2020

Recommendations for culvert sizing in the New Zealand forest Road Engineering Manual

ENFO410 – SHORT PROJECT

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Problem:

The New Zealand Forest Road Engineering Manual (NZ FREM) presents a nomograph method for sizing culverts, whereby it uses flow rate (m^3/s) and water head (He/D) to provide a design culvert. This method of sizing culverts is taught in classes at the School of Forestry at the University of Canterbury and also used widely in industry.

This report aims to evaluate if the current method for sizing culverts is right for the application of non-notified NES-PF culverts where the water head does not exceed the height of the culvert. A recommendation will be made about the use of this nomograph.

Overview:

The nomograph used in the Road Engineering Manual has a long history, with one of its first appearances being in the U.S. Department of Commerce, Bureau of Public Roads' Hydraulic Charts for the Selection of Highway Culverts, 1961 (United States. Bureau of Public, 1961). The procedure described in this document is very similar to the method used in the Forest Road Engineering Manual, whereby the Nomographs presented in the 1961 document is for concrete and corrugated metal pipe culverts (included in Appendix 3).

In the United States this same nomograph is referenced in the Federal Highway Administration's Hydraulic Design Series number 5 and has continued to be published in multiple updates of this document. A metric version of the nomograph in the NZ FREM is referenced to a 1998 print of the HDS-5 where the nomograph is in customary units.

This same nomograph can be found more recently in the Concrete Pipe Association of Australia. A publication in 1986 first used the nomograph with their more recent revised publication "Hydraulics of Precast Concrete Conduits" reiterating its importance. The chart currently listed in the New Zealand Forest Roading Engineering manual is specifically designed for Concrete pipe culverts with differing inlet controls. These inlet controls include square edged culverts with headwalls, socket ends with headwalls and socket ends projecting. (Concrete Pipe Association of Australasia, 2012). Figure 1 below shows two of the three types of concrete culverts the Culvert design chart was designated for.

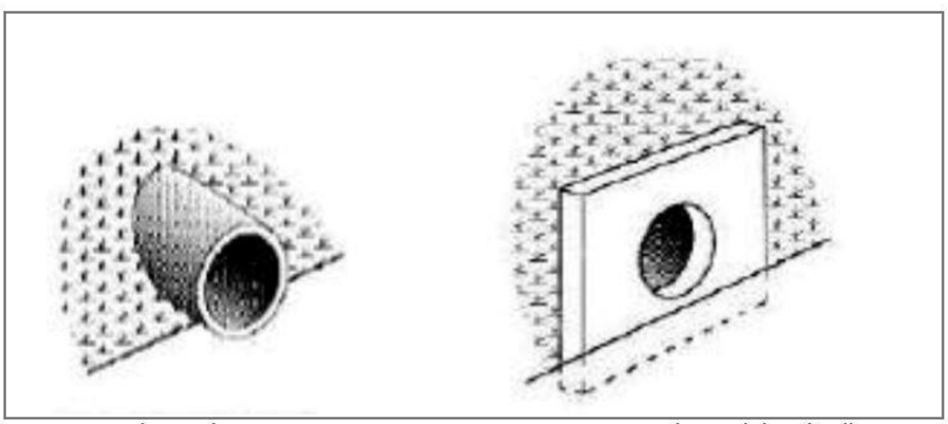


Figure 1. Socket end projecting and square edge with headwall. Zumrawi, M. (2014).

The Low Volume Roads Engineering: Best Management Practices (Keller and Sherar 2003) supplies three nomographs, one for corrugated metal pipes, one for concrete pipes and one for concrete box culverts, all of which assume inlet control and are adapted from FHWA, HDS-5 1998. The NZ FREm has one nomograph for circular concrete pipes.

Comparing the nomograph in the NZFREM to other sources and manuals we can see other discrepancies. The Columbia County Stormwater Management Design Manual includes significantly more nomographs for differing scenarios including varying; material, shape, flow control, headwalls, inlet edges, wingwalls, and rise to span ratios (Columbia County Georgia, 2009). This range of nomographs are referenced to the Federal Highway Association (1973). For these varying scenarios, the culvert designs that differ with inlet or outlet control have both respective nomographs displayed. The wide range of nomographs present in this manual give a varying range of results. This supports that using solely the concrete circular pipe chart for inlet control displayed in the NZ FREM may not be representative of the full picture. Below is an example of these varying nomographs. It shows the headwater depth for circular pipe culverts with bevelled ring inlet control.

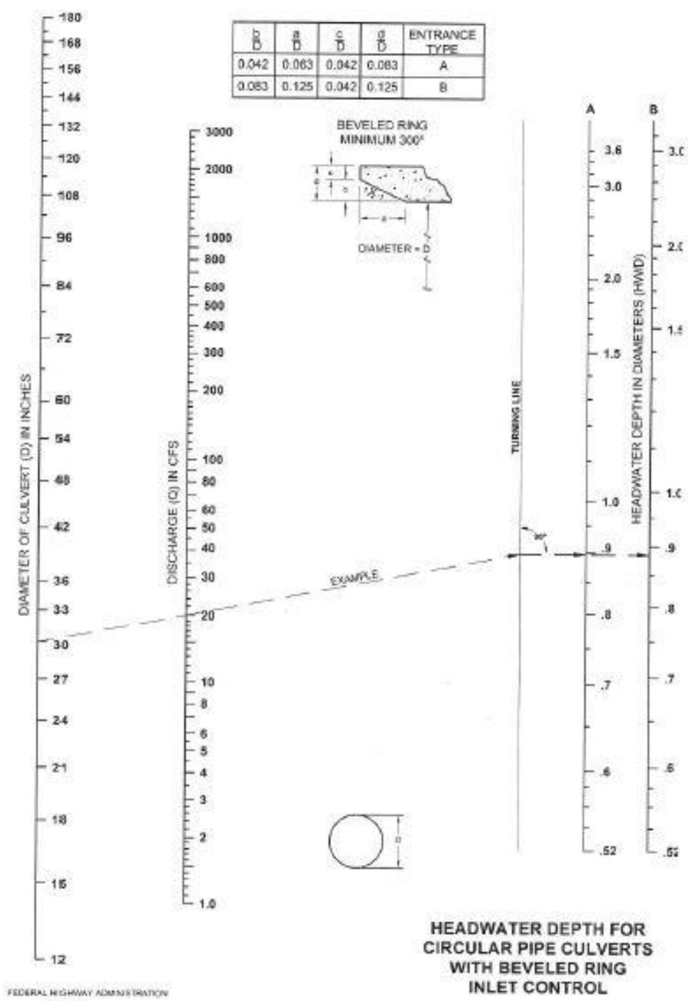


Figure 2. Nomograph for a circular pipe culvert with bevelled ring inlet control

The Culvert Design and Operation Guide states that the factors affecting culvert performance under inlet control are the upstream water surface level and inlet geometry, in particular; barrel shape, cross-sectional area and the nature of the inlet edge (Balkham, Fosbeary, Kitchen, & Rickard, 2010). This supports the inclusion of the above nomograph found in the Columbia county stormwater management design manual, which considers inlet edge.

Factors affecting culvert flow

There are several factors that affect culvert flow. Flow can be controlled by the inlet flow, outlet flow and more general factors that impact flow are culvert entrance, slope and, head water.

Control types:

Laboratory test and field observations show two major types of culvert flow: (1) flow with inlet control and (2) flow with outlet control (CSPPacific). Each type of control has different factors which effect its potential flow, these are outlined in the following sections.

Inlet control

Under inlet control the culvert flow is restricted to the discharge which can pass through the inlet at a given headwater level. The discharge is controlled by the depth of headwater, the cross-section area at the inlet and the geometry of the inlet edge. The inlet discharge is not considerably impacted by other specific culvert variables like roughness, length and slope. Inlet controlled culverts are often not full flowing at any point expect specifically the inlet itself. It is rarely immediately obvious which pattern of flow a culvert will adopt, whether it be inlet or outlet controlled, however, inlet-controlled culverts which the specified design chart are for are generally short and steep (Concrete Pipe Association of Australasia, 2012), (Balkham, Fosbeary, Kitchen, & Rickard, 2010).

Generally, in New Zealand forestry roads are planned to minimise the gradient, for ease of machinery operation and safety. Therefore, if inlet control is a feature of steep culverts it does not appear logical for the nomograph in the NZ FREM to be designed based upon inlet control.

Outlet control

In a case specific to outlet flow it was shown that the roughness of a given design material will have a significant impact on outlet flow. A study carried out in 1950 at the university of Minnesota highlighted the difference in Manning's roughness co-efficient, n, between concrete and corrugated metal circular culvert pipes. With Manning's roughness co-efficient being inversely proportional to discharge, an increase in flow can be related to a decrease in roughness. The study compared concrete and corrugated metal culverts across a range of differing diameters whilst keeping length consistent. The results showed that culverts experiencing outlet flow can have differing discharge rates due to the type of material being used to transport the water. It was shown that concrete and metal corrugated pipes with the same diameter across a range of values consistently gave differing roughness values. Concrete being the smoother material had a roughness which was half that of the corrugated metal culverts. (Straub. L, Morris, H, 1950). With the inversely proportional ratio to discharge concrete therefore experienced larger flow rates. This evidence shows that culverts installed experiencing outlet flow will have changing discharge rates depending on the material used and therefore there is an element of risk in standardising all culvert design to one material and flow type.

