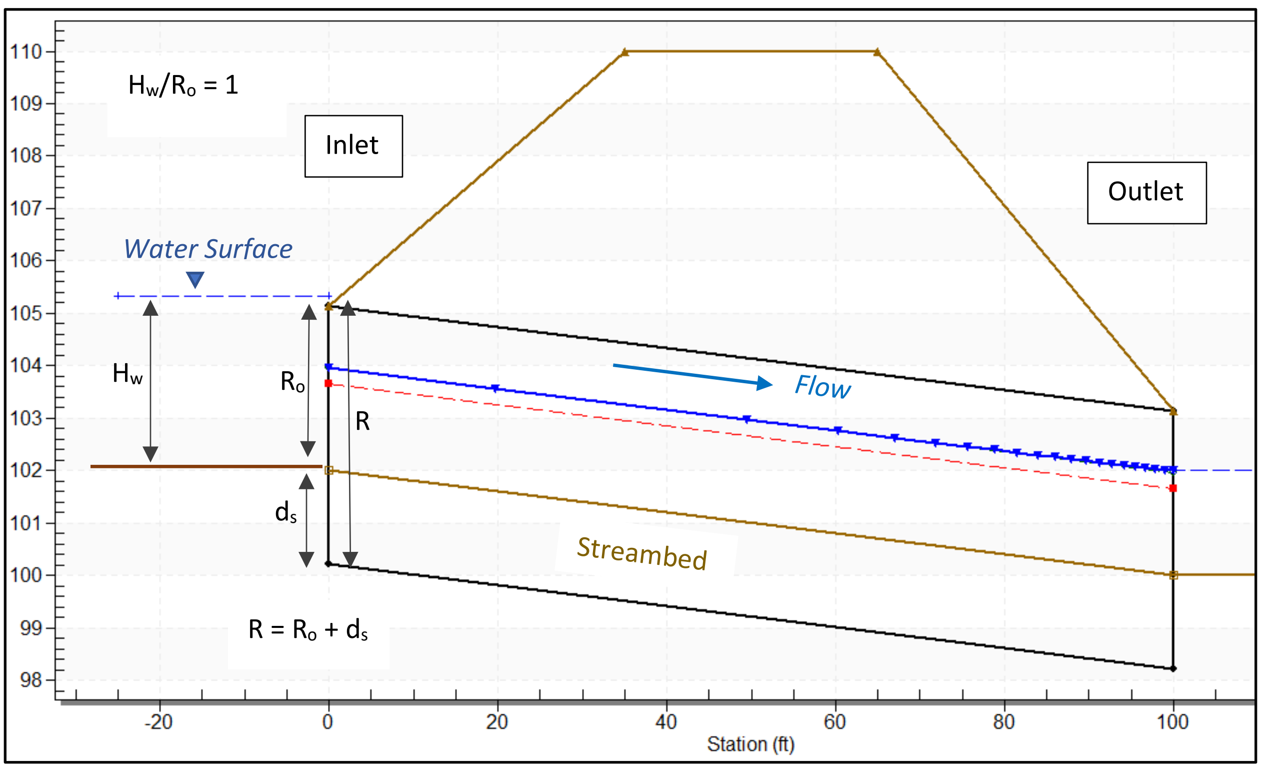
Maine DOT Hydraulic Capacity Standard & Guidance

Culverts proposed under this program must satisfy the hydraulic sizing standard, that at the 100-year flow Q_{100}, the water is no deeper than "just full" or "100% full" at the inlet. The water at the inlet is called the "headwater" H_w. This condition is expressed as the "headwater depth ratio" H_w/R_o where R_o is the height of the opening through which water flows:

$$H_w/R_o <= 1 \text{ @ } Q_{100}$$

At large flows such as Q_{100}, the water is generally deeper at the inlet than inside the culvert. For simple round pipes without streambed, this is the familiar Headwater-Diameter ratio "H_w/D", where D is the diameter.

Figure 1. Culvert flowing "just full" or "100% full" at the inlet



Sizing according to bankfull width (BFW) (BFW or 1.2 x BFW) almost always results in headwater depths H_w less than "just full" ($H_w/R_o < 1$) and thus hydraulic capacity generally is not an issue. However, it is important to check the capacity, for two reasons:

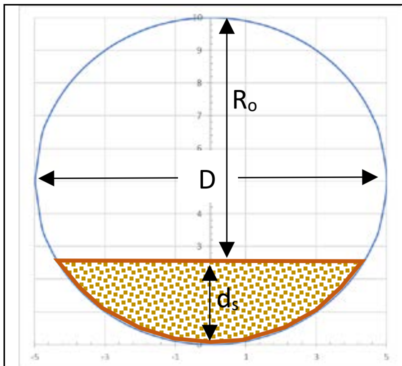
1. To catch those rare instances where capacity might be an issue
2. To avoid oversizing structures by simply "making things bigger, just to be safe"

MaineDOT sizes large culvert structures (span S or diameter D >= 5') according to this hydraulic standard $H_w/R_o <= 1$, in addition to meeting any other applicable requirements.

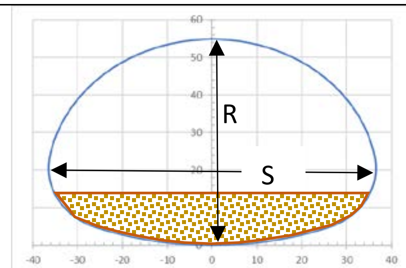
Simple equations and charts are given here for performing hydraulic checks on round culverts, box culverts and corrugated metal pipe arches. It is assumed that a streambed will be built inside the culvert. Flow capacity is lost to the area occupied by the streambed; this procedure accounts for lost capacity by upsizing the culvert.

