n value for retardance Class C based on the vR value from Step 3.

5. Use Manning's Equation (equation 5.1) or Figure 5-2 to find the velocity using the hydraulic radius from Step 1, Manning's n value from Step 4, and appropriate bottom slope.

6. Compare the velocity values from Steps 2 and 5. If the values are not reasonably close, return to Step 1 and repeat the calculations.

7. Add an appropriate freeboard to the final depth from Step 6. Generally, 20 percent is adequate.



Reference: USDOT, FHWA, HEC-15 (1986).

Figure 5-6 Protection Length, Lp, Downstream Of Channel Bend

5.7 Riprap Design

5.7.1 Assumptions

The following procedure is based on results and analysis of laboratory and field data (Maynord, 1987; Reese, 1984; Reese, 1988). This procedure applies to riprap placement in both natural and prismatic channels and has the following assumptions and limitations:

1. Minimum riprap thickness equal to d_{100}
2. The value of d_{85}/d_{15} less than 4.6
3. Froude number less than 1.2
4. Side slopes up to 2:1
5. A safety factor of 1.2
6. Maximum velocity less than 18 feet per second

If significant turbulence is caused by boundary irregularities, such as installations near obstructions or structures, this procedure is not applicable.

5.7.2 Procedure

Following are the steps in the procedure for riprap design.

1. Determine the average velocity in the main channel for the design condition. Use the higher value of velocity calculated both with and without riprap in place (this may require iteration using procedures in Section 5.4.5). Manning's n values for riprap can be calculated from the equation:

$$\mathbf{n = 0.0395\ (d_{50})^{1/6}} \qquad \textbf{(5.11)}$$

   Where: n = Manning's roughness coefficient for stone riprap
   d_{50} = Diameter of stone for which 50 percent, by weight, of the gradation is finer (ft)

2. If rock is to be placed at the outside of a bend, multiply the velocity determined in Step 1 by the bend correction coefficient, C_b, given in Figure 5-7 for either a natural or prismatic channel. This requires determining the channel top width, T, just upstream from the bend and the centerline bend radius, R_b.

3. If the specific weight of the stone varies significantly from 165 pounds per cubic foot, multiply the velocity from Step 1 or 2 (as appropriate) by the specific weight correction coefficient, C_g, from Figure 5-8.

4. Determine the required minimum d_{30} value from Figure 5-9, based on the equation:

$$\mathbf{d_{30}/D = 0.193\ Fr^{2.5}} \qquad \textbf{(5.12)}$$

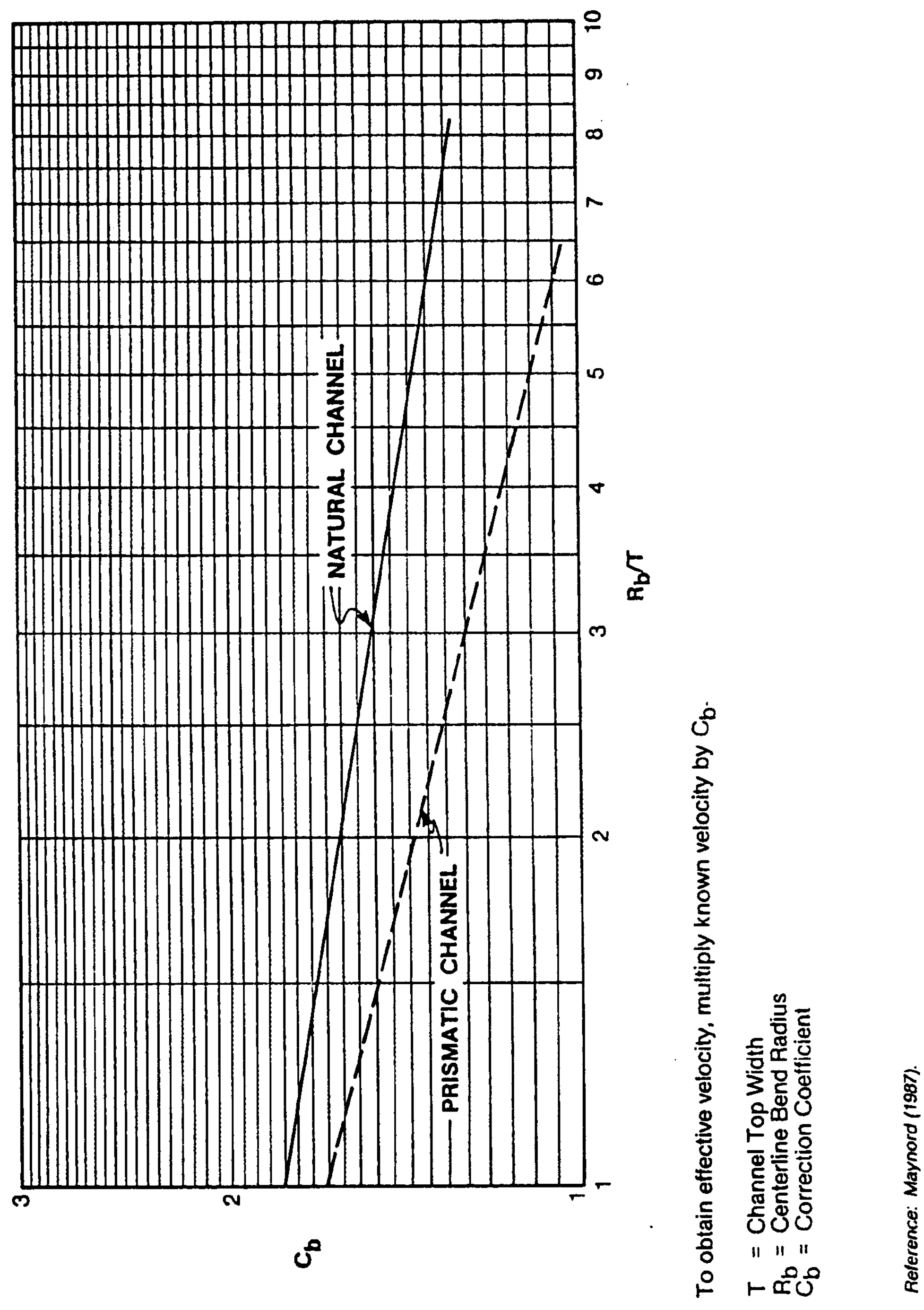


Figure 5-7 Riprap Lining Bend Correction Coefficient

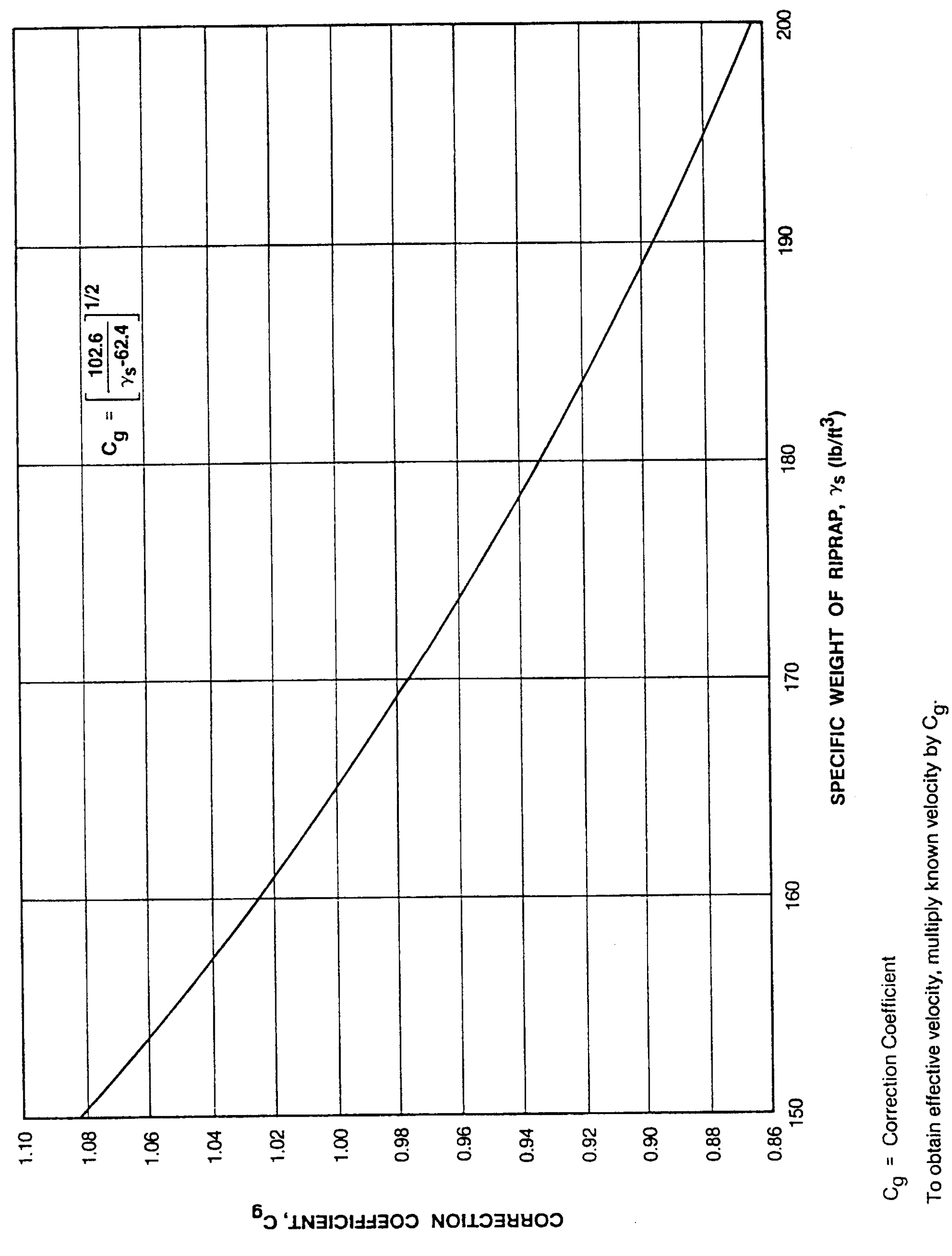


Figure 5-8 Riprap Lining Specific Weight Correction Coefficient

Where: d_{30} = diameter of stone for which 30 percent, by weight, of the gradation is smaller (ft)

D = depth of flow above stone (ft)
Fr = Froude number (see equation 5.8), (dimensionless)
v = mean velocity above the stone (ft/s)
g = acceleration of gravity (32.2 ft/s^2)

5. Determine available riprap gradations. A well graded riprap is preferable to uniform size or gap graded. The diameter of the largest stone, d_{100}, should not be more than 1.5 times the d_{50} size. Blanket thickness should be greater than or equal to d_{100} except as noted below. Sufficient smaller stones (below d_{15}) should be available to fill the voids in the larger rock sizes. The weight for a selected stone size can be calculated from the equation:

$$\mathbf{W = 0.5236\ (SW_s)\ d^3} \qquad \textbf{(5.13)}$$

Where: W = stone weight (lbs)
SW_s = specific weight of stone (lbs/ft^3)
d = selected stone diameter (ft)

Filter fabric or a filter stone layer should be used under the riprap layer to prevent turbulence or groundwater seepage from removing bank material through the stone or to serve as a foundation for unconsolidated material. Layer thickness should be increased by 50 percent for underwater placement.

6. If d_{85}/d_{15} is between 2.0 and 2.3 and a smaller d_{30} size is desired, a thickness greater than d_{100} can be used to offset the smaller d_{30} size. Figure 5-10 can be used to make an approximate adjustment using the ratio of d_{30} sizes. Enter the y-axis with the ratio of the desired d_{30} size to the standard d_{30} size and find the thickness ratio increase on the x-axis. Other minor gradation deficiencies may be compensated for by increasing the stone blanket thickness.

7. Perform preliminary design, ensuring that adequate transition is provided to natural materials both up and downstream to avoid flanking and that toe protection is provided to avoid riprap undermining.

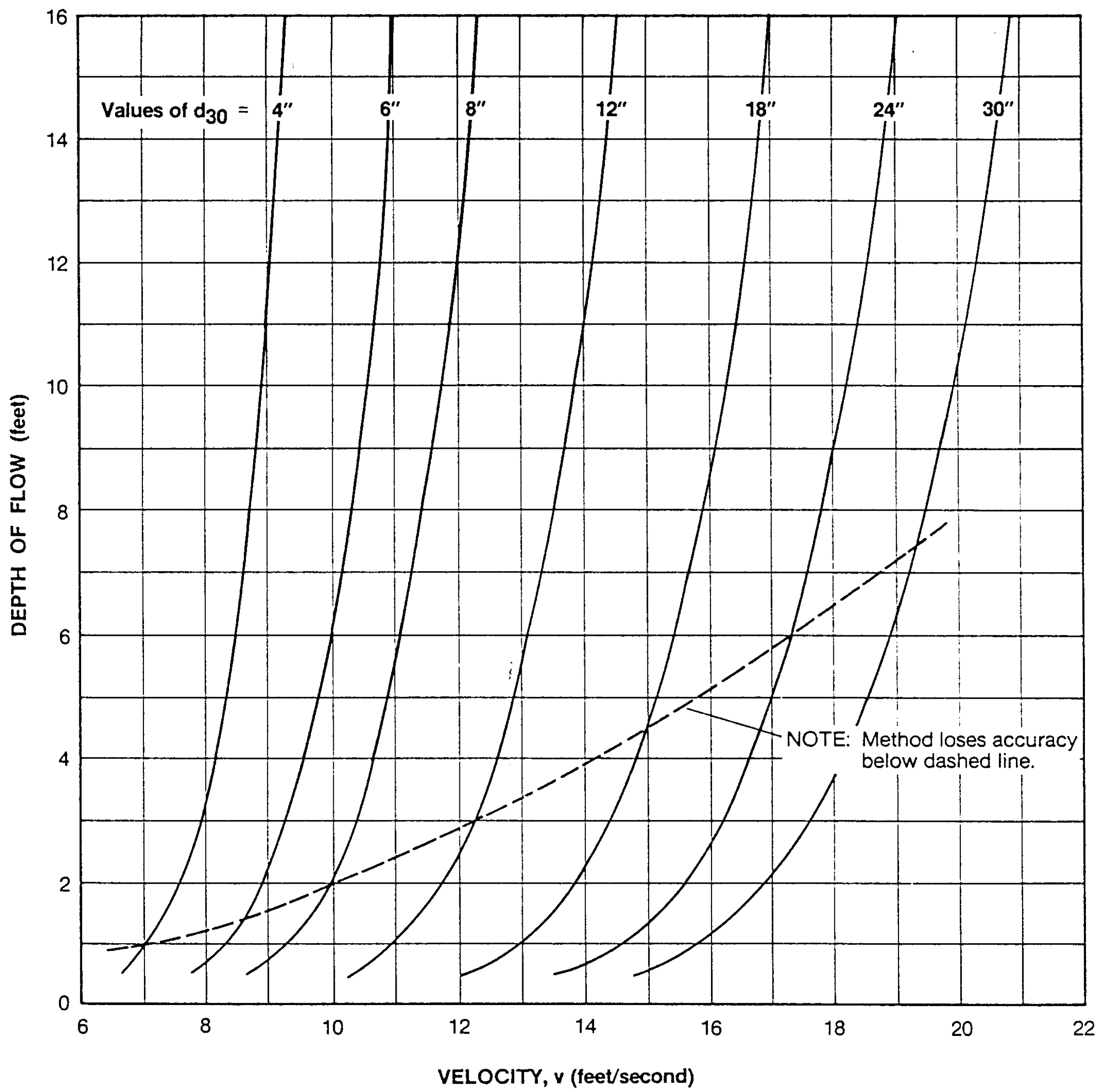
5.8 Uniform Flow - Example Problems

5.8.1 Example 1 - - Direct Solution of Manning's Equation

Use Manning's Equation to find the velocity, v, for an open channel with a hydraulic radius value of 0.6 ft, an n value of 0.020, and slope of 0.003 ft/ft. Solve using Figure 5-2:

1. Connect a line between the slope scale at 0.003 and the roughness scale at 0.020 and note the intersection point on the turning line.

2. Connect a line between that intersection point and the hydraulic radius scale at 0.6 ft and read the velocity of 2.9 ft/s from the velocity scale.



Reference: Reese (1988).

Figure 5-9 Riprap Lining d_{30} Stone Size - Function Of Mean Velocity And Depth

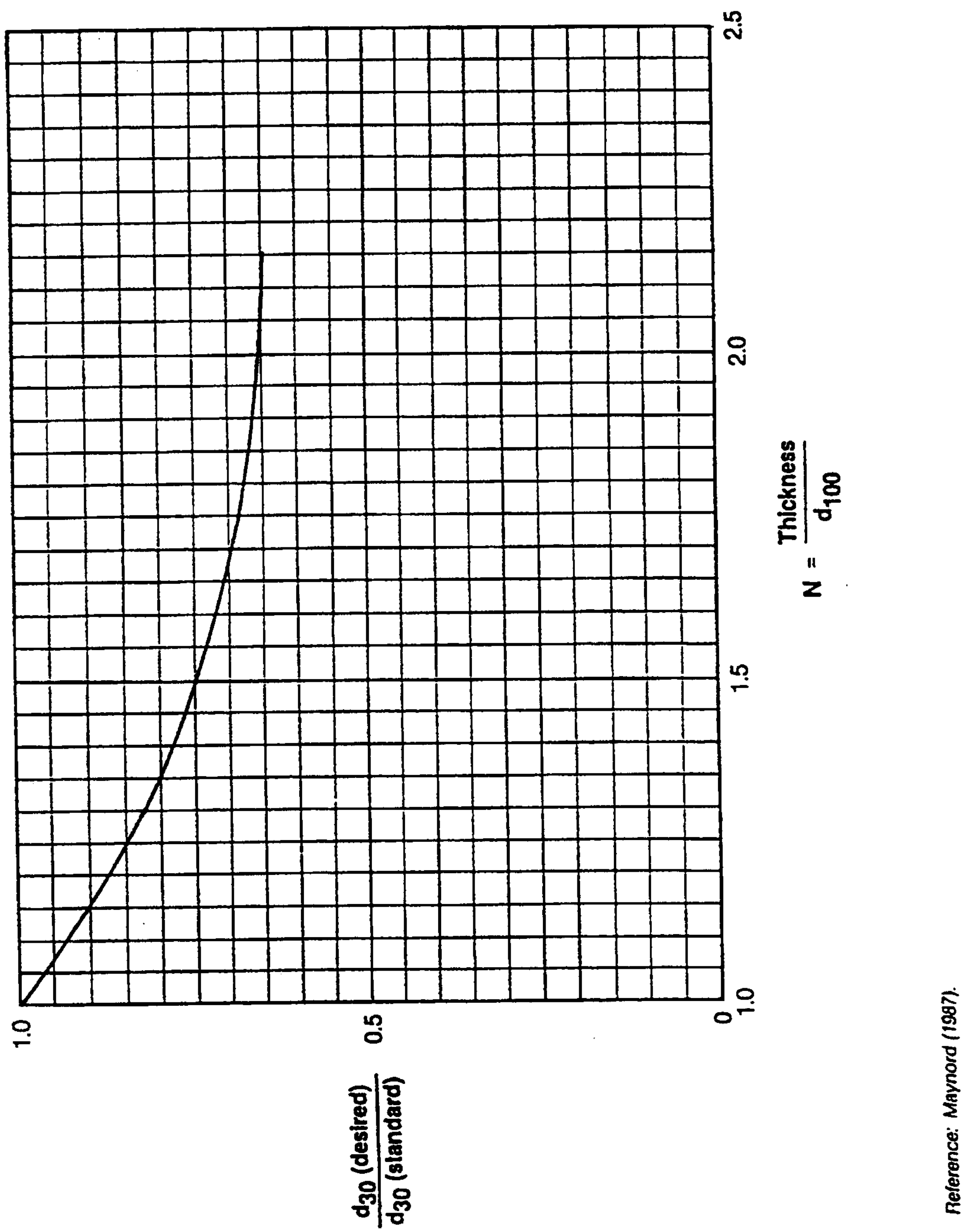


Figure 5-10 Riprap Lining Thickness Adjustment For d_{85}/d_{15} = 2.0 to 2.3

5.8.2 Example 2 - - Grassed Channel Design Stability

A trapezoidal channel is required to carry 50 cfs at a bottom slope of 0.015 ft/ft. Find the channel dimensions required for design stability criteria (retardance Class D) for a grass mixture.

1. From Table 5-3, the maximum velocity, v_m, for a grass mixture with a bottom slope less than 5 percent is 4 ft/s.

2. Assume an n value of 0.035 and find the value of vR from Figure 5-1. vR = 5.4

3. Use equation 5.9 to calculate the value of R: R = 5.4/4 = 1.35 ft

4. Use equation 5.10 to calculate the value of vR:
   $vR = [1.49\ (1.35)^{5/3}\ (0.015)^{1/2}]/0.035 = 8.60$

5. Since the vR value calculated in Step 4 is higher than the value obtained from Step 2, a higher n value is required and calculations are repeated. The results from each trial of calculations are presented below:

Assumed n Value	vR (Figure 5-1)	R (equation 5.9)	vR (equation 5.10)
0.035	5.4	1.35	8.60
0.038	3.8	0.95	4.41
0.039	3.4	0.85	3.57
0.040	3.2	0.80	3.15

   Select n = 0.040 for stability criteria.

6. Use Figure 5-3 to select channel dimensions for a trapezoidal shape with 3:1 side slopes.

   Qn = (50) (0.040) = 2.0
   S = 0.015
   For b = 10 ft, d = (10) (0.098) = 0.98 ft
   b = 8 ft, d = (8) (0.14) = 1.12 ft

   Select: b = 10 ft, such that R is approximately 0.80 ft
   z = 3
   d = 1 ft
   v = 3.9 ft/s (equation 5.1)
   Fr = 0.76 (equation 5.8)
   Flow is subcritical

   Design capacity calculations for this channel are presented in Example 3 below.

5.8.3 Example 3 - - Grassed Channel Design Capacity

Use a 10-ft bottom width and 3:1 side-slopes for the trapezoidal channel sized in Example 2 and find the depth of flow for retardance Class C.

1. Assume a depth of 1.0 ft and calculate the following (see Figure 5-5):
   A = (b + zd) d = [10 + (3) (1)] (1) = 13.0 square ft

$R = \{[b + zd]\, d\}/\{b + [2d(1 + z^2)^{1/2}]\} = \{[10+(3)(1)](1)\}/\{10+[(2)(1)(1+3^2)^{1/2}]\}$
$R = 0.796$ ft

2. Find the velocity. $v = Q/A = 50/13.0 = 3.85$ ft/s

3. Find the value of vR. $vR = (3.85)\,(0.796) = 3.06$

4. Using the vR product from Step 3, find Manning's n from Figure 5-1 for retardance Class C.
   $n = 0.047$

5. Use Figure 5-2 or equation 5.1 to find the velocity for $S = 0.015$, $R = 0.796$, and $n = 0.047$.
   $v = 3.34$ ft/s

6. Since 3.34 ft/s is less than 3.85 ft/s, a higher depth is required and calculations are repeated. Results from each trial of calculations are presented below:

Assumed Depth (ft)	Area (ft^2)	R (ft)	Velocity = Q/A (ft/sec)	vR	Manning's n (Fig. 5-1)	Velocity (Eq. 5.1) (ft/sec)
1.00	13.00	0.796	3.85	3.06	0.047	3.34
1.05	13.81	0.830	3.62	3.00	0.047	3.39
1.10	14.63	0.863	3.42	2.95	0.048	3.45
1.20	16.32	0.928	3.06	2.84	0.049	3.54

7. Select a depth of 1.1 with an n value of 0.048 for design capacity requirements. Add at least 0.2 ft for freeboard to give a design depth of 1.3 ft. Design data for the trapezoidal channel are summarized as follows:

   Vegetation lining = Grass Mixture, $v_m = 4$ ft/s

   $Q = 50$ cfs

   $b = 10$ ft, $d = 1.3$ ft, $z = 3$, $S = 0.015$ ft/ft

   Top width = (10) + (2) (3) (1.3) = 17.8 ft

   n(stability) = 0.040, d = 1.0 ft, v = 3.9 ft/s, Froude number = 0.76 (equation 5.8)

   n(capacity) = 0.048, d = 1.1 ft, v = 3.45 ft/s, Froude number = 0.64 (equation 5.8)

5.8.4 Example 4 -- Riprap Design

A natural channel has an average bankfull channel velocity of 8 ft per second with a top width of 20 ft and a bend radius of 50 ft. The depth over the toe of the outer bank is 5 ft. Available stone weight is 170 lbs/ft^3. Stone placement is on a side slope of 2:1 (horizontal:vertical).