Table 1. Manning's roughness coefficients for different culver types. (FHWA 2012).

B.1. Manning's n Values for Culverts.[1]			
Type of Culvert	Roughness or Corrugation	Manning's n	Reference
Concrete Pipe	Smooth	0.010-0.011	Straub et al. 1960 May et al. 1986 Tullis 1986 & 1991a
Concrete Boxes	Smooth	0.012-0.015	FHWA 1961
Spiral Rib Metal Pipe	Smooth	0.012-0.013	Tullis 1983 & 1991b
Corrugated Metal Pipe[2] (Helical Corrugations)	2-2/3 by 1/2 in 68 by 13 mm	0.011-0.023	FHWA 1980 Tullis 1991c
Corrugated Metal Pipe[2] (Helical Corrugations)	6 by 1 in 150 by 25 mm	0.022-0.025	FHWA 1980
Corrugated Metal Pipe[2], Pipe-Arch and Box (Annular Corrugations)	2-2/3 by 1/2 in 68 by 13 mm	0.022-0.027	FHWA 1980
Corrugated Metal Pipe[2], Pipe-Arch and Box (Annular Corrugations)	5 by 1 in 125 by 25 mm	0.025-0.026	FHWA 1980
Corrugated Metal Pipe[2], Pipe-Arch and Box (Annular Corrugations)	3 by 1 in 75 by 25 mm	0.027-0.028	FHWA 1980
Corrugated Metal Structural Plate[2] (Annular Corrugations)	6 by 2 in 150 by 50 mm	0.033-0.035	FHWA 1980
Corrugated Metal Structural Plate[2] (Annular Corrugations)	9 by 2-1/2 in 230 by 64 mm	0.033-0.037	FHWA 1980
Corrugated Polyethylene	Smooth	0.009-0.015	Barfuss & Tullis 1988 Tullis et al. 1990
Corrugated Polyethylene	Corrugated	0.018-0.025	Clyde 1980 USBR 1985
Polyvinyl chloride (PVC)	Smooth	0.009-0.011	Neale and Price 1964 Bishop and Jeppson 1975

[1]The Manning's n values indicated in this table were obtained in the laboratory and are supported by the provided reference. Actual field values for culverts may vary depending on the effect of abrasion, corrosion, deflection, and joint conditions.
[2]See Figure B.3, Manning's n varies with barrel size.

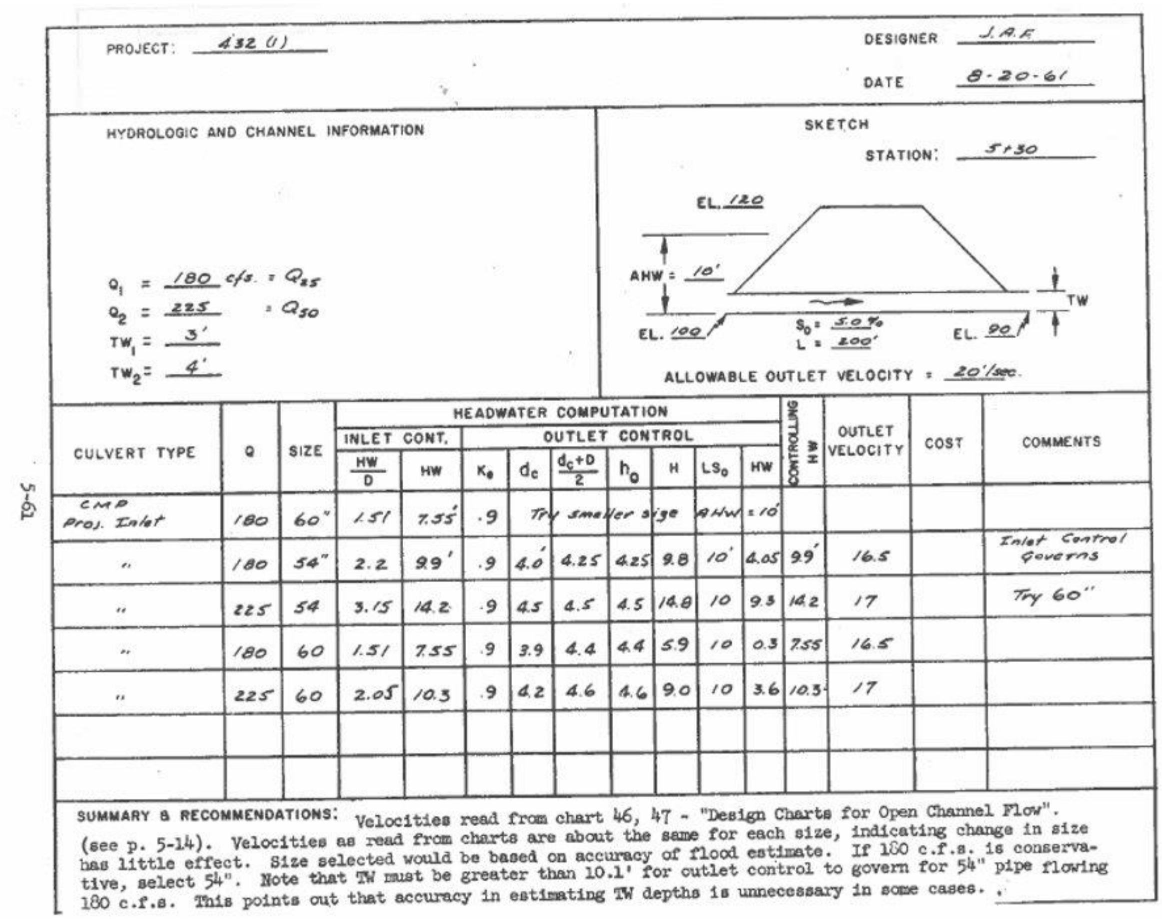
The Federal Highway Administration (FHWA) of the United States third edition document on Hydraulic Design of Highway Culverts provides

Table 1 that outlines the difference in Manning's roughness coefficients for the different types of culverts, further supporting the variability between using different culvert materials.

Design Procedure

A full design procedure for a culvert should include the following procedure: (Ramsbottom, D. et al., 1997), (Flavell, D., & Austroads., 1994)

1. Assemble Site Data
2. Determine Design Flood Discharge
3. Commence Summarising Data on Design Form



PROJECT: 432 (1)

DESIGNER J.A.F.

DATE 8-20-61

HYDROLOGIC AND CHANNEL INFORMATION

Q_1 = 180 c/s. = Q_{25}

Q_2 = 225 = Q_{50}

TW_1 = 3'

TW_2 = 4'

SKETCH

STATION: 5+30

EL. 120

AHW = 10'

TW

EL. 100

S_0 = 5.0%

L = 200'

EL. 90

ALLOWABLE OUTLET VELOCITY = 20'/sec.

CULVERT TYPE	Q	SIZE	HEADWATER COMPUTATION									CONTROLLING HW	OUTLET VELOCITY	COST	COMMENTS
			INLET CONT.		OUTLET CONTROL										
			HW/D	HW	K_e	d_c	$\frac{d_c+D}{2}$	h_o	H	LS_o	HW				
CMP Proj. Inlet	180	60"	1.51	7.55'	.9	Try smaller size				AHW = 10'					
"	180	54"	2.2	9.9'	.9	4.0'	4.25	4.25	9.8	10'	4.05	9.9'	16.5		Inlet Control Governs
"	225	54	3.15	14.2	.9	4.5	4.5	4.5	14.8	10	9.3	14.2	17		Try 60"
"	180	60	1.51	7.55	.9	3.9	4.4	4.4	5.9	10	0.3	7.55	16.5		
"	225	60	2.05	10.3	.9	4.2	4.6	4.6	9.0	10	3.6	10.3	17		

SUMMARY & RECOMMENDATIONS: Velocities read from chart 46, 47 - "Design Charts for Open Channel Flow". (see p. 5-14). Velocities as read from charts are about the same for each size, indicating change in size has little effect. Size selected would be based on accuracy of flood estimate. If 180 c.f.s. is conservative, select 54". Note that TW must be greater than 10.1' for outlet control to govern for 54" pipe flowing 180 c.f.s. This points out that accuracy in estimating TW depths is unnecessary in some cases.