Round pipes are described by one parameter, the diameter D. Boxes and arches are described by two parameters, the Span S (i.e., width) and the Rise R (i.e., height). For a round pipe, S and R are the same as D. For round pipes and arches, it is assumed that the streambed is 25% of the total rise R (or D; $d_s = 0.25 \times R$ & $R_o = 0.75 \times R$) and the culvert is 75% open (by vertical dimension). For box culverts, a 2-ft streambed depth d_s is assumed and $R_o = R - 2$. When R = 8-ft (generally recommended when possible), $R_o = 0.75 \times R$ as for the other shapes. These assumptions are for this preliminary analysis only; final design may be different. This same procedure can also be applied to open-bottom (three-sided) designs. There is not a structure rise R and the focus is limited to R_o above the natural streambed; "lost capacity" is not an issue.

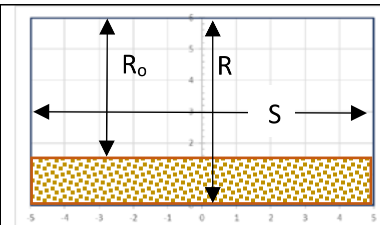
Figure 2. Culvert Shapes



ROUND



PIPE ARCH



BOX

The equations given here apply to a wide, continuous range of sizes. However, culverts only come in limited, discrete sizes. The following MaineDOT experience may prove informative. Building a streambed inside a culvert can present significant constructability challenges. As a practical matter, round pipes should be no smaller than 5-ft D, but 6-ft or 8-ft is preferable, even if the calculations indicate that a smaller pipe is acceptable, simply because construction is that much easier in a large pipe.

Round corrugated metal pipes (CMP) are readily available in 1-ft increments from 5-ft through 10-ft D. Reinforced concrete pipes (RCP) are readily available as 5-ft, 6-ft, 8-ft and 10-ft D. The "odd" sizes are not widely employed and relatively more expensive, so it is standard practice to use an 8-D RCP where analysis says that a 7-ft D is acceptable and similarly for 9-ft D RCP.

MaineDOT usually employs concrete box culverts once diameters or stream widths greater than 8-ft are encountered. RCP commonly comes in 8-ft section lengths. CMP commonly come in 20-ft or 10-ft sections; the sections can be cut to individual lengths as needed.

Smaller concrete boxes commonly come in 8-ft section lengths, 2-ft increments for span S and 1-ft increments for rise R. Larger boxes may come in smaller section lengths due to weight constraints; they may also come as “clamshells”, with a top half and bottom half. Clamshells make it easier to build the streambed, since the gravel and rock can simply be dropped into the open culvert before the top half is set. However, this advantage can be offset by the additional labor and machine time needed to set twice as many pieces.

Corrugated metal pipe arches (CMPA) are specified in inches; commonly available sizes for 3” x 1” corrugations are given in Table 1 below. CMPA’s are particularly useful when road cover over the culvert is a limitation and they are also usually less expensive than the corresponding concrete box culvert when round pipes cannot be used.

As noted above, it is almost always the case that sizing for BFW will automatically satisfy the Q_{100} hydraulic standard. This is especially true of round pipes and CMPA’s, since the span S (usually determined by BFW) automatically determines the rise R:

Round: $D = S = R$

Arch: $R = 1.15 \times S^{0.76}$ (R & S in ft) $= 2.08 \times S^{0.76}$ (R & S in inches)

However, the box culvert rise R is set independently of the span (width) S. It is recommended that the box culvert open rise R_o (above the streambed) be at least 6-ft, for reasons of constructability and maintenance; $R_o = 4'$ is the minimum acceptable. Streambed depth d_s is added to R_o to get the structure rise R:

$$R = R_o + d_s$$

For a streambed depth of 2-ft, this gives a structure rise of 6-ft minimum with 8-ft preferred. Greater streambed depths d_s will result in larger structure rises R.

The procedures for checking hydraulic capacity given here are for feasibility and preliminary design only. For each pipe shape, two methods are given: calculation and graphical look-up. The user should use both methods and verify that the same results are obtained by both methods. Only those shapes under consideration need be analyzed; this may be just one, two or all three shapes.

The final design should be checked again for hydraulic performance by a Professional Engineer as part of the project design. Simplifying assumptions used here (streambed depth, inlet control) may not apply to the final design. Also, the elevation of the road surface above the streambed may limit the structure rise that can be achieved; the desired culvert may not “fit”. A conservative rule of thumb is that 2 – 3-ft is required from pavement surface to top of culvert. This should be checked even at this preliminary stage.

