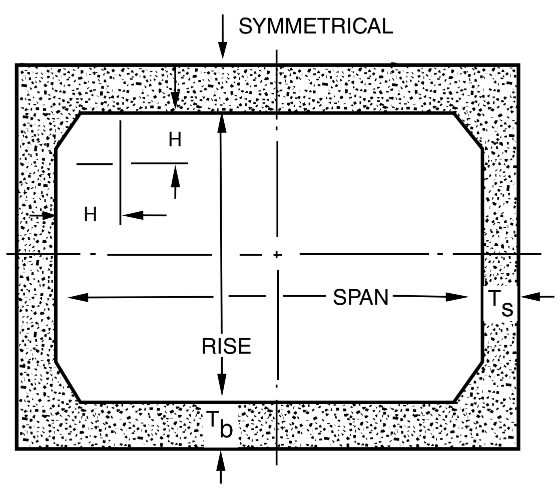
Partial Flow Conditions of Box Culverts

Sewers, both sanitary and storm, are designed to carry a peak flow based on anticipated land development. The hydraulic capacity of sewers or culverts constructed of precast box sections flowing full under gravity conditions on a known slope is readily calculated from the Manning Formula. Most sewers, however, are designed to operate under partial flow conditions. Culverts operate under either inlet control or outlet control. The type of control under which a particular culvert operates is dependent upon all the hydraulic factors present. Culverts operating under inlet control will always flow partially full while those operating under outlet control can flow full or partially full.

Determination of the depth and velocity of flow in pipe flowing partially full is therefore frequently necessary. This design data presents a method for determining the values of the partial flow depth and velocity in concrete box sections through the use of a series of partial flow curves which eliminate tedious trial and error computations.

A complete discussion on hydraulic properties of precast concrete box sections can be found in Design Data 15.

Figure 1 Standard Box Sections



Note: The haunch dimension H, is equal to the wall thickness T_S.

STANDARD DESIGNS

Table 1 indicates the sizes specified as standard in ASTM C1433 and C1577. *Figure 1* depicts the box shape utilized for the standard designs. The standard sizes have 45-degree haunches with leg dimensions equal to the sidewall thickness. The availability and construction details of box sections should be discussed with local concrete pipe producers. Precast box designs other than standard may be available through American Concrete Pipe Association member companies.

HYDRAULICS OF PRECAST BOX SECTIONS

The hydraulic characteristics of precast concrete box sections are similar to those for circular, arch and elliptical pipe. The most widely accepted formula for evaluating the hydraulic capacity of nonpressure conduit is the Manning Formula. This formula is:

Table 1 Standard Box, Sizes and Wall Thicknesses.

RISE (feet) \ SPAN (feet)	3	4	5	6	7	8	9	10	11	12
2	■	■								
3	■	■	■	■						
4		■	■	■	■	■			■	■
5			■	■	■	■	■	■		
6				■	■	■	■	■	■	■
7					■	■	■	■		
8						■	■	■	■	■
9							■	■		
10								■	■	■
11									■	
12										■
T_s (inches)	4	5	6	7	8	8	9	10	11	12

$$Q = \frac{1.486}{n} \times A \times R^{2/3} \times S^{1/2} \quad (1)$$

Where:

- Q = flow quantity, cubic feet per second
- n = Manning's roughness coefficient
- A = cross-sectional area of flow, square feet
- R = hydraulic radius, feet
- S_O = Slope of conduit, feet of vertical drop per foot of horizontal distance

For each of the standard size box sections, *Table 2* lists the full flow area A_F, hydraulic radius R, and a constant C. For a specific box section under full flow conditions, the first three terms of the right hand side of Manning's Formula equal a constant (C = 1.486/n x A x $R^{2/3}$). Values of C are presented for the two more commonly used values, 0.012 and 0.013, for the roughness coefficient, n, for precast concrete conduits. Utilizing the appropriate value C from *Table 2,* and calculating $S_O^{1/2}$, the flow quantity, Q_F of any standard size precast box section flowing full may be determined from Manning's Formula conveniently expressed as:

$$Q_F = C \times S_O^{1/2} \quad (2)$$

Once the flow quantity, Q_F has been determined, the average velocity, V_F for full flow conditions may be calculated from the basic hydraulic relationship:

$$V_F = Q_F / A_F \quad (3)$$

Where:

- Q_F = flow quantity, flowing full, cubic feet per second
- V_F = the average velocity, flowing full, feet per second
- A_F = cross sectional area, flowing full, square feet

PARTIAL FLOW HYDRAULIC ELEMENTS

For any size box section, curves showing the partial flow relationship of the hydraulic elements; flow quantity, area of flow, and velocity of flow in terms of the full flow conditions can be plotted. *Figures 2 - 10* provide such hydraulic element curves for the standard size precast concrete box sections. All of the standard sizes of box sections have been consolidated into groups with common span to rise ratios ranging from 1:1 through 3:1. These partial flow curves for each group were developed based on a composite box section with dimensions calculated as the average of all box sizes included in each Figure. The partial flow curves for a given range of span to rise ratios are valid for any box section with a span to rise ratio falling with in that range and may be used to determine the value of any partial flow hydraulic element provided the full flow values of the elements are obtained by appropriate methods. The error in determining the values of any hydraulic element through the use of these partial flow curves is less than the inherent probable error in any series of hydraulic computations. The maximum value for each of the hydraulic elements, except the area of flow, occurs at the point where the depth of flow has reached with in an infinitesimal distance of the rise which results in an abrupt break in each curve at this point.

