USING CHANNEL GEOMETRY TO SIMPLIFY THE USE OF THE SIZING TABLE FOR CULVERTS ON TYPE N STREAMS

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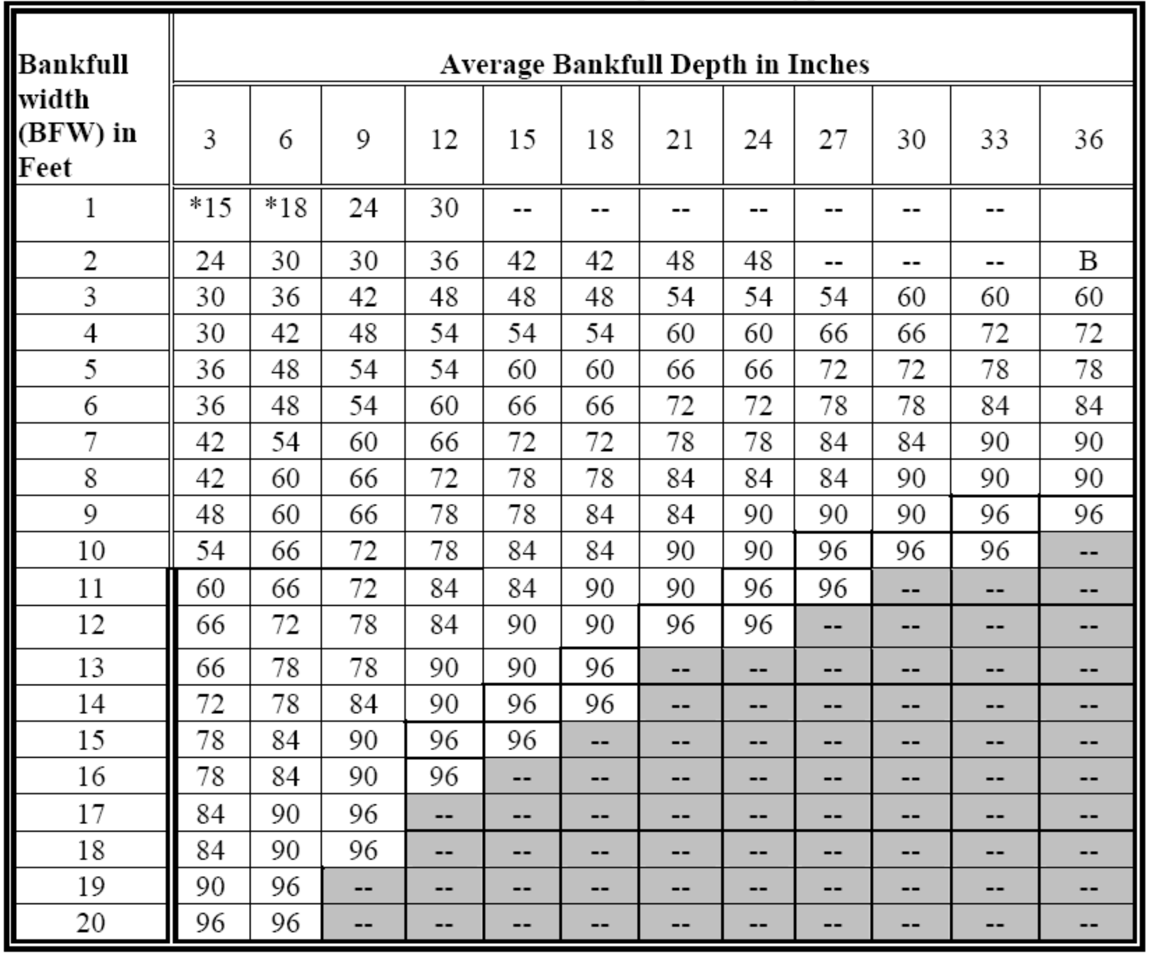
INTRODUCTION:

Although forest roads can adversely impact watershed processes by adding sediment and constraining stream channels, adequately sized road crossing structures can reduce such impacts. According to Washington State Forest Practice Rules, Type N Water crossing structures must be sized to accommodate the "100 year flood event with consideration for the passage of debris" (WAC 222-24-040). The Forest Practices Board Manual describes three approved methods for determining culvert sizing: A) the Sizing Table Method; B) the Bankfull Width Method and C) the Hydraulic Design Method. In this paper, we address the Sizing Table Method (Table 1), which we observe to be commonly used in the Skagit Basin.