Hydraulic Capacity Check – Round Pipe

Procedure by Calculation:

1. Measure Bankfull Width (BFW) in the field. If measurement is unavailable, use calculated value $BFW_{calc} = 10.58 \times A_{ws}^{0.43}$: BFW = __________

2. Obtain Q_{100} from StreamStats : Q_{100} = ___________

3. BFW Sizing – $D_{bfw} = 1.2 \times BFW$: D_{bfw} = ___________

4. Calculate diameter D_h for Q_{100} : D_h = __________

   $D_h = 0.856 \times Q_{100}^{0.4}$

5. Set pipe size: use larger of (D_{bfw}, D_h) values : D = __________

   (prefer D >= 6' if building streambed)

6. Round to common pipe diameter: D = ___________ *Preliminary Design*

Procedure by Graphical Look-up (use Figure 1):

1. Measure Bankfull Width (BFW) in the field. If measurement is unavailable, use calculated value $BFW_{calc} = 10.58 \times A_{ws}^{0.43}$: BFW = __________

2. Obtain Q_{100} from StreamStats : Q_{100} = ___________

3. BFW Sizing – $D_{bfw} = 1.2 \times BFW$: D_{bfw} = _____________

4. Locate Q_{100} value on horizontal (bottom) axis – place a "dot"on axis

5. Draw line straight up to curve – place a "dot" on curve

6. Draw line straight over to vertical (left side) axis – place a "dot" on axis

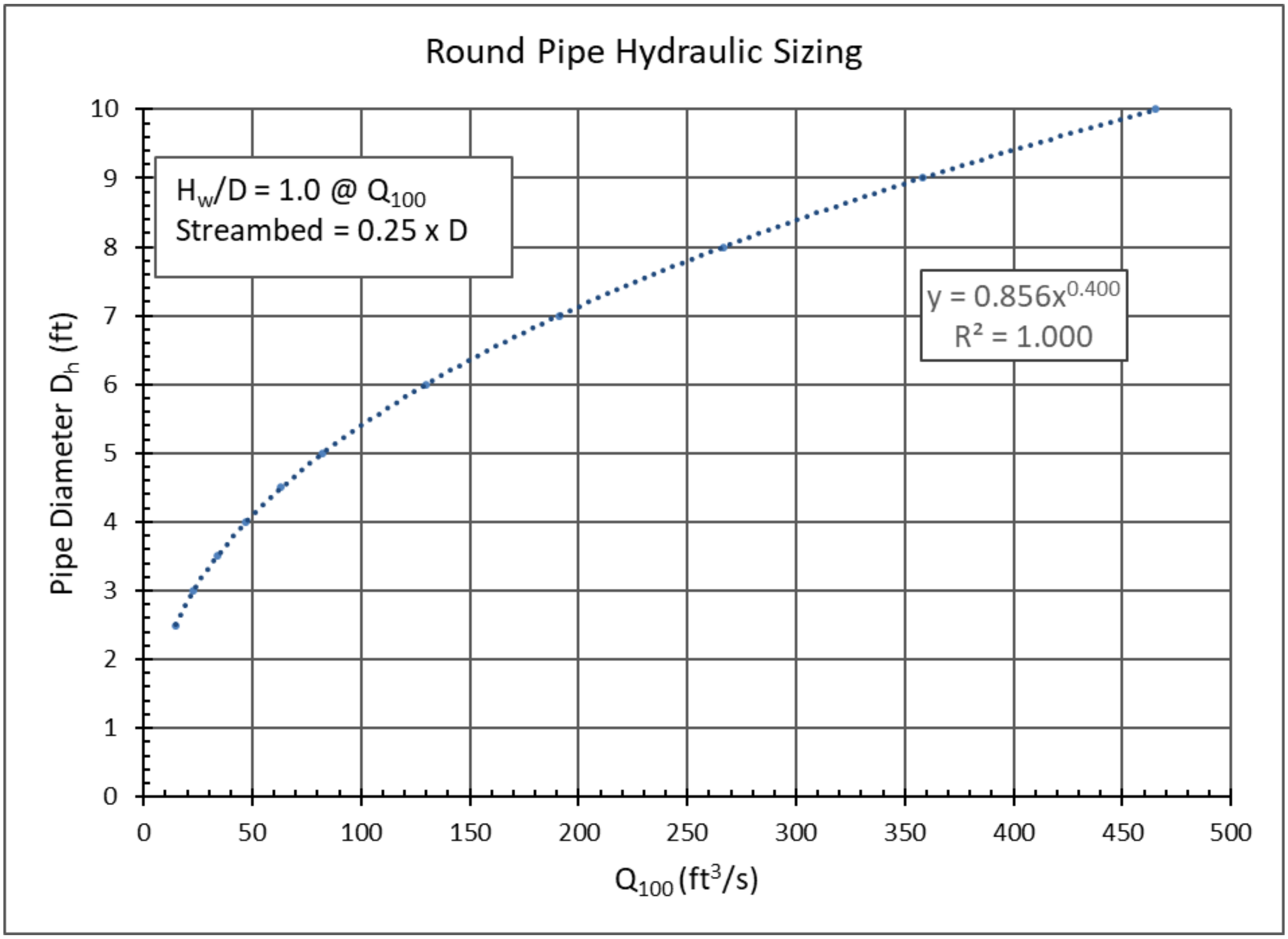
7. Read Pipe Diameter D_h value on vertical axis: D_h = ___________

8. Set pipe size: use larger of (D_{bfw}, D_h) values : D = __________

   (prefer D >= 6' if building streambed)

9. Round to common pipe diameter: D = ___________ *Preliminary Design*

Figure 1. Round Pipe Hydraulic Sizing



Hydraulic Capacity Check – Box Culvert

This procedure estimates the box culvert open rise R_o needed to meet the hydraulic standard H_w/R_o at Q_{100}. In most cases, a minimum box rise of R = 8' (R_o = 6', assuming 2' streambed) should be used for constructability, regardless of calculations; R = 6' or 7' may be necessary and is acceptable. When using Bankfull sizing for the box span (width) S, it rarely necessary to go taller than R = 8' (assuming 2' streambed).