DESIGN METHOD

To determine the value of anyone of the partial flow hydraulic elements in precast concrete boxes, the following four step design method is suggested:

1. Determine the full flow quantity, Q_F, and velocity, V_F, utilizing *Table 2* or other appropriate methods for the box section under consideration.
2. Determine the span to rise ratio of the box section.
3. Determine the value of the ratio of partial flow to full flow of the known hydraulic elements.
4. Determine the values of the unknown hydraulic elements through use of the partial flow curves.

Size Span x Rise (Feet)	A Area (Square Feet)	R Hydraulic Radius (A/P Feet)	$C = 1.486/n(AxR^{2/3})$*	
			n = 0.012	n = 0.013
3 x 2	5.78	0.63	520	480
3 x 3	8.78	0.78	920	850
4 x 2	7.65	0.69	740	690
4 x 3	11.65	0.89	1,340	1,240
4 x 4	15.65	1.04	1,990	1,840
5 x 2	9.50	0.74	960	890
5 x 3	14.50	0.98	1,770	1,630
5 x 4	19.50	1.16	2,660	2,460
5 x 5	24.50	1.30	3,620	3,340
6 x 3	17.32	1.04	2,200	2,030
6 x 4	23.32	1.25	3,350	3,100
6 x 5	29.32	1.42	4,590	4,240
6 x 6	35.32	1.56	5,880	5,430
7 x 3	20.11	1.09	2,640	2,440
7 x 4	27.11	1.33	4,050	3,740
7 x 5	34.11	1.52	5,580	5,160
7 x 6	41.11	1.68	7,200	6,650
7 x 7	48.11	1.82	8,880	8,200
8 x 3	23.11	1.13	3,110	2,870
8 x 4	31.11	1.39	4,790	4,420
8 x 5	39.11	1.60	6,630	6,120
8 x 6	47.11	1.78	8,570	7,920
8 x 7	55.11	1.94	10,610	9,790
8 x 8	63.11	2.07	12,710	11,730
9 x 4	34.88	1.44	5,500	5,080
9 x 5	43.88	1.67	7,650	7,060
9 x 6	52.88	1.87	9,950	9,180
9 x 7	61.88	2.05	12,350	11,400
9 x 8	70.88	2.20	14,840	13,700
9 x 9	79.88	2.33	17,400	16,060
10 x 4	38.61	1.48	6,220	5,740
10 x 5	48.61	1.73	8,690	8,020
10 x 6	58.61	1.95	11,330	10,460
10 x 7	68.61	2.14	14,110	13,030
10 x 8	78.61	2.31	17,010	15,700
10 x 9	88.61	2.46	19,990	18,450
10 x 10	98.61	2.59	23,040	21,270
11 x 4	42.32	1.52	6,930	6,390
11 x 5	53.32	1.79	9,720	8,970
11 x 6	64.32	2.02	12,720	11,750
11 x 7	75.32	2.22	15,900	14,670
11 x 8	86.32	2.41	19,200	17,720
11 x 9	97.32	2.57	22,620	20,880
11 x 10	108.32	2.72	26,120	24,110
11 x 11	119.32	2.85	29,710	27,420
12 x 4	46.00	1.55	7,630	7,050
12 x 5	58.00	1.83	10,750	9,930
12 x 6	70.00	2.08	14,120	13,040
12 x 7	82.00	2.30	17,690	16,330
12 x 8	94.00	2.50	21,420	19,770
12 x 9	106.00	2.67	25,280	23,340
12 x 10	118.00	2.83	29,250	27,000
12 x 11	130.00	2.98	33,320	30,760
12 x 12	142.00	3.11	37,470	34,580

Table 2 Full Flow Section and Hydraulic Properties - Precast Concrete Box Sections

* Values have been rounded due to the empirical nature of the terms used to calculate the constant.

EXAMPLE 1

Given: 6 ft. x 4 ft. precast concrete box sections installed as a sanitary trunk sewer on a slope of 0.0055 feet per foot is carrying 185 cfs. For sanitary sewers a value of 0.013 for Manning's *n*, the roughness coefficient, is recommended.

Find: The depth of flow and velocity.