1. Use 8 ft per second as the design velocity, because the reach is short and the bend is not protected.

2. Determine the bend correction coefficient for the ratio of $R_b/T = 50/20 = 2.5$. From Figure 5-7, $C_b = 1.55$. The adjusted effective velocity is (8) (1.55) = 12.4 ft/s.

3. Determine the correction coefficient for the specific weight of 170 lbs/ft^3 from Figure 5-8 as 0.98. The adjusted effective velocity is (12.4) (0.98) = 12.15 ft/s.

4. Determine minimum d_{30} from Figure 5-9 or equation 5.12 as about 10 inches.

5. Use a gradation with a minimum d_{30} size of 12 inches which is acceptable. Usually those have enough fines that a filter course will not be required.

6. (Optional) Another gradation is available with a d_{30} of 8 inches. The ratio of desired to standard stone size is 8/10 or 0.8. From Figure 5-10, this gradation would be acceptable if the blanket thickness was increased from the original d_{100} (diameter of the largest stone) thickness by 35 percent (a ratio of 1.35 on the horizontal axis).

7. Perform preliminary design. Make sure that the stone is carried up and downstream far enough to ensure stability of the channel and that the toe will not be undermined. The downstream length of protection for channel bends can be determined using Figure 5-6.

5.9 Gradually Varied Flow

The most common occurrence of gradually varied flow in storm drainage is the backwater created by culverts, storm sewer inlets, or channel constrictions. For these conditions, the flow depth will be greater than normal depth in the channel and the water surface profile should be computed using backwater techniques.

Many computer programs are available for computation of backwater curves. The most general and widely used programs are, HEC-2 and HEC-RAS, developed by the U.S. Army Corps of Engineers and Bridge Waterways Analysis Model (WSPRO) developed for the Federal Highway Administration. These programs can be used to compute water surface profiles for both natural and artificial channels.

For prismatic channels, the backwater calculation can be computed manually using the direct step method. For an irregular nonuniform channel, the standard step method is recommended, although it is a more tedious and iterative process. The use of HEC-2 is recommended for standard step calculations.

Cross sections for water surface profile calculations should be normal to the direction of flood flow. The number of sections required will depend on the irregularity of the stream and flood plain. In general, a cross section should be obtained at each location where there are significant changes in stream width, shape, or vegetal patterns. Sections should usually be no more than 4 to 5 channel widths apart or 100 ft apart for ditches or streams and 500 ft apart for flood plains, unless the channel is very regular.

5.10 Rectangular, Triangular, And Trapezoidal Design Figures

5.10.1 Introduction

The Federal Highway Administration has prepared numerous design figures to aid in the design of open channels. Copies of these figures, a brief description of their use, and several example design problems are presented. For design conditions not covered by the figures, a trial-and-error solution of the Manning's Equation must be used.

5.10.2 Description Of Figures

Figures given in Appendix A, B, and C at the end of this chapter are for the direct solution of the Manning's Equation for various sized open channels with rectangular, triangular, and trapezoidal cross sections. Each figure (except for the triangular cross section) is prepared for a channel of given bottom width and a particular value of Manning's n.

The figures for rectangular and trapezoidal cross section channels (Appendix A) are used the same way. The abscissa scale of discharge in cubic feet per second (cfs), and the ordinate scale is velocity in feet per second (ft/s). Both scales are logarithmic. Superimposed on the logarithmic grid are steeply inclined lines representing depth (ft), and slightly inclined lines representing channel slope (ft/ft). A heavy dashed line on each figure shows critical flow conditions. Auxiliary abscissa and ordinate scales are provided for use with other values of n and are explained in the example problems. In the figures, interpolations may be made not only on the ordinate and abscissa scales but between the inclined lines representing depth and slope.

The chart for a triangular cross section in (Appendix B) is in nomograph form. It may be used for street sections with a vertical (or nearly vertical) curb face. The nomograph also may be used for shallow V-shaped sections by following the instructions on the chart.

5.10.3 Instructions For Rectangular And Trapezoidal Figures

Figures in Appendix A provide a solution of the Manning's Equation for flow in open channels of uniform slope, cross section, and roughness, provided the flow is not affected by backwater and the channel has a length sufficient to establish uniform flow.

For a given slope and channel cross section, when n is 0.015 for rectangular channels or 0.03 for trapezoidal channels, the depth and velocity of uniform flow may be read directly from the figure for that size channel. The initial step is to locate the intersection of a vertical line through the discharge (abscissa) and the appropriate slope line. At this intersection, the depth of flow is read from the depth lines, and the mean velocity is read on the ordinate scale.

The procedure is reversed to determine the discharge at a given depth of flow. Critical depth, slope, and velocity for a given discharge can be read on the appropriate scale at the intersection of the critical curve and a vertical line through the discharge.

Auxiliary scales, labeled Qn (abscissa) and Vn (ordinate), are provided so the figures can be used for values of n other than those for which the charts were basically prepared. To use these scales, multiply the discharge by the value of n and use the Qn and Vn scales instead of the Q and V scales, except for computation of critical depth or critical velocity. To obtain normal velocity V from a value on the Vn scale, divide the value by n. The following examples will illustrate these points.

<u>Example - Design Problem 1</u>

Given: A rectangular concrete channel 5 ft wide with Manning's n = 0.015, 0.06 percent slope (S = 0.0006 ft/ft), discharging 60 cfs.

Find: Depth, velocity, and type of flow

Procedure:

1. From Appendix A select the rectangular figure for a 5 ft width (Figure 5-11).
2. From 60 cfs on the Q scale, move vertically to intersect the slope line at S = 0.0006, and from the depth lines read normal depth of flow = 3.7 ft.
3. Move horizontally from the same intersection and read the normal velocity, V = 3.2 ft/s, on the ordinate scale.
4. The intersection lies below the critical curve, and the flow is therefore in the subcritical range.

<u>Example - Design Problem 2</u>

Given: A trapezoidal channel with 2:1 side slopes and a 4 ft bottom width, with Manning's n = 0.030, 0.2 percent slope (S = 0.002 ft/ft), discharging 50 cfs.

Find: Depth, velocity, and type of flow.

Procedure:

1. From Appendix A select the trapezoidal figure for b = 4 ft (Figure 5-12).
2. From 50 cfs on the Q scale, move vertically to intersect the slope line S = 0.002 and from the depth lines read depth in feet = 2.2 ft.
3. Move horizontally from the same intersection and read the normal velocity, V = 2.75 ft/s, on the ordinate scale.
4. The intersection lies below the critical curve, the flow is therefore subcritical.

<u>Example - Design Problem 3</u>

Given: A rectangular cement rubble masonry channel 5 ft wide, with Manning's n = 0.025, 0.5 percent slope (S = 0.005 ft/ft), discharging 80 cfs.

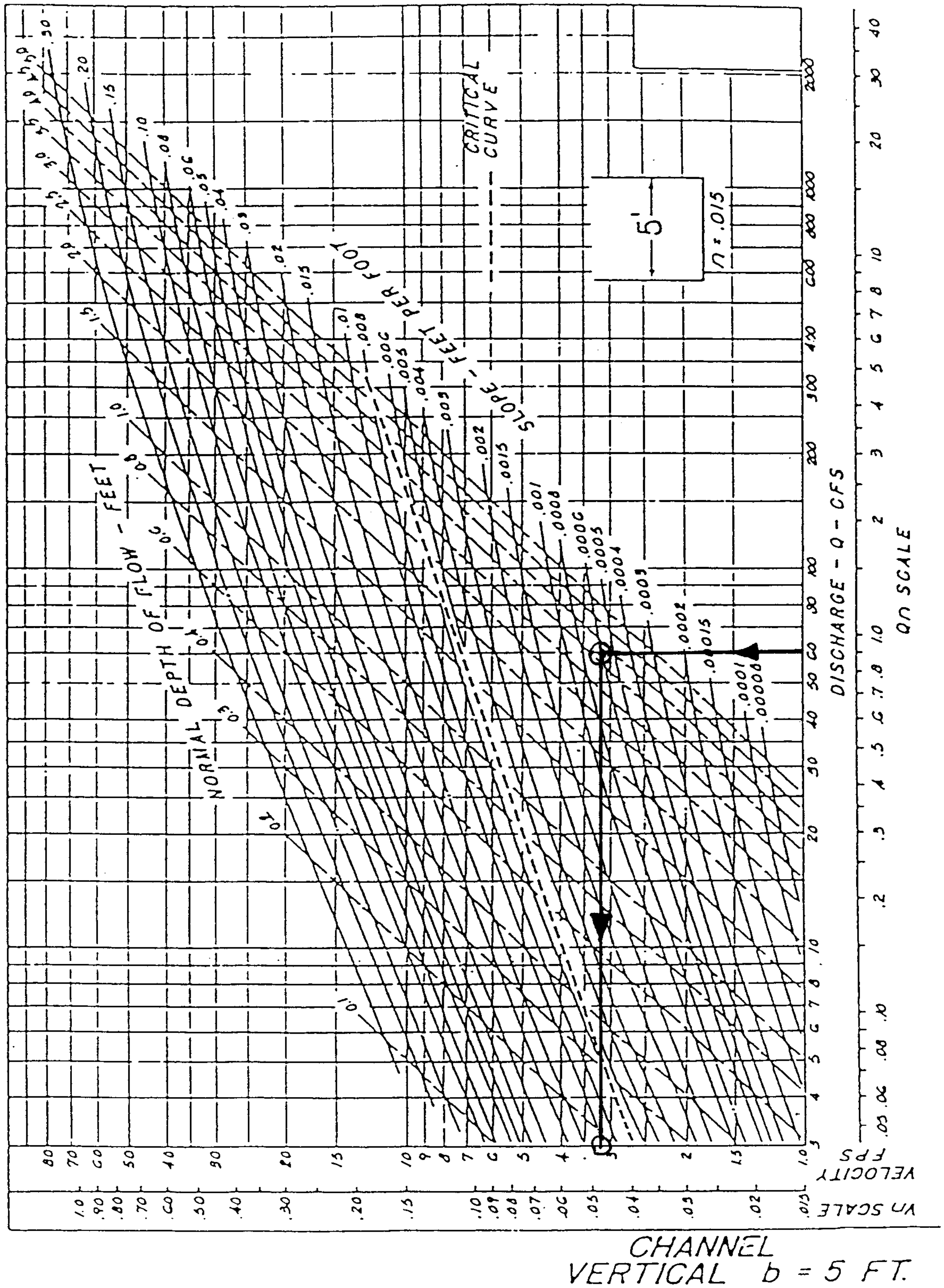
Find: Depth, velocity, and type of flow

Procedure:

1. From Appendix A select the rectangular figure for a 5 ft width (Figure 5-13).
2. Multiply Q by n to obtain Qn: 80 x 0.025 = 2.0.
3. From 2.0 on the Qn scale, move vertically to intersect the slope line, S = 0.005, and at the intersection read normal depth of flow = 3.1 ft.
4. Move horizontally from the intersection and read Vn = 0.13, then Vn/n = 0.13/0.025 = 5.2 ft/s.

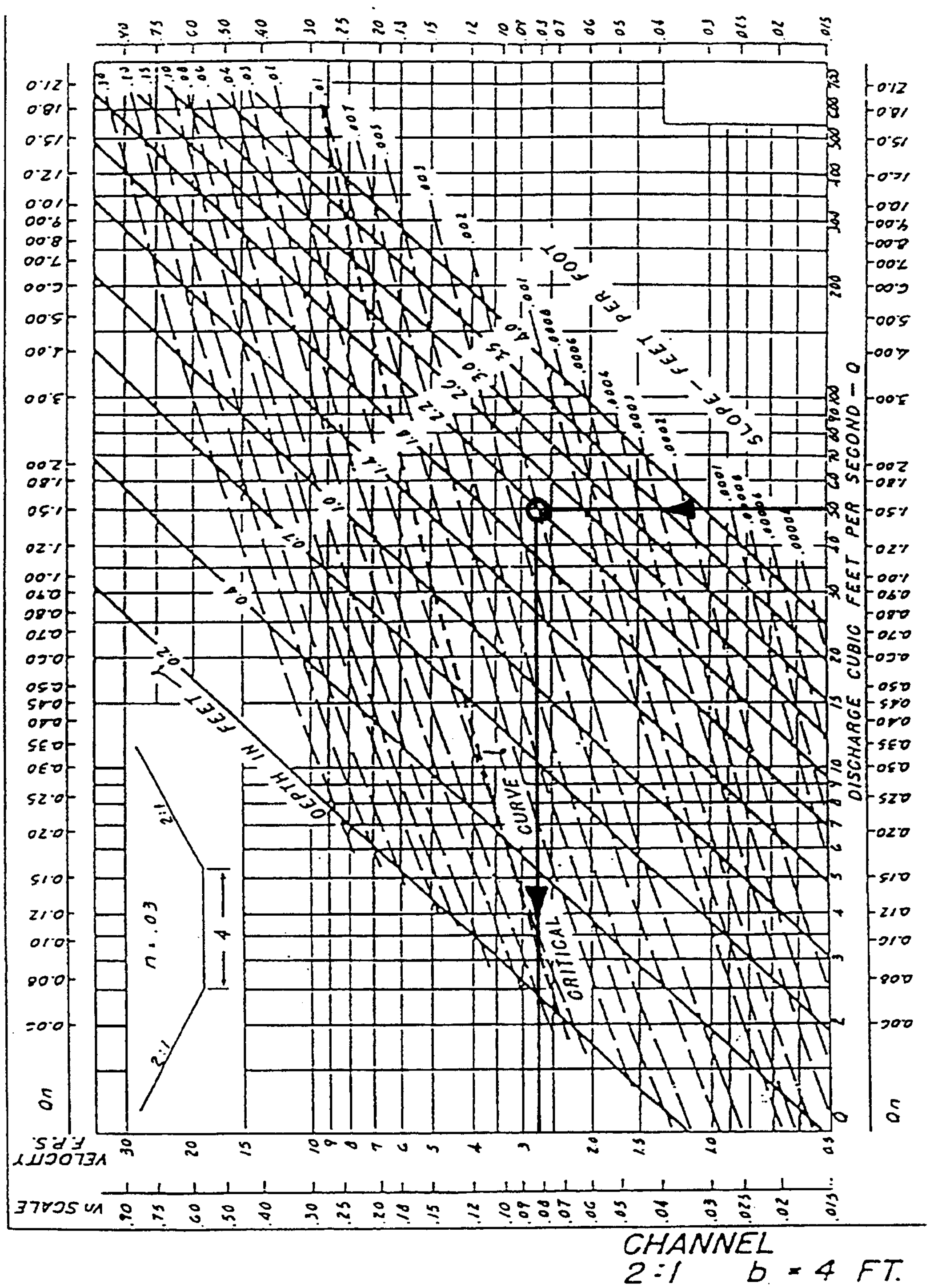
5. Critical depth and critical velocity are independent of the value of n so their values can be read at the intersection of the critical curve with a vertical line through the discharge. For 80 cfs, on Figure 5-13, d_c = 2.0 ft and V_c = 7.9 ft/s. The normal velocity, 5.2 ft/s (from step 4), is less than the critical velocity, and the flow is therefore subcritical. It will also be noted that the normal depth, 3.1 ft, is greater than the critical depth, 2.0 ft, which also indicates subcritical flow.

6. To determine the critical slope for Q = 80 cfs and n = 0.025, start at the intersection of the critical curve and a vertical line through the discharge, Q = 80 cfs, finding d_c (2.0 ft) at this point. Follow along this d_c line to its intersection with a vertical line through Qn = 2.0 (step 2), at this intersection read the slope value S_c = 0.015 ft/ft.



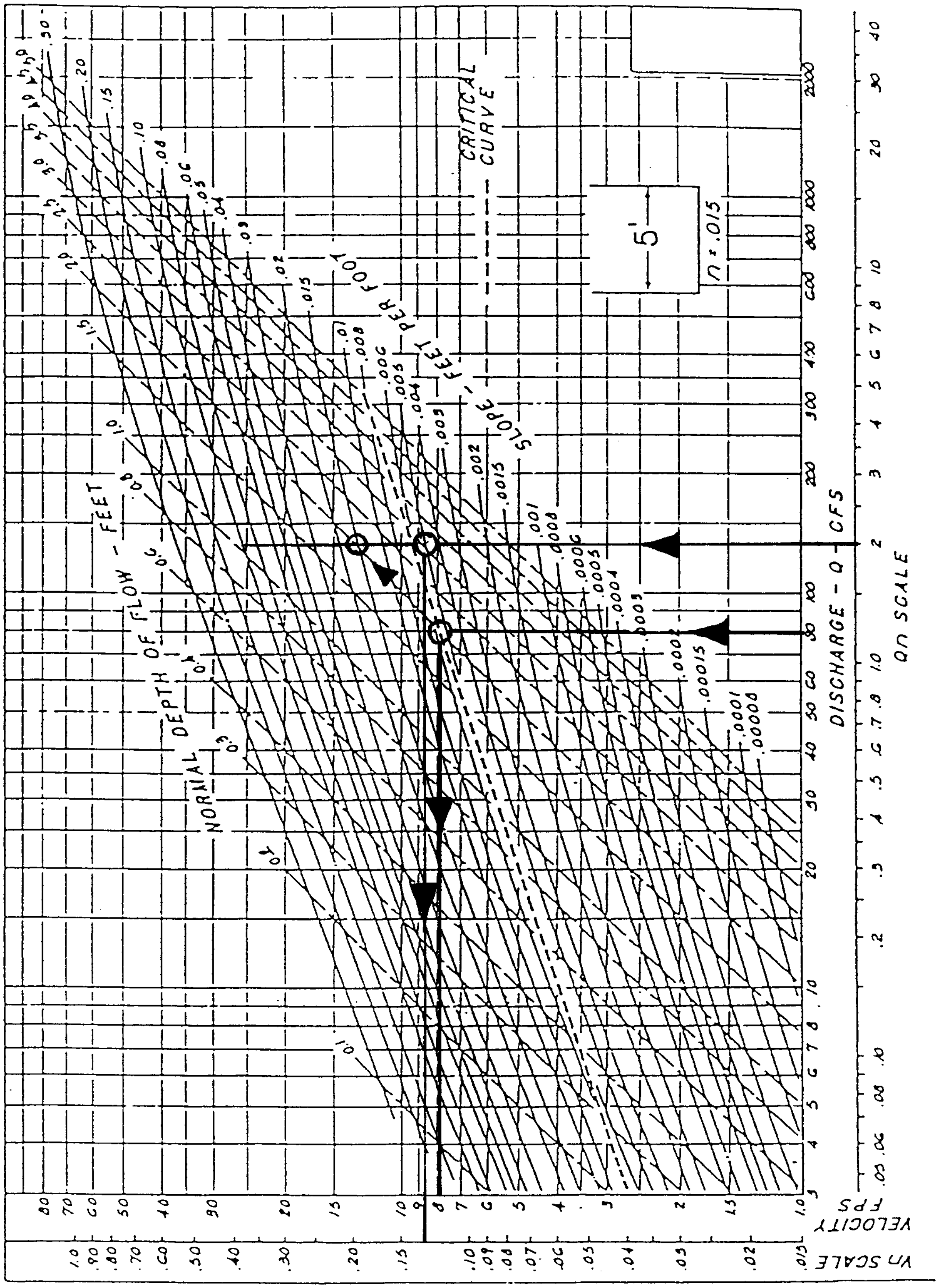
Source: Federal Highway Administration

Figure 5-11



Source: Federal Highway Administration

Figure 5-12



CHANNEL
VERTICAL b = 5 FT.

Source: Federal Highway Administration

Figure 5-13

5.10.4 Grassed Channel Figures

The Manning's Equation can be used to determine the capacity of a grass-lined channel, but the value of n varies with the type of grass, development of the grass cover, depth, and velocity of flow. The variable value of n complicates the solution of the Manning's Equation. The depth and velocity of flow must be estimated and the Manning's Equation solved using the n value which corresponds to the estimated depth and velocity. The trial solution provides better estimates of the depth and velocity for a new value of n and the equation is again solved. The procedure is repeated until a depth is found that carries the design discharge.

To prevent excessive erosion, the velocity of flow in a grass-lined channel must be kept below some maximum value (referred to as permissible velocity). The permissible velocity in a grass-lined channel depends upon the type of grass, condition of the grass cover, texture of the soil comprising the channel bed, channel slope, and to some extent the size and shape of the drainage channel. To guard against overtopping, the channel capacity should be computed for taller grass than is expected to be maintained, while the velocity used to check the adequacy of the protection should be computed assuming a lower grass height than will likely be maintained.

To aid in the design of grassed channels the Federal Highway Administration has prepared numerous design figures. Copies of these figures are in Appendix C at the end of this chapter. Following is a brief description of instructions on how to use the figures, and several example design problems. For design conditions not covered by the figures, a trial-and-error solution of the Manning's Equation must be used.

5.10.5 Description Of Figures

The figures in Appendix C are designed for use in the direct solution of the Manning's Equation for various channel sections lined with grass. The figures are similar in appearance and use to those for trapezoidal cross sections described earlier. However, their construction is much more difficult because the roughness coefficient (n) changes as higher velocities and/or greater depths change the condition of the grass. The effect of velocity and depth of flow on n is evaluated by the product of velocity and hydraulic radius, v times R. The variation of Manning's n with the retardance (Table 5-6) and the product v times R is shown in Figure 5-1. As indicated in Table 5-6, retardance varies with the height of the grass and the condition of the stand. Both of these factors depend upon the type of grass, planting conditions, and maintenance practices. Table 5-6 is used to determine retardance classification.

The grassed channel figures each have two graphs, the upper graph for retardance D and the lower graph for retardance C. The figures are plotted with discharge in cubic feet per second on the abscissa and slope in feet per foot on the ordinate. Both scales are logarithmic. Superimposed on the logarithmic grid are lines for velocity in feet per second and lines for depth in feet. A dashed line shows the position of critical flow.

5.10.6 Instructions For Grassed Channel Figures

The grassed channel figures provide a solution of the Manning's Equation for flow in open grassed channels of uniform slope and cross section. The flow should not be affected by backwater and the channel should have length sufficient to establish uniform flow. The figures are sufficiently accurate for design of drainage channels of fairly uniform cross section and slope, but are not appropriate for irregular natural channels.

The design of grassed channels requires two operations: (1) selecting a section which has the capacity to carry the design discharge on the available slope and (2) checking the velocity in the channel to insure that the grass lining will not be eroded. Because the retardance of the channel is largely beyond the control of the designer, it is good practice to compute the channel capacity using retardance C and the velocity using retardance D. The calculated velocity should then be checked against the permissible velocities listed in Table 5-3. The use of the figures is explained in the following steps:

(1) Select the channel cross section to be used and find the appropriate figure.

(2) Enter the lower graph (for retardance C) on the figure with the design discharge value on the abscissa and move vertically to the value of the slope on the ordinate scale. At this intersection, read the normal velocity and normal depth and note the position of the critical curve. If the intersection point is below the critical curve, the flow is subcritical; if it is above, the flow is supercritical.

(3) To check the velocity developed against the permissible (Table 5-3), enter the upper graph on the same figure and repeat step 2. Then compare the computed velocity with the velocity permissible for the type of grass, channel slope, and erosion resistance of the soil. If the computed velocity is less, the design is acceptable. If not, a different channel section must be selected and the process repeated.