*Table 1***.** Method A, culvert sizing table for Type N Waters *(Source: Washington Forest Practices Board Manual Section 3, Table 3.3).*



Bankfull width (BFW) in Feet	**Average Bankfull Depth in Inches**											
	3	6	9	12	15	18	21	24	27	30	33	36
1	*15	*18	24	30	--	--	--	--	--	--	--	
2	24	30	30	36	42	42	48	48	--	--	--	B
3	30	36	42	48	48	48	54	54	54	60	60	60
4	30	42	48	54	54	54	60	60	66	66	72	72
5	36	48	54	54	60	60	66	66	72	72	78	78
6	36	48	54	60	66	66	72	72	78	78	84	84
7	42	54	60	66	72	72	78	78	84	84	90	90
8	42	60	66	72	78	78	84	84	84	90	90	90
9	48	60	66	78	78	84	84	90	90	90	96	96
10	54	66	72	78	84	84	90	90	96	96	96	--
11	60	66	72	84	84	90	90	96	96	--	--	--
12	66	72	78	84	90	90	96	96	--	--	--	--
13	66	78	78	90	90	96	--	--	--	--	--	--
14	72	78	84	90	96	96	--	--	--	--	--	--
15	78	84	90	96	96	--	--	--	--	--	--	--
16	78	84	90	96	--	--	--	--	--	--	--	--
17	84	90	96	--	--	--	--	--	--	--	--	--
18	84	90	96	--	--	--	--	--	--	--	--	--
19	90	96	--	--	--	--	--	--	--	--	--	--
20	96	96	--	--	--	--	--	--	--	--	--	--

* See WAC 222-24-040(3) for details relating to size restrictions when installing culverts.

The Sizing Table Method requires a two-step process described in the Board Manual Section 3, Guidelines for Forest Roads. In short, once it is determined that the stream is Type N Water (i.e. non-fish-bearing), the method requires measuring the bankfull width and average bankfull depth. These measurements are then used in the sizing table to determine the diameter of the culvert to be installed.

This paper is not intended to explore the appropriateness of the sizing table method or the origins of the table but rather to simplify and improve the field implementation of the method. The objective of this paper is to use a local sample of field surveyed channel measurements to highlight the channel dimensions in the table that most commonly occur in the northwestern Cascades. This would, in effect, simplify the sizing table method by reducing the dependence on an accurate bankfull depth measurement which is the most difficult part of the culvert sizing process and likely contains the largest amount of error.

Channel Measurement

Bankfull width is an estimate of the lateral extent of the water surface at a flow that fills the channel. For the complete description of the methods for measuring both bankfull width and depth refer to the Board Manual Section 2, Standard Methods for Identifying Bankfull Channel Features and Channel Migration Zones. To identify the bankfull width, the Board Manual suggests looking for indicators such as: 1) changes in topography such as slope breaks; 2) a change in vegetation from annual to perennial or upland species; or 3) a change in the size distribution of surface sediments (Figure 1). Once the bankfull channel indicators are identified, the bankfull width is measured as the distance between the channel edges, perpendicular to flow. Identifying bankfull width indicators in the field is not always straightforward, particularly in headwater channels that do not have the typical floodplain morphology shown in Figure 1; however, once the bankfull channel edges are identified, measurement is simple and quick.

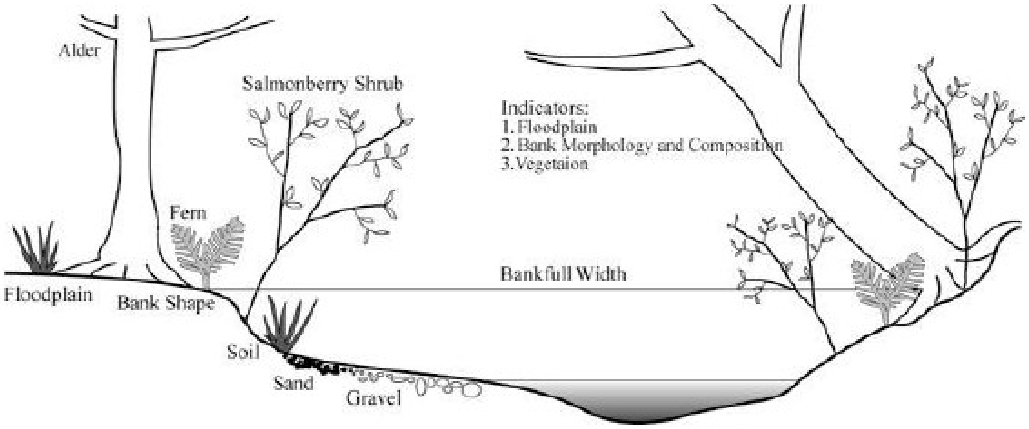
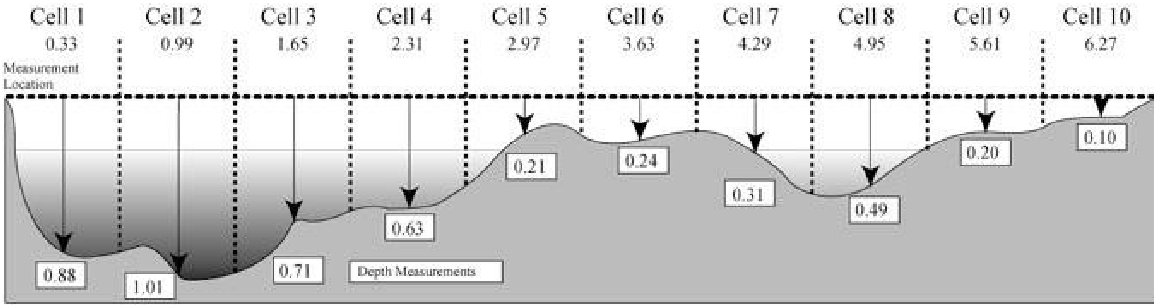