Solution:

1. Determine Full Flow Quantity, Q_F and Velocity, V_F.
   From *Table 2*, a 6 x 4 box with an *n* value of 0.013, C = 3100 and A_F = 23.32 ft.^{2}
   Using equation 2:
   $Q_F = 3100 \times (0.0055)^{1/2}$
   $Q_F = 230$ cfs
   Using equation 3:
   $V_F = 230/23.32$
   $V_F = 9.9$ fps.
2. Determine Span to Rise Ratio.
   Ratio = span:rise
   Ratio = 6:4
   Ratio = 1.50:1
   Therefore, use *Figure 6*.
3. Determine Value of the Ratio of Partial Flow to Full Flow.
   Since Q_P of 185 cfs was given, the value of the ratio of Q_P to Q_F will be calculated:
   Ratio = $Q_P : Q_F$
   Ratio = 185 : 230
   Ratio = 0.80
4. Determine Value of Partial Flow Hydraulic Elements.
   Enter *Figure 6* along the horizontal scale at 0.80, proceed vertically until the curve representing flow, Q is intersected; from this point proceed horizontally to the right until the curve representing velocity, V is intersected and from this point of intersection drop vertically to the horizontal scale and read V_P/A_F = 1.13; from the original point of intersection on the Q curve, proceed horizontally to the left until the area, A curve is intersected and from this point drop vertically to the horizontal scale and read A_P/A_F = 0.71; also from the original point of intersection on the Q curve, continue horizontally to the left to the vertical scale and read depth over rise ratio, = 0.70.
   Therefore,
   $V_P = 9.9 \times 1.13$ $A_P = 16.6$ ft.^{2}
   $V_P = 11.2$ fps $D_P = 0.70 \times 4$
   $A_P = 23.32 \times 0.71$ $D_P = 2.8$ ft.

Answer: Therefore, a 6 ft. x 4 ft. precast concrete box sewer on a slope of 0.0055 feet per foot carrying 185 cfs will flow at a depth of 2.8 feet with a velocity of 11.2 feet per second.

EXAMPLE 2

Given: A box culvert constructed of 10 ft. x 5 ft. precast concrete box sections on a slope of 0.006 feet per foot. When discharging a flow of 600 cubic feet per second, the culvert was found to operate under outlet control with a headwater depth at the inlet of 7.6 feet above the invert.

Find: The depth of flow, D_P, in the culvert and the velocity of flow, V_P, for a Manning's *n* of 0.012.

Solution:

1. Determine Full Flow Quantity, Q_F and Velocity, V_F.
   From *Table 2*, a 10 x 5 box with an *n* value of 0.012, C =8690 and A_F = 48.61 ft.^{2}.
   Using equation 2:
   $Q_F = 8690 \times (0.006)^{1/2}$
   Q_F = 673 cfs
   Using equation 3:
   V_F =673/48.61
   V_F =13.8 fps
2. Determine the Span to Rise Ratio.
   Ratio = 10:5
   Ratio = 2:1
   Therefore, use *Figure 3*.
3. Determine Value of the Ratio of Partial Flow to Full Flow.
   Ratio = Q_P: Q_F
   Ratio = 600: 673
   Ratio = 0.89
   Enter *Figure 3* on the horizontal scale at 0.89, proceed vertically until the curve for flow, Q is intersected. From this point proceed horizontally to the left until the vertical scale is intersected and read depth: rise ratio = 0.75. From the point of intersection on the Q curve, proceed horizontally to the right until the curve representing velocity, V is intersected and drop vertically from this point to the horizontal scale and read V_P:V_F = 1.18.
4. Determine Value of Partial Flow Hydraulic Elements.
   D_P = 5.0 x 0.75
   D_P = 3.75 ft.
   V_P = 13.8 x 1.18
   V_P = 16.3 fps

Answer: The depth of flow in the 10 ft. x 5 ft. box culvert carrying 600 cfs will be 3.75 feet with a velocity of 16.3 feet per second.