<u>Example - Design Problem 1</u>

Given: A trapezoidal channel in easily eroded soil, lined with a grass mixture with 4:1 side slopes, and a 4 ft bottom width, on a slope of 2.0 percent (S=0.02 ft/ft), discharging 20 cfs.

Find: Depth, velocity, type of flow, and adequacy of grass to prevent erosion

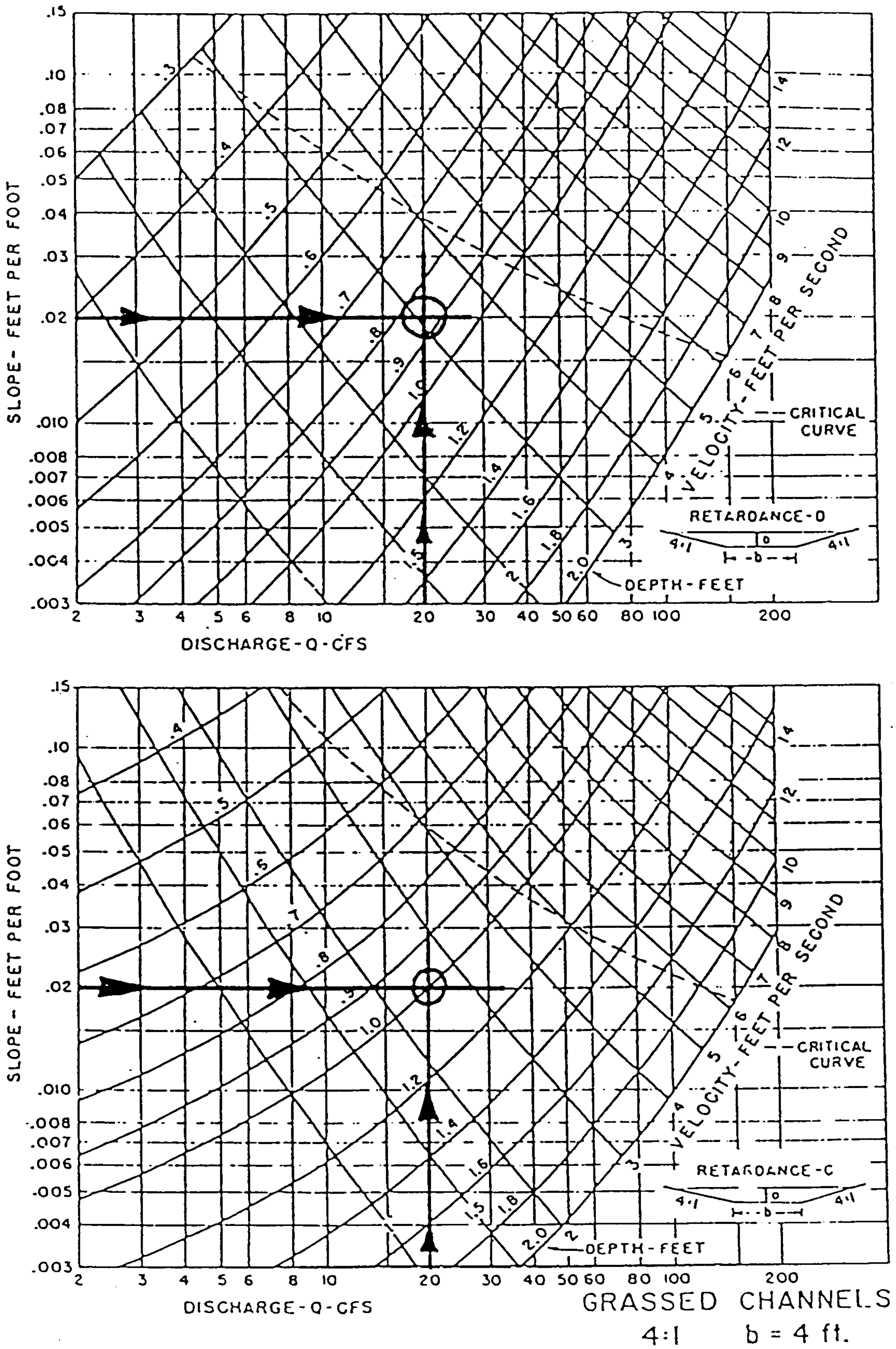
Procedure:
1. From Appendix C select figure for 4:1 side slopes (Figure 5-14).
2. Enter the lower graph with Q = 20 cfs, and move vertically to the line for S=0.02. At this intersection, read d_n = 1.0 ft, and normal velocity V_n = 2.6 ft/s.
3. The velocity for checking the adequacy of the grass cover should be obtained from the upper graph, for retardance D. Using the same procedure as in step 2, the velocity is found to be 3.0 ft/s. This is about three-quarters of that listed as permissible, 4 ft/s in Table 5-3.

<u>Example - Design Problem 2</u>

Given: The channel and discharge of Example 1 above

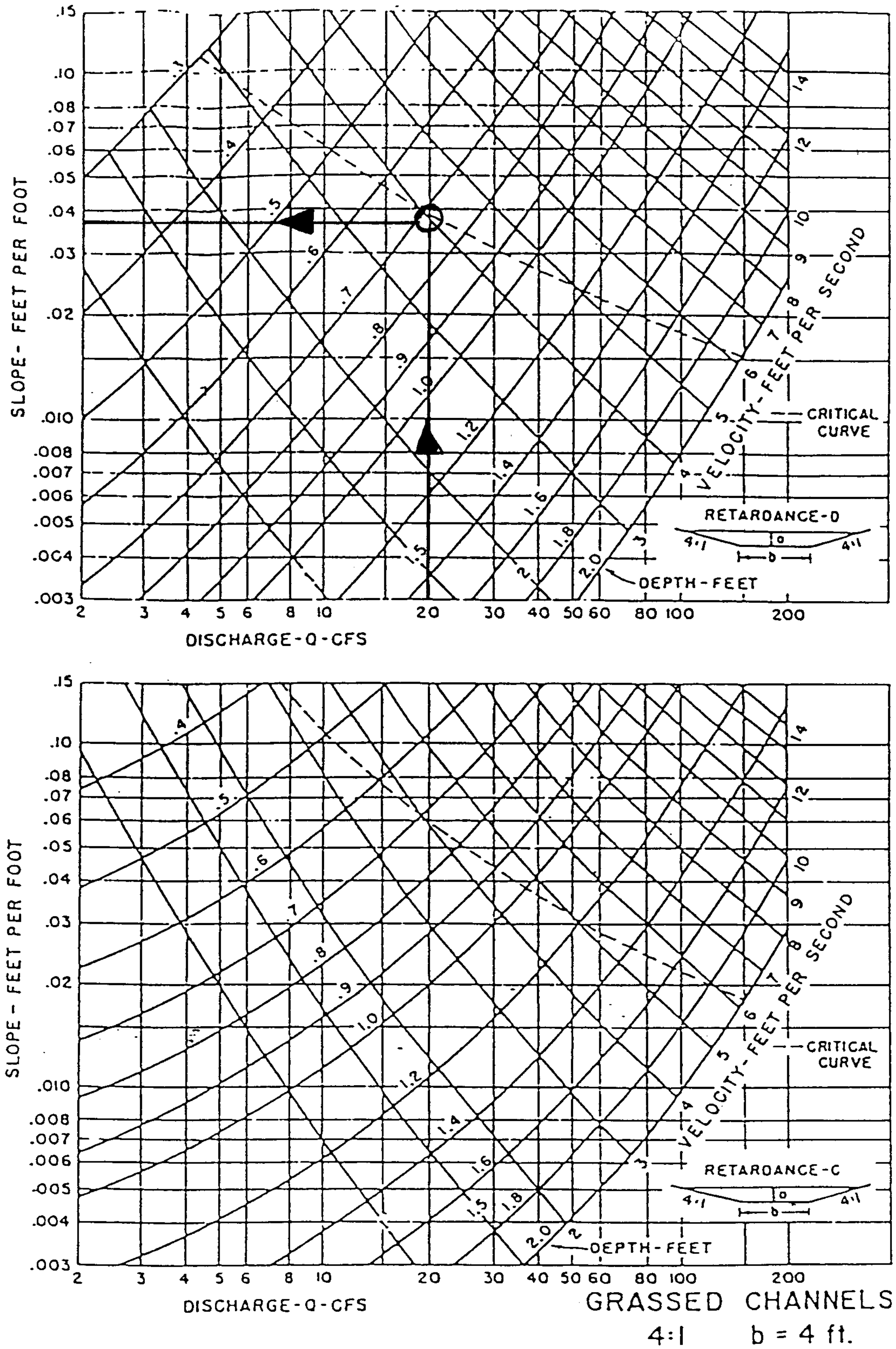
Find: The maximum grade on which the 20 cfs could safely be carried

Procedure:
1. With an increase in slope (but still less than 5%), the allowable velocity is estimated to be 4 ft/s (see Table 5-3). On the upper graph (Figure 5-15) for short grass, the intersection of the 20 cfs line and the 4 ft/s line indicates a slope of 3.7 percent and a depth of 0.73 ft.



Source: Federal Highway Administration

Figure 5-14



Source: Federal Highway Administration

Figure 5-15

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Appendix A - Open Channel Design Figures

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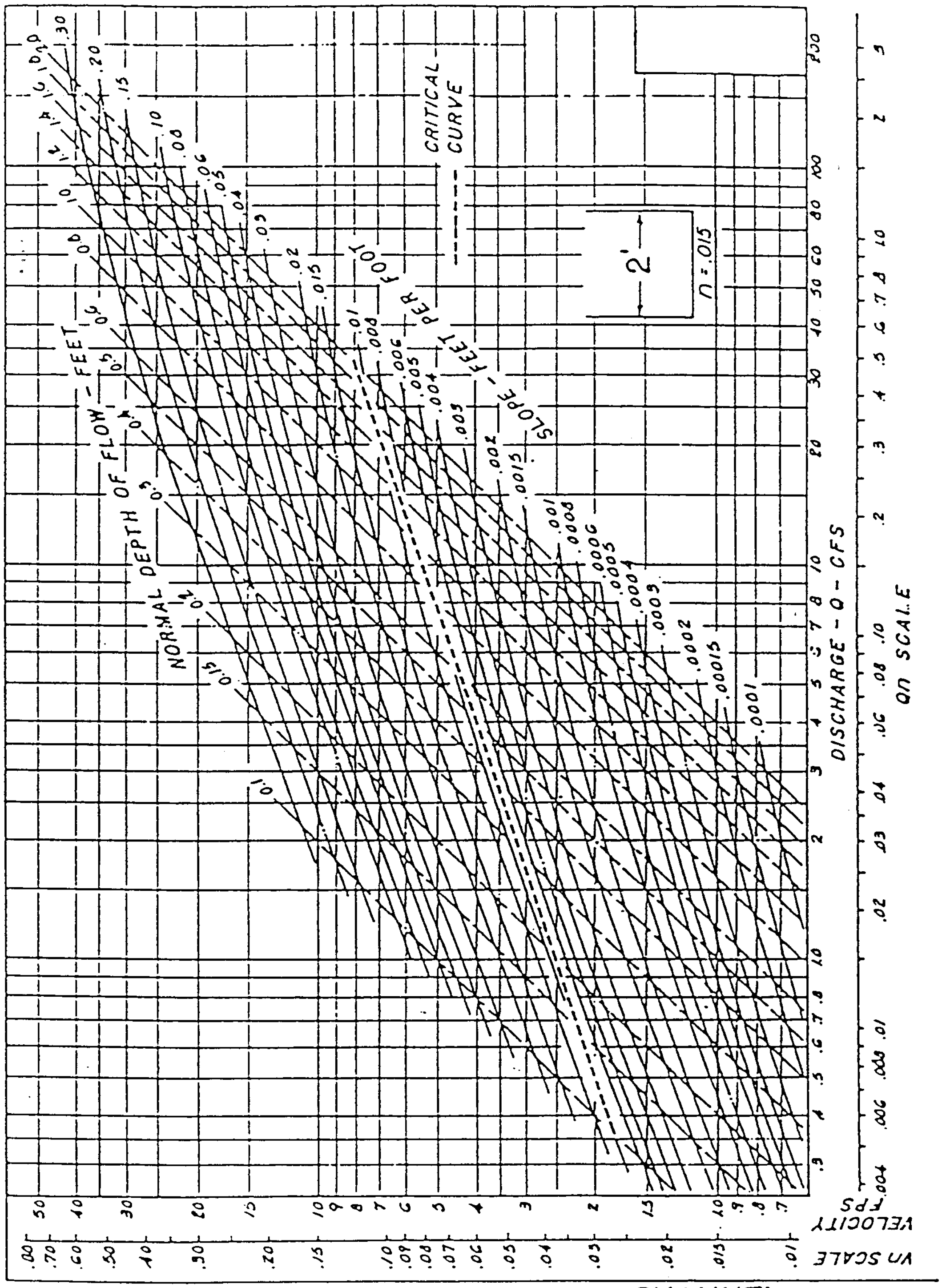
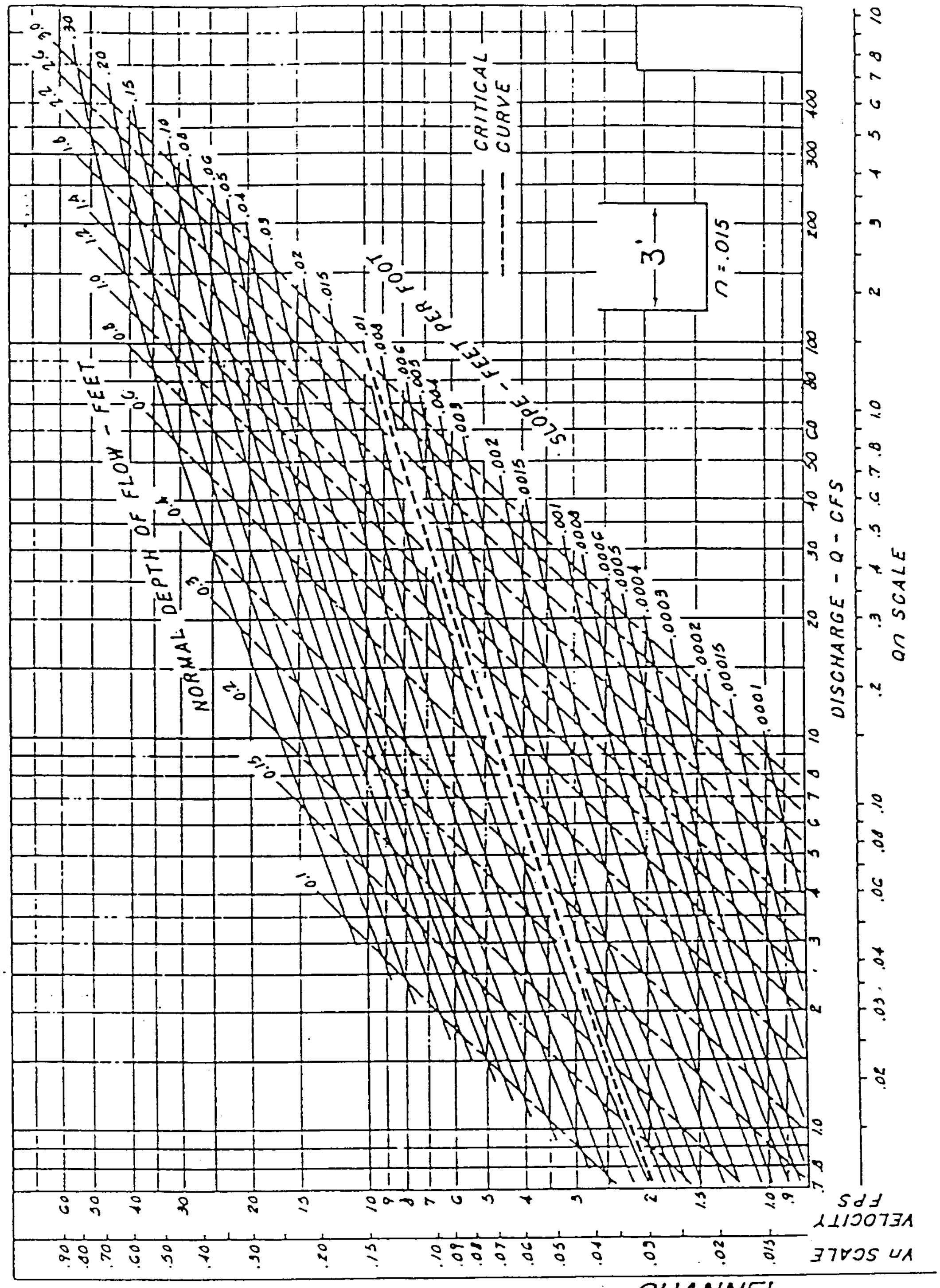


CHANNEL
VERTICAL b = 2 FT.

Source: Federal Highway Administration



CHANNEL
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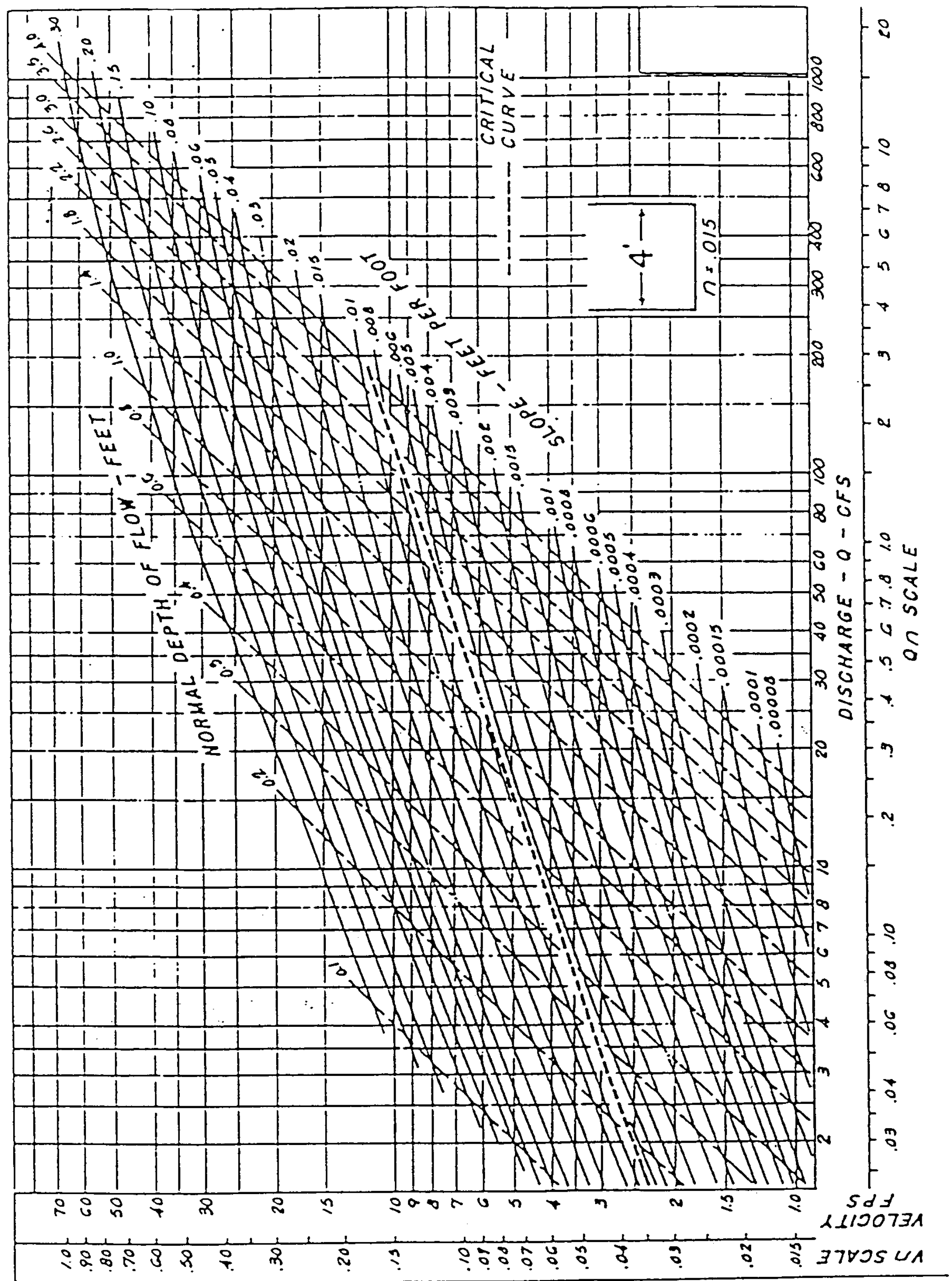

CHANNEL
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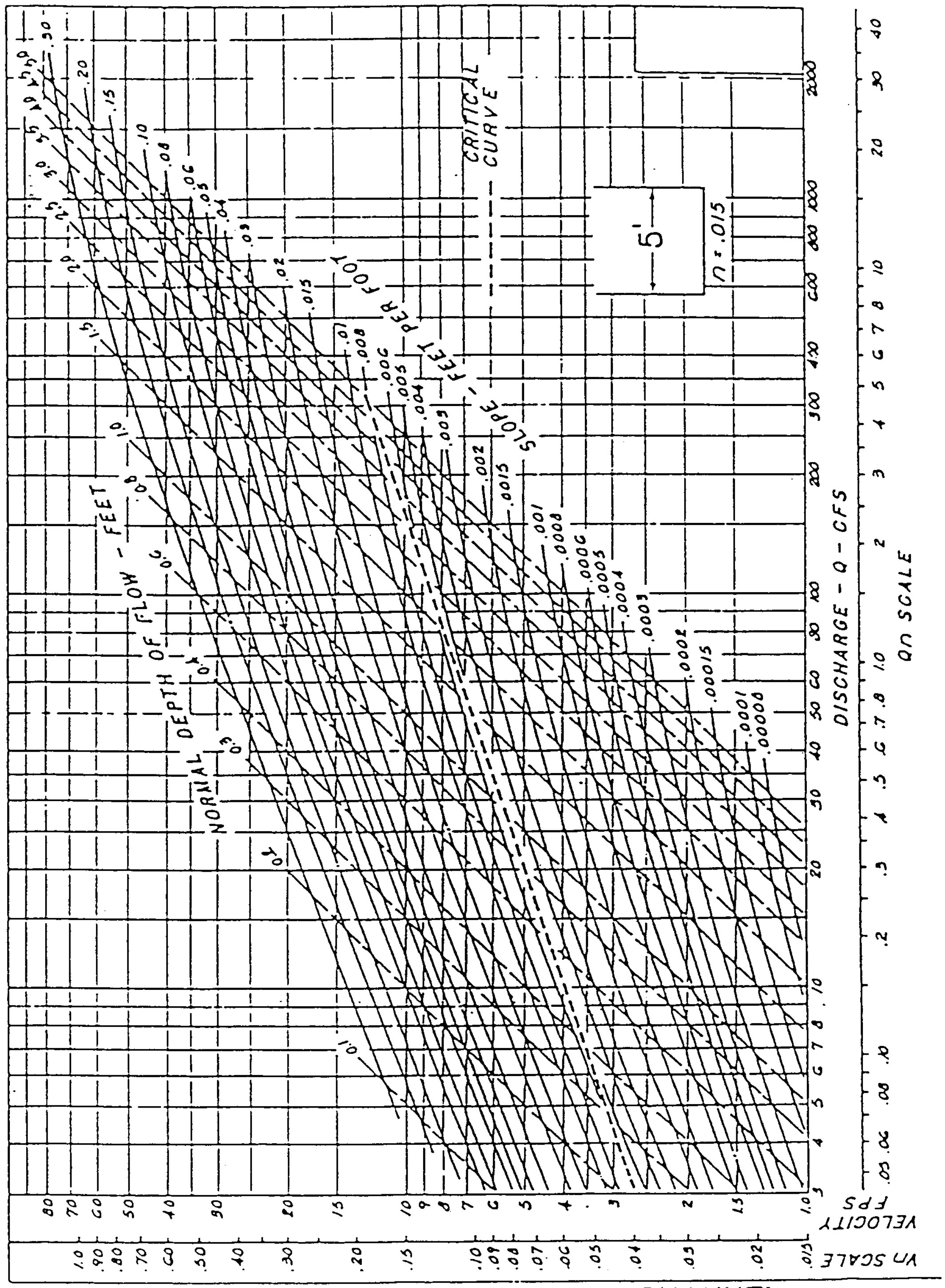
Source: Federal Highway Administration