Figure 1. Indicators for determining bankfull width (Source: Washington Forest Practices Board Manual Section 2, Figure 1 – adapted from Pleus and Schuett-Hames, 1998).

Bankfull depth is the average vertical distance between the channel bed and the estimated water surface that would completely fill the channel. Bankfull depth is more difficult to measure in the field than bankfull width. To measure the average bankfull depth, the board manual suggests extending a measuring tape across the channel and dividing the bankfull width into ten evenly spaced sections (Figure 2). The average bankfull depth is then calculated by dividing the sum of all depth measurements taken at the center of each section by the number of measurements.

Because of the time required to complete these measurements using such a detailed method (Figure 2) for the purpose of culvert sizing, bankfull depth is often visually estimated rather than measured. It is our experience that visual estimates of average bankfull depth are relatively inconsistent due to the intricacy of the measurement and differing interpretations between observers. Estimating channel depth is particularly difficult for high gradient (>20%) forest streams dominated by step-pool sequences or cascades which are common in headwater systems.



Bankfull Width = 6.6 m
Cell Interval = Bankfull Width * 10% = 0.66 m
Average Bankfull Depth = Sum of depth measurements / 10 = 0.478 m

Figure 2. *Measurement of bankfull depth using the 10% cell method (Source: Washington Forest Practices Board Manual Section 2, Figure 2 – adapted from Pleus and Schuett-Hames, 1998).*

METHODS:

For this analysis, we utilized data collected by the authors for a study of the function of headwater channels. The 28 study reaches were located in non-fish-bearing headwater basins throughout the region as represented in Figure 3.