Figure 2 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

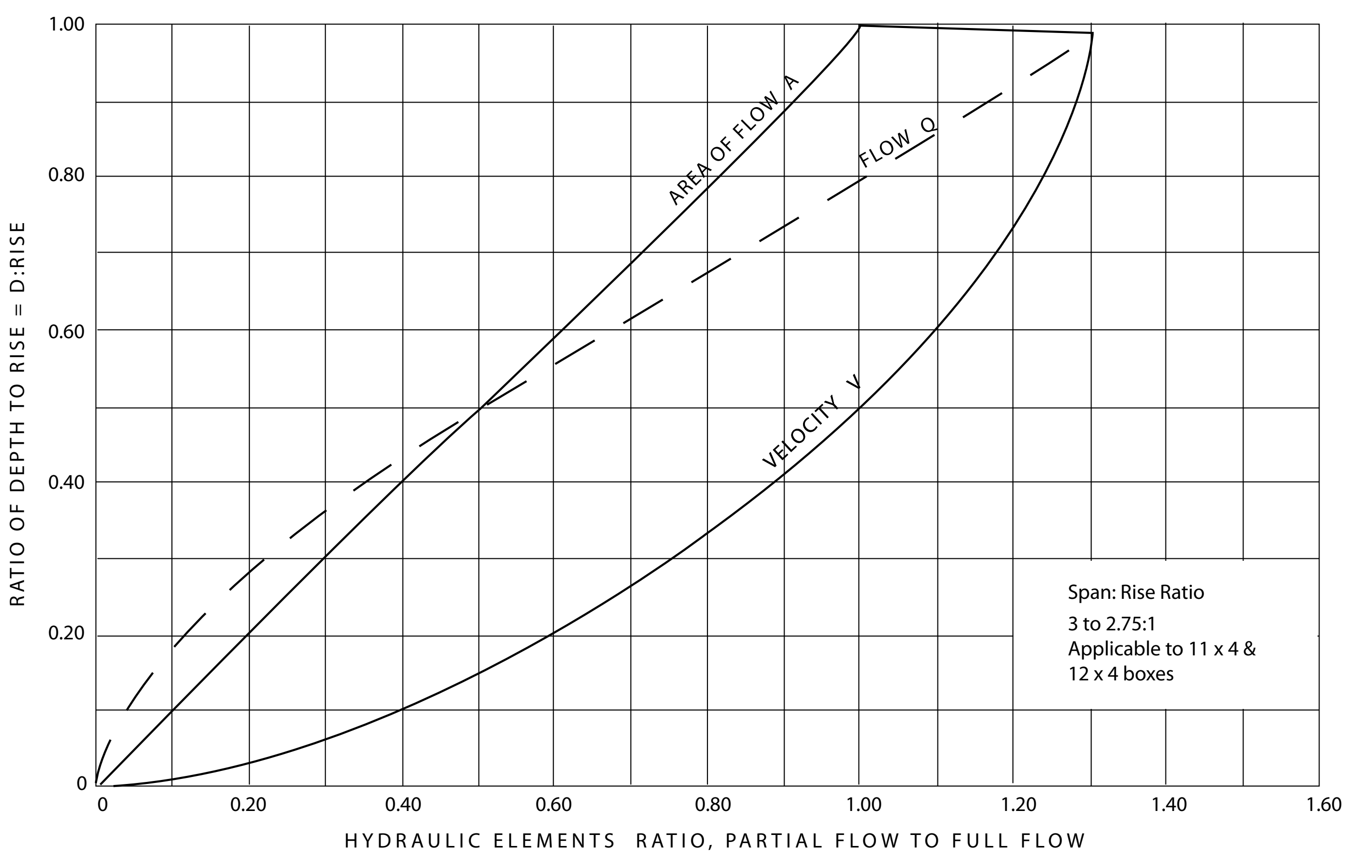


Figure 3 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