CHANNEL
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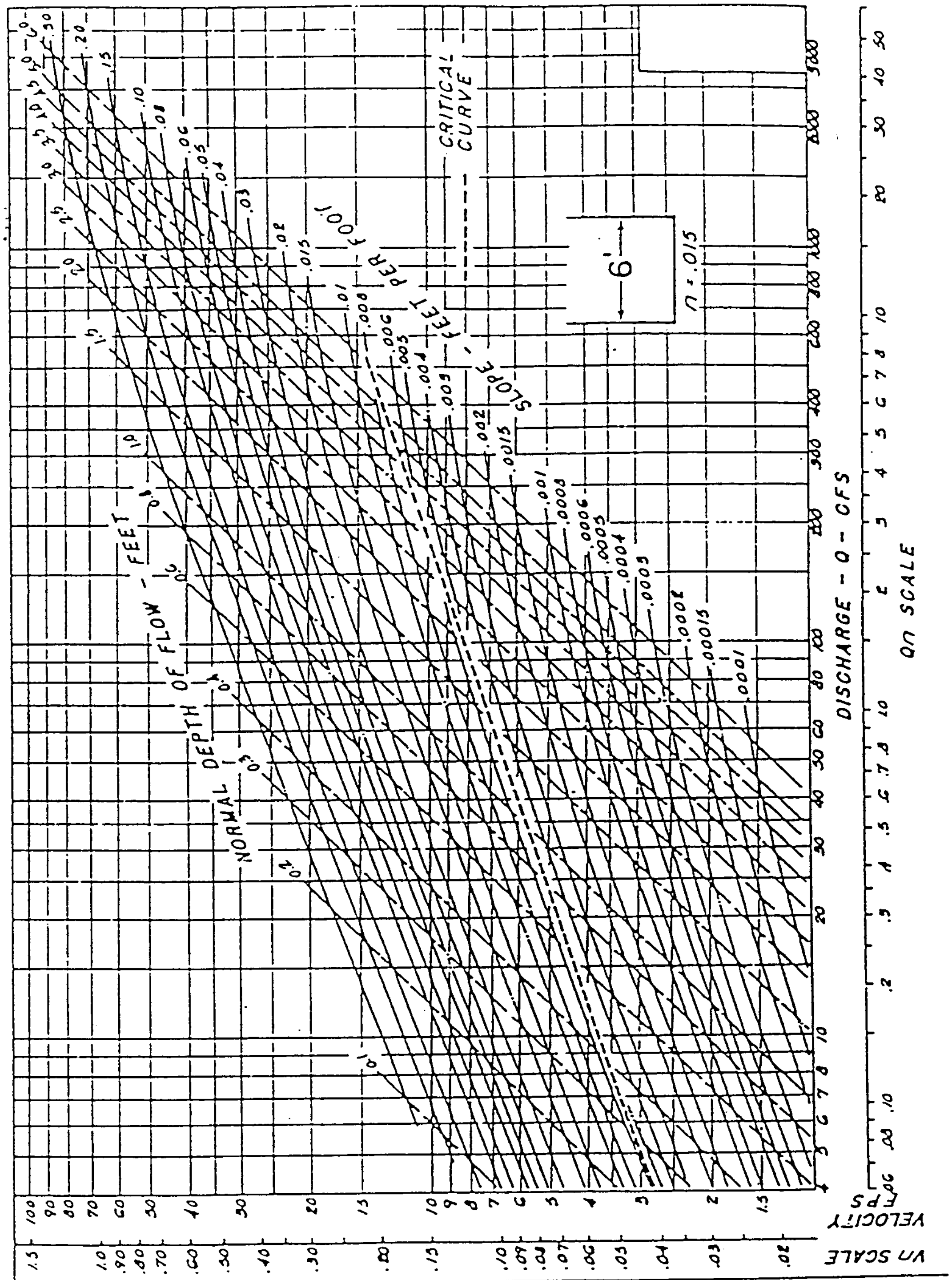
Source: Federal Highway Administration



CHANNEL
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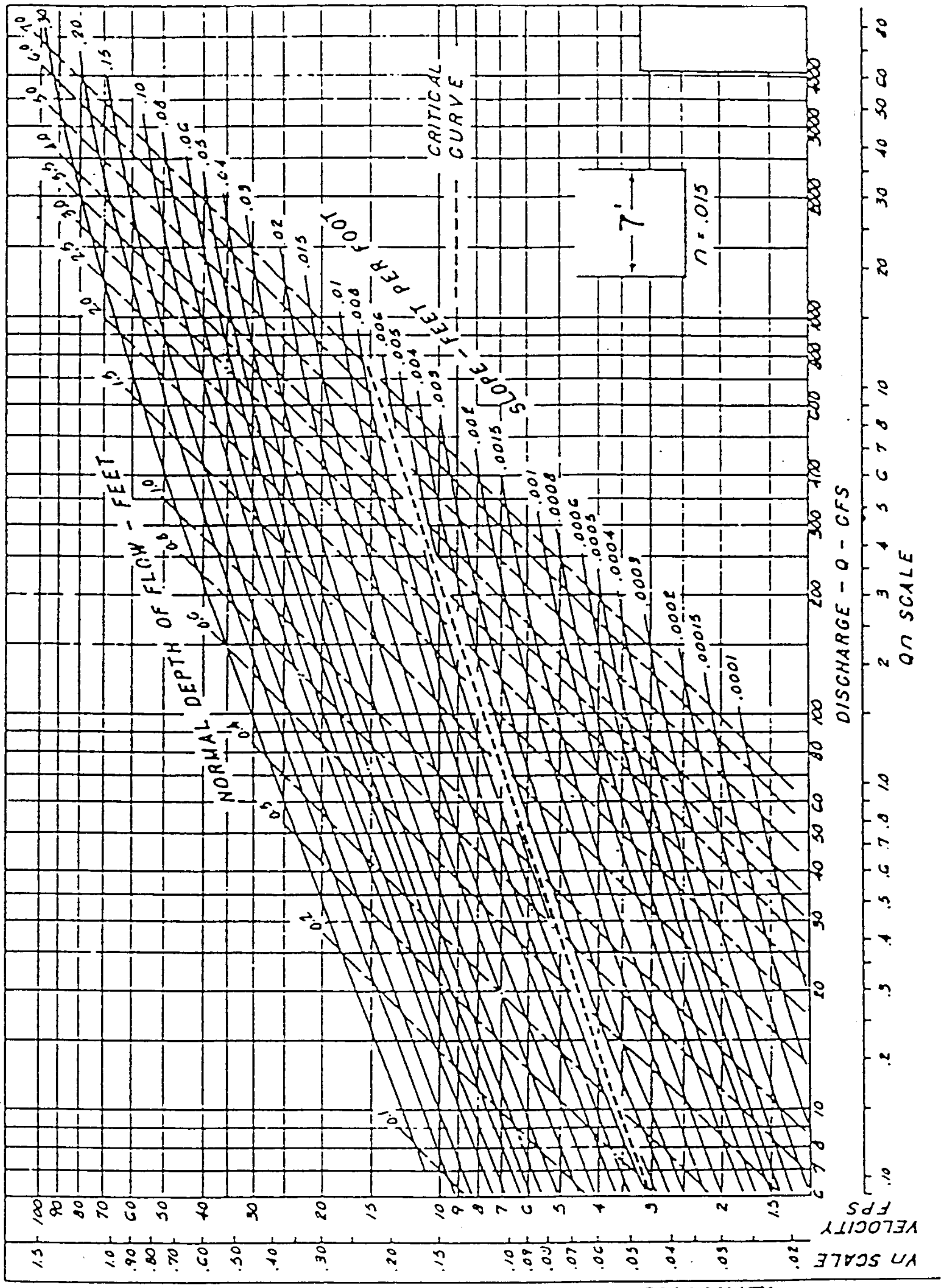
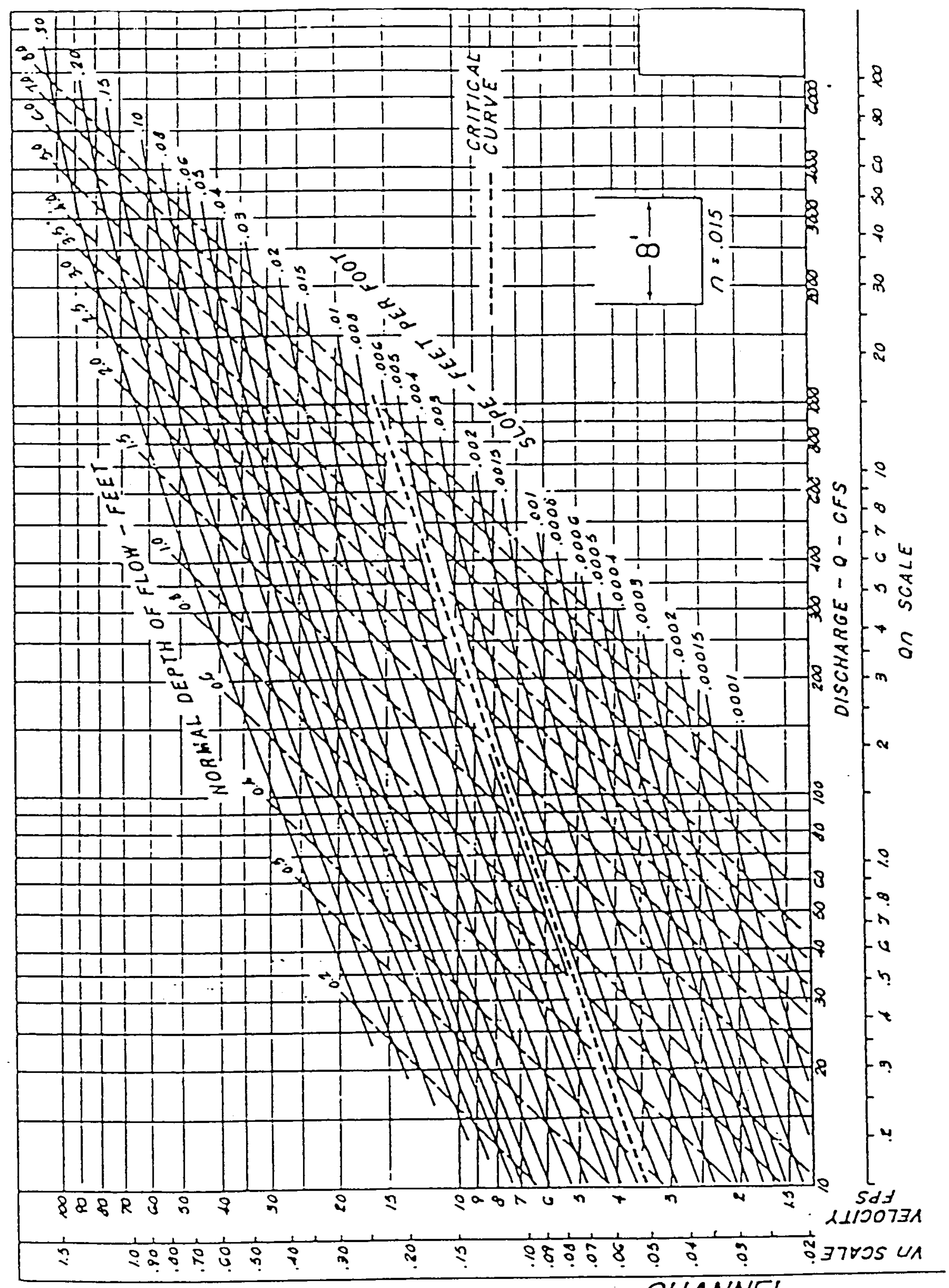
Source: Federal Highway Administration



CHANNEL
VERTICAL b = 7 FT.

Source: Federal Highway Administration



CHANNEL
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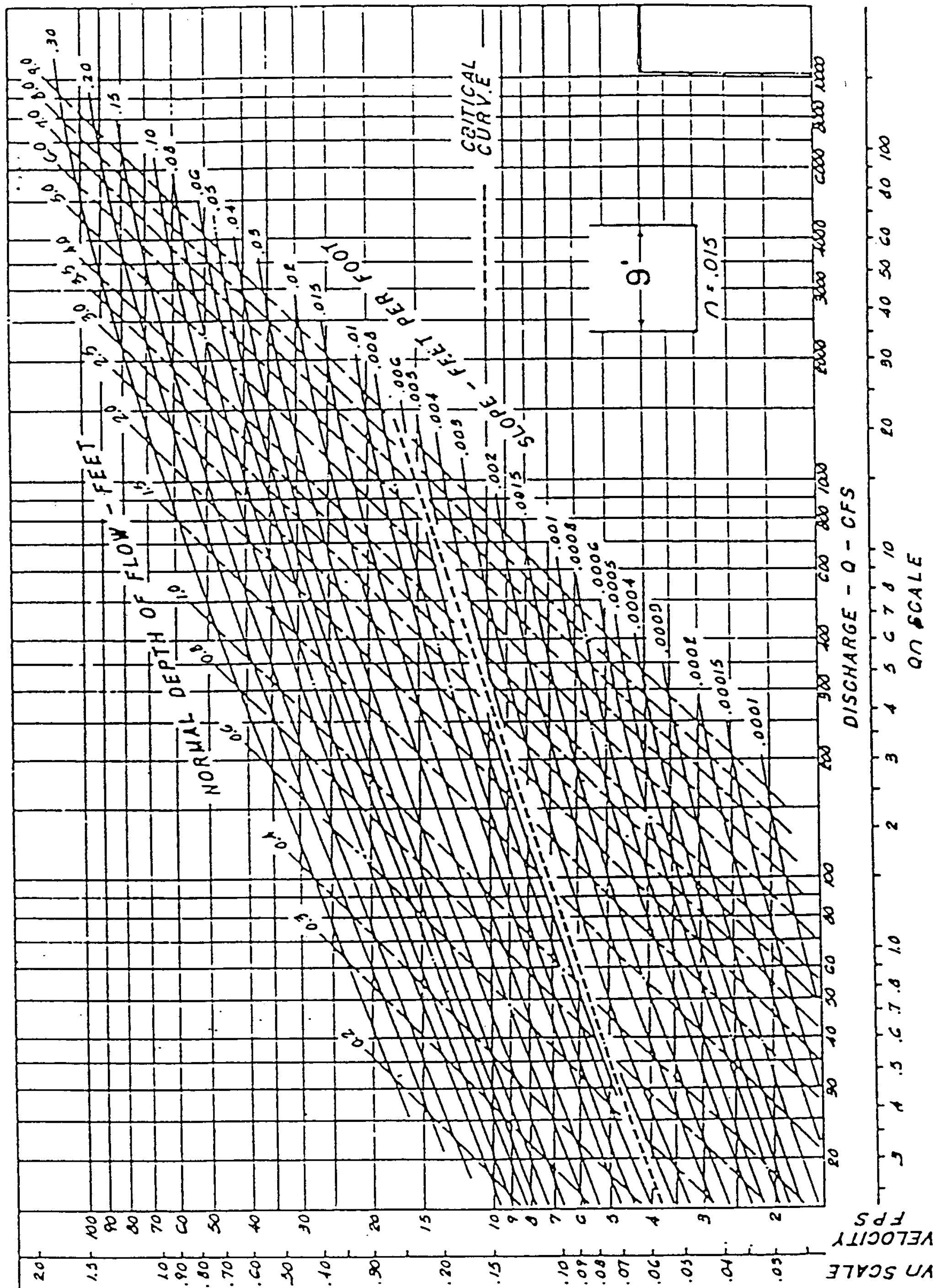
Source: Federal Highway Administration



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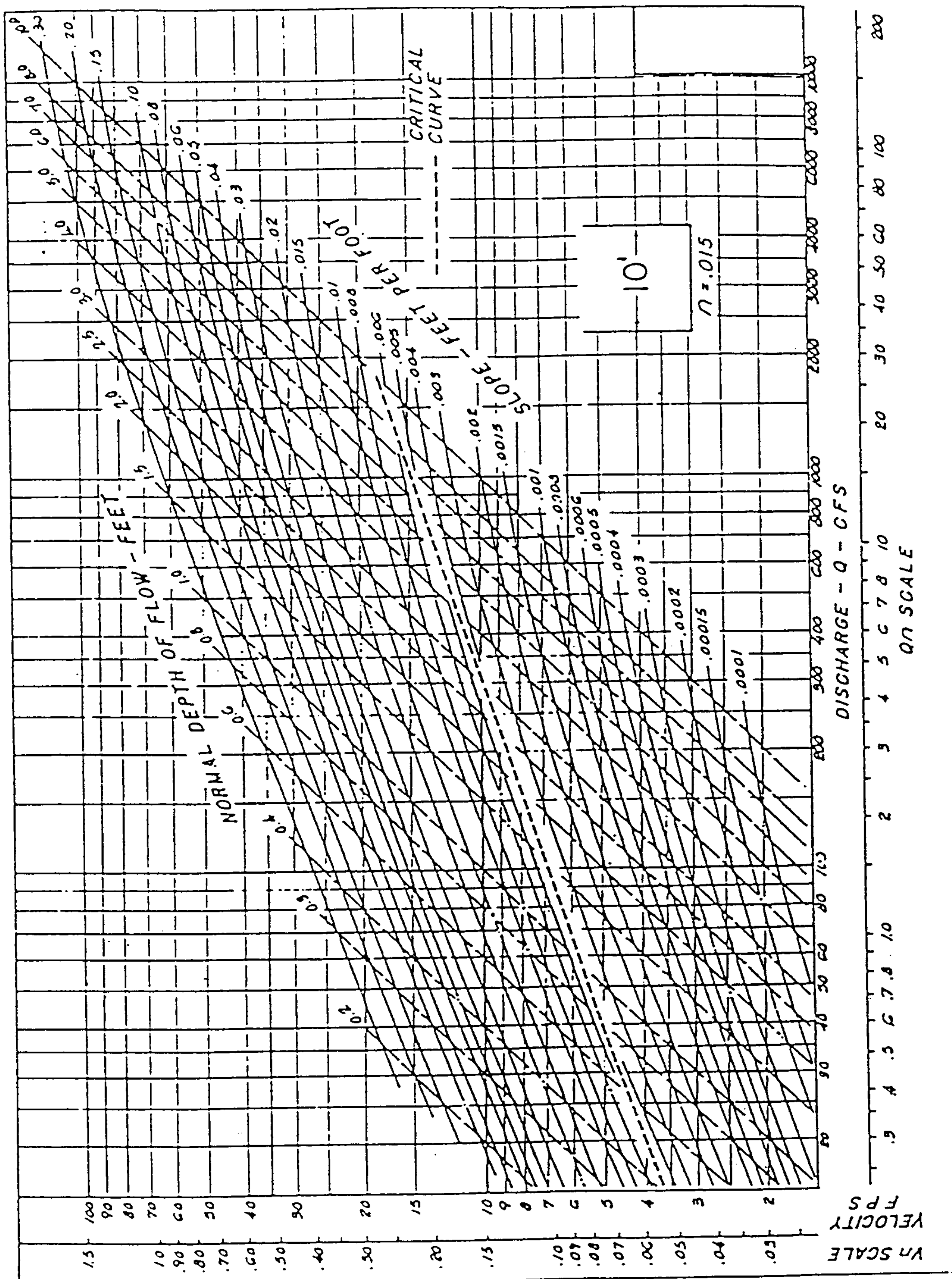
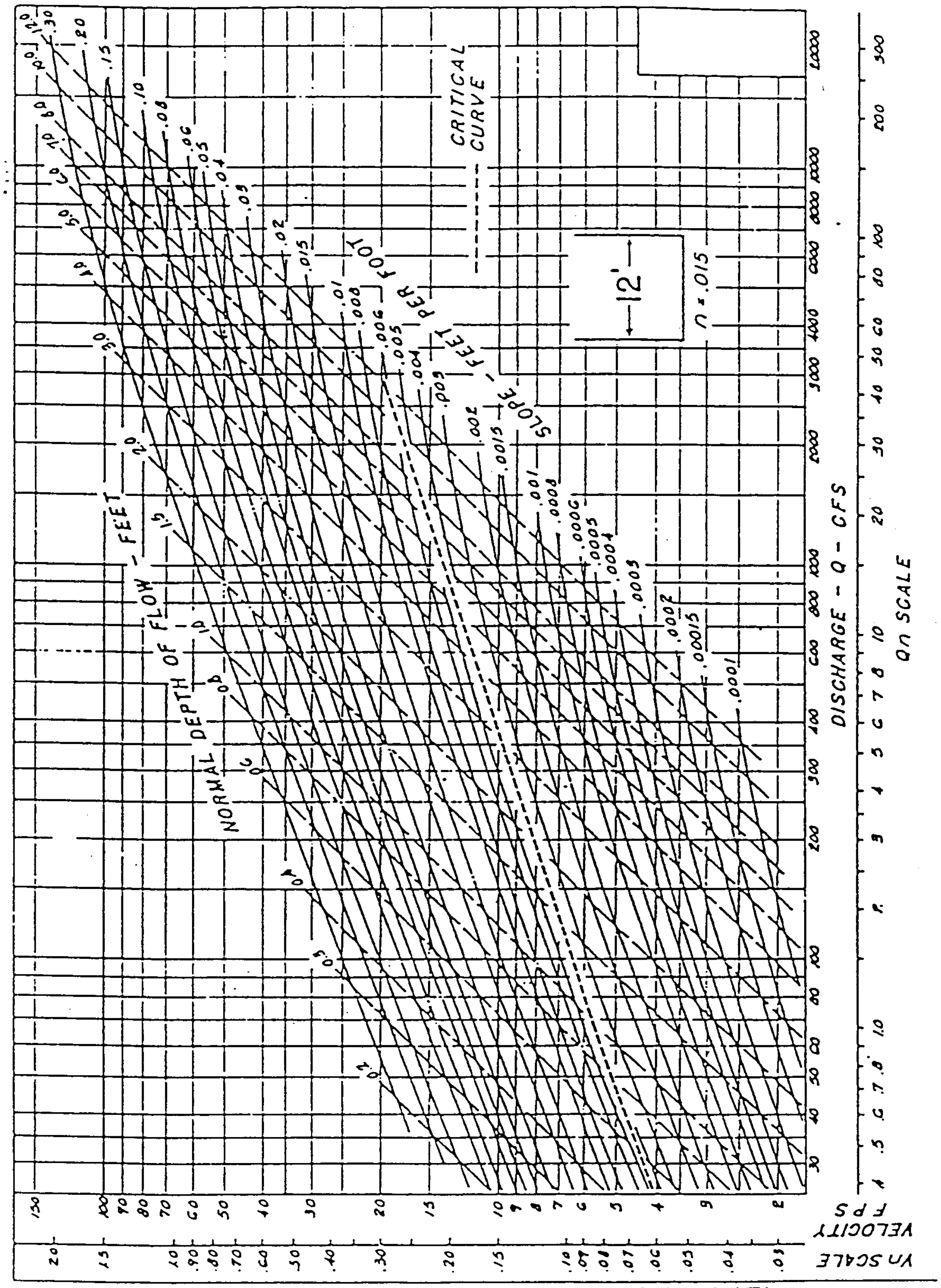
VERTICAL b = 9 FT.

Source: Federal Highway Administration



CHANNEL
VERTICAL b = 10 FT.