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Figure 3. example design form for culvert calculations (U.S. Bureau of Public Roads, 1961)

A summarized procedure is showed in the Figure 4:

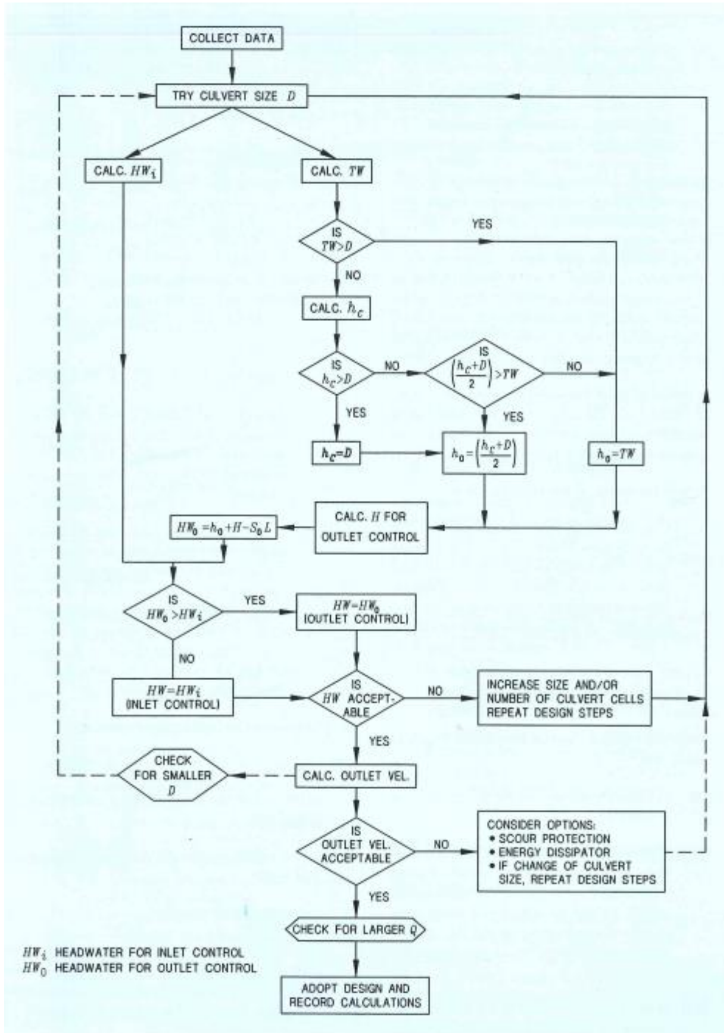


Figure 4. *Design Flow chart* (Flavell, D., & Austroads., 1994)

Different methods of culvert design

An Independent study conducted by Costley (2019) surveyed 10 forestry employees from around New Zealand regarding their culvert designs. The survey gathered information surrounding flow calculation techniques, culvert materials and issues encountered. Most participants (8/10) stated that they used charts such as the one found in the NZ FREM. In conjunction with this fact, two respondents failed to say whether they adjusted flow calculations based upon the design material, whilst the other 8 participants said they did not adjust flow calculations for changing culvert material type. The range of materials used for culvert construction by the participants included Plastic, Metal and Concrete. The reasons for use of each material varied depending on river velocity, culvert size, cost and the ease of installation. Permanent culverts tended to be made of plastic as they are cheaper and temporary culverts made of concrete as less deformation is experienced upon placement/extraction.

Culvert design approach used in FHWA HDS-5

The nomograph used in the NZ FREM was adapted from the customary units (imperial) nomograph for inlet control of culverts in the Hydraulic Design Series – 5 published by the Federal Highway Administration (1998). This publication has been updated and is now in its third edition, which was released in April 2012. The HDS-5 provides nomographs for inlet control culverts for both concrete and corrugated metal pipe, which are referenced to the Bureau of Public Roads, January 1963. (DoT, 1963) As the Bureau of Public Roads became the Federal Highway Administration, and they are republishing these nomographs as part of their culvert design procedures it should be assumed that these charts remain relevant today.

The method for culvert design recommended in the HDS-5 requires that both inlet control and outlet control flow be used to size a culvert appropriately. Following this initial sizing, outlet velocity and scour are also considered to ensure that the outlet of the culvert and the any flow dissipaters used are not compromised during high flows. The Road engineering manual has taken the nomograph in HDS-5 out of its intended use by failing to use it with the other steps in the HDS-5 design procedure.

Culvert design in Mining and Farming

When evaluating resources used in one industry, it can be advantageous to look to similar industries to compare our techniques and methods with theirs. Already, the nomograph currently used to design culverts has originated from the Bureau of Public Roads in the United States. In order then to evaluate the effectiveness of the nomograph it would be useful to compare it with the methods used in similar primary industries.

The United States Bureau of Mines in 2001 produced a document on the Design of Surface Mine Haulage Roads (Walter W. Kaufman, 2001). The document provides guidance on all aspects of mine road design and construction, including culvert design, installation and placement. The design method proposed in this publication is as simple as, if not more so than the method in our Forest Road Engineering Manual. It is based on a chart, instead of a nomograph, and requires the entrance capacity (Flow Rate) in cubic feet seconds, and the amount of head that is allowed in inches. The chart is shown below in Figure 5.

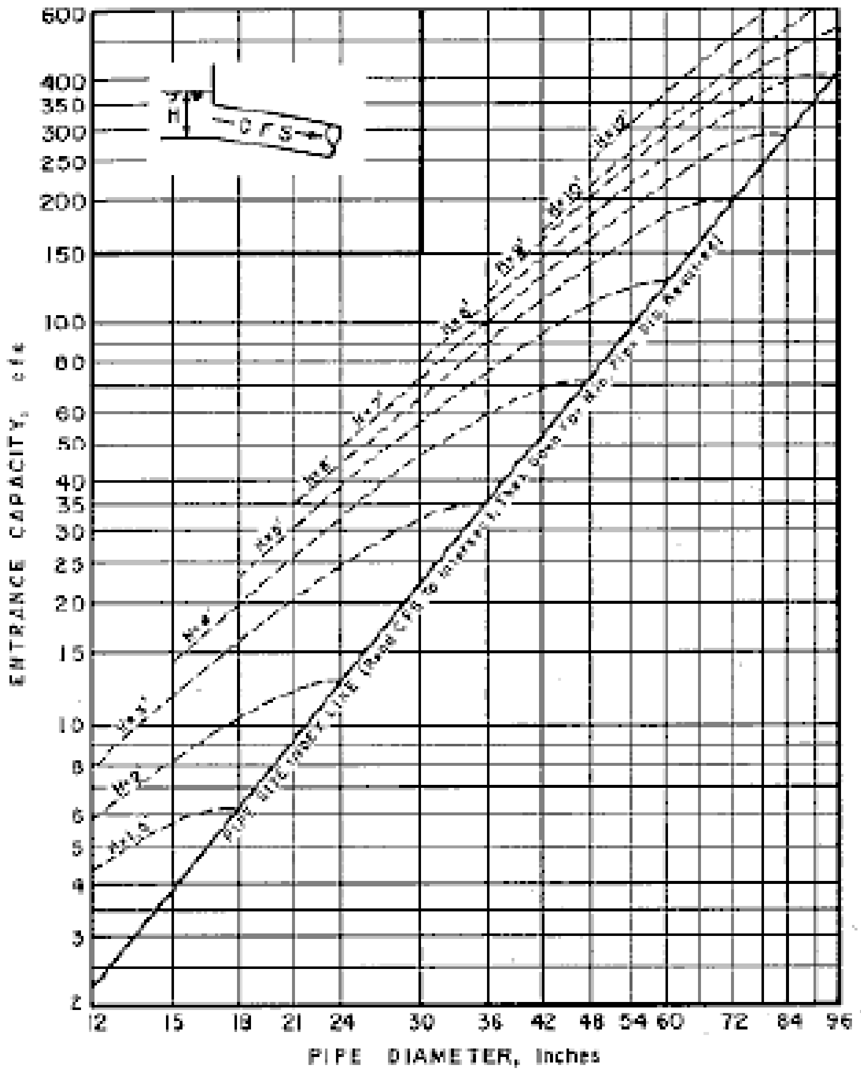


FIGURE 22. - Graph showing pipe culvert capacity.

Figure 5. Culvert sizing chart from the Bureau of Mines (Walter W. Kaufman, 2001)

To compare the mining chart to both the concrete pipe and corrugated metal pipe nomographs, each chart was used to determine culvert size for a range of flow rates, from 1m^3/s up to 15m^3/s. Each chart assumed a circular culvert with a headwall, inlet control and no headwater allowed to build up. The results are shown below in Figure 6. Culvert diameter derived from the nomograph(s) and mining chart for a selection of flow rates

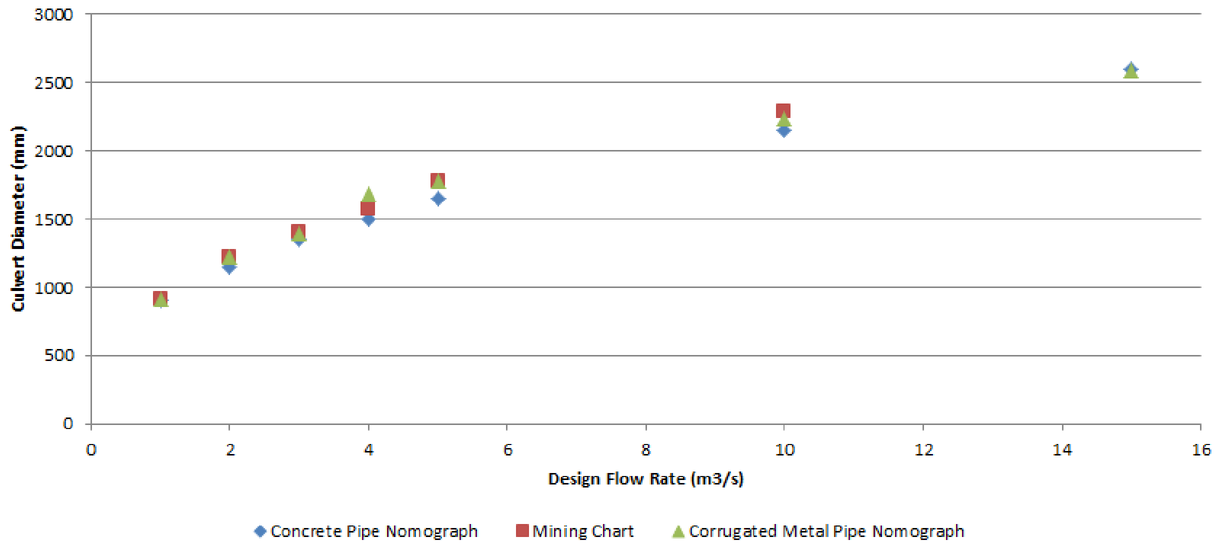


Figure 6. Culvert diameter derived from the nomograph(s) and mining chart for a selection of flow rates

The mining chart produces more conservatively sized culverts, but the difference is not too large as to be a serious discrepancy. More importantly, both charts appear to follow the same trend with increasing flow rate, indicating a reasonable relationship between the two methods.