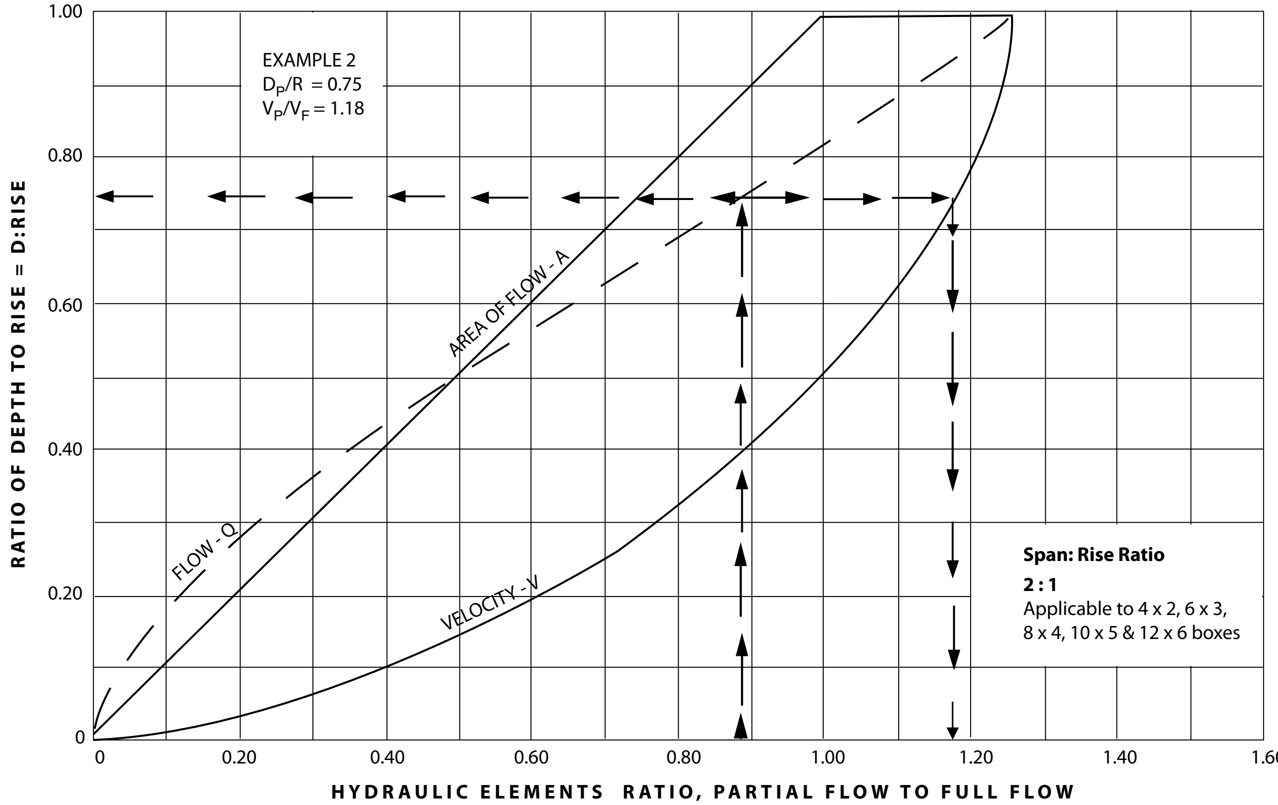


Figure 4 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

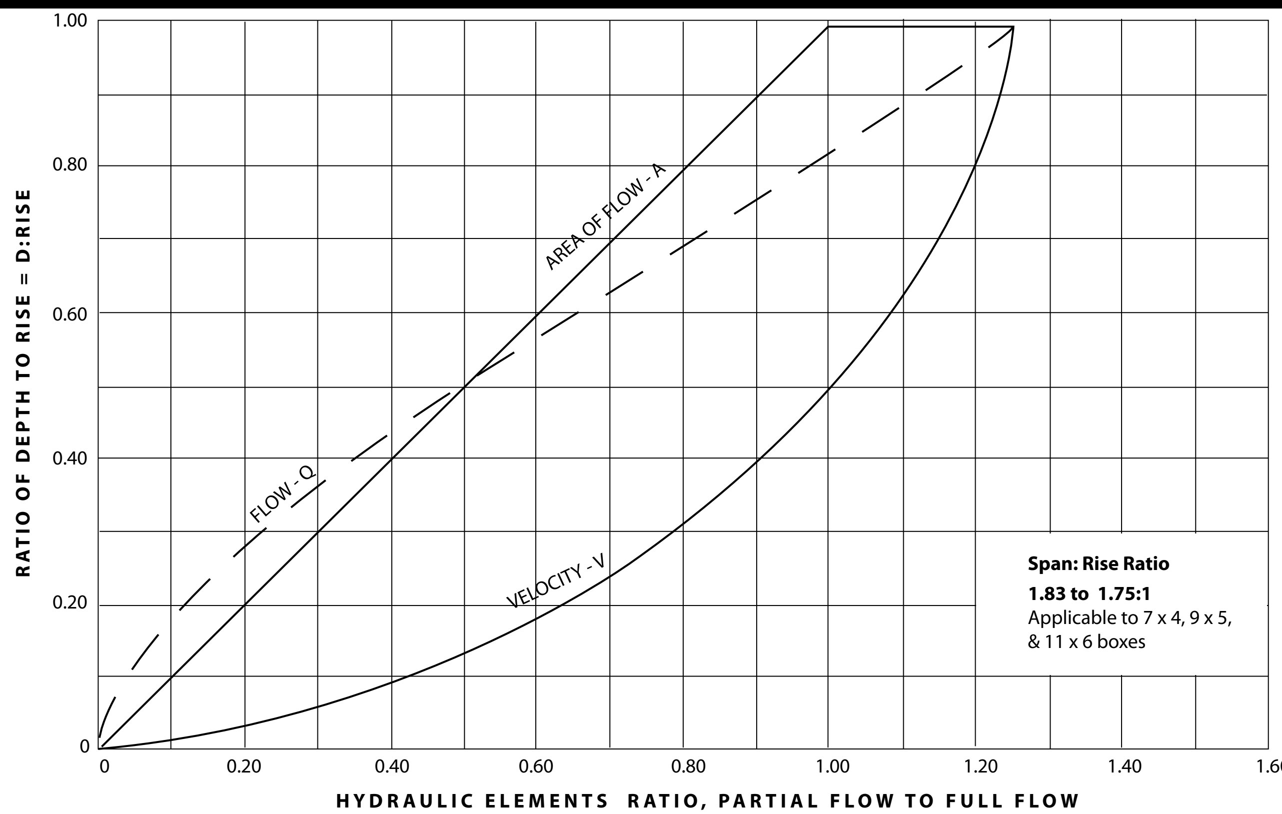


Figure 5 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