Procedure by Calculation:

1. Measure Bankfull Width (BFW) in the field. If measurement is unavailable, use calculated value $BFW_{calc} = 10.58 \times A_{ws}^{0.43}$: BFW = __________ = S

   (BFW is the culvert Span (width) "S" used in the calculations below)

2. Obtain Q_{100} from StreamStats : Q_{100} = ___________

3. Calculate normalized flow $Q^* = Q_{100} / \{S^2 \times (32.2 \times S)^{1/2}\}$: Q* = ____________

4. Calculate rise ratio "r" for Q* value : r = ____________

   $r = 1.682 \times Q^{*0.667}$

5. Calculate hydraulic open rise $R_o = S \times r$ = _____ x _____ R_o = _____________

6. Use larger of R_o or 6' : R_o = _____________

7. Add streambed thickness d_s to get culvert rise R R = _____________

   ($R = R_o + d_s$; d_s = 2' is a good preliminary value)

8. BFW Span sizing multiplier: S = 1.2 x BFW S = ______________

9. Round calculated sizes to common box dimensions (S x R) : S _____ x R _____

Procedure by Graphical Look-Up (Use Figure 2):

1. Measure Bankfull Width (BFW) in the field. If measurement is unavailable, use calculated value $BFW_{calc} = 10.58 \times A_{ws}^{0.43}$: BFW = _________ = S

   (BFW is the culvert Span (width) "S" used in the calculations below)

2. Obtain Q_{100} from StreamStats : Q_{100} = __________

3. Locate Q_{100} on vertical (left) axis of top graph – place a "dot" on axis

4. Draw horizontal line from "dot" to line corresponding to initial Span S value (estimate position between lines for odd-value span)

5. Draw a vertical line down, through horizontal axis (Q*) into next graph and stop where it hits curve – place a "dot" on curve

6. Draw horizontal line from "dot" to vertical axis (r) – place a "dot"

7. Record "r" value on vertical axis: r = __________

8. Calculate hydraulic open rise R_o : $R_o = S \times r$ = _____ x _____ R_o = _________

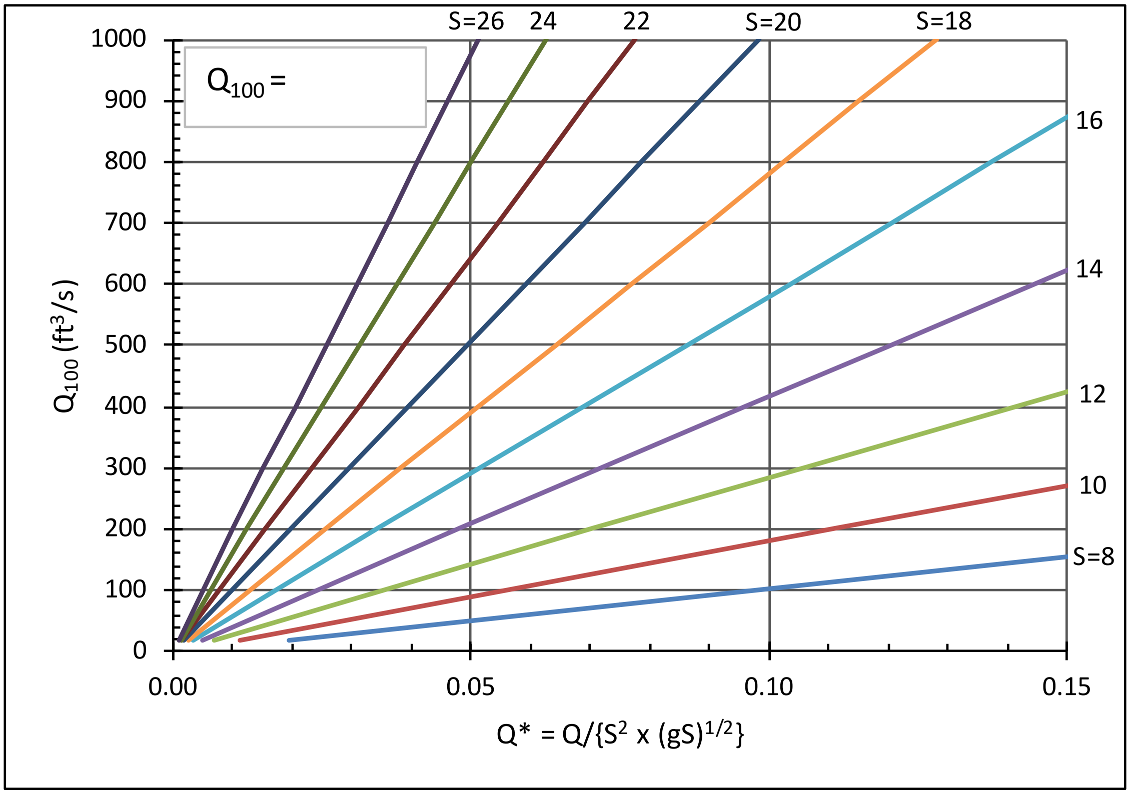
9. Use larger of R_o or 6' : R_o = ____________