Source: Federal Highway Administration



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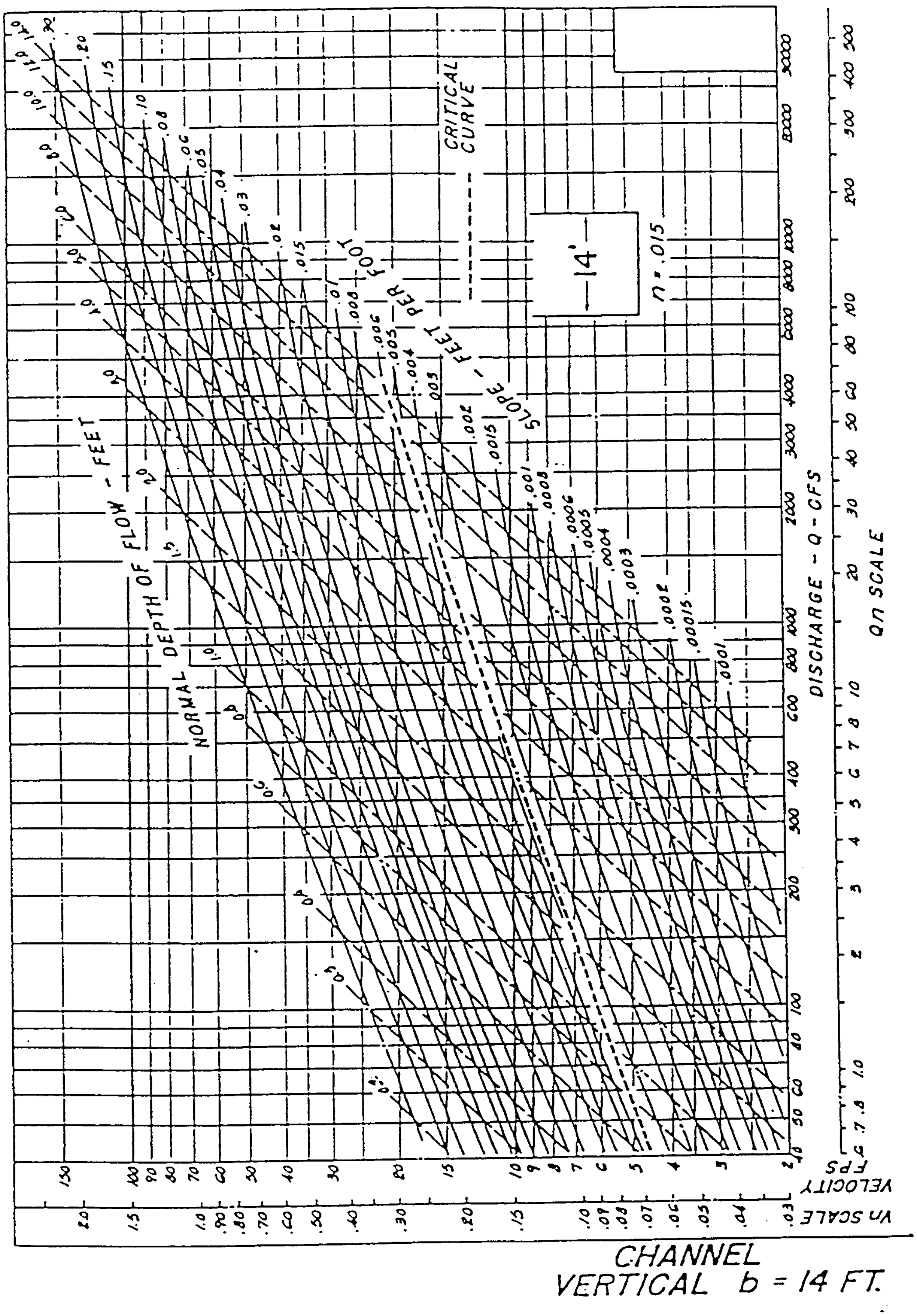
Source: Federal Highway Administration



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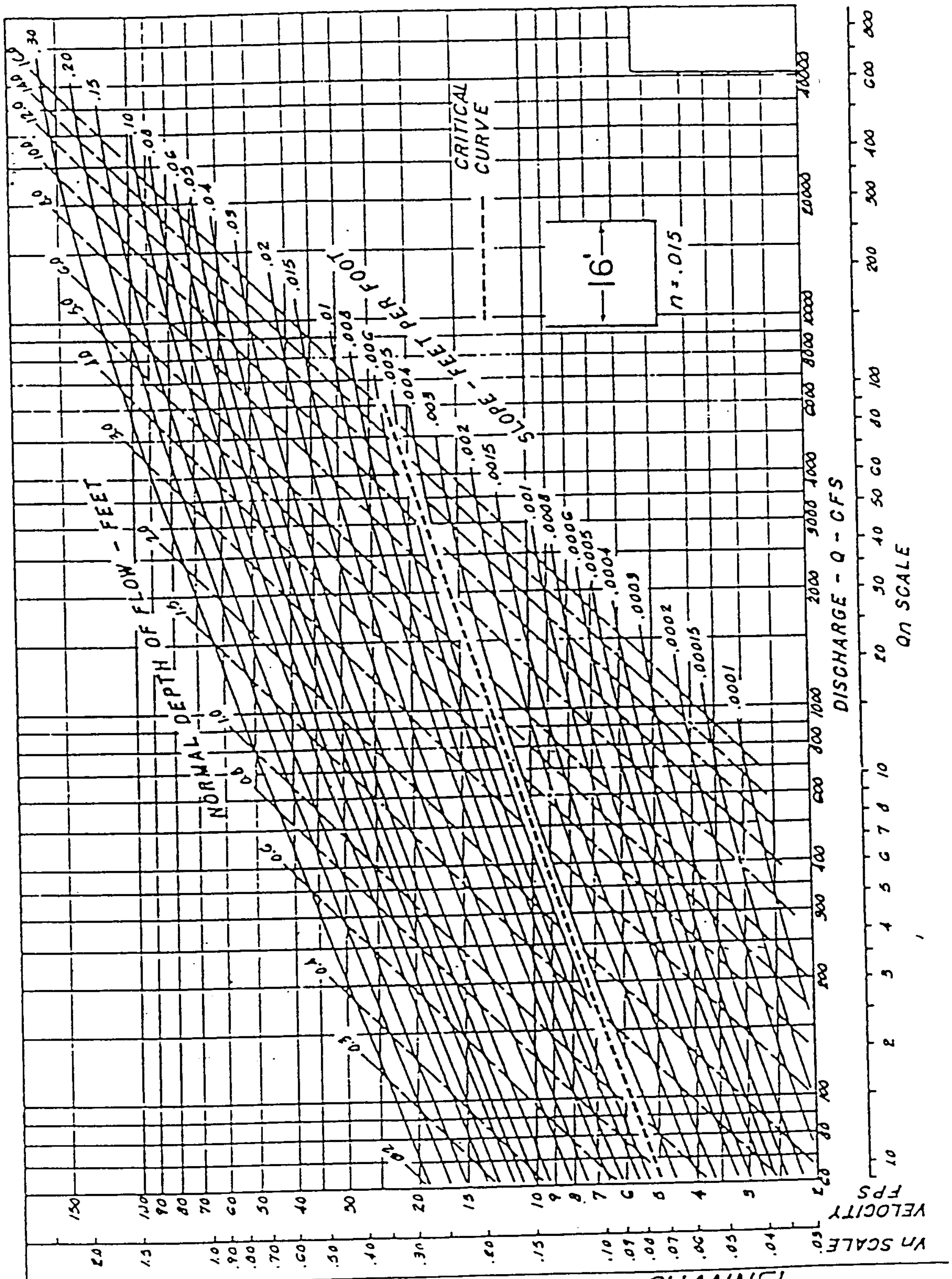
Source: Federal Highway Administration.



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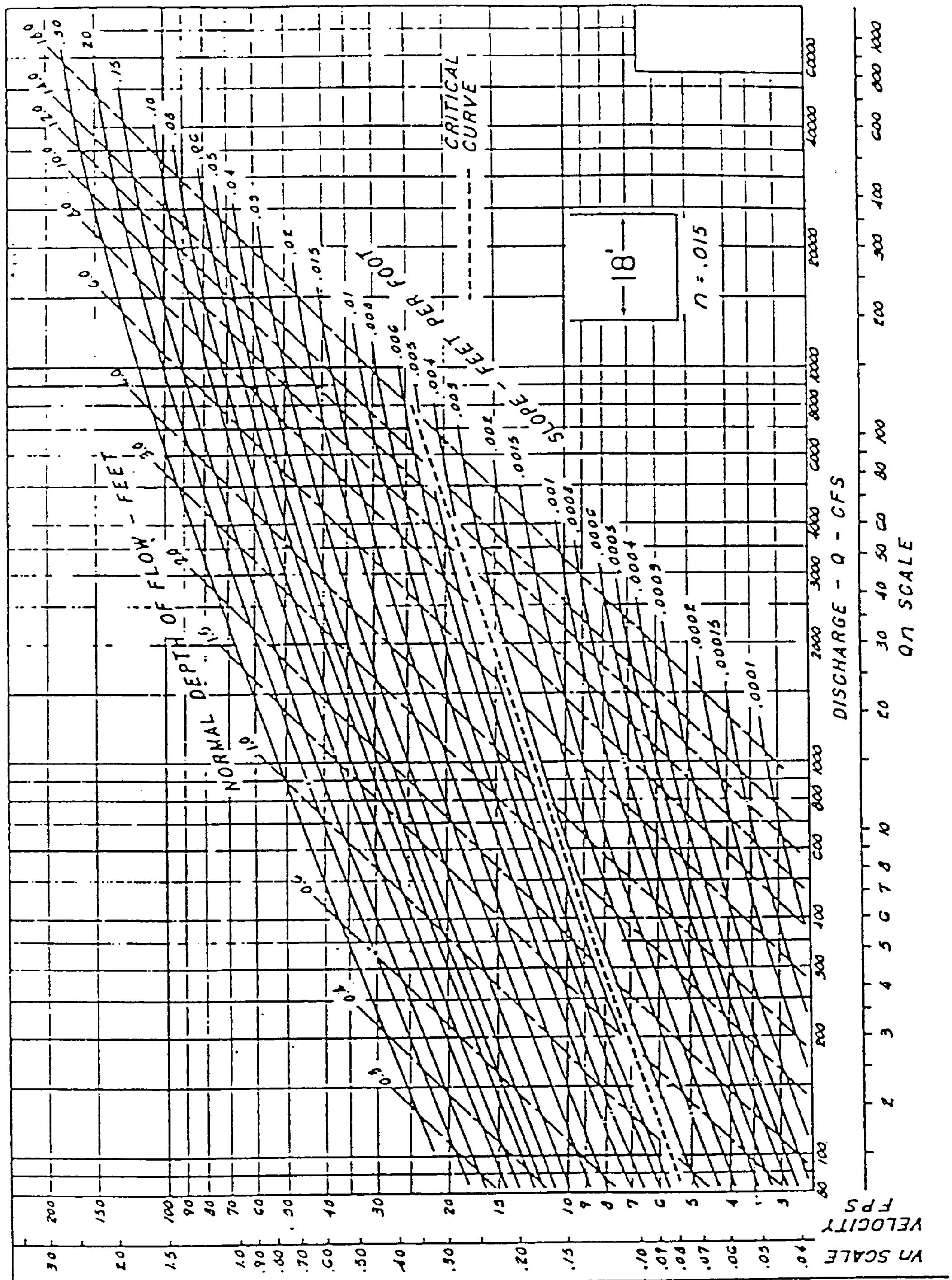

CHANNEL
VERTICAL b = 18 FT.

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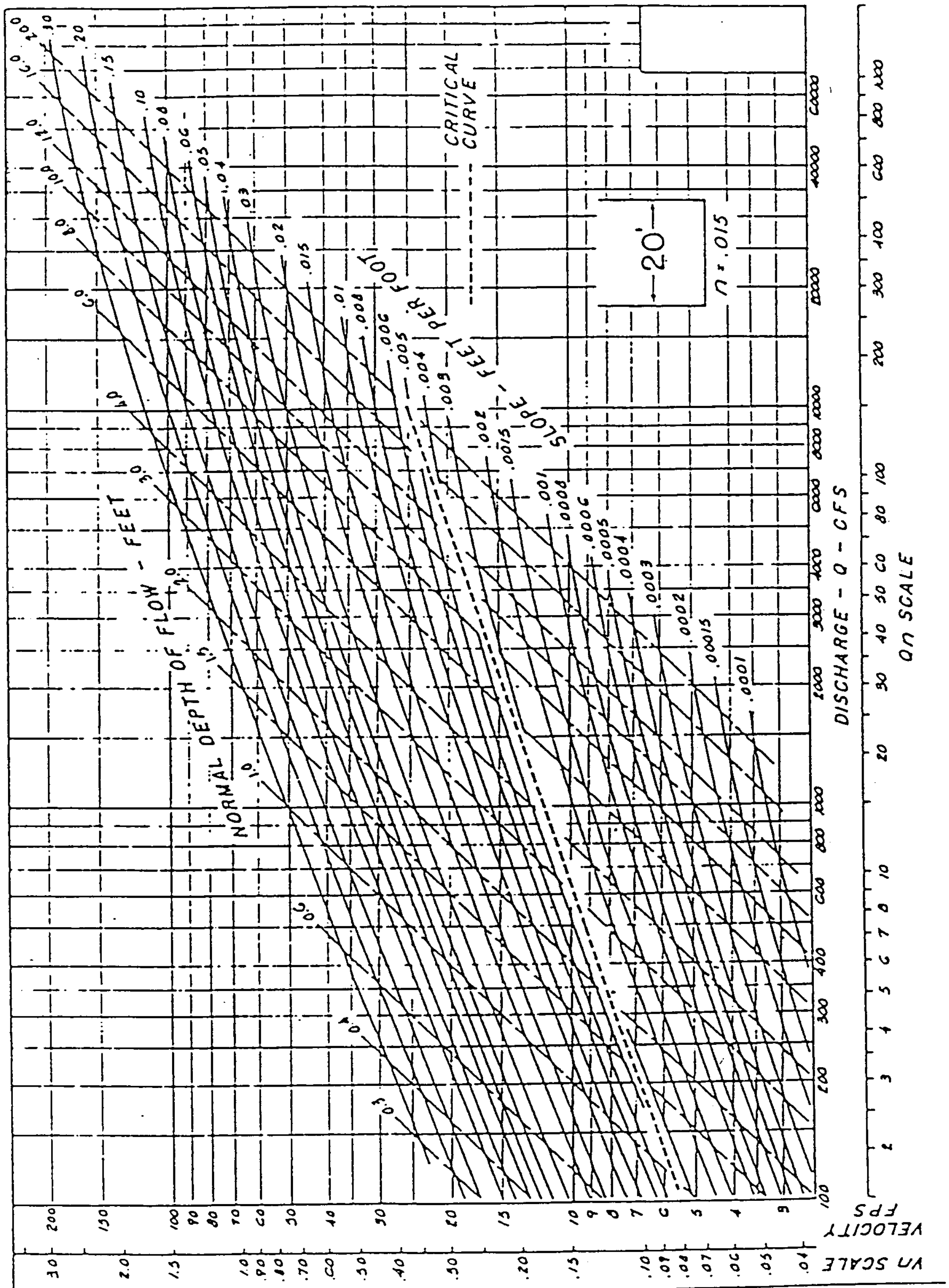

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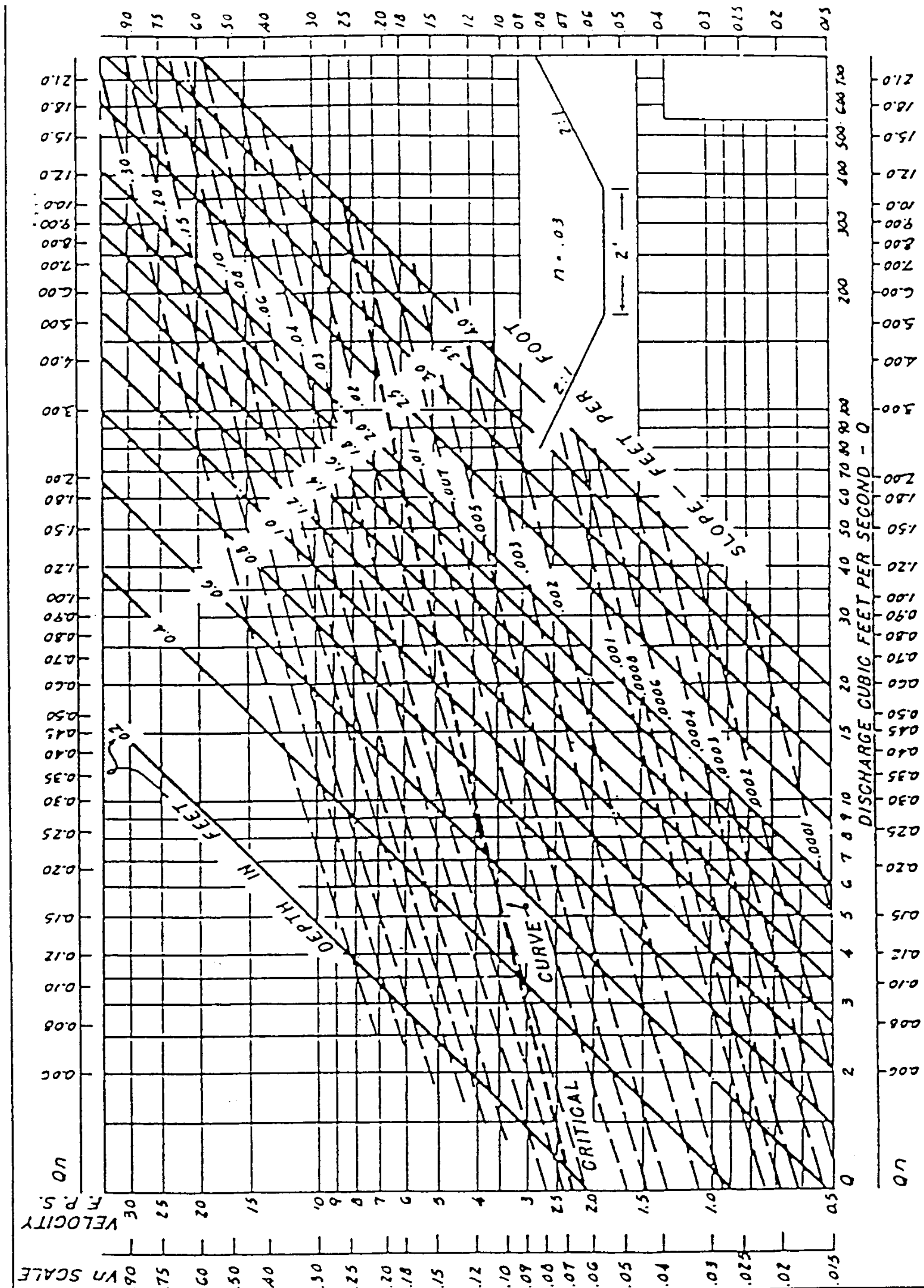
Source: Federal Highway Administration



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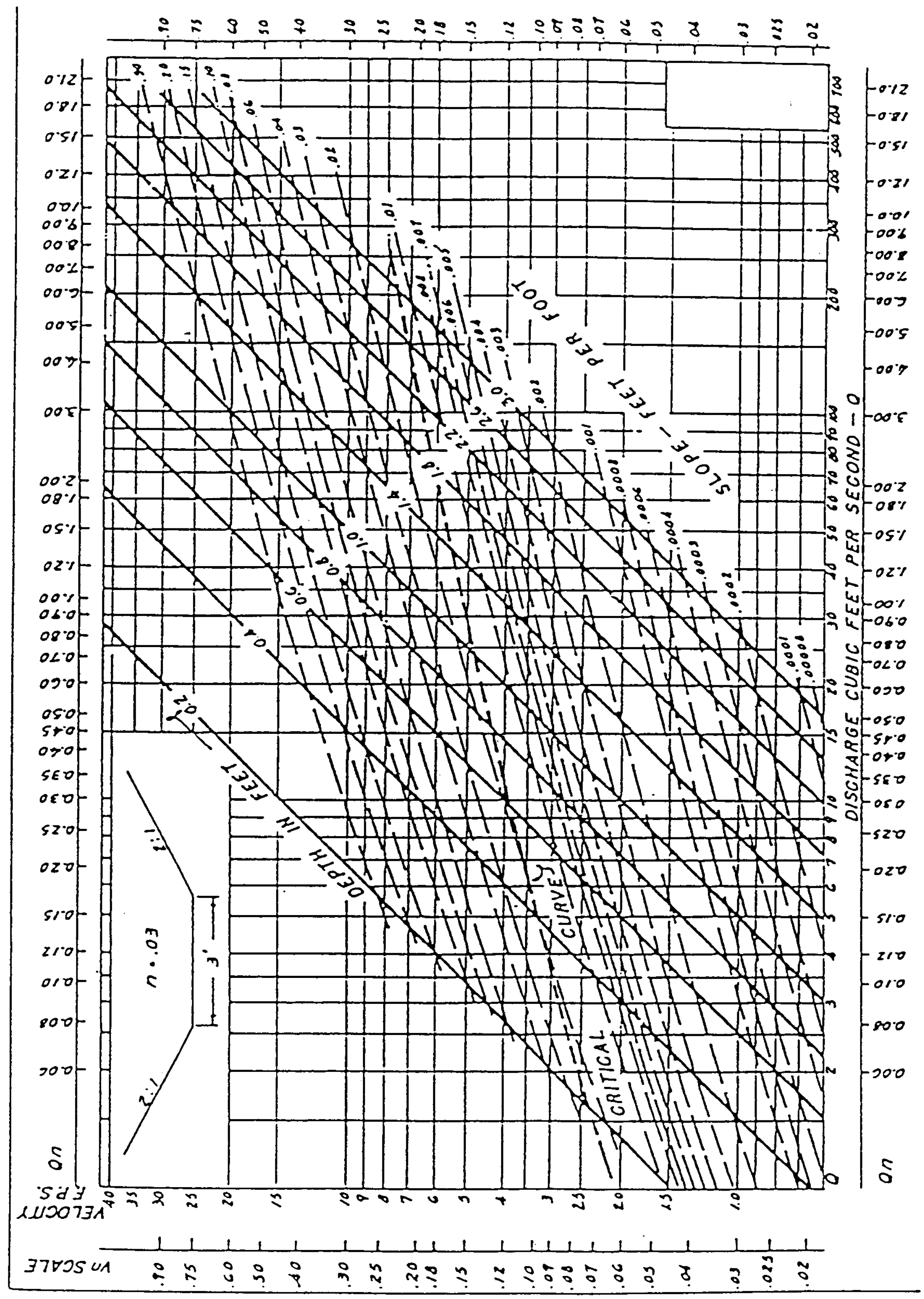
2:1 b = 2 FT.

Source: Federal Highway Administration



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2:1 b = 3 FT.