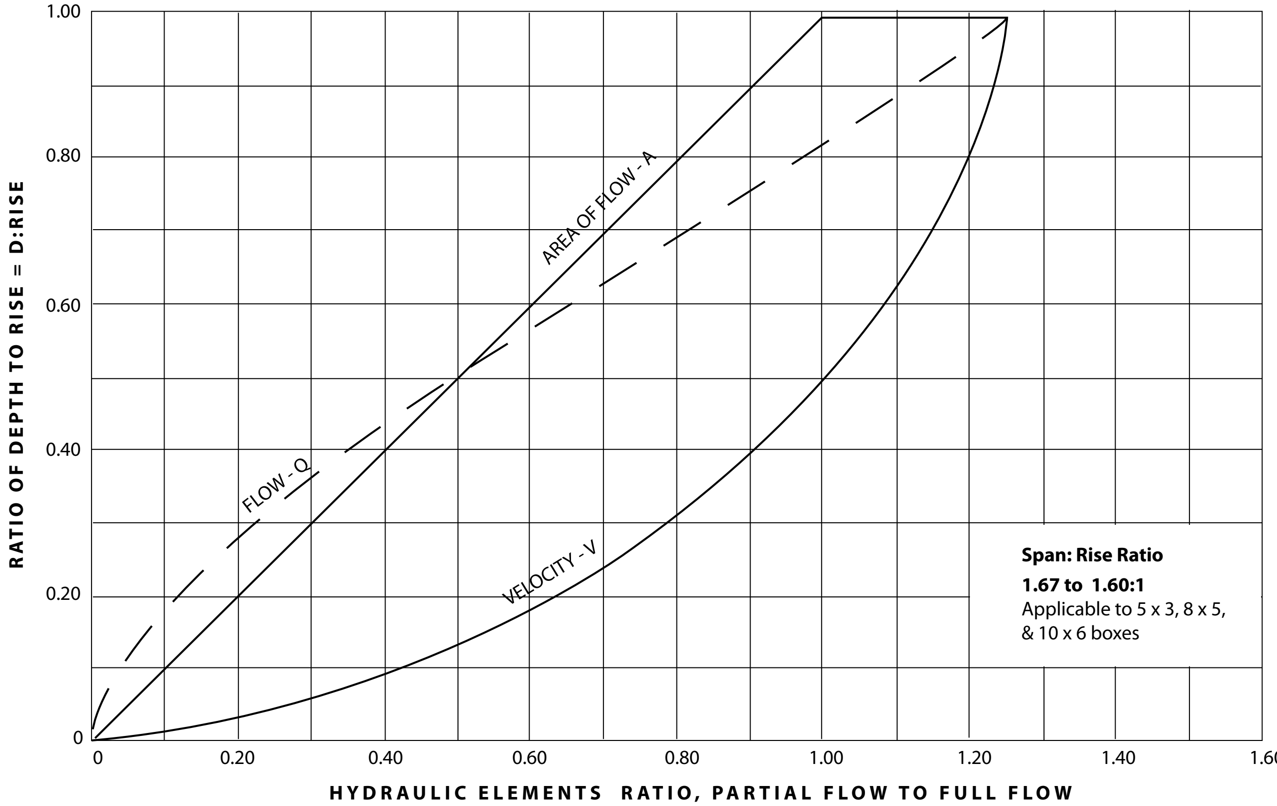


Figure 6 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

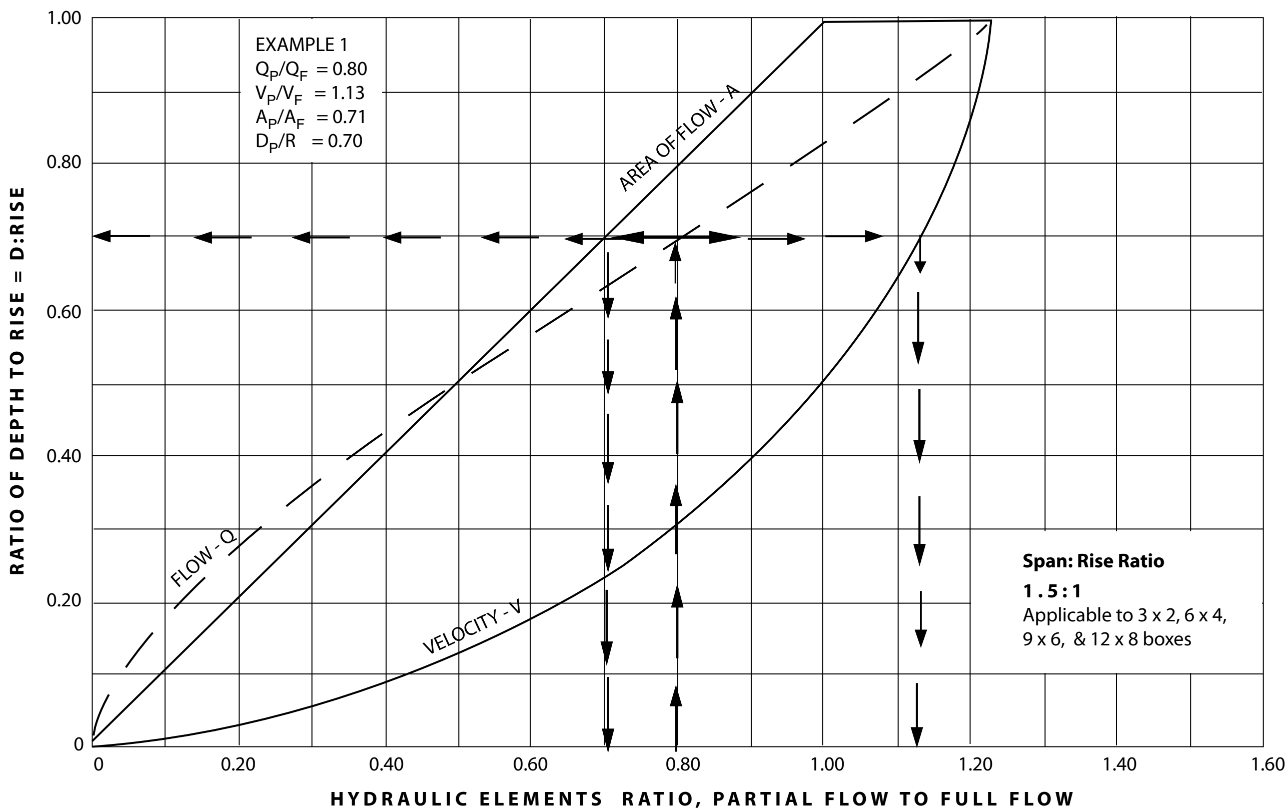


Figure 7 