There are two limitations that should be noted from this simple analysis. First, the nomograph in the NZFOA Forest Road Engineering Manual is for concrete pipe culverts, whereas the mining chart is for corrugated metal pipes. As such the comparison is not exact in nature. Secondly, a full and complete comparison was not possible, as the nomograph extends to higher flow rates than the mining chart, which allows for a maximum of 600 ft^3/s (17 m^3/s). In this respect our chart in forestry is more comprehensive, due to a larger range of applicable flows.

The farming industry in New Zealand is connected in many ways to the Forestry industry, and often the two industries are direct neighbours on very similar topographies. The Ministry for the Environment, in association with Fonterra produced a document, Culvert and Bridge Construction: Guidelines for Farmers in October 2004. (Environment, 2004) The document is aimed at farmers themselves, with the goal of assisting them in obtaining resource consent for any new stream crossing that they wish to install.

This is another Table based method for culvert sizing, with very little reliance on calculation, as it has been intended for use by farmers, not engineers. The method is restricted in its ability to be applied under the following circumstances:

- Any situation where overtopping could result in flooding to nearby houses/buildings
- Within 1km of a residential area, or if a backup could result in flood problems
- High bedload or debris loading is likely (Gravel, logs etc.)
- Locations where embankment above culvert is > 1.5m above the soffit and/or overtopping could cause bank failure
- Steep hill catchments

- Catchments >500 ha

The method involves determining the size of catchment above the location of the proposed culvert, either from simple GIS (Google Earth) or topographic maps, and the rainfall band the catchment is in, using NIWA's HIRDS model. Using these two parameters, the culvert can be sized to withstand a 1 in 5-year storm using the selections of Tables below in Figure 7. Culvert sizing tables from Culvert and Bridge Construction – Guidelines for Farmers (MfE, 2004)

	Very low
5 ha	300 mm
10 ha	375 mm
15 ha	450 mm
20 ha	525 mm
30 ha	600 mm
40 ha	675 mm
50 ha	825 mm
100 ha	975 mm
150 ha	1200 mm
200 ha	1350 mm
250 ha	1600 mm
300 ha	1600 mm
350 ha	1600 mm
400 ha	1800 mm
450 ha	1800 mm
500 ha	1950 mm
	Very low

	Low
5 ha	300 mm
10 ha	450 mm
15 ha	525 mm
20 ha	600 mm
30 ha	675 mm
40 ha	825 mm
50 ha	900 mm
100 ha	1200 mm
150 ha	1350 mm
200 ha	1600 mm
250 ha	1800 mm
300 ha	1800 mm
350 ha	1800 mm
400 ha	1950 mm
450 ha	2100 mm
500 ha	2100 mm
	Low

	Low–medium
5 ha	375 mm
10 ha	450 mm
15 ha	600 mm
20 ha	675 mm
30 ha	825 mm
40 ha	900 mm
50 ha	975 mm
100 ha	1350 mm
150 ha	1600 mm
200 ha	1800 mm
250 ha	1950 mm
300 ha	1950 mm
350 ha	2100 mm
400 ha	2100 mm
450 ha	2550 mm
500 ha	2550 mm
	Low–medium

	Medium
5 ha	375 mm
10 ha	525 mm
15 ha	600 mm
20 ha	675 mm
30 ha	825 mm
40 ha	975 mm
50 ha	1050 mm
100 ha	1350 mm
150 ha	1600 mm
200 ha	1950 mm
250 ha	2100 mm
300 ha	2100 mm
350 ha	2550 mm
400 ha	2550 mm
450 ha	2550 mm
500 ha	n/a
	Medium

	High
5 ha	450 mm
10 ha	600 mm
15 ha	675 mm
20 ha	750 mm
30 ha	900 mm
40 ha	1050 mm
50 ha	1200 mm
100 ha	1600 mm
150 ha	1800 mm
200 ha	2100 mm
250 ha	2550 mm
300 ha	2550 mm
350 ha	2550 mm
400 ha	2550 mm
450 ha	n/a
500 ha	n/a
	High

	Very high
5 ha	450 mm
10 ha	600 mm
15 ha	675 mm
20 ha	825 mm
30 ha	975 mm
40 ha	1200 mm
50 ha	1200 mm
100 ha	1600 mm
150 ha	1950 mm
200 ha	2550 mm
250 ha	2550 mm
300 ha	2550 mm
350 ha	2550 mm
400 ha	n/a
450 ha	n/a
500 ha	n/a
	Very high

	Extreme
5 ha	525 mm
10 ha	675 mm
15 ha	825 mm
20 ha	975 mm
30 ha	1200 mm
40 ha	1350 mm
50 ha	1600 mm
100 ha	1800 mm
150 ha	2550 mm
200 ha	2550 mm
250 ha	n/a
300 ha	n/a
350 ha	n/a
400 ha	n/a
450 ha	n/a
500 ha	n/a
	Extreme

Figure 7. Culvert sizing tables from Culvert and Bridge Construction – Guidelines for Farmers (MfE, 2004)

It is difficult to directly compare the method proposed above to the culvert sizing nomograph, as the nomograph depends on a flow rate, while this method depends on area and rainfall intensity. It can however be compared to Talbots formula to some extent. To do this, a culvert was sized for a 50Ha forested catchment with Talbots formula (C=0.7). Talbots formula called for an 874mm diameter culvert, which is just slightly larger than the diameter called for a 50Ha catchment in a Very Low Rainfall Band region (825mm). In this case, compared to Talbots, the Farming method underestimates the diameter, however, as the rainfall band increases in severity, the culvert diameter increases in kind, better accommodating the expected rainfall in the region.

The nomograph is dependent on the flow rate, which is a function of the catchment size, ground conditions and rainfall intensity during a given storm. The farming method uses very similar input parameters, but it does so in a much more practical way, through visual charts and tables, where one can see both the region they are in, but also the neighbouring region, and also the next size up of culvert that could be installed – it makes for fast and easy comparison between solutions that is potentially missing from the forestry nomograph.

NES-PF

The NES-PF states that for single culverts “at installation, the culvert invert must be located so that at least 20% of the culvert’s diameter is below the riverbed level” for the culvert installation to be classed as a permitted activity (Figure 8. NES-PF's specific regulation regarding culvert design installation). The current design approach used by the FHWA HDS-5 does not account for this loss in area for the culvert. This would have a significant effect on the amount of water that can flow through the culvert and should be accounted for in the culvert design process in NZ forestry.

46 Permitted activity conditions specific to various classes of river crossings

Single culverts

(1) The following conditions apply to single culverts:

(a) the calculated 5% AEP storm flow from the catchment above the river crossing point must be no greater than 5.5 m^3 per second:

(b) the culvert must be designed to pass a 5% AEP flood event without heading up:

(c) the culvert diameter must be at least 450 mm:

(d) the highest point of the river crossing, measured at the inlet end, must be no greater than 3.5 m above the river bed:

(e) the fill depth and construction must comply with the culvert manufacturer's specifications:

(f) at installation, the culvert invert must be located so that at least 20% of the culvert's diameter is below the river bed level:

(g) where the bankfull channel width is 3 m or more, the bed invert gradient must be no greater than 6%, measured 50 m upstream and downstream of the river crossing:

(h) the culvert inlet (entry point) and outlet (exit point) must be protected from erosion:

(i) culvert approaches and fill must be constructed using successively compacted layers of clean fill that is free of organic matter.

Figure 8. NES-PF's specific regulation regarding culvert design installation

Within the culvert survey carried about by Costley (2019) a notable response was generated by question 5, “Which part of the culvert design process do you find the most difficult to generate an accurate answer for?”. They responded stating the specific importance and requirement of having 20% of the culvert diameter submerged to allow a passage for fish to spawn. Although it cannot be assumed that the respondents do not account for this loss in their culvert design it appears as though it is of less concern as the issue was only raised by one of the ten surveyed.

Numerous respondents stated that they use a chart to calculate required diameter but the responses within the survey do not explicitly state which or what type of chart was being used. The responses from the survey indicated that the diameters calculated from the charts were the ones used in the final design of designated culverts as there was no reference to adjusting calculations. Furthermore, if these diameters were used and then submerged 20% to adhere to the legal requirement stated in NES-PF a reduction in diameter for storm flow would occur. This would mean the culvert design fails to meet one of the two required standards whether it is being submerged or not.

Further importance is placed on culvert diameters allowing for fish passage in the NZ guidelines for water structures up to 4 meters which states “culverts must have 20-50% of the diameter submerged to allow for the passage of fish”. In most cases in New Zealand, it will be required that passage be provided for all fish species and life stages expected to be normally resident or migrating through the site of the structure

A loss of 20% of the culvert's diameter to riverbed material translates to a 16.6% loss of effective culvert area. The new reduced area would have a diameter that is 8% less than the original area. This means that the final culvert diameter designed using the nomograph needs to be increased by 8% in order to account for the loss of effective culvert area (Appendix 2). Figure 9 gives an example of area loss for a culvert that has been submerged below the riverbed to allow for fish passage.