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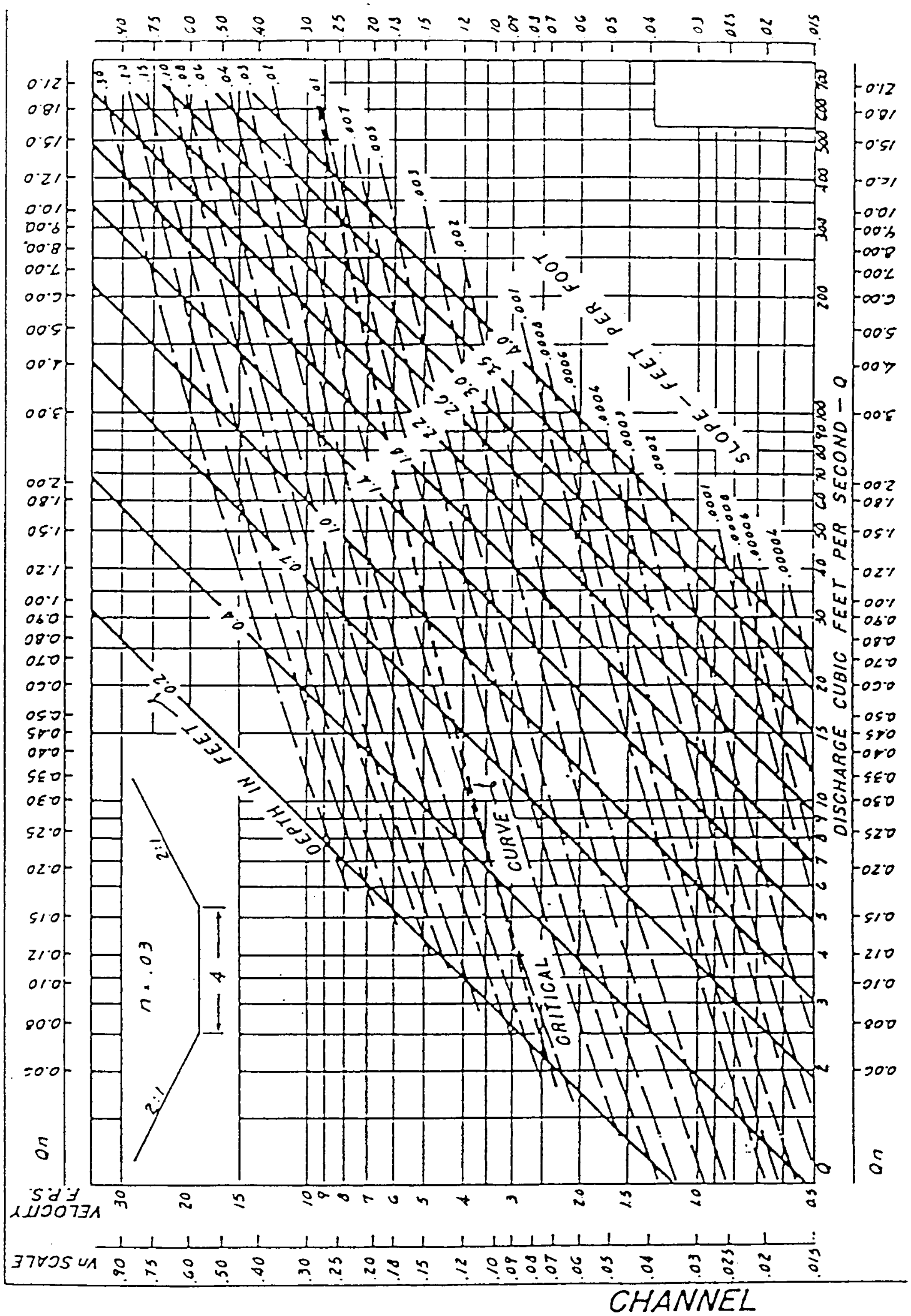

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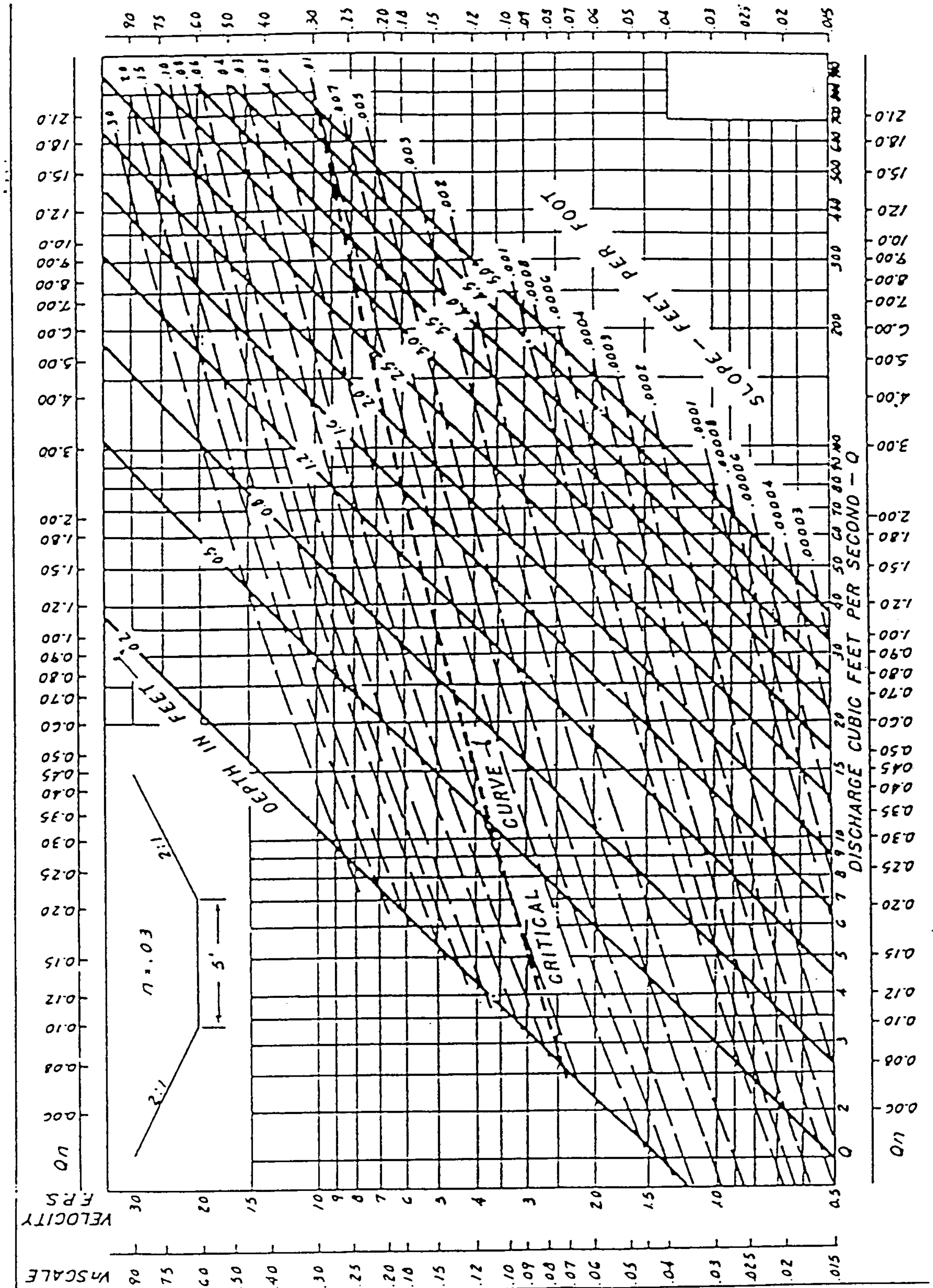
Source: Federal Highway Administration



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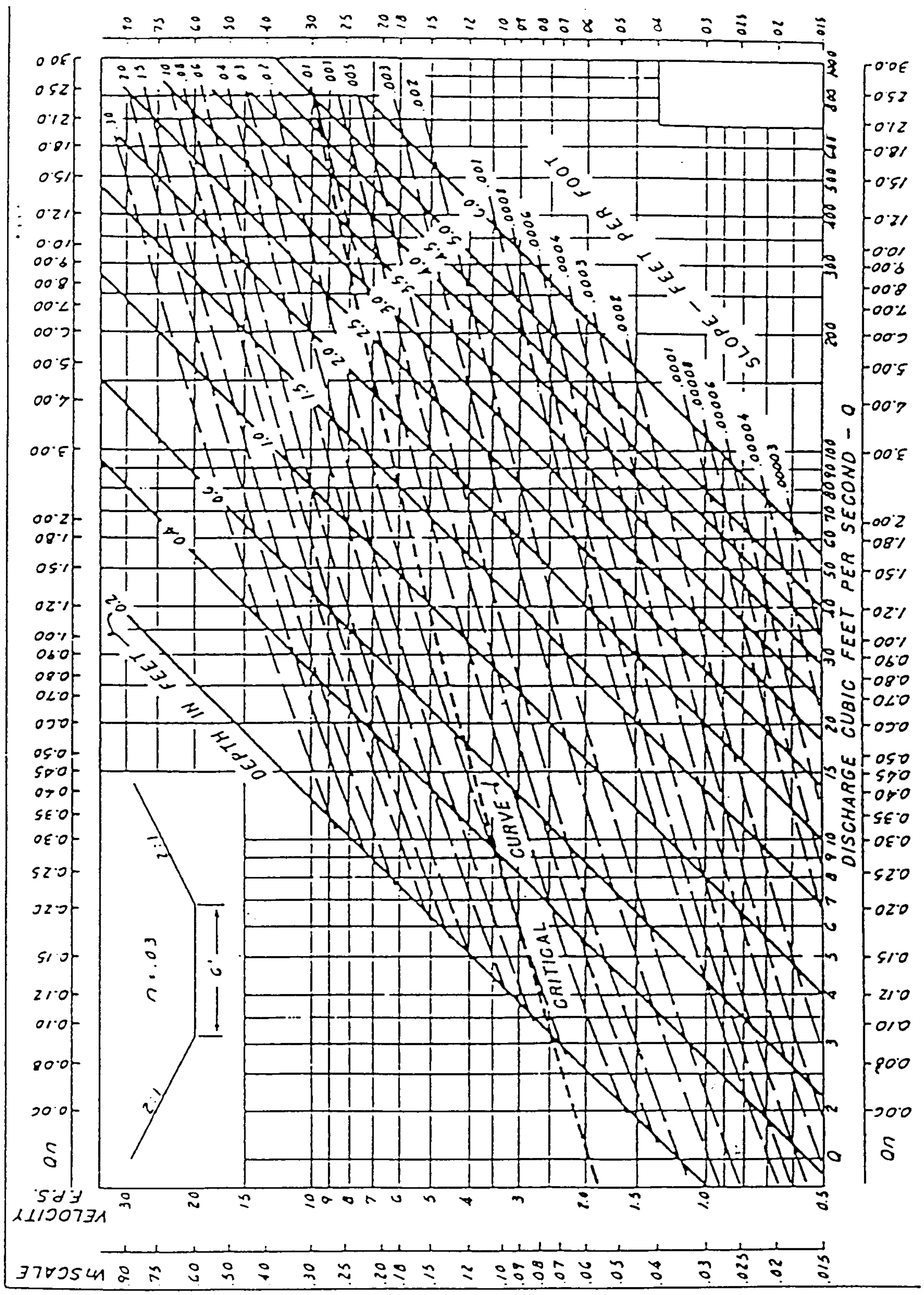
2:1 b = 5 FT.

Source: Federal Highway Administration



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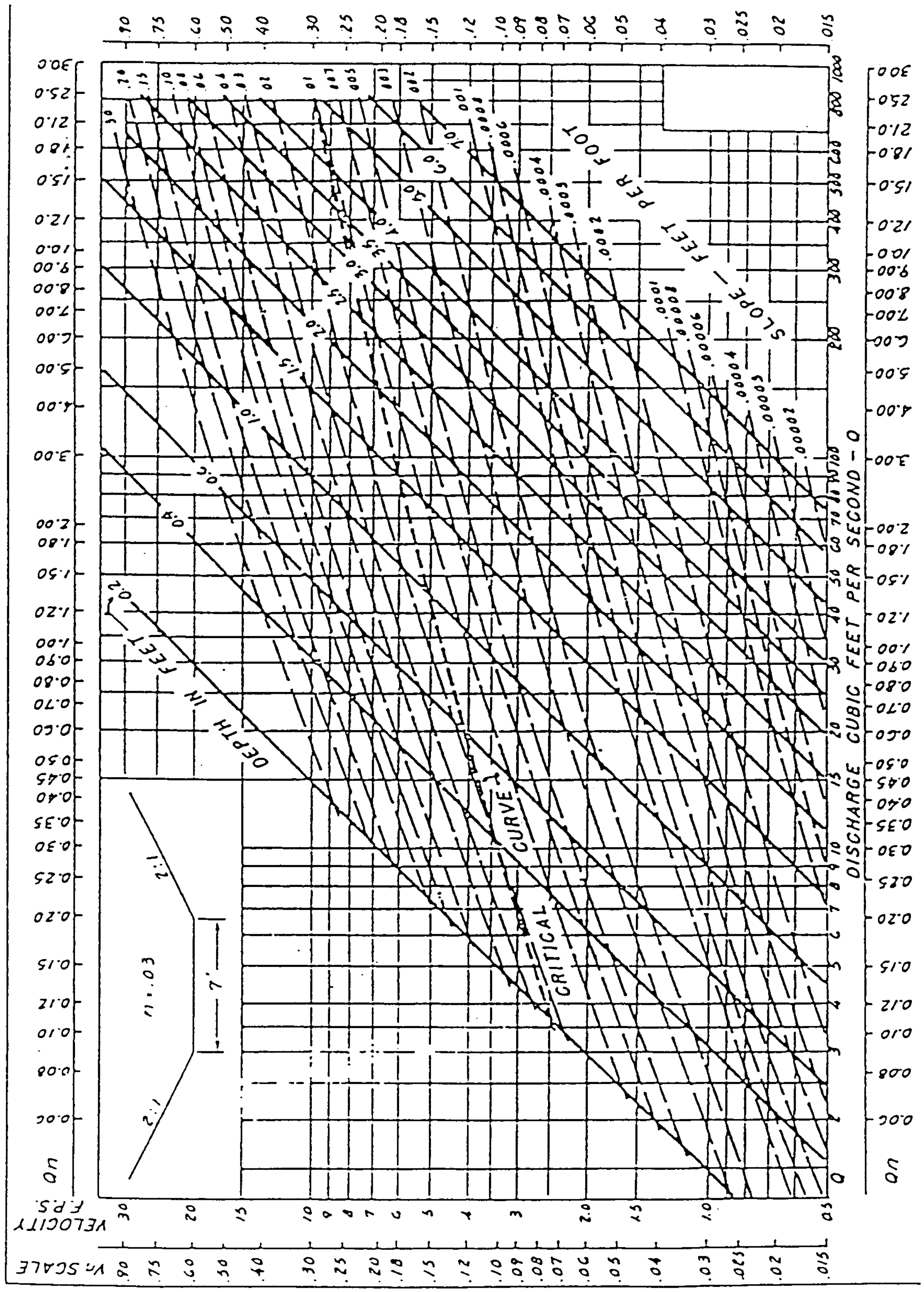
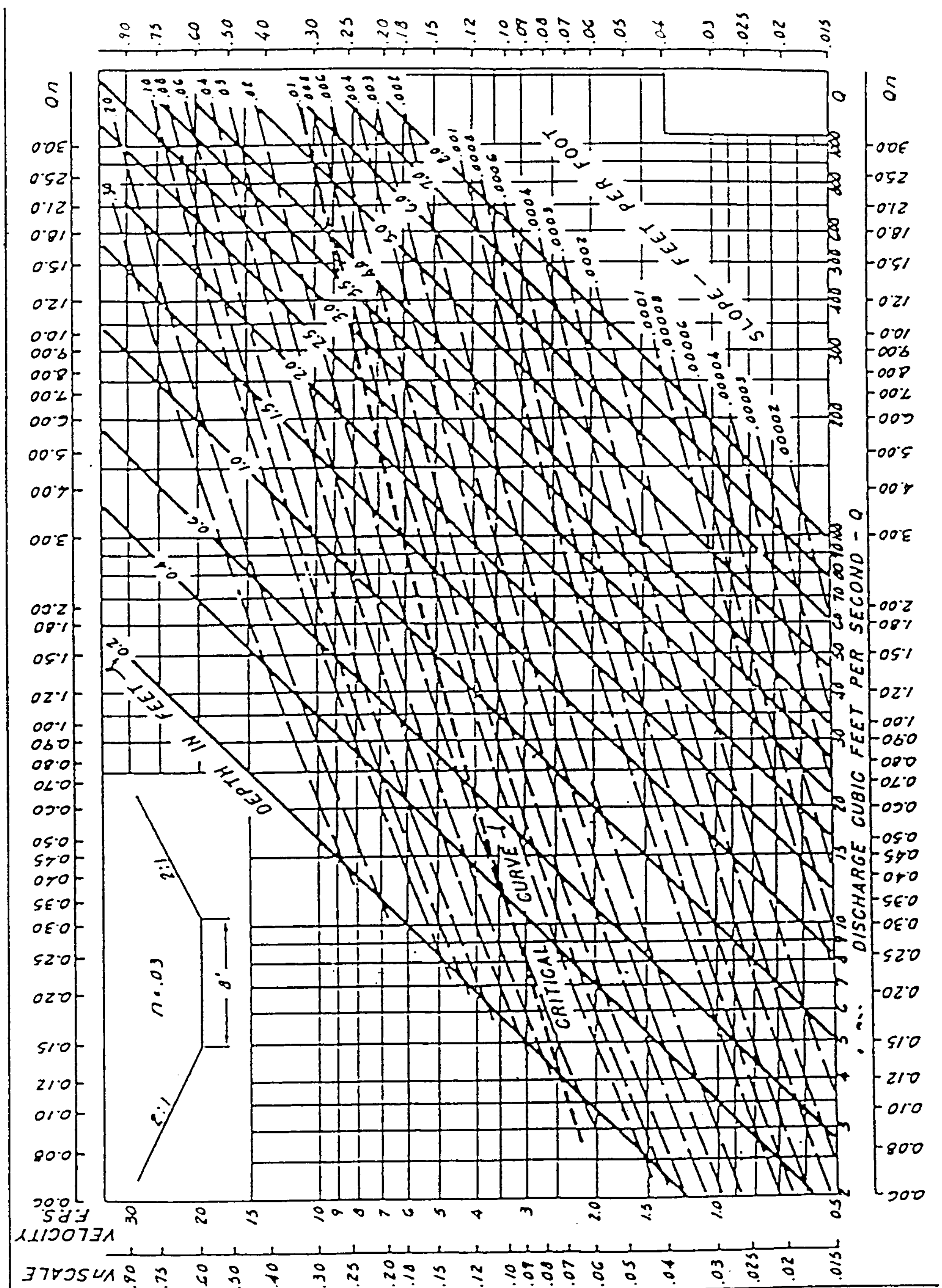
2:1 b = 6 FT.

Source: Federal Highway Administration



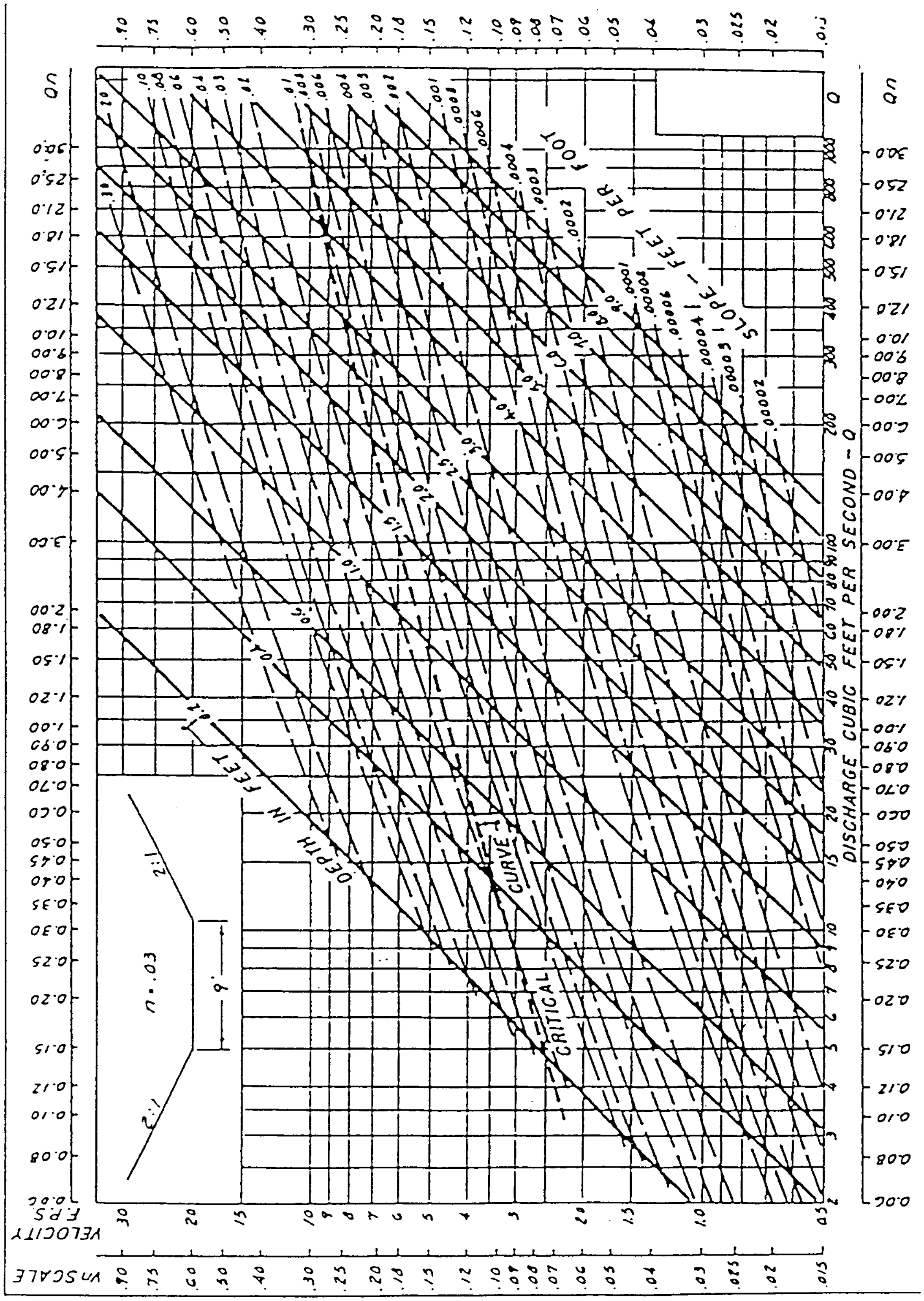
CHANNEL
2:1 b = 7 FT.

Source: Federal Highway Administration



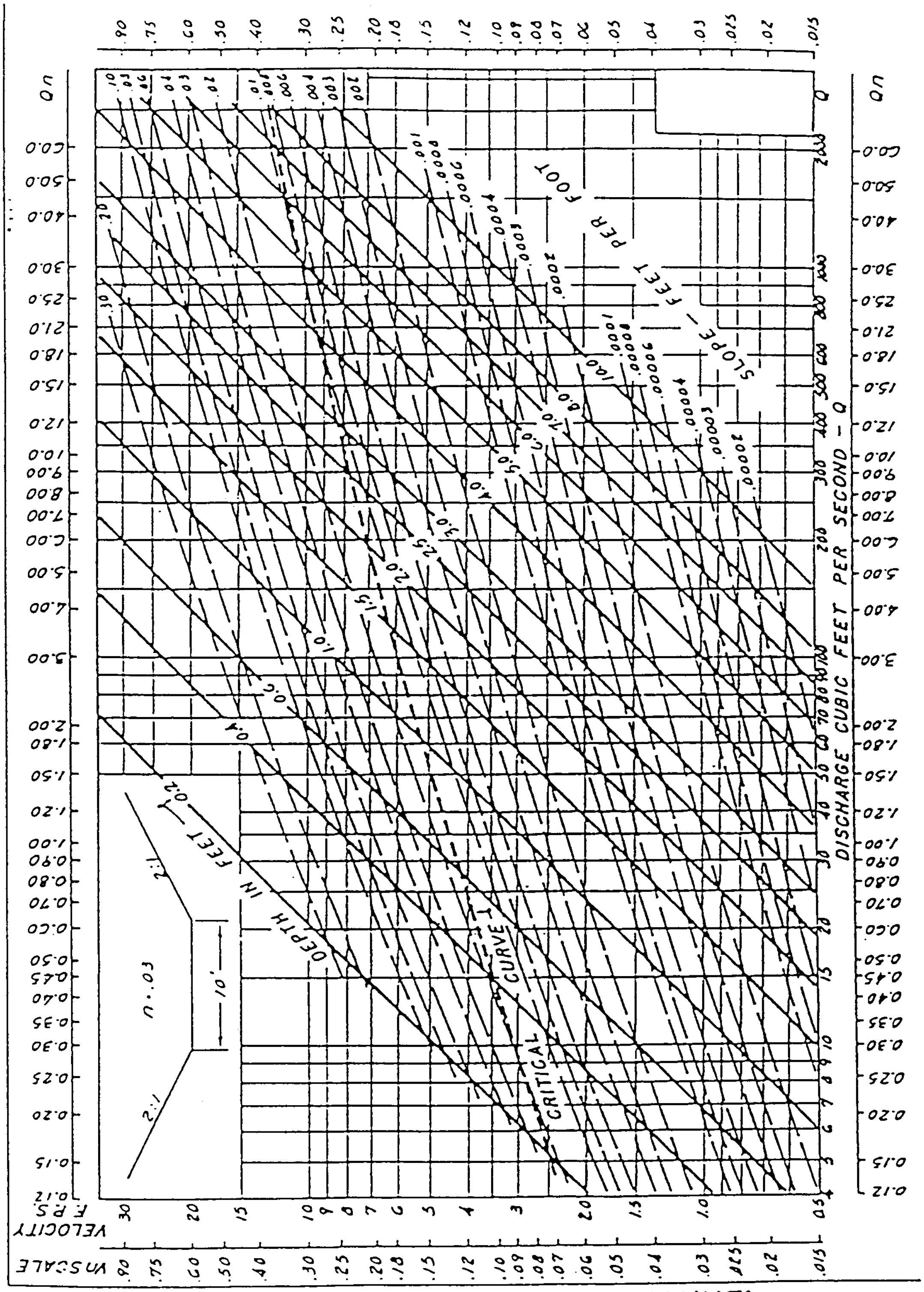
CHANNEL
2:1 b = 8 FT.