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

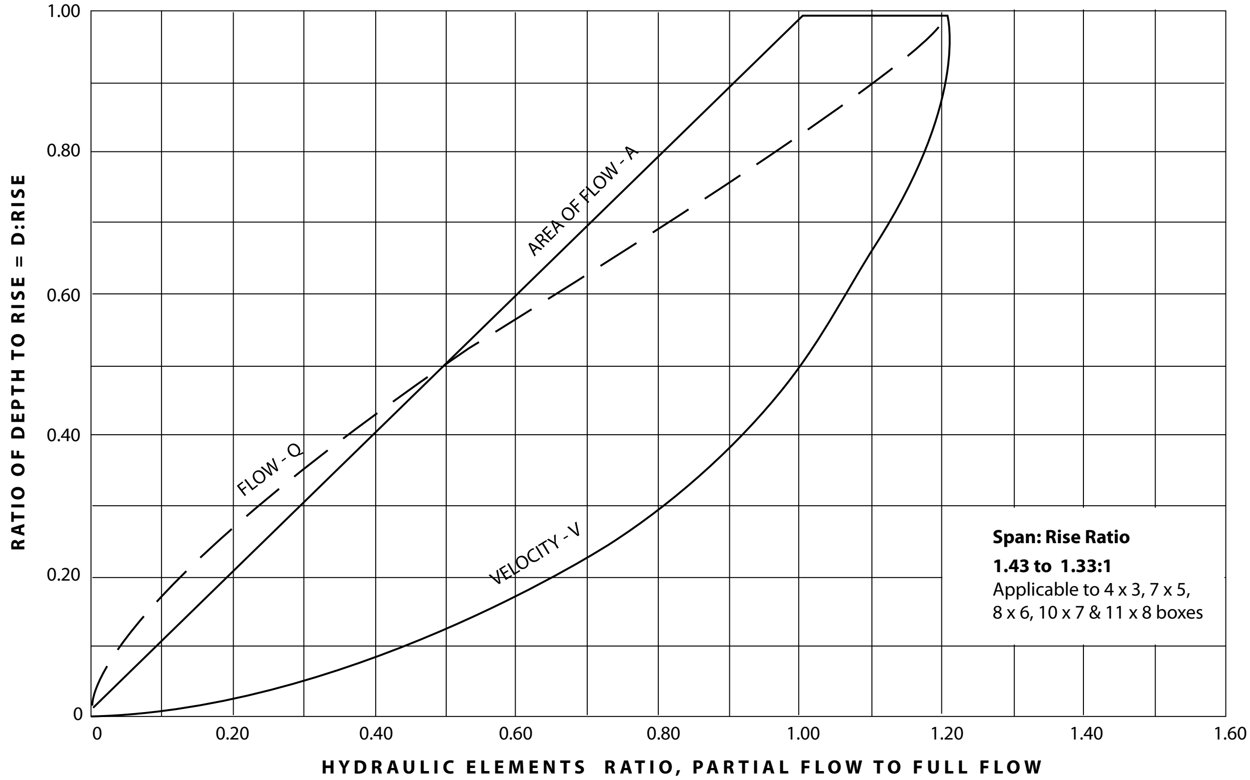


Figure 8 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

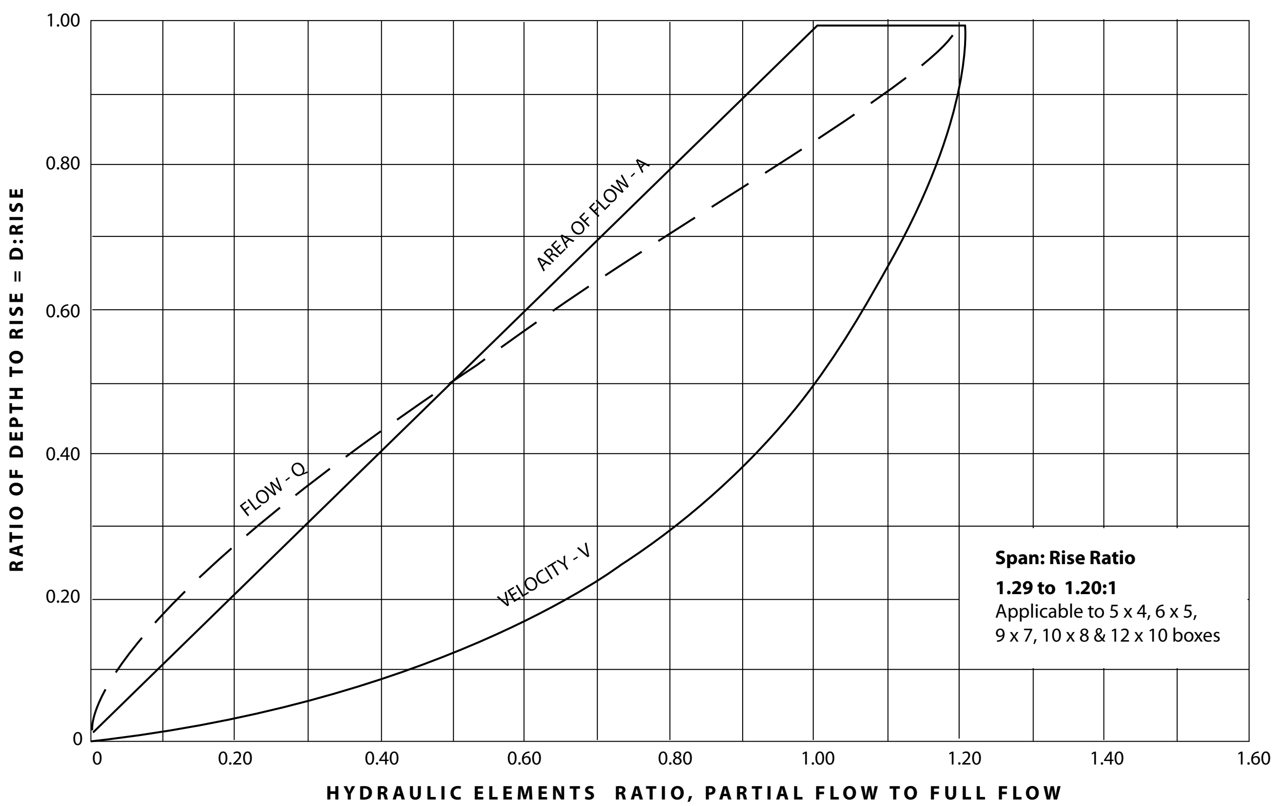