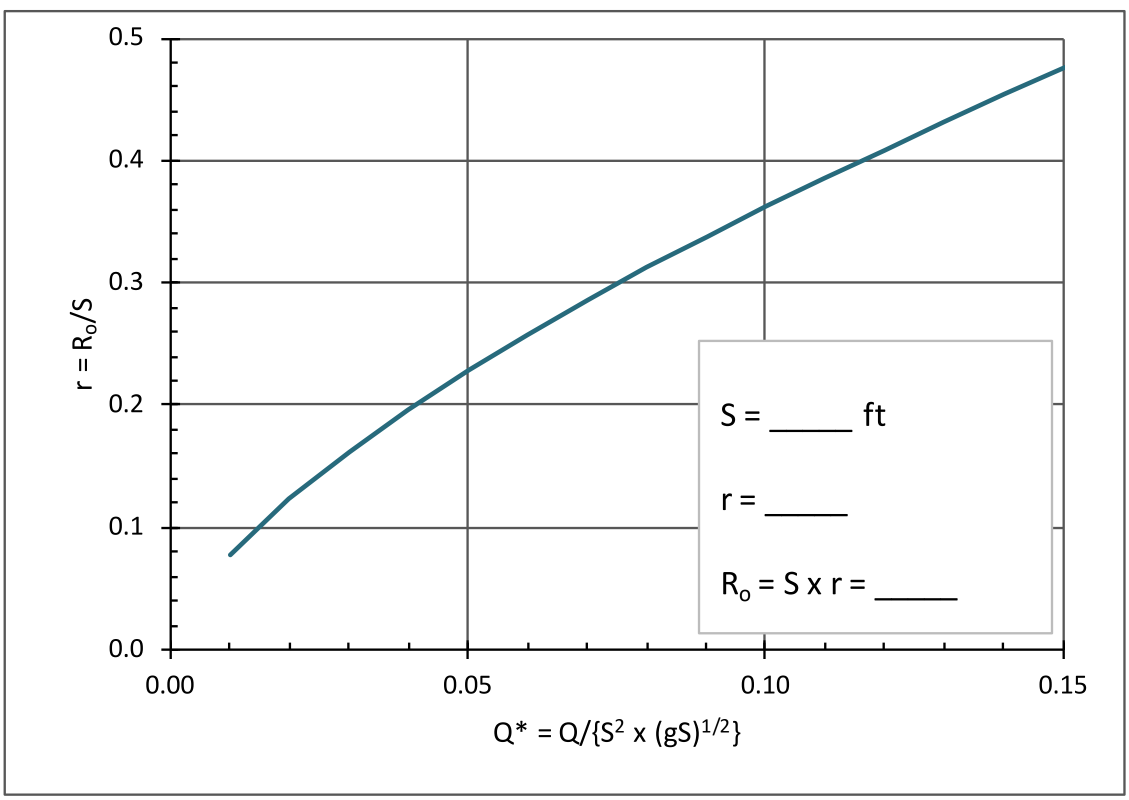
10. Add streambed thickness d_s to get culvert rise R R = ____________
    ($R = R_o + d_s$; d_s = 2' is a good preliminary value)

11. BFW Span sizing multiplier: S = 1.2 x BFW S = _____________

12. Round calculated sizes to common box dimensions (S x R) : _____ x _____

Figure 2. Box Culvert Hydraulic Sizing for Open Rise R_o (H_w/R_o = 1 @ Q_{100})





Hydraulic Capacity Check – Corrugated Metal Pipe Arch

This procedure estimates the CMPA open rise R_o needed to meet the hydraulic standard H_w/R_o at Q_{100} . The streambed d_s is assumed to be 25% of the arch rise R; R_o is 75% of R.

Procedure by Calculation:

1. Measure Bankfull Width (BFW) in the field. If measurement is unavailable, use calculated value $BFW_{calc} = 10.58 \times A_{ws}^{0.43}$: BFW = _________

   (BFW is the culvert Span (width) "S" used in the calculations below)

2. Obtain Q_{100} from StreamStats : Q_{100} = ___________

3. BFW Span sizing: $S_{bfw} = 1.2 \times BFW$ S_{bfw} (ft) = ___________

4. Calculate hydraulic sizing Arch Span S_h (ft) for Q_{100} : S_h (ft) = ____________

   $S = 0.708 \times Q^{0.473}$

5. Choose larger of S_h & S_{bfw} : S (ft) = ___________

6. Convert S to inches (x 12) : S (in) = ___________

7. Round S to nearest available arch span (Table 1);

   record dimensions in (inches): S _____ x R ______

Table 1. Commonly Available Pipe Arch Sizes (3" x 1" corrugation)

Span (in)	Rise (in)	End Area (ft²)	Span (in)	Rise (in)	End Area (ft²)
60	46	15.6	103	71	42.4
66	51	19.3	112	75	48.0
73	55	23.2	117	79	54.2
81	59	27.4	128	83	60.5
87	63	32.1	137	87	67.4
95	67	37.0	142	91	74.5

Procedure by Graphical Look-Up (Use Figure 3):

1. Measure Bankfull Width (BFW) in the field. If measurement is unavailable, use calculated value $BFW_{calc} = 10.58 \times A_{ws}^{0.43}$: BFW = _________

   (BFW is the culvert Span (width) "S" used in the calculations below)