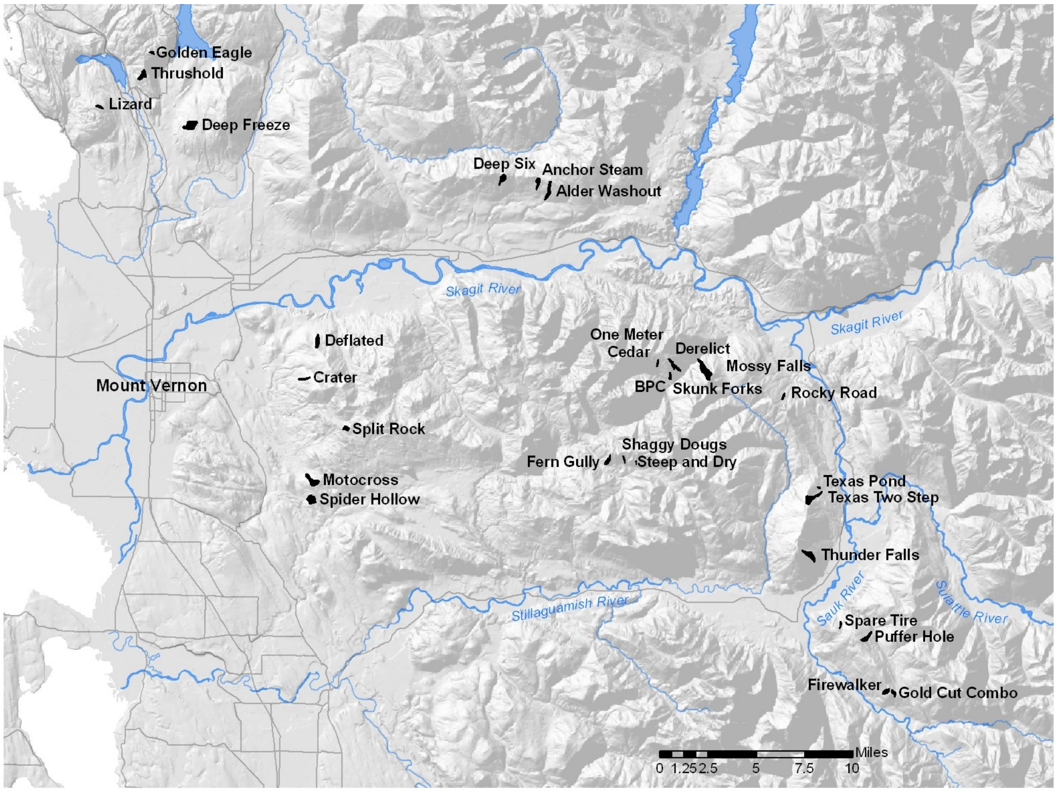


Figure 3. Location map of headwater study basins in the northwestern Cascades.

In the headwater study design, sites were selected to represent: 1) two forest types (unlogged and previously logged); 2) two locally prevalent bedrock types (sedimentary and phyllite); 3) a wide range of channel gradients (9 % - 61%) and 4); and a range of channel widths (3 ft -12 ft). Table 2 contains some of the site characteristics of each of the study basins. Study streams were located in randomly-selected blocks of forest land with the appropriate forest and bedrock types. Within the selected blocks, the first stream found in the field within the range of channel widths and channel gradient was chosen for the study. Stream segments were located to avoid road crossings, debris flows and tributary junctions.

Table 2. Headwater site characteristics.

Name	Basin	Forest	Rock	Elevation (ft)	Grad. (%)	Basin Area (acres)	Average Channel Width (ft)
Alder Washout	Skagit	second growth	Phyllite	1340	30	66.2	9.2
Anchor Steam	Skagit	second growth	Phyllite	2040	19	47.4	5.6
Black Pl. Culvert	Skagit	second growth	Phyllite	1410	30	15.5	5.2
Crater	Skagit	second growth	Phyllite	1680	27	21.2	4.3
Deep Freeze	Samish	second growth	Phyllite	1120	20	129.8	9.2
Deep Six	Skagit	second growth	Phyllite	2420	31	54.4	5.6
Deflated	Skagit	second growth	Phyllite	2000	38	63.8	11.2
Derelict	Skagit	old growth	Phyllite	1940	59	28.1	5.6
Fern Gully	Stillaguamish	second growth	Sedimentary	2300	39	37.1	12.1
Firewalker	Sauk	old growth	Phyllite	1970	15	37.1	7.5
Gold Cut Combo	Sauk	old growth	Phyllite	2160	40	22.5	6.2
Golden Eagle	Samish	second growth	Sedimentary	1880	36	9.4	3.6
Lizard	Samish	second growth	Phyllite	1720	13	17.3	4.9
Mossy Falls	Skagit	old growth	Phyllite	840	32	174.8	10.8
Motocross Cr	Skagit	second growth	Sedimentary	800	20	95.0	12.5
One Meter Cedar	Skagit	old growth	Phyllite	2460	44	9.3	5.2
Puffer hole	Sauk	second growth	Phyllite	1660	40	53.4	8.9
Rocky Road	Sauk	old growth	Phyllite	1680	36	12.5	3.9
Shaggy Dougs	Stillaguamish	old growth	Sedimentary	2560	41	5.4	6.9
Skunk Forks	Skagit	second growth	Phyllite	1400	48	25.6	5.6
Spare Tire	Sauk	old growth	Phyllite	1860	40	9.1	5.2
Spider Hollow	Skagit	second growth	Sedimentary	560	9	87.6	6.2
Split Rock	Skagit	old growth	Phyllite	3080	12	30.8	11.8
SteepnDry	Stillaguamish	second growth	Sedimentary	2600	61	3.4	4.9
Texas Pond	Sauk	old growth	Phyllite	1480	19	5.3	5.2
Texas Two Step	Sauk	old growth	Phyllite	1290	17	97.7	8.9
Thrushold	Samish	second growth	Sedimentary	1150	15	66.1	6.9
Thunder Falls	Sauk	second growth	Phyllite	1560	24	83.9	9.8

There were three types of data collected in the headwater study: 1) channel surveys; 2) woody debris inventory; and 3) riparian forest inventory. In this paper, we are specifically examining the cross sectional bed elevation component of the channel surveys. Survey cross sections were placed at set distances within the study reaches and the bed elevation was surveyed at stations across the channel using a stadia rod and level. Channel edges were noted in each cross-section from bankfull features described above and signs of scour.