Figure 9 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow

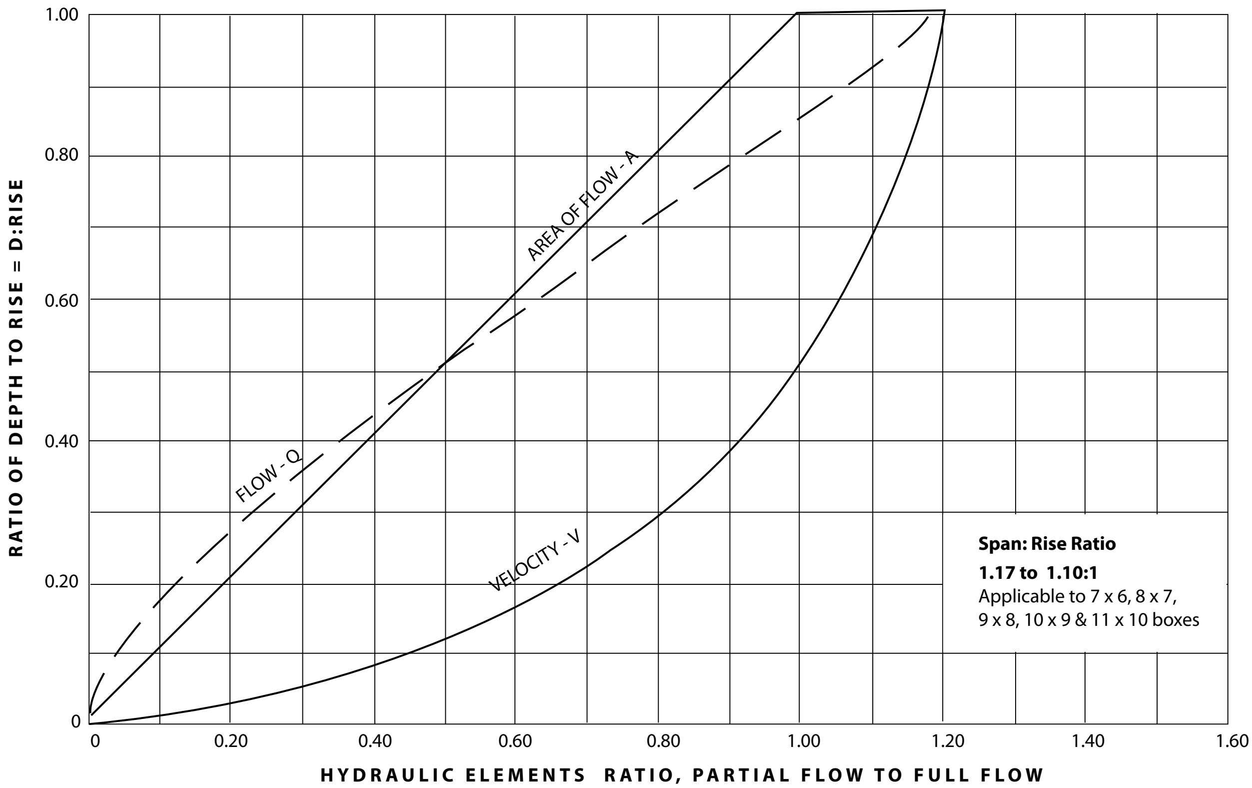


Figure 10 Relative Velocity and Flow in Rectangular Sections for any Depth of Flow