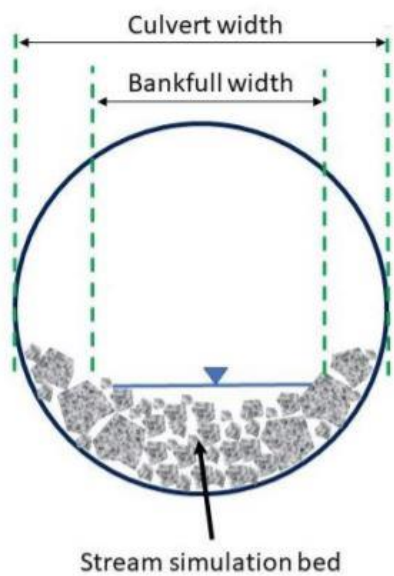


Figure 9. Example of culvert area being lost to riverbed material.

Comparisons with other methods of culvert sizing

HDS-5 inlet control equations

Under inlet control, culvert discharge capacity is a function of the available upstream energy and the culvert inlet geometry. The inlet control culvert flow capacity is typically quantified using empirical, quasi-dimensionless head-discharge relationships. Different relationships are used for submerged (headwater above the crown of the culvert at the inlet) and unsubmerged (headwater below the crown of the culvert at the inlet) culvert inlet conditions.

The following estimation method are widely adopted and recommended by HDS-5 (Ramsbottom, D. et al., 1997), (Tullis, B. P., Anderson, D. S., & Robinson, S. C., 2008).

The method is presented below:

Determine discharge intensity $\frac{1.811Q}{AD^{0.5}}$ for the culvert

Where
Q is the design discharge
A is the total cross-sectional area of the culvert barrel
D is the internal height of the culvert barrel above bed level

If $\frac{1.811Q}{AD^{0.5}} < 3.5$ the culvert is under unsubmerged condition

If $\frac{1.811Q}{AD^{0.5}} > 4.0$ the culvert is under submerged condition

Unsubmerged equations

$$HW_i/D = \frac{H_c}{D} + \mathrm{K}\left[\frac{1.811Q}{AD^{0.5}}\right]^M - 0.5S$$

Where $H_c = y_c + \frac{V_c^2}{2g}$

Submerged equation:

$$HW_i/D = c\left[\frac{1.811Q}{AD^{0.5}}\right]^2 + Y - 0.5S$$

Where Y, c, K, M is the constant coefficients differed from material and shape

Table 2. Inlet structure design coefficient (Tullis, B. P., Anderson, D. S., & Robinson, S. C., 2008)

Culver Type & Inlet End Treatment	Unsubmerged				Submerged	
	Form 1		Form 2			
	K	M	K	M	c	Y
HDS-5 Circular CMP						
Projecting	0.03	1.50	-	-	0.06	0.54
Mitered to Slope	0.02	1.33	-	-	0.05	0.75
Headwall	0.01	2.00	-	-	0.04	0.69
HDS-5 Circular						
Beveled ring, 45° bevels	0.00	2.50	-	-	0.03	0.74
Smooth tapered inlet throat	-	-	0.534	0.555	0.02	0.90
Rough tapered inlet throat	-	-	0.519	0.640	0.02	0.90

By using the example data from the chart, results could be obtained:

- Headwall/square edge: 1.84
- Mitred: 2.19
- Projecting: 2.27

Fifth-degree polynomial equation

Inlet control occurs when the culvert barrel can convey more flow than the inlet will accept. Inlet control is possible when the culvert slope is hydraulically steep (dc > du). The control section of a culvert operating under inlet control is located just inside the entrance. When the flow in the barrel is free surface flow, critical depth occurs at or near this location, and the flow regime immediately downstream is supercritical. Depending on conditions downstream of the culvert inlet, a hydraulic jump may occur in the culvert. Under inlet control, hydraulic characteristics downstream of the inlet control section do not affect the culvert capacity. Upstream water surface elevation and inlet geometry (barrel shape, cross-sectional area, and inlet edge) are the major flow controls.

A fifth-degree polynomial equation based on regression analysis is used to model the inlet control headwater for a given flow. Analytical equations based on minimum energy principles are matched to the regression equations to model flows that create inlet control heads outside of the regression data range. The following equation (1) only applies when 0.5 < HWic/D < 3.0. (Thomason.C., 2019)

$HW_i = [a + bF + cF^2 + dF^3 + eF^4 + fF^5]D - 0.5DS$ (1)

- where:
- HW_{ic} = inlet control headwater (ft. or m)
- D = rise of the culvert barrel (ft. or m)
- a to f = regression coefficients for each type of culvert (see the following table)
- S_0 = culvert slope (ft./ft. or m/m)
- F = function of average outflow discharge routed through a culvert; culvert barrel rise; and for box and pipe-arch culverts, width of the barrel, B, shown in Equation 8-5.($F = \frac{1.8113Q}{WD^{\frac{3}{2}}}$)

Table 3 Regression Coefficient for inlet control equations (Thomason.C., 2019)

Table 8-1: Regression Coefficients for Inlet Control Equations

Shape and Material	Entrance Type	a	b	c	d	e	f
RCP	Square edge w/headwall	0.087483	0.706578	-0.2533	0.0667	-0.00662	0.000251
-	Groove end w/headwall	0.114099	0.653562	-0.2336	0.059772	-0.00616	0.000243
-	Groove end projecting	0.108786	0.662381	-0.2338	0.057959	-0.00558	0.000205
-	Beveled ring	0.063343	0.766512	-0.316097	0.08767	-0.00984	0.000417
-	Improved (flared) inlet	0.2115	0.3927	-0.0414	0.0042	-0.0003	-0.00003
CMP	Headwall	0.167433	0.53859	-0.14937	0.039154	-0.00344	0.000116
-	Mitered	0.107137	0.757789	-0.3615	0.123393	-0.01606	0.000767
-	Projecting	0.187321	0.567719	-0.15654	0.044505	-0.00344	0.00009
-	Improved (flared) inlet	0.2252	0.3471	-0.0252	0.0011	-0.0005	-0.00003

For HWi/D > 3.0, Equation (2), an orifice equation, is used to estimate headwater:

- Determine the potential head from the centroid of the culvert opening, which is approximated as the sum of the invert elevation and one half the rise of the culvert. The effective area, A, and orifice coefficient, C, are implicit.
- Determine the coefficient, k, by rearranging Equation (2) using the discharge that creates a HW/D ratio of 3 in the regression equation, Equation (3).

$$HW_i = \left[\frac{Q}{k}\right]^2 + \frac{D}{2} \quad (2)$$

Equation 8-6.

where:

- *HWi* = inlet control headwater depth (ft. or m)
- *Q* = design discharge (ft3/s or m3/s)
- *k* = orifice equation constant
- *D* = rise of culvert (ft. or m).

$$k = 0.6325\frac{Q_{3.0}}{D^{1/2}} \quad (3)$$

- where:
- *Q3.0* = discharge (cfs or m3/s) at which HW/D = 3.

Results

Table 4 calculated results for D=0.9m, Q=1.8m^3/s

SHAPE&MATERIAL	D	S	ENTRANCE TYPE	a	b	c	d	e	f	F	HW	HW/D
CMP	0.9	0.037	Headwall	0.16743	0.53859	-0.1494	0.03915	-0.0034	0.00012	4.24284	1.60237	1.8
	0.9	0.037	Mitered	0.10714	0.75779	-0.3615	0.12339	-0.0161	0.00077	4.24284	1.863819	2.1
	0.9	0.037	Projecting	0.18732	0.56772	-0.1565	0.04451	-0.0034	0.00009	4.24284	1.950991	2.2

Issues

Based on the study (Tullis, B. P., Anderson, D. S., & Robinson, S. C., 2008), it indicates, entrance loss coefficients and inlet control head-discharge relationships for buried-invert culverts designed for fish passage applications are either ignored or approximated using traditional culvert In current practice, design data due to a lack of data specific to these alternative culvert geometries.

In this case, the value calculated use HDS-5 would be different with the value obtained from the chart.