2. Obtain Q_{100} from StreamStats : Q_{100} = ___________

3. BFW Span sizing: $S_{bfw} = 1.2 \times BFW$ S_{bfw} = ___________

4. Locate Q_{100} on horizontal axis – mark a "dot"

5. Draw vertical line up from dot to curve – mark a "dot"

6. Draw horizontal line over to vertical axis – mark a "dot"

7. Record pipe arch hydraulic sizing Span S_h: S_h (ft) = _________

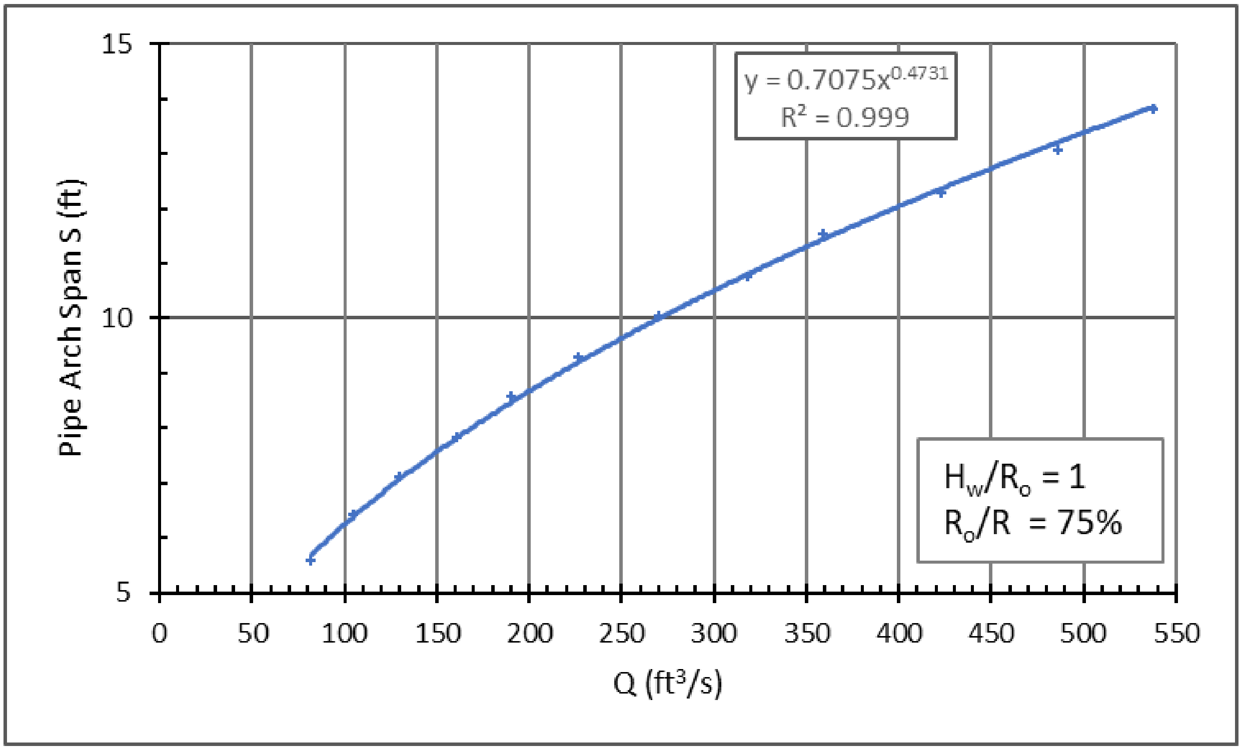
8. Choose larger of S_h & S_{bfw} : S (ft) = _________

9. Convert S to inches (x 12) : S (in) = ___________

10. Round S to nearest available arch span (Table 1);

    record dimensions in (inches): S _____ x R ______

Figure 3. Corrugated Metal Pipe Arch Hydraulic Sizing



Example – Round Pipe Sizing (assuming streambed $d_s = 0.25 \times D$)

From StreamStats: $A_{ws} = 0.25\ mi^2$ & NWI = 3%

1. BFW = 6’

2. StreamStats: $Q_{100} = 70\ ft^3/s$

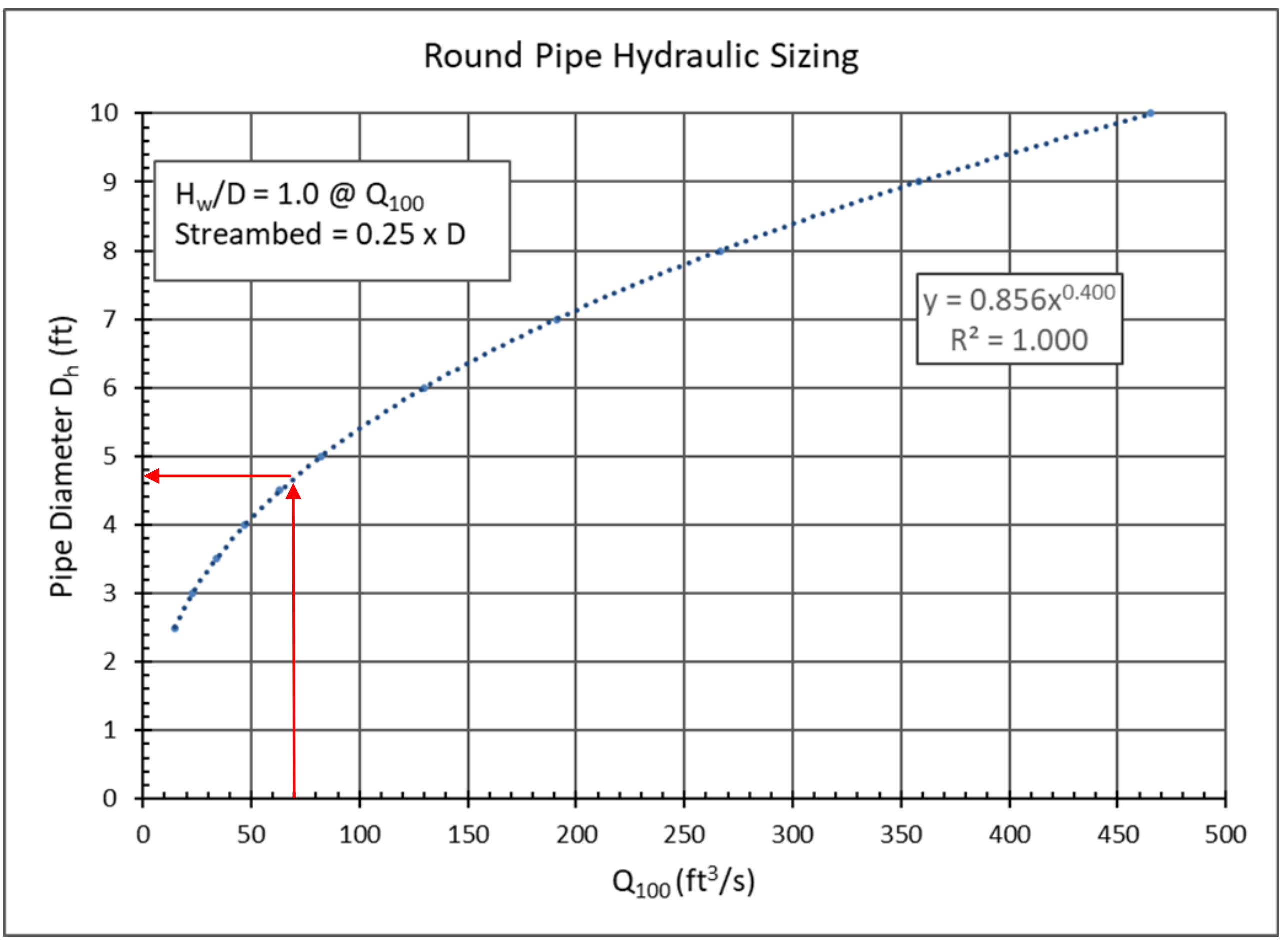
3. Calculate BFW Sizing: $D_{bfw} = 1.2 \times BFW = 7.2'$