Width-to-Depth Ratios

Width-to-depth (W/d) ratios were calculated from the cross section surveys. Width-to-depth ratios are a commonly used index for classifying stream channels and describing channel shape. Channels with high width-to-depth ratios are relatively shallow and wide while channels with low width-to-depth ratios are relatively narrow and deep. Width-to-depth ratios are to some extent controlled by stream size (i.e. large rivers tend to be relatively wide and shallow when compared with headwater channels), as well as by local channel and watershed conditions.

Width-to-depth ratios were calculated for each channel, at a range of stage heights within the surveyed cross section. To accomplish this, the water surface width (W), average depth (d), and cross sectional area of the wetted channel (A) were calculated for a selected range of stage heights from low flow to bankfull. Selected stage heights increased in 6-inch increments beginning near the channel bottom (low flow) to above the height that filled the channel. At each stage, the surface width (W) was measured directly from the survey data while the cross section area (A) was calculated using an online resource for stream channel hydraulic geometry created at the University of Cambridge, UK. The program, called River Slice, allows the user to enter surveyed cross section data and a series of stage heights of interest and returns the area, wetted perimeter, maximum depth, and hydraulic radius for each stage height value chosen. The average depth (d) at each stage was then calculated using the equation $d = A/W$. Finally, once W, d and A were known, the W/d ratio could be calculated.

RESULTS AND DISCUSSION:

Calculated W/d values from all sites at the stage closest to bankfull (based on field notes and cross section plots) ranged from approximately 3.7 to 17.9 with a mean of 8.2 (Figure 4). Values from all but one site ('Deflated' where W/d = 17.9) varied to an even lesser degree from 3.7 to 14.

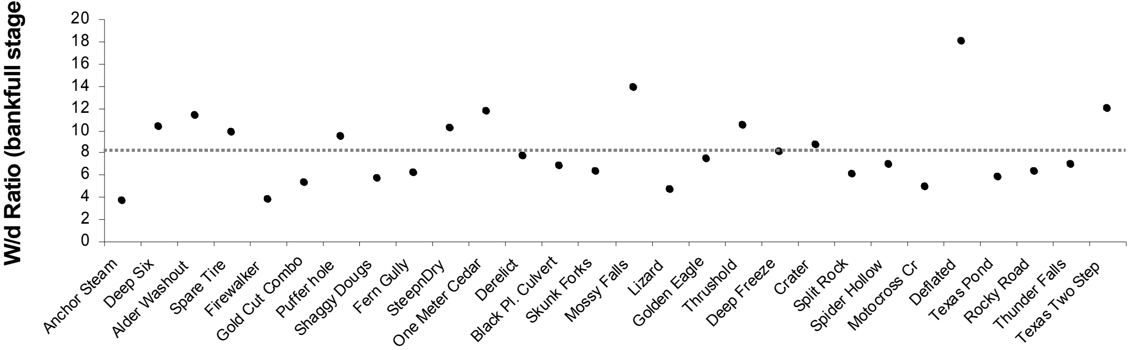


Figure 4. Width-to-depth ratios at estimated bankfull flow stage for surveyed cross sections of headwater streams.

In the following section, three headwater cross section examples are used to illustrate the sensitivity of $^{W}/_{d}$ values to stage height: 1) ‘Anchor Steam’ (Figure 5), a narrow and deep channel cross section; 2) ‘Derelict’ (Figure 6) a typically shaped channel cross section; and 3) ‘Deflated’ (Figure 7) an exceptionally wide and shallow channel cross section.

The ‘Anchor Steam’ site had the lowest width-to-depth ratio (3.7) at the stage height estimated as bankfull. The low width-to-depth ratio is represented by a channel geometry that is distinctively U-shaped with steep sided banks. The width-to-depth ratio varies at this site from 3.7 to 13.3 depending on the stage height (Figure 5).

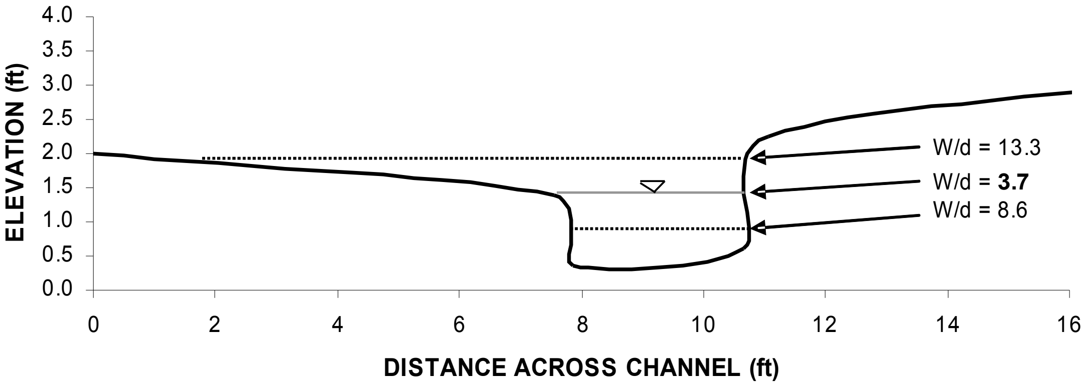


Figure 5. The ‘Anchor Steam’ headwater site is an example of a narrow and deep channel (W/d = 3.7 at estimated bankfull flow).