Source: Federal Highway Administration



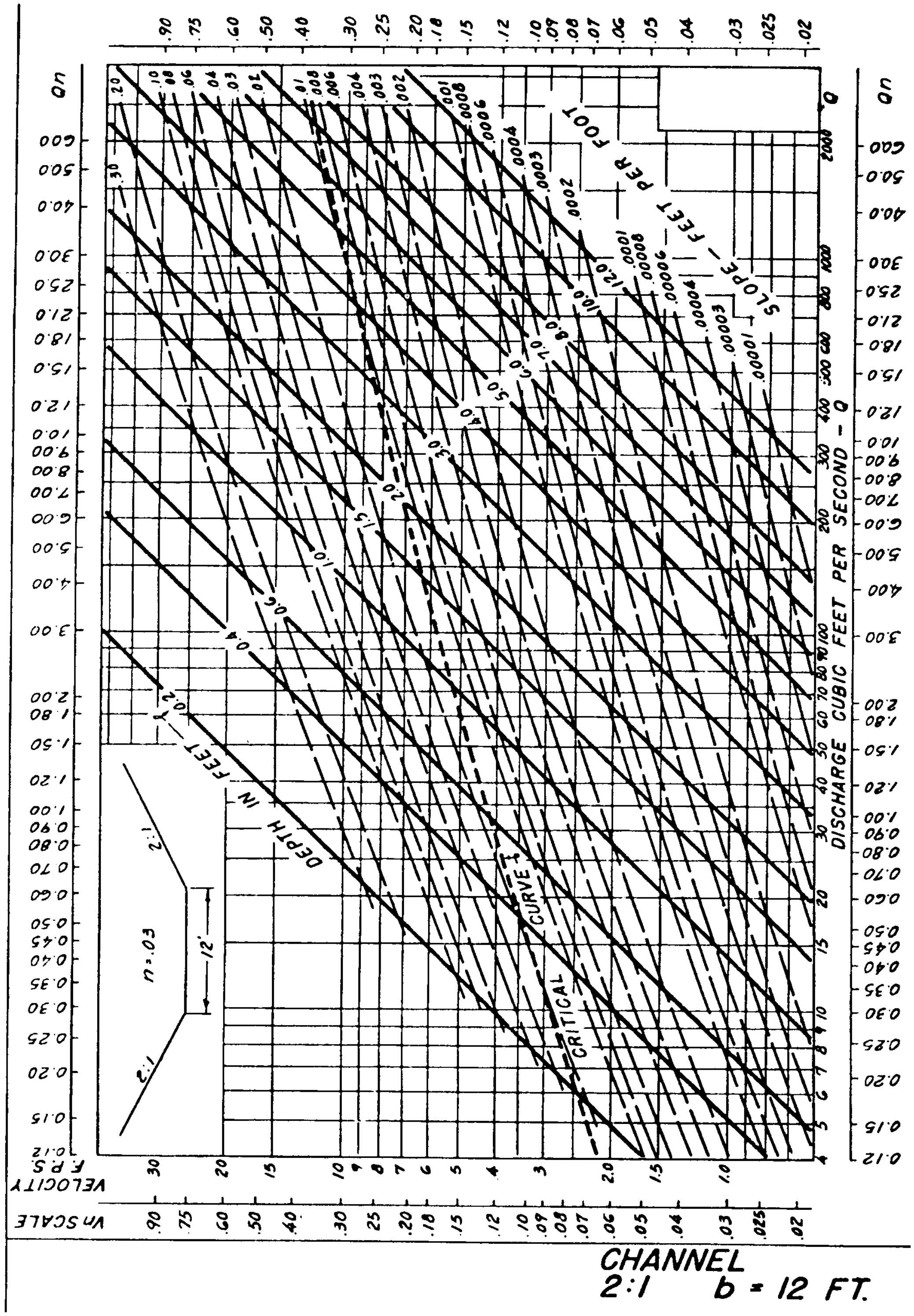
CHANNEL
2:1 b = 9 FT.

Source: Federal Highway Administration

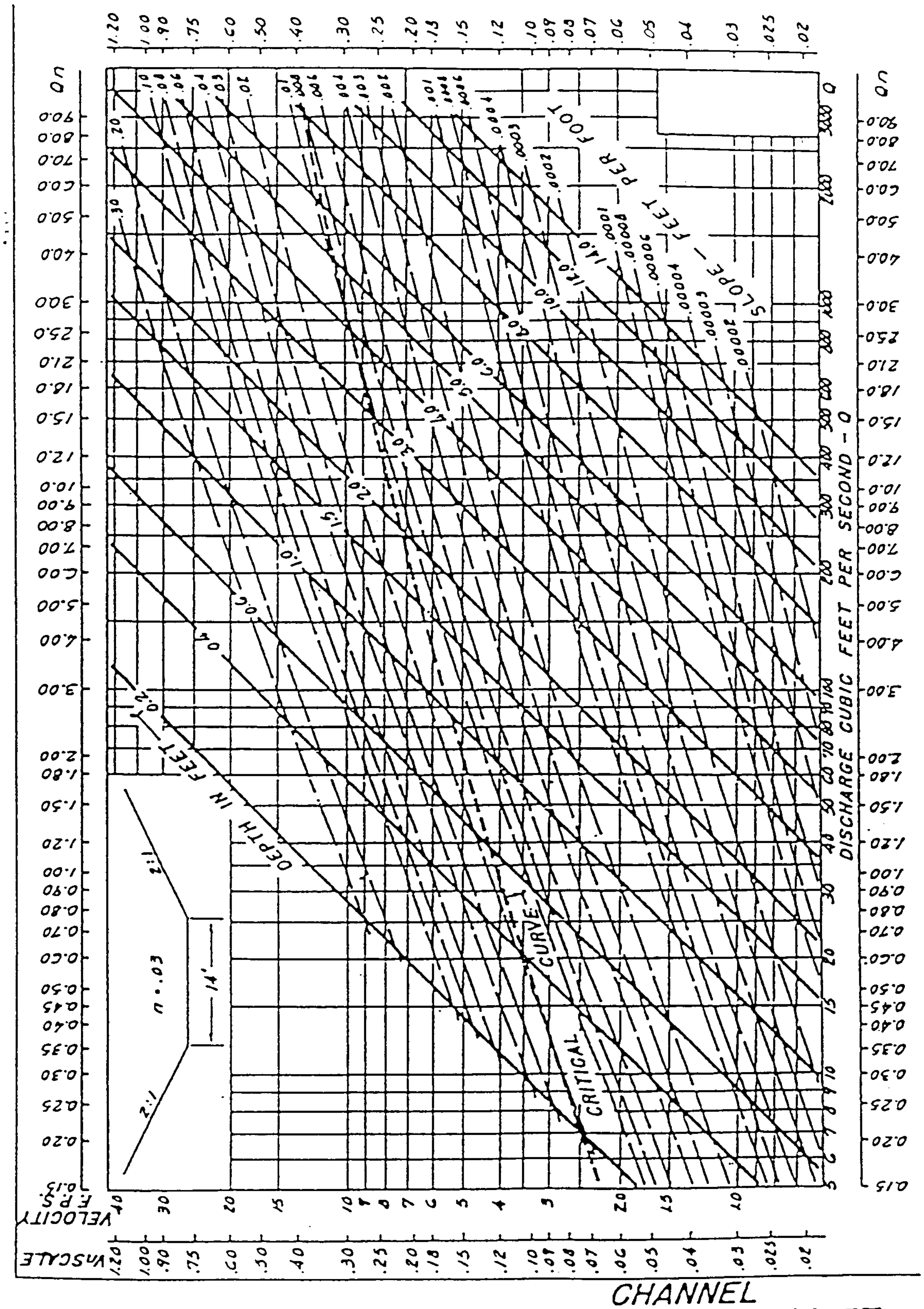


CHANNEL
2:1 b = 10 FT.

Source: Federal Highway Administration

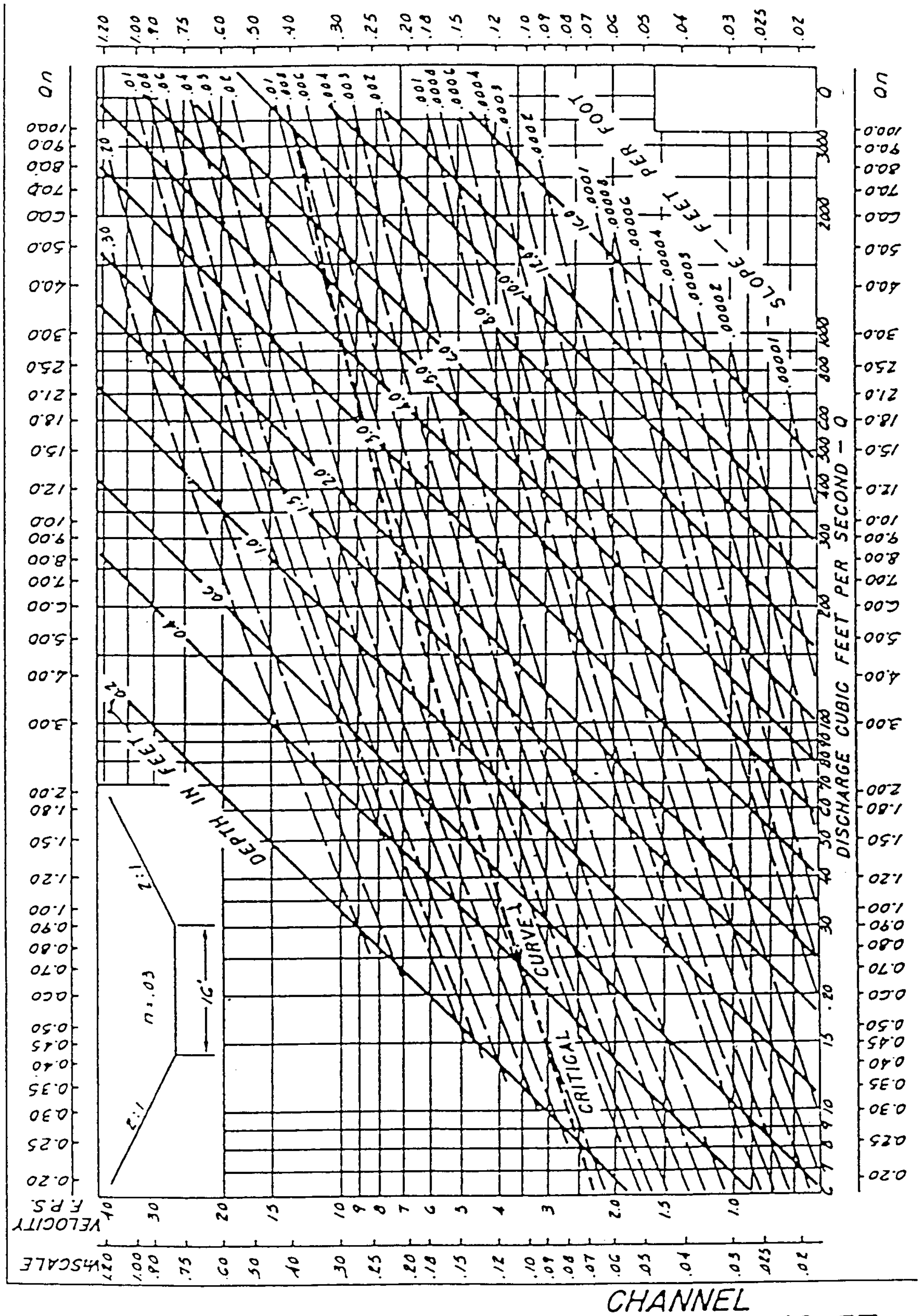


Source: Federal Highway Administration



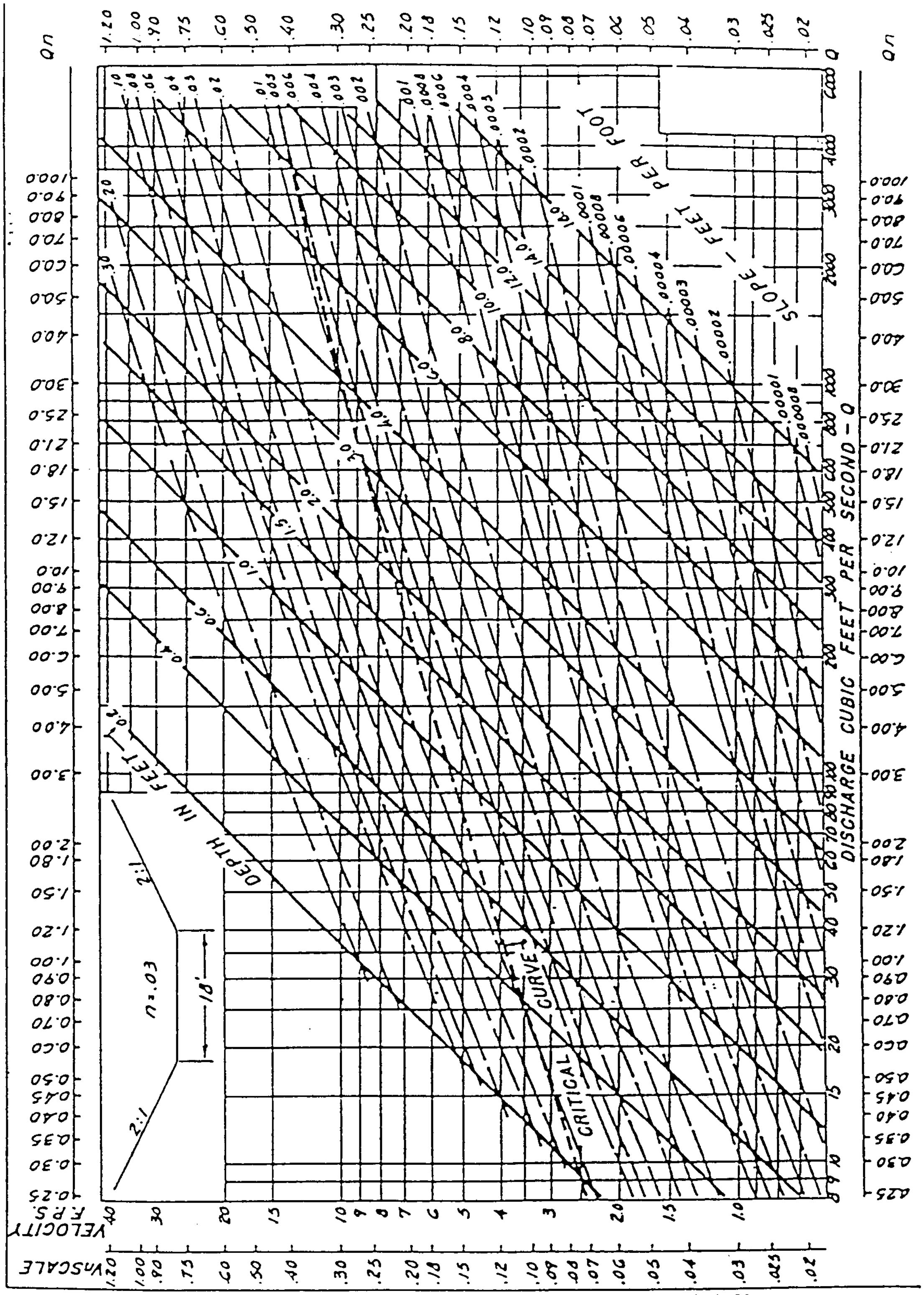
CHANNEL
2:1 b = 14 FT.

Source: Federal Highway Administration



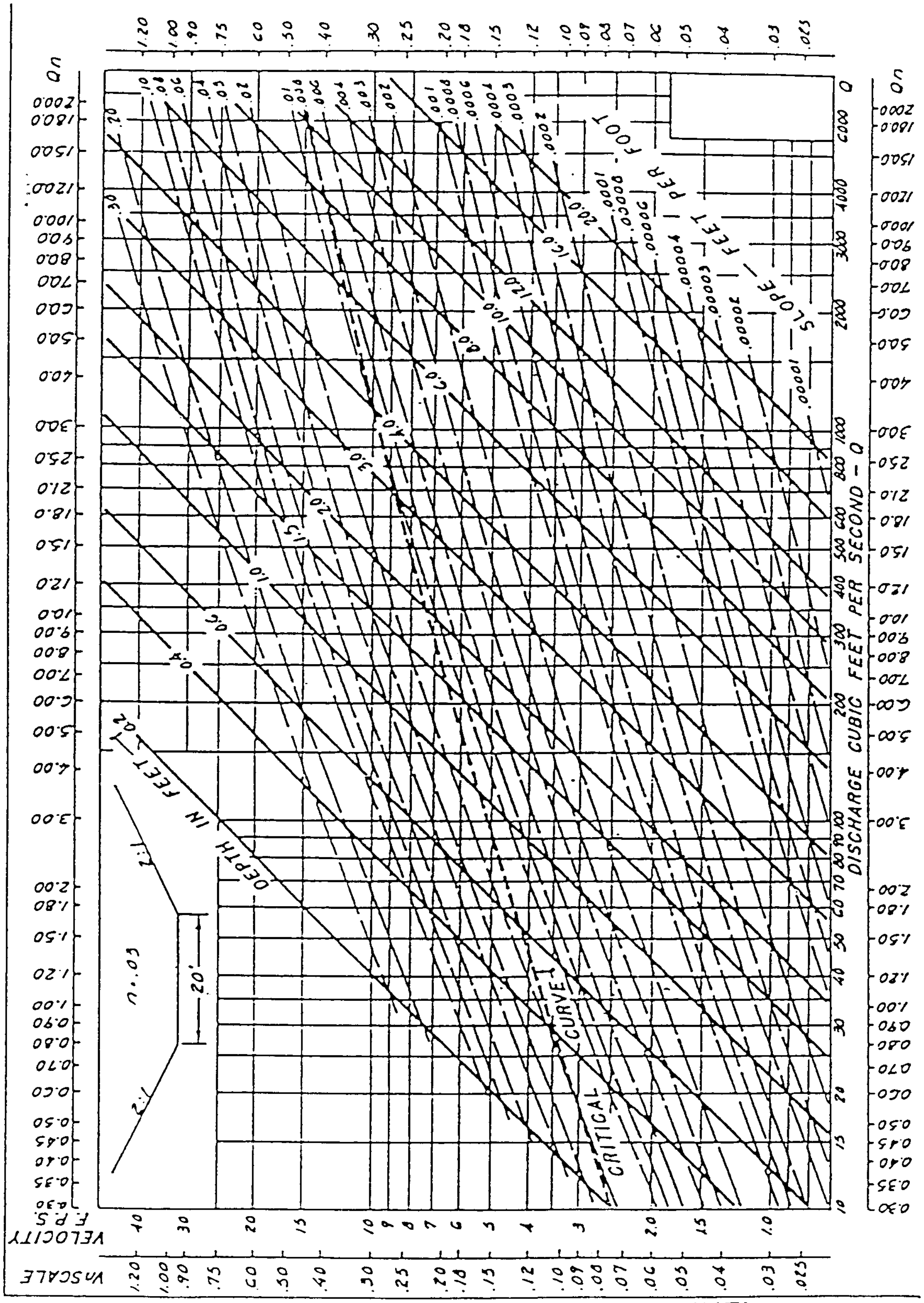
CHANNEL
2:1 b = 16 FT.

Source: Federal Highway Administration



CHANNEL
2:1 b = 18 FT.

Source: Federal Highway Administration



CHANNEL
2:1 b = 20 FT.