4. Hydraulic sizing:
   a. Calculate $D_h = 0.856 \times (70)^{0.4} = 4.7$ ft
   b. Look up hydraulic sizing from chart: $D_h = 4.7'$ from chart

5. Use larger of D_{bfw} or D_h: max (7.2, 4.7) = 7.2’

6. Round to common pipe size: D = 7’D *preliminary design*

7. Check that this fits under road



Example – Box Culvert ***(assuming d_s = 2' streambed)***

From StreamStats: A_{ws} = 0.80 mi^2 & NWI = 3%

1. BFW = 9.6' – use 9' as initial box span S

2. StreamStats: Q_{100} = 175 ft^3/s

3. By Calculation:
   a. Normalized flow: $Q^* = Q_{100} / \{S^2 \times (32.2 \times S)^{1/2}\}$

      $= 175 / \{9^2 \times (32.2 \times 9)^{1/2}\} = 0.13$

   b. Rise ratio: $r = 1.682 \times (0.13)^{0.667} = 0.43$

4. By Graphical Look-up:
   a. Rise ratio: r = 0.43

5. Calculate open rise R_o: $R_o = S \times r = 9 \times 0.43 = 3.9$

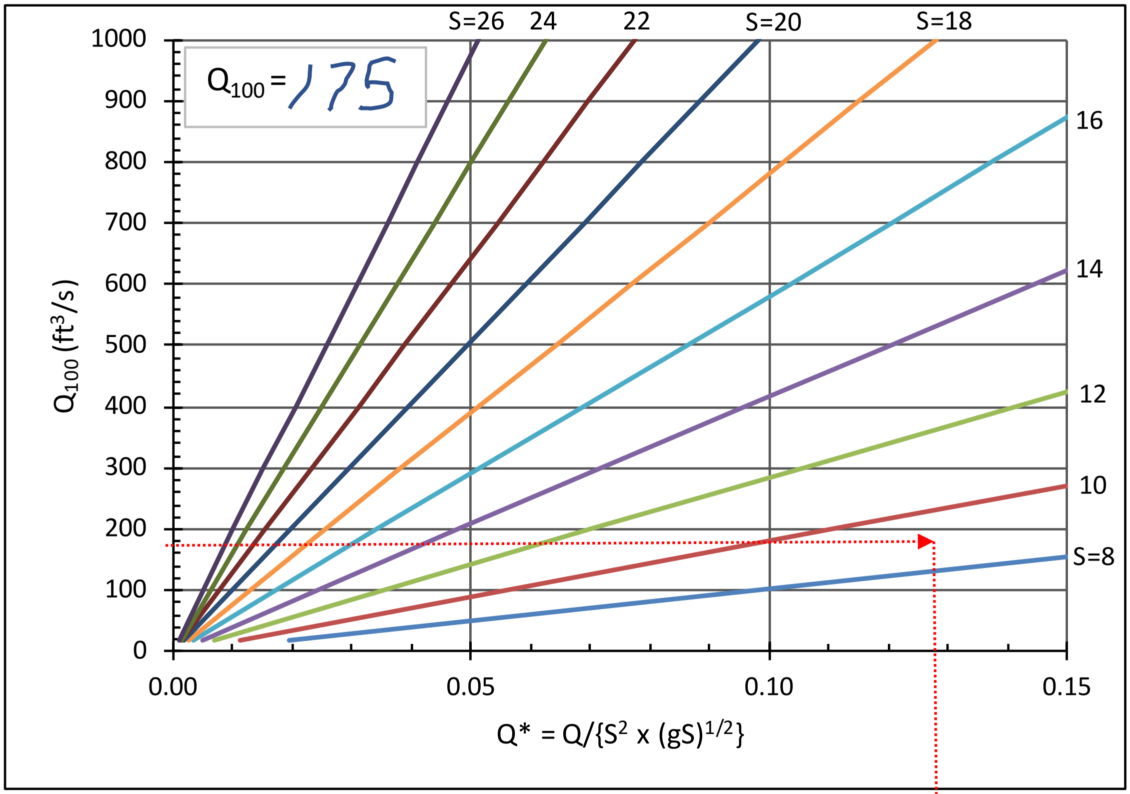
6. Use larger of calculated R_o or 6': R_o = max (3.9', 6') = 6' (but 5'or 4' is acceptable)