The 'Derelict' site has an average width-to-depth ratio of 7.9 at bankfull. This value corresponds to the typical channel geometry found in headwater channels where the channel width and depth are more balanced. At this site, the width-to-depth ratio varied less as a function of stage height from 5.8 to 9.5 (Figure 6).

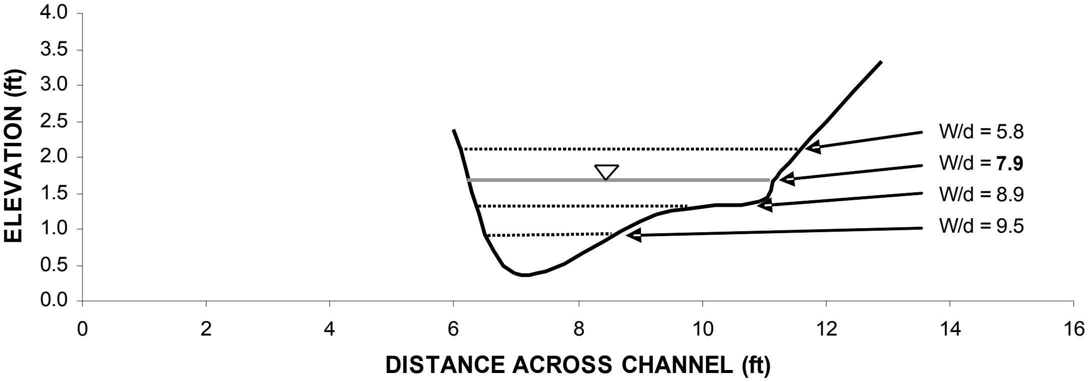


Figure 6. The 'Derelict' headwater site is an example of an average channel geometry (W/d = 7.9 at estimated bankfull flow).

The 'Deflated' site had an average width-to-depth ratio of 17.9 at the stage height estimated as bankfull. The high value at this site corresponds with a channel geometry that is wide and shallow with low angle banks or no banks. At this site, the width-to-depth ratio varied from 13.4 to 20.1 depending on the stage height (Figure 7).

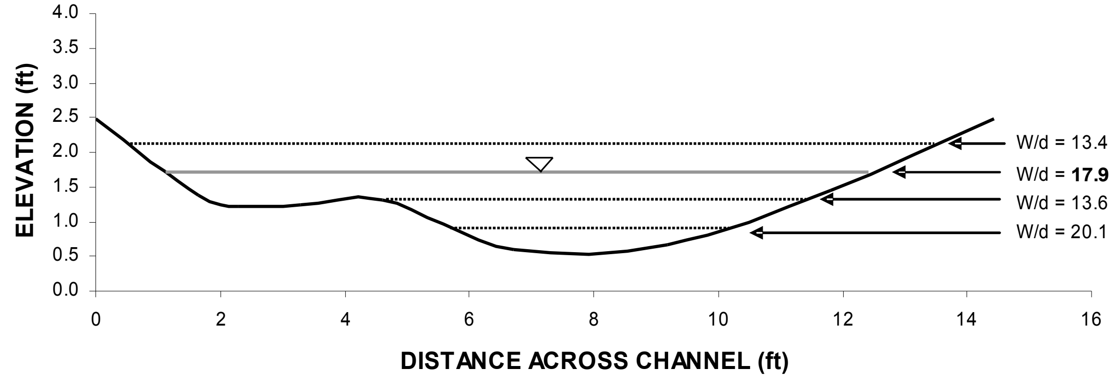


Figure 7. The 'Deflated' headwater site is an example of a wide and shallow channel (W/d = 17.9 at estimated bankfull flow).

It is interesting to note that the width-to-depth ratios calculated for various stage heights above and below bankfull for each cross section were within a similar range (3.7-20) as those calculated at the bankfull flow stage at all sites. In other words, the width-to-depth ratio does vary as a function of stage and also between sites but all within the same range.