Table 5 Buried-invert culvert inlet control regression constants (Tullis, B. P., Anderson, D. S., & Robinson, S. C., 2008)

End Treatment	% Invert burial, culvert shape	Unsubmerged				Submerged		% Error of Estimate†		
		Form 1		Form 2						
		K	M	K	M	c	Y	Form 1	Form 2	Submerged
Thin-wall projecting, ponded	20%, circular	0.09	0.58	0.44	0.64	0.03	0.57	5.6%	0.9%	1.1%
	40%, circular	0.08	0.76	0.47	0.69	0.05	0.68	2.3%	0.5%	2.2%
	50%, circular	0.11	0.69	0.50	0.71	0.06	0.53	2.4%	0.5%	0.5%
	50%, elliptical	0.12	0.59	0.53	0.67	0.07	0.46	7.9%	2.2%	2.0%
Thin-wall projecting, channelized	20%, circular	0.07	0.45	0.42	0.62	0.03	0.62	4.1%	0.6%	0.8%
	40%, circular	0.09	0.59	0.48	0.66	0.04	0.51	2.6%	0.6%	0.7%
	50%, circular	0.10	0.58	0.50	0.68	0.06	0.47	1.5%	0.3%	1.7%
	50%, elliptical	0.10	0.54	0.50	0.67	0.06	0.13	5.0%	1.7%	1.1%
Mitered to 1.5H:1V fill slope	20%, circular	0.04	0.58	0.40	0.63	0.02	0.63	6.0%	0.7%	2.4%
	40%, circular	0.03	0.78	0.42	0.69	0.04	0.64	6.6%	0.7%	2.6%
	50%, circular	0.04	0.59	0.44	0.68	0.05	0.48	4.7%	0.6%	2.2%
	50%, elliptical	0.08	0.43	0.49	0.65	0.04	0.61	11.3%	1.7%	2.2%
Square-edged inlet with vertical headwall	20%, circular	0.05	0.45	0.40	0.63	0.02	0.67	11.9%	1.0%	0.5%
	40%, circular	0.05	0.72	0.44	0.68	0.03	0.66	3.7%	0.5%	0.5%
	50%, circular	0.06	0.59	0.45	0.70	0.04	0.63	2.4%	0.4%	0.7%
	50%, elliptical	0.06	0.60	0.45	0.70	0.03	0.68	5.0%	1.0%	0.5%
45° beveled inlet with vertical headwall	20%, circular	0.03	0.56	0.39	0.63	0.02	0.71	8.8%	0.7%	0.4%
	40%, circular	0.04	0.64	0.42	0.67	0.02	0.73	10.4%	0.9%	0.7%
	50%, circular	0.04	0.41	0.44	0.69	0.03	0.66	8.3%	0.8%	0.8%
	50%, elliptical	0.06	0.61	0.48	0.67	0.05	0.51	5.8%	1.3%	0.9%

Talbot's Equation

The Talbot method is a semi-empirical formula that was developed in 1887 and is still widely used today. The formula directly estimates the culvert area required to carry flood flows, the formula requires two inputs, the drainage area of the catchment and a Talbot's run-off coefficient. The catchment area can easily be found using GIS and the 'C' value is estimated depending on the terrain and land cover of the catchment. The equation, its inputs, and the range of 'C' values can be seen in Figure 10. Talbot's equation and variable definitions provided in the NZFREM.

$a = C * A^{3/4}$

- a = Required section of waterway in square feet
- A = Drainage area in acres
- C = Talbot's coefficient

Typical run-off coefficients:

- 1.0: steep terrain, low infiltration, urban setting
- 0.7: steep terrain, moderate infiltration
- 0.4: gently rolling agricultural land
- 0.2: nearly level, non-flooding areas.

An on-line calculator can be found at www.sd-w.com/civil/talbots_formula.html.

Figure 10. Talbot's equation and variable definitions provided in the NZFREM

The method is still popular to this day due to its simplicity of the required computations, and it provides a reasonable estimate for the number of inputs it requires. However, the method is known to generally overestimate which can be good in terms of providing a conservative answer but may not provide the best economic solution. The method does not account for several factors that have an impact on the flood flow passing through a culvert such as culvert inlet type and material, and the probability of a reoccurring flood event. A requirement in the NES-PF is that culverts must be designed to pass a 5% AEP flood event without heading up, Talbot's method does not take this into consideration.

Within the NZ FREM, it provides the Talbot method and the specified chart as methods for gaining the desired culvert diameter. It was determined that it would be a good idea to compare the highlighted chart against the Talbot method for determining culvert diameter. It is stated within in the NZFREM that the Talbot method is best used to estimate culvert size for small catchments. For this comparison a small catchment has been defined as 120ha or less. The Talbots formula produces a culvert area which was then adjusted to culvert diameter. It will be compared against the nomograph diameters produced by using flows calculated from the Rational method. The acceptable catchment size for use of the rational method can vary by source having maximum area values of 50ha, 120ha, 10km^2 and 250km^2 (Costley, 2019). Using the range of sources, it was felt a maximum value of 120ha would be acceptable. The results are plotted on the following graph.

Data gathered by Costley (2019) provided areas, Rational C values and rational flow values for 50 catchments within the Canterbury and West Coast region. Twenty-two catchments with an area of 120ha or less were used within this analysis. Using Figure 11 for Talbot's method and a descriptive table for rational method values of "C", the rational coefficients for each of the catchments used were adjusted to best suit Talbot's coefficient for the catchment topography.

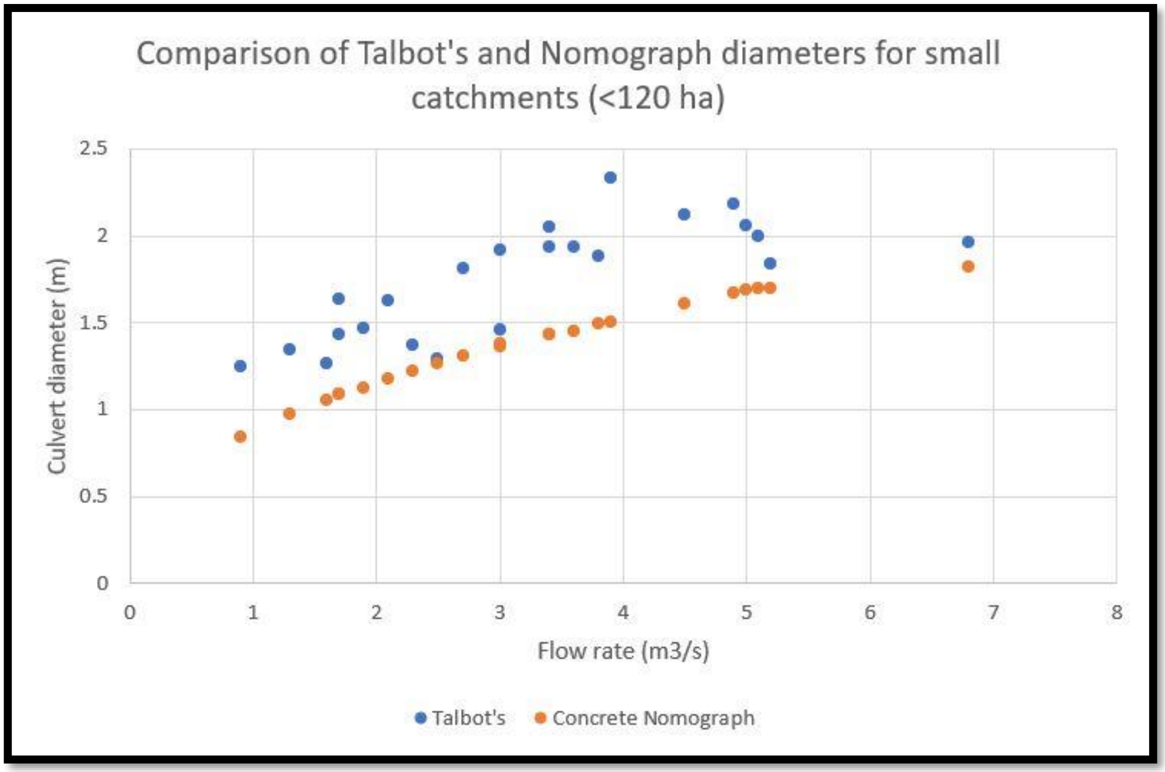


Figure 11. Comparison of culvert diameters for small catchment using nomograph and Talbot's.

From the graph Talbot's method does tend to overestimate and is quite variant when compared to the nomograph for concrete culverts under inlet control. However, it does follow the same trend as the nomograph data, proving that it is still relevant for providing a rough estimate of the required culvert diameter, that will help gain a quick understanding of the catchment with minimal inputs and computations. Because the Talbot's method is heavily reliant on choosing an acceptable 'C' factor this could explain the variance seen on the graph as choosing an acceptable 'C' factor requires a good understanding of the catchment as well as good judgement. The comparison covered catchment areas ranging from 19 ha to 118 ha to provide a good range of data points, as well as using catchments with a range of 'C' values.

UCAN model difference

The University of California Outreach uses the same nomograph, although it has been adapted slightly to include an indicator for culverts larger than 96 inches (~2.4m) to be installed as bridge or open-bottomed pipe arches (Figure 12. (Culvert sizing nomograph sourced from University of California)).