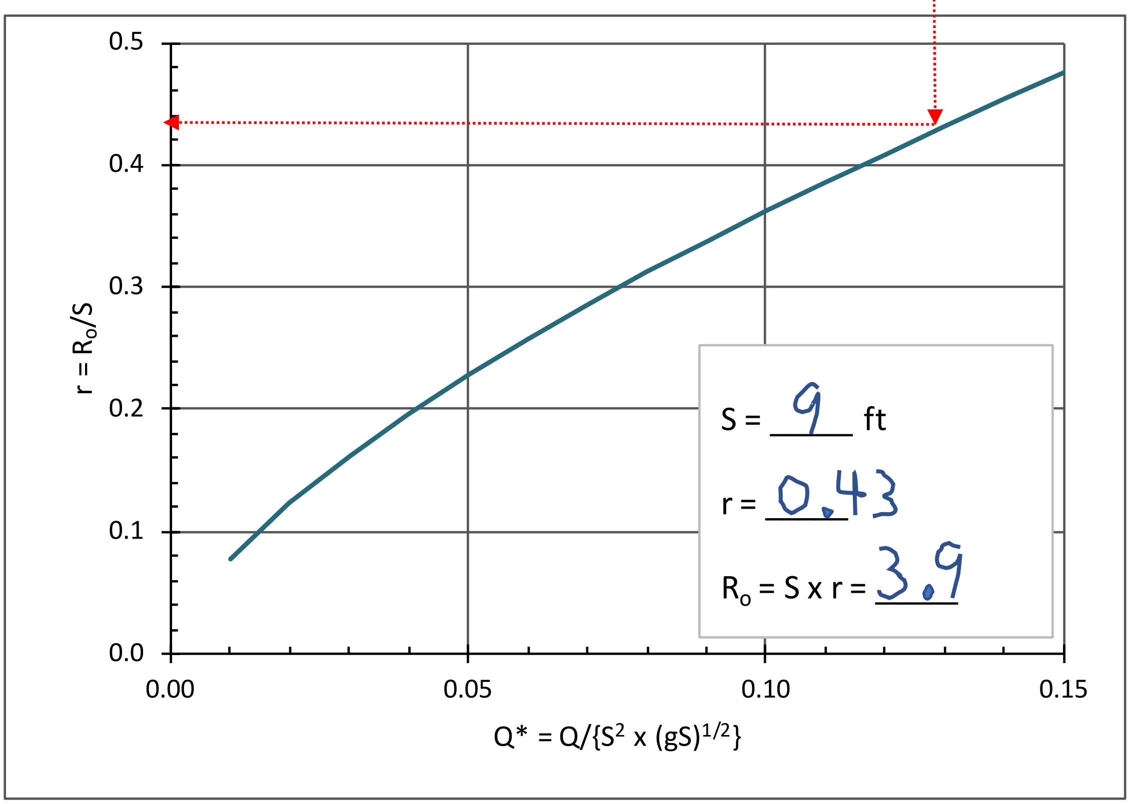
7. Box structure rise: $R = R_o + d_s$ = 6' + 2' (assumed) = 8' (but 7' or 6' is acceptable)

8. BFW Span sizing: 1.2 x 9' = 10.8'

9. Round to common box dimensions: *Preliminary Box size: 11' Span x 8'R*

10. Check that this fits under road


S=26
24
22
S=20
S=18
16
14
12
10
S=8
Q_{100} = 175
Q_{100} (ft³/s)
1000
900
800
700
600
500
400
300
200
100
0
0.00
0.05
0.10
0.15
Q* = Q/{S² x (gS)^1/2}


r = R_o/S
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.05
0.10
0.15
Q* = Q/{S² x (gS)^1/2}
S = 9 ft
r = 0.43
R_o = S x r = 3.9

Example – Pipe Arch Sizing (assuming streambed $d_s = 0.25 \times R$; 3" x 1" corrugation)

From StreamStats: $A_{ws} = 0.4\ mi^2$ & NWI = 3%

1. BFW = 7'
2. StreamStats: $Q_{100} = 100\ ft^3/s$
3. Calculate BFW Sizing: $S_{bfw} = 1.2 \times BFW = 8.4'$
4. Hydraulic sizing Arch Span S_h (ft) for Q_{100} :
   By Calculation: $S_h = 0.708 \times Q^{0.473}$ — S_h (ft) = __6.3____
   By Graphical Look-up: — S_h (ft) = __6.2____
5. Choose larger of S_h & S_{bfw} : — S (ft) = ___8.4___

   Max (6.3, 8.4) = 8.4
6. Convert S to (inches; x 12) : — S (in) = ___101____
7. Round S to nearest available arch span; record dimensions: — _ 103"_ x _ 71" _
8. Check that this fits under road