The analysis above may be used to identify the most likely bankfull depth that corresponds to a given bankfull width and therefore, the appropriate culvert size. The results from this analysis were used to modify the culvert sizing table by: 1) identifying areas of the table that are not likely to represent the geometry of actual stream channels in this region; and 2) highlight the average depth (and thus culvert size) for a given bankfull width in a normal-shaped channel.

The range of width-to-depth ratios among the sample streams (3.7 to 17.9) is considerably narrower than the width and depth combinations in the sizing table. To identify areas of the table that do not likely represent local headwater channel geometry, W/d values were calculated for each cell by converting bankfull width to inches and dividing by the bankfull depth. Cells with a W/d value of less than 3.7 or greater than 18 are represented in the adapted table by the culvert sizes in dark gray squares (Table 3). The dark gray squares represent uncommon width-to-depth ratios as they are outside the range of any that were surveyed in this study.

Identifying the unlikely channel dimensions reduces the useful coverage of the sizing table. In the adapted sizing table, the coverage is reduced from a maximum channel bankfull width of 20 feet to a maximum channel bankfull width of 16 feet. The maximum bankfull depth is also reduced from 36 to 30 inches. In the latest revision of the board manual sizing table, cells producing culverts larger than 96 inches were eliminated (Table 1, light gray squares) because a bridge would be preferable.

Regression Analysis

Next, the most likely depth for a given width was determined by fitting the channel dimensions with a power regression model of the form: $y = 0.3596x^{0.4576}$ (Figure 8) where y is average bankfull depth (feet) and x is bankfull width (feet). Ordinary least squares linear regression or simply using the mean W/d of 8.2 also resulted in similar culvert sizes (within one size) but did not fit the data as well.

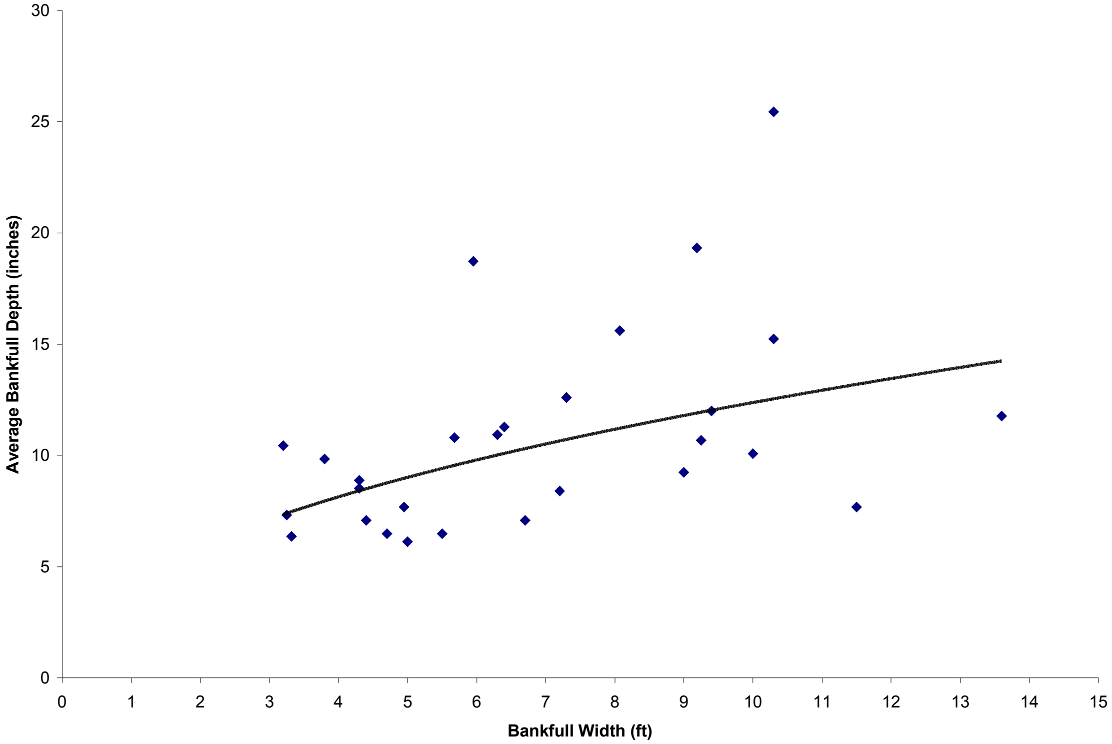


Figure 8. Power regression model. The black line represents the best fit to the data (F significance= 0.005, R^2 = 0.26).