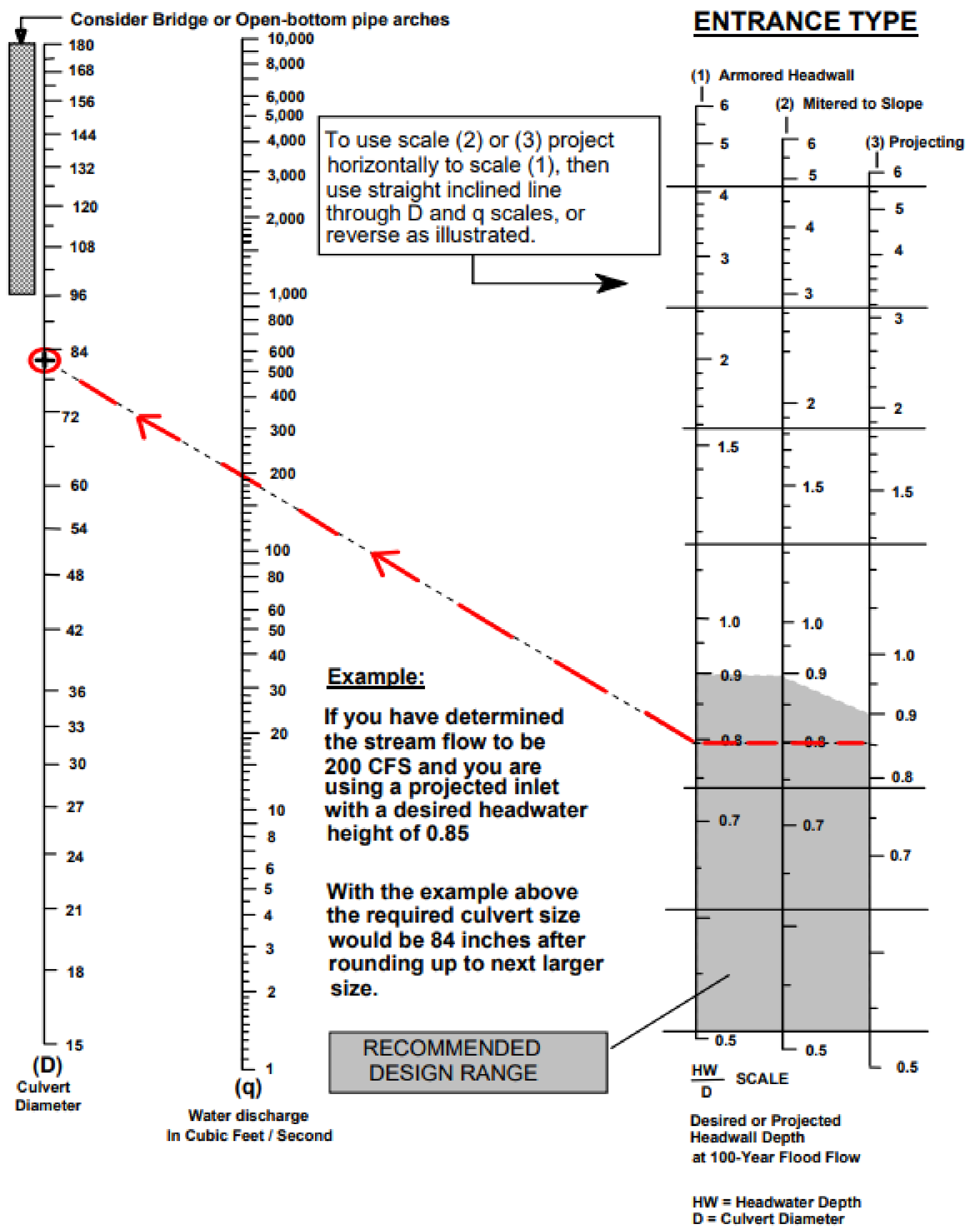


Figure 12. (Culvert sizing nomograph sourced from University of California)

The nomograph used in the NZ Road Engineering Manual does not include the same prompt to consider a design change. The fact that it has been included in the UCAN version of the chart implies that the consideration is often overlooked, which perhaps suggests that the NZREM version needs revision.

An Australian method of culvert design

Forestry Corporation NSW has developed its own method for designing culverts. This method is more comprehensive than that used in the NZ FREM as it considers more than just the flow rate through the culvert as fundamental to the design. Although not directly relevant to culvert design the program also includes other drainage feature calculators as well as circular culverts (Figure 14). The interface for the design program is a Macro enabled Excel file.

Inlet control is used to initially size the culvert and assess the peak flow criteria. The culvert size can be changed until it meets the peak flow requirement, or multiple culverts added in parallel. Once peak flow is satisfied the water head is assessed to ensure that it is within the allowable limit for the application. Following from this the outflow velocity is checked and compared to the velocity at which different materials will scour. The material used at the culvert outlet can be changed so that it will resist scour, but if it is not practical to do this then the culverts can be resized or more added in parallel to satisfy the outflow velocity constraint. Figure 14 shows the calculator interface.

Direct comparison between this calculator and other methods is difficult as some of the required inputs during the initial sizing are different or absent in other models and as this program is owned by Forestry Corporation, additional detail about the mathematical analysis that powers this program is unavailable at this time due to the commercial sensitivity. The simple interface of this method of complete culvert design could be beneficial if it was adapted for use in New Zealand. Although more than culvert size is considered during this design process it makes other assessments of the culvert much easier.

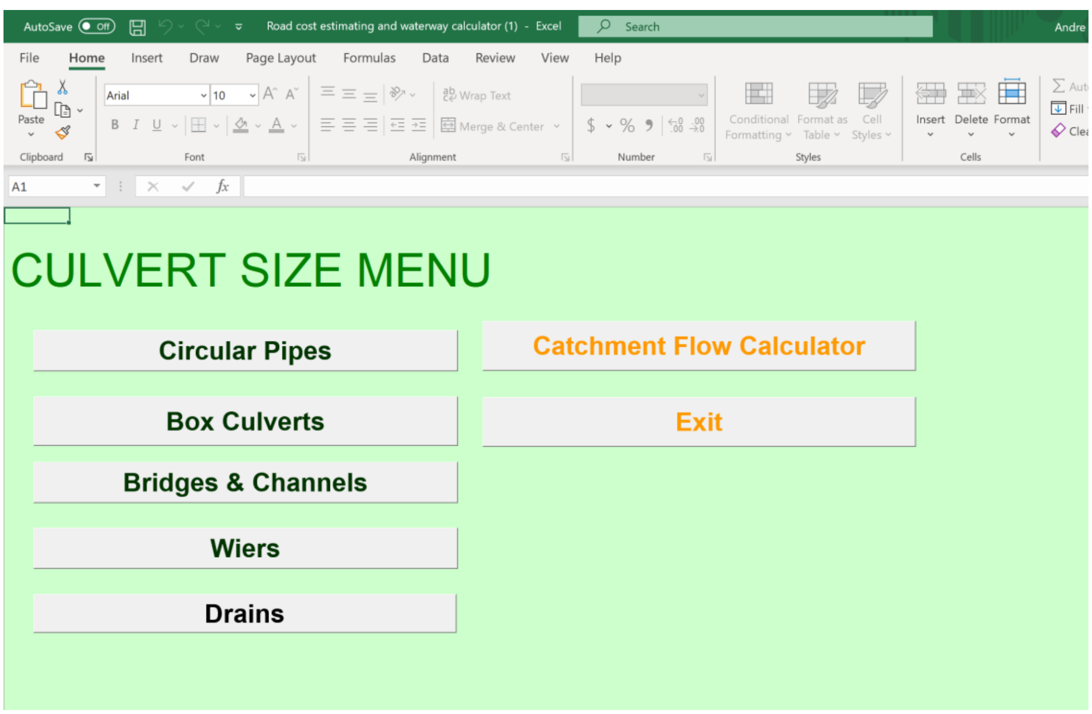


Figure 13. Menu for culvert sizing program of FCNSW

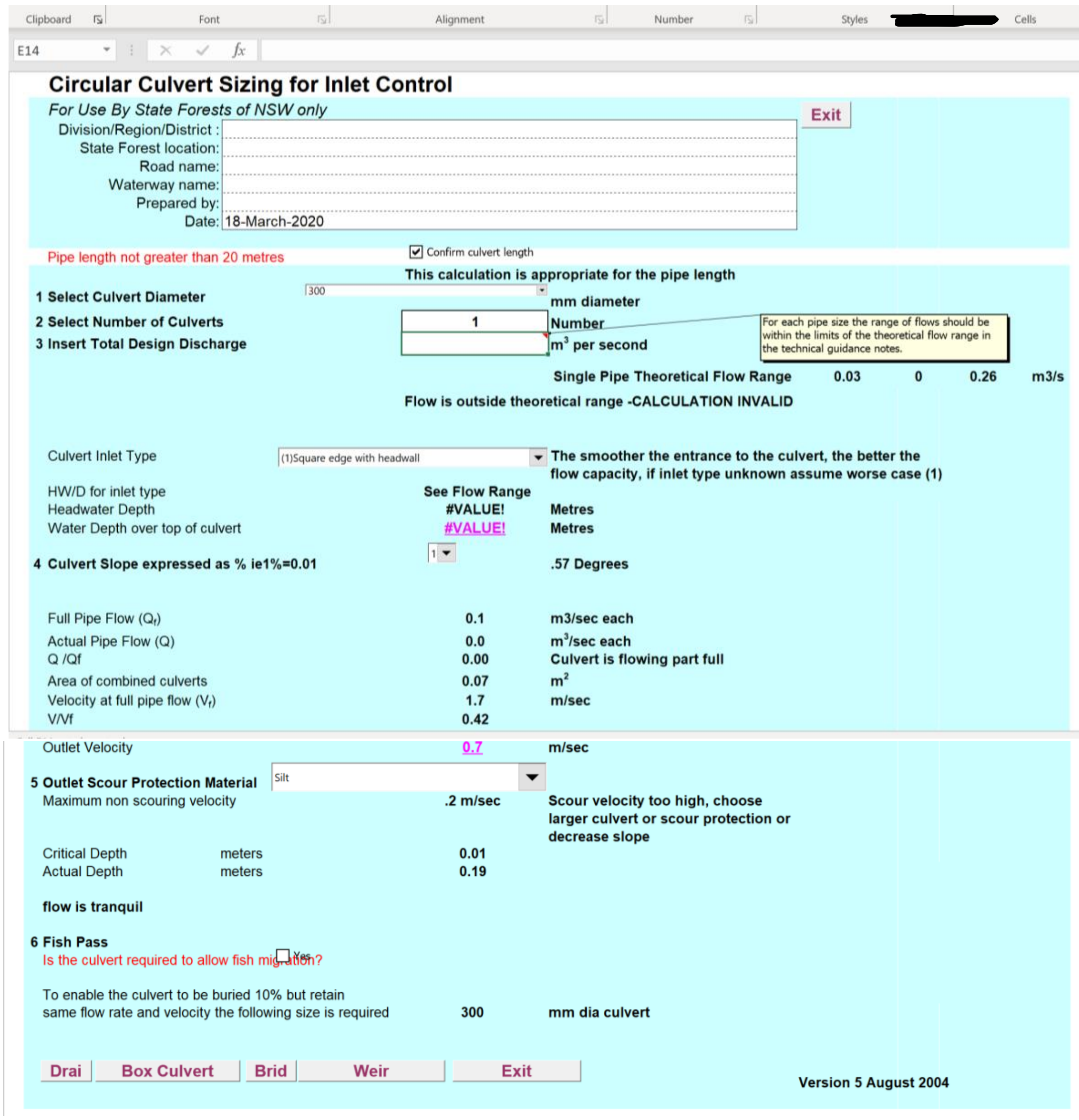


Figure 14. FCNSW culvert calculator with drop down menus and inputs to design a culvert.