Source: Federal Highway Administration

Appendix B - Triangular Channel Nomograph

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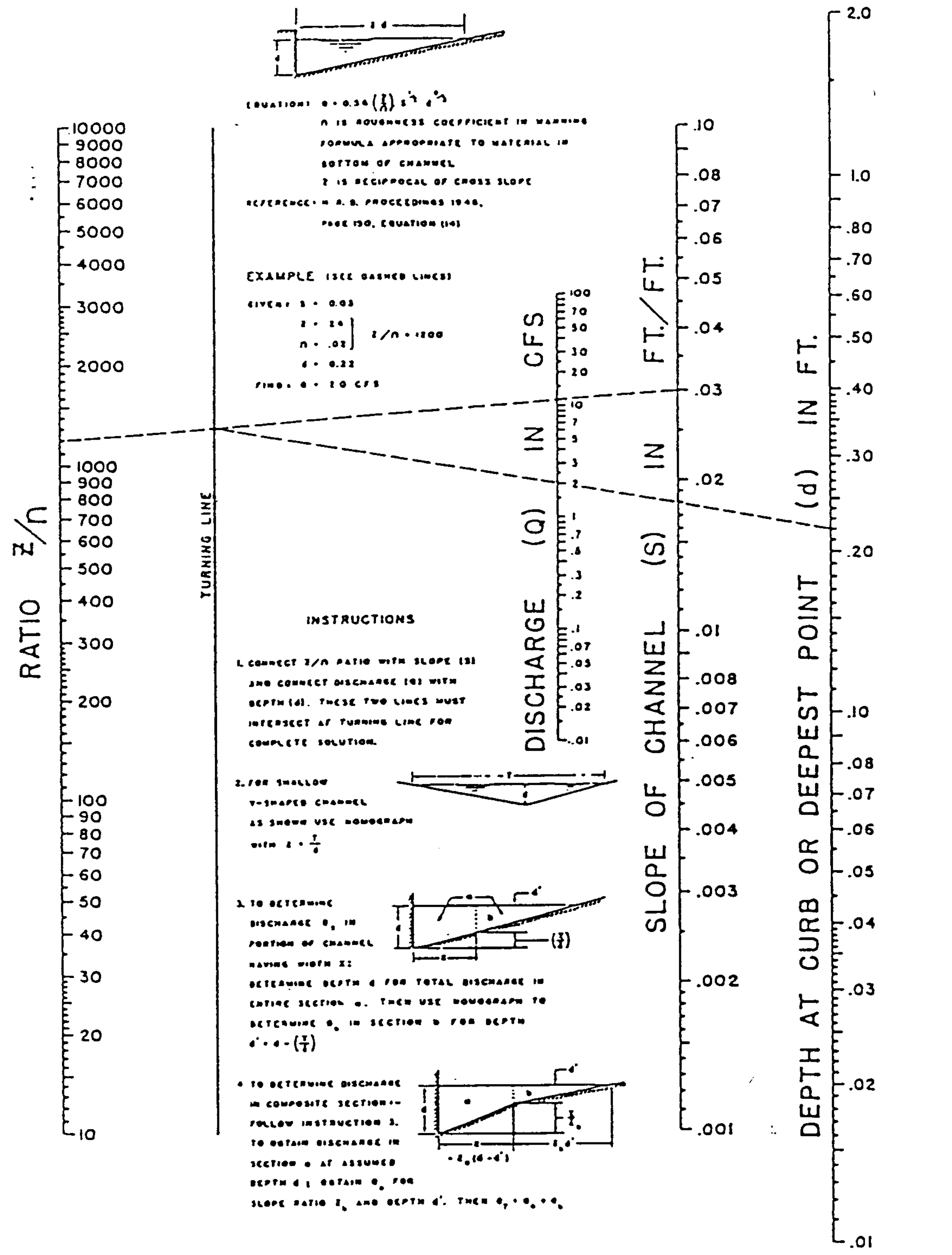

NOMOGRAPH FOR FLOW IN TRIANGULAR CHANNELS

Source: Federal Highway Administration

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Appendix C - Grassed Channel Design Figures

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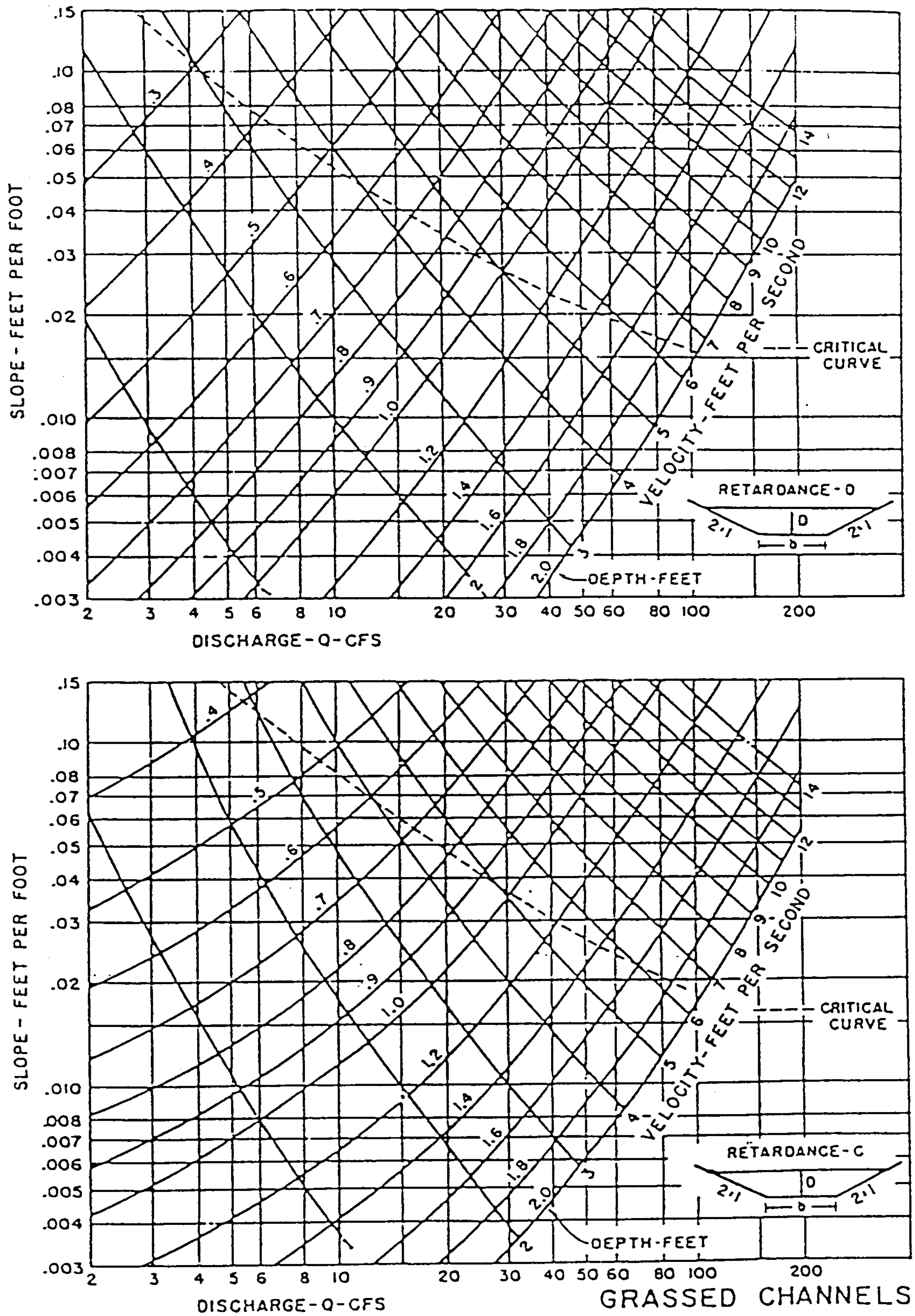
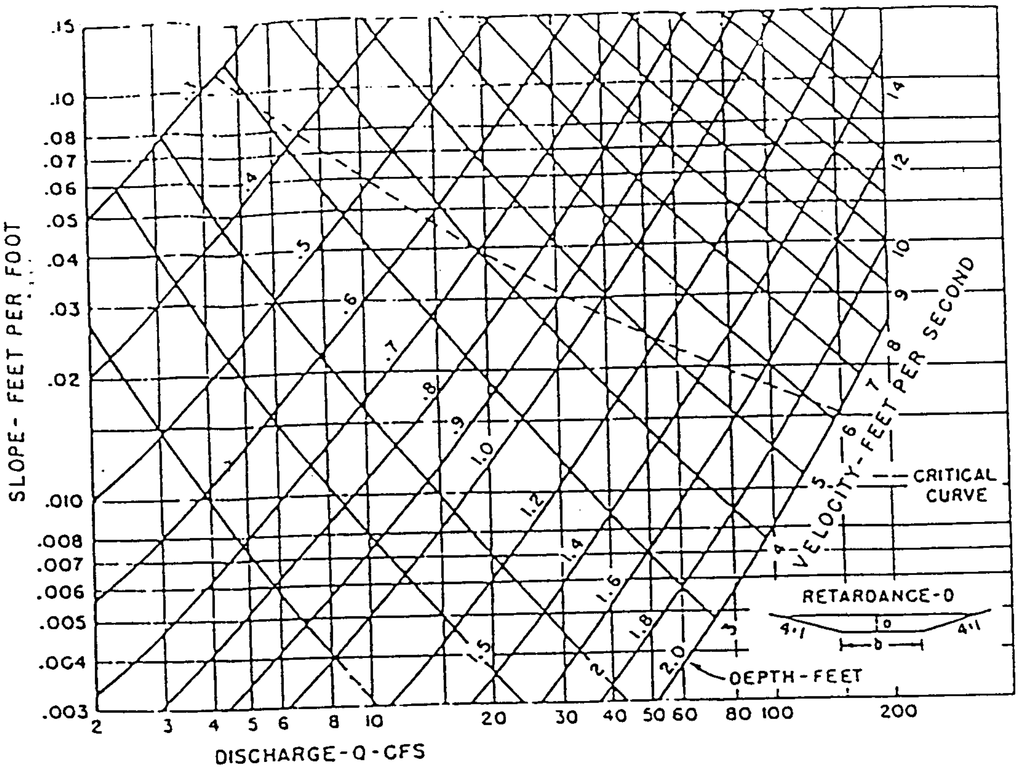
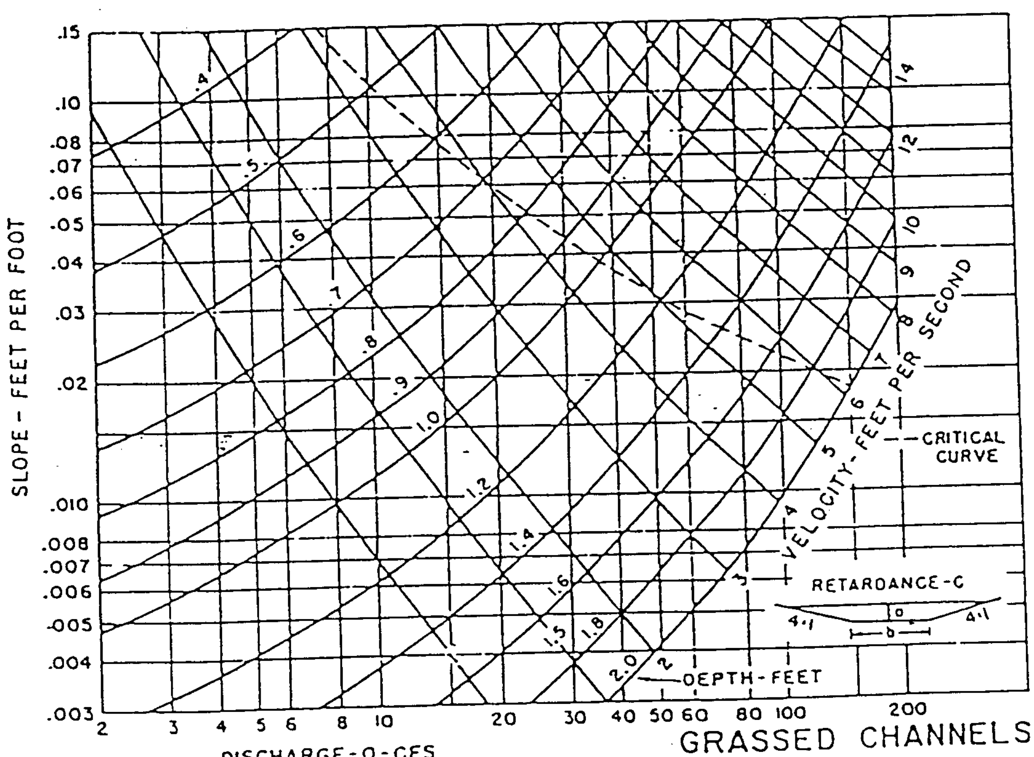


GRASSED CHANNELS
2:1 b = 4 ft.

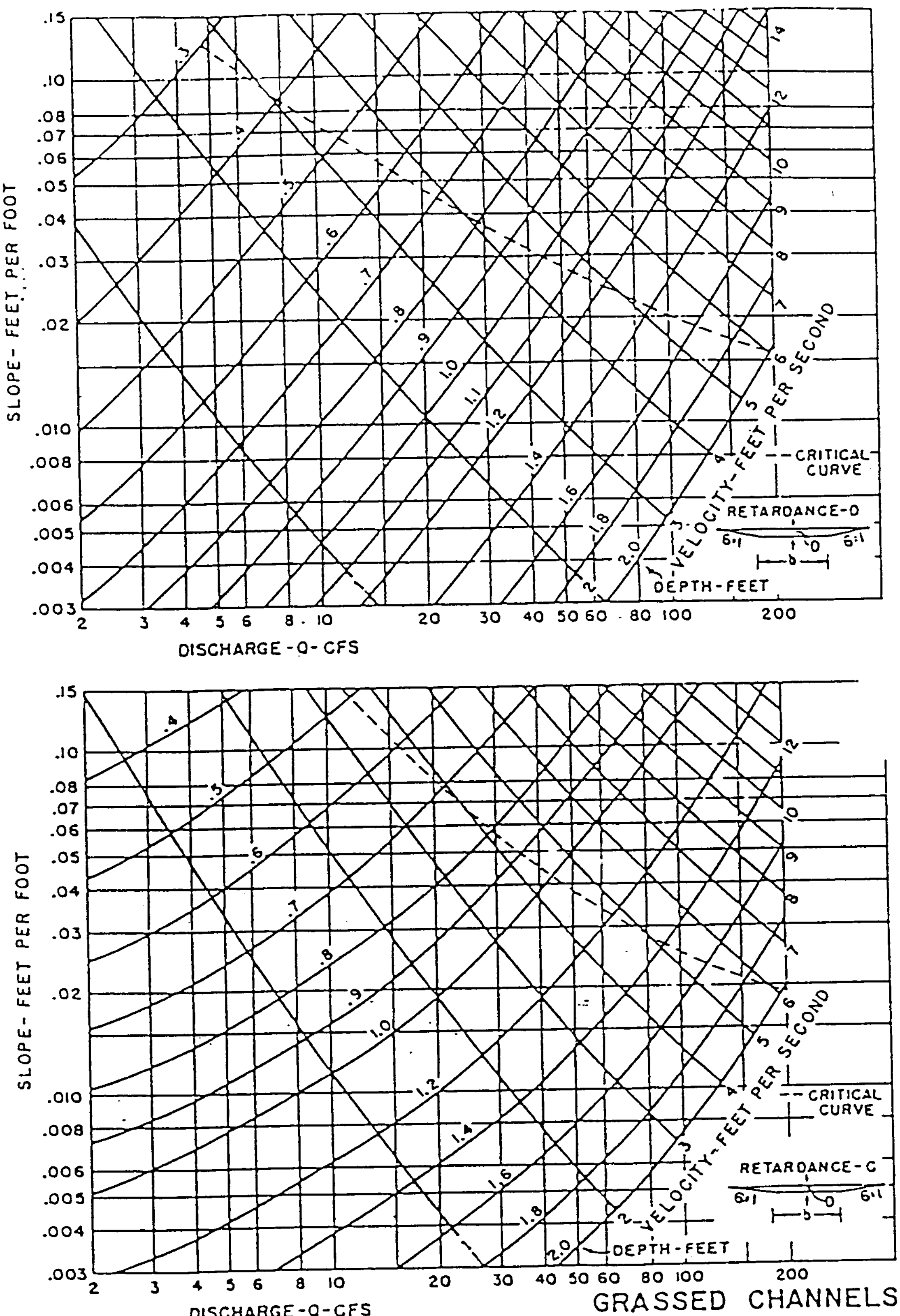
Source: Federal Highway Administration





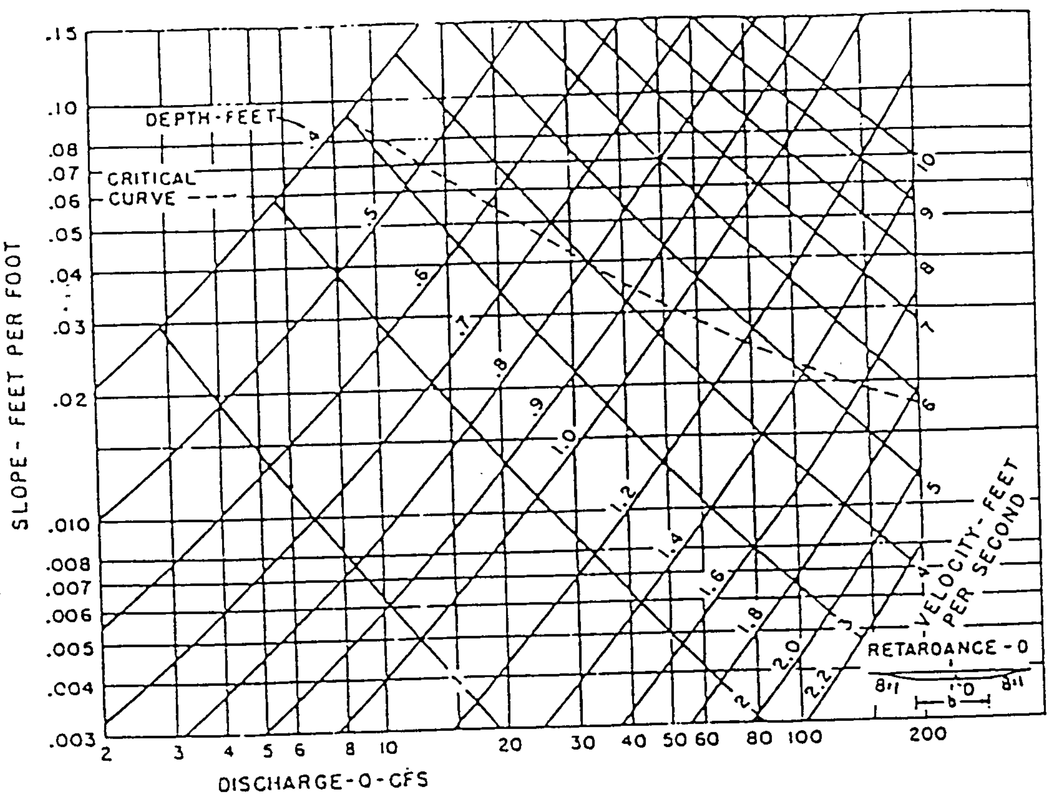
GRASSED CHANNELS
4:1 b = 4 ft.

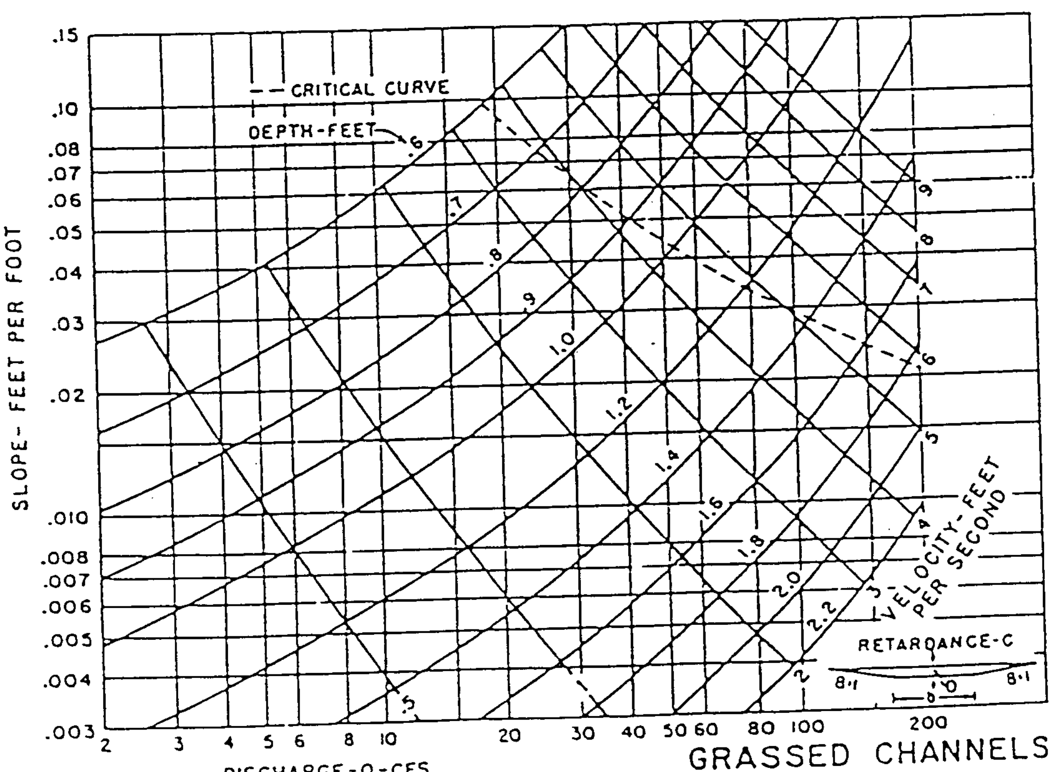
Source: Federal Highway Administration



GRASSED CHANNELS
6:1 b = 4 ft.

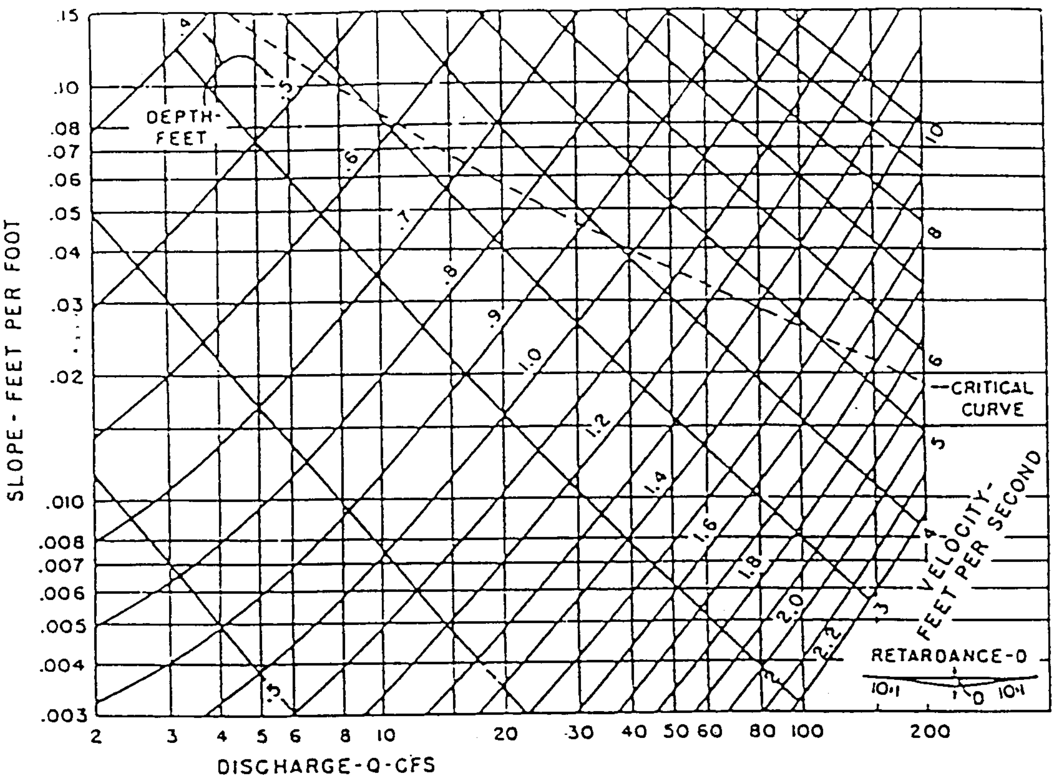
Source: Federal Highway Administration

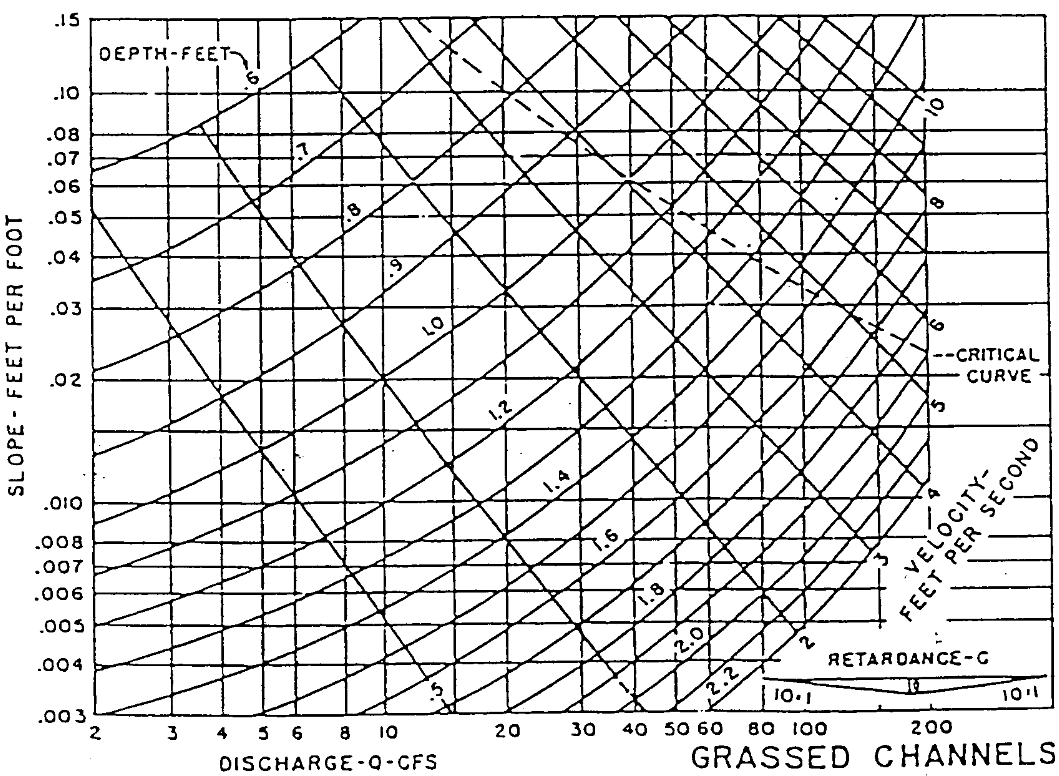




GRASSED CHANNELS
8:1 b = 4 ft.

Source: Federal Highway Administration





GRASSED CHANNELS
10:1

Source: Federal Highway Administration