The bold culvert sizes with the asterisk symbol in Table 3 represent the culvert size for the bankfull width and depth combination that is closest to the power regression model results (Table 3). Where the model fit falls almost equally between two sizes, both sizes are highlighted. For channels that are wider and shallower than typical, the appropriate culvert size to select will be one or two sizes to the left (smaller) of size in bold depending on the geometry; alternatively, for channels that are narrower and deeper than normal, the appropriate culvert size to select will be one or two sizes to the right (larger) of the size in bold. Our analysis results indicate that the culvert sizes highlighted with the asterisks in the table were the correct size for about half of the study streams (based on surveyed channel dimensions) and were within one culvert size (6 inch change in diameter) for 90% of the channels. For calibration, field bankfull depth measurements should be compared with results from the sizing table.

Table 3. Modified culvert sizing table for Type N waters using method A (Adapted from Washington Forest Practices Board Manual Section 3, Table 3.3)

Table for sizing culverts on Type N Waters

Average bankfull depth (Bf_d)in inches

Bf_W (ft)	3	6	9	12	15	18	21	24	27	30
1	**15	**18	24	30	--	--	--	--	--	--
2***	24	*30	30	36	42	42	48	48	--	--
3	30	*36	42	48	48	48	54	54	54	60
4	30	*42	*48	54	54	54	60	60	66	66
5	36	48	*54	54	60	60	66	66	72	72
6	36	48	*54	60	66	66	72	72	78	78
7	42	54	*60	*66	72	72	78	78	84	84
8	42	60	66	*72	78	78	84	84	90	90
9	48	60	66	*78	78	84	84	90	90	90
10	54	66	72	*78	84	84	90	90	96	96
11	60	66	72	*84	84	90	90	96	96	--
12	66	72	78	*84	*90	90	96	96	--	--
13	66	78	78	90	*90	96	--	--	--	--
14***	72	78	84	90	*96	96	--	--	--	--
15***	78	84	90	96	*96	--	--	--	--	--
16***	78	84	90	96	--	--	--	--	--	--

** Culvert size that is closest to the power regression model ($y = 0.3596x^{0.4576}$). Two sizes are highlighted where the model predictions is between depths.*
*** See sizing restrictions in WAC 222-24-040(3)*
**** Confidence is lower because channel widths less than 3 feet and larger than 13 feet are outside the stream channel data used for the analysis,*

Recommended steps for using this table:

1. Inspect a sufficient portion of the channel to determine the average bankfull width using field indicators and other methods in the Board Manual Section 3.
2. Visually determine if the channel shape is typical (e.g. Figure 6 above) or relatively wide or narrow.
3. If the channel has a typical shape, consider using the culvert size in bold with the asterisk from the table above.
4. If the channel is relatively narrow and deep (e.g. Figure 5), measure the channel depth and locate the appropriate culvert size above. It will likely be a cell in the right-hand portion of the unshaded area.
5. Similary, if the channel is relatively wide and shallow (e.g. Figure 7), measure the channel depth and locate the appropriate culvert size above. It will likely be a cell in the left-hand portion of the unshaded area.

6. If the channel dimensions are outside the unshaded portion, make sure you have looked at an adequate stream length, as this is an atypical channel shape.
7. Regardless of channel shape, the culvert size may need to be adjusted for debris passage. Look at the channel upstream from the crossing and evaluate the abundance of frequently mobilized woody debris. If there are many moveable pieces longer than the proposed culvert diameter, upsize to reduce risk of plugging.

CONCLUSION

The analysis above uses the width-to-depth ratios from surveyed headwater stream channels to identify the most likely bankfull depth that corresponds to a given bankfull width. The results were used to modify the sizing table by: 1) identifying areas of the table that represent the geometry of surveyed stream channels; 2) highlight the most common culvert size for a given bankfull width (sizes in bold with asterisks); and 3) eliminating areas of the sizing table coverage where appropriate (Table 3). The modified sizing table simplifies the procedure by reducing the dependence on an accurate bankfull depth measurement, which is the most difficult and time consuming part of the procedure. Analysis of width-to-depth ratios of surveyed streams indicates that:

- bankfull width-to-depth ratios of surveyed channels varied over a relatively small range (3.7 to 18), much smaller than represented by the width and depth combinations in the sizing table;
- width-to-depth from all stage heights at all sites also varied over a similar range (3.7 to 20). In other words, the range of width-to-depth ratios is similar regardless of what elevation is determined to be the bankfull);
- the modified sizing table reduces the channel size coverage from a maximum channel bankfull width of 20 feet down to 16 feet because all channel dimensions in this range are either unrealistically shallow or too large for a culvert crossing. For channels 14 to 16 feet wide, the modified table is only applicable for channels that are particularly wide and shallow;
- the culvert size highlighted in the adapted sizing table would be the correct size for about half of the study streams and was within ± 1 culvert size for 90% of the study channels.