Future relevance and other considerations

Due to being much easier to handle thanks to their lighter weight and lower prices, high density polyethylene plastic pipes (HDPE) are beginning to find favour in forest roadworks (Ryan, Phillips, Ramsay, & Dempsey, 2004). These pipes are lighter and easier to handle which provides a significant health and safety benefit. As we see increase in favour towards other types of material we will see a further decrease in relevance of the nomograph designed for concrete culverts, displayed in the NZFREM.

Also, culverts come in a range of standard sizes that, with the minimum diameter normally being 450 mm. Adjusting the culvert diameter scale of the nomograph to reflect these sizes would make the chart easier to use.

Recommendation

After a review of the culvert sizing method outlined in the NZ FREM, it appears that the nomograph is a sufficiently accurate solution when used correctly (following the FHWA guide). However, the NZFREM only includes a nomograph for concrete culverts, which means the wrong chart is being used when the culvert material is not concrete. In saying this, the nomograph still provides a more accurate answer than alternative sizing methods such as using Talbot's equation, which is a reason for this method being used without issue in the NZ forest industry for so long based on assumptions that it is correct. Inlet control is also used as a to size culverts in forestry in Australia, although the exact method to do this is unable to be examined due to commercial ownership of the application.

If it were a requirement that culvert sizing methods must include complete consideration of all inputs, an adaptation of the standard culvert sizing method used by the Forestry Corporation of New South Wales should be undertaken. The method used by Forestry Corporation NSW allows entry of the complete range of inputs using a digital spreadsheet, it is a clear and simple method and could be beneficial for the NZ forest industry. A collaboration with the Forestry Corporation NSW should be considered, there are potential benefits for both parties including the ability to carry out a wider review of the process and facilitate further improvement of the culvert sizing method.

Acknowledgements

Shubhangi Kelekar at the California Department of Transportation Library in Sacramento, CA for providing us with photocopies of a reference we required.

Forestry Corporation NSW for allowing us to look at, and briefly test their culvert sizing program.

References:

Alan J . Campbell, R. C. (1982). *Prediction of Peak Flows for Culvert Design on Small Watersheds in Oregon.* Oregon: School of Forestry, Oregon State University.

Concrete Pipe Association of Australasia. (2012). *Hydraulics of precast concrete conduits, pipes and culverts, section 3.*

Costley, B. (2019). *Culvert design for New Zealand forestry.* University of Canterbury.

CSPPacific. (n.d.). *Culvert Hydraulics.* Retrieved from CSPPacific: https://www.csppacific.co.nz/uploads/literature/technical/Hydraulics_Data.pdf

Douglass, J. E. (1974). *Flood Frequencies and Bridge and Culvert Sizes.* North Carolina: USDA Forest Service General Technical Report.

DoT. (1963). *Hydraulic engineering circular*: Washington: U.S. Dept. of Transportation, Federal Highway Administration

Franklin. P, Gee. E, Baker. C, Bowie, S. (2018). *New Zealand Fish Passage Guidelines, For Structures up to 4 metres.* Department of Conservation

James D. Schall, P. L. (2012). *HYDRAULIC DESIGN OF HIGHWAY CULVERTS.* Colorado: U.S. Department of Transportation.

Environment, M. f. t. (2004). *Culvert and Bridge Construction - Guidelines for Farmers*. Wellington, New Zealand: Ministry for the Environment.

Flavell, D., & Austroads. (1994). Waterway design: A guide to the hydraulic design of bridges, culverts and floodways. Sydney [N.S.W.]: AUSTROADS.

NZFOA. (2012). *New Zealand Forest Road Engineering Manual.* Wellington: New Zealand Forest Owners Association

Ramsbottom, D. M., Day, R., Rickard, C., & Construction Industry Research and Information Association (1997). Culvert design manual. London: Construction Industry Research and Information Association.

Straub. L, Morris, H. (1950). *Hydraulic data comparison of concrete and corrugated metal culvert pipes.* University of Minnesota.

Thomason.C, P.E. (2019) *Hydraulic Design Manual:* Effective Date: September 12, 2019. Retrieved from http://onlinemanuals.txdot.gov/txdotmanuals/hyd/manual_notice.htm

Tullis, B. P., Anderson, D. S., & Robinson, S. C. (2008). Entrance loss coefficients and inlet control Head-Discharge relationships for buried-invert culverts. Journal of Irrigation and Drainage Engineering, 134(6), 831-839. doi:10.1061/(ASCE)0733-9437(2008)134:6(831)

United States. Bureau of Public, R. (1961). *Hydraulic charts for the selection of highway culverts*. Washington: U.S. Dept. of Commerce, Bureau of Public Roads.

Guidelines for Forest Roads. University of California: https://ucanr.edu/sites/forestry/files/138031.pdf

Walter W. Kaufman, J. C. A. (2001). *Design of Surface Mine Haulage Roads*. Retrieved from Pittsbugh, Pensylvania: https://www.cdc.gov/niosh/mining/userfiles/works/pdfs/ic8758.pdf

Zumrawi, M. (2014). *The impacts of poor drainage on road performance in Khartoum.*

Appendix 1

DESIGN GUIDELINE 1
CULVERT DESIGN USING NOMOGRAPHS

DG 1.1 BACKGROUND

Culvert design can be accomplished using design aids in this manual to manually determine the appropriate culvert size, shape (box or circle) and material that will accommodate a design flood at a given highway crossing. Section DG 1.2 provides the design procedure steps that should be followed. Section DG 1.3 applies the design steps to a circular shape. Section DG 1.4 applies the design procedure steps to a rectangular shape.

DG 1.2 DESIGN PROCEDURE

The following are the general steps that are followed to design a straight culvert (see Figure 3.18):

Step 1. Summarize hydrology data (Section 2.1) and site data (Section 2.2) for the culvert at the top of the Culvert Design Form. This information will have been collected or calculated prior to performing the actual culvert design. In addition, the site assessments (Section 2.3) have been completed.

Step 2. Select a preliminary culvert shape (Section 1.3.1), material (Section 1.3.2), size from standard plans, and entrance configuration from standard plans.

Step 3. Perform inlet control headwater (HW_i) calculations for the design flow rate (Section 3.3.2).

Step 4. Perform outlet control headwater (HW_o) calculations for the design flow rate (Section 3.3.3).

Step 5. The controlling headwater is the higher of HW_i and HW_o.

Step 6. Evaluate Results (Section 3.3.5) to determine if controlling HW is near allowable HW and less. If not close enough or higher, return to Step 2 and try another alternative.

Step 7. Calculate outlet velocity (V_o) for the controlling HW (Section 3.1.6) and compare with downstream channel velocity. If velocity is not acceptable, consider an energy dissipator (HEC-14) or a rougher material (return to Step 2).

Step 8. Check that culvert dimensions fit embankment and stream. If dimensions are satisfactory, repeat steps 3 through 5 for performance curve discharges (Section 3.2) and document the design.

DG 1.3 CIRCULAR CULVERT

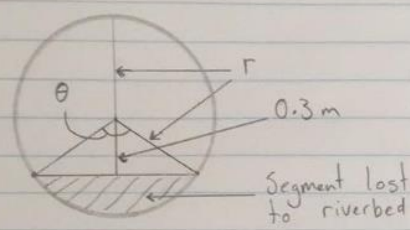
Design a straight, circular culvert with no depression for a new rural roadway crossing for the 25-year flood. Use the standard practice of providing 2 ft (0.61 m) of freeboard below the subgrade shoulder.

FHWA HDS-5 (Page 272)

Appendix 2

J.V

Determining area of culvert lost to riverbed and new required culvert diameter



Culvert diameter $= 1m = d$
Culvert radius $= 0.5m = r$
Culvert area $= 0.7854\,m^2$
$d - 20\% = 0.8m$

$$\theta = \cos^{-1}\left(0.3/1\right) \times 2$$

$$\theta = 106.26^{\circ}$$

$$\text{Segment Area} = \left(\frac{\theta\pi}{360} - \frac{\sin\theta}{2}\right) r^2$$

$$= \left(\frac{106.26 \times \pi}{360} - \frac{\sin 106.26}{2}\right)(0.5)^2$$

$$\text{Segment Area} = 0.1118\ m^2$$

$$\text{Effective Area} = 0.7854\,m^2 - 0.1118\,m^2 = 0.6736\,m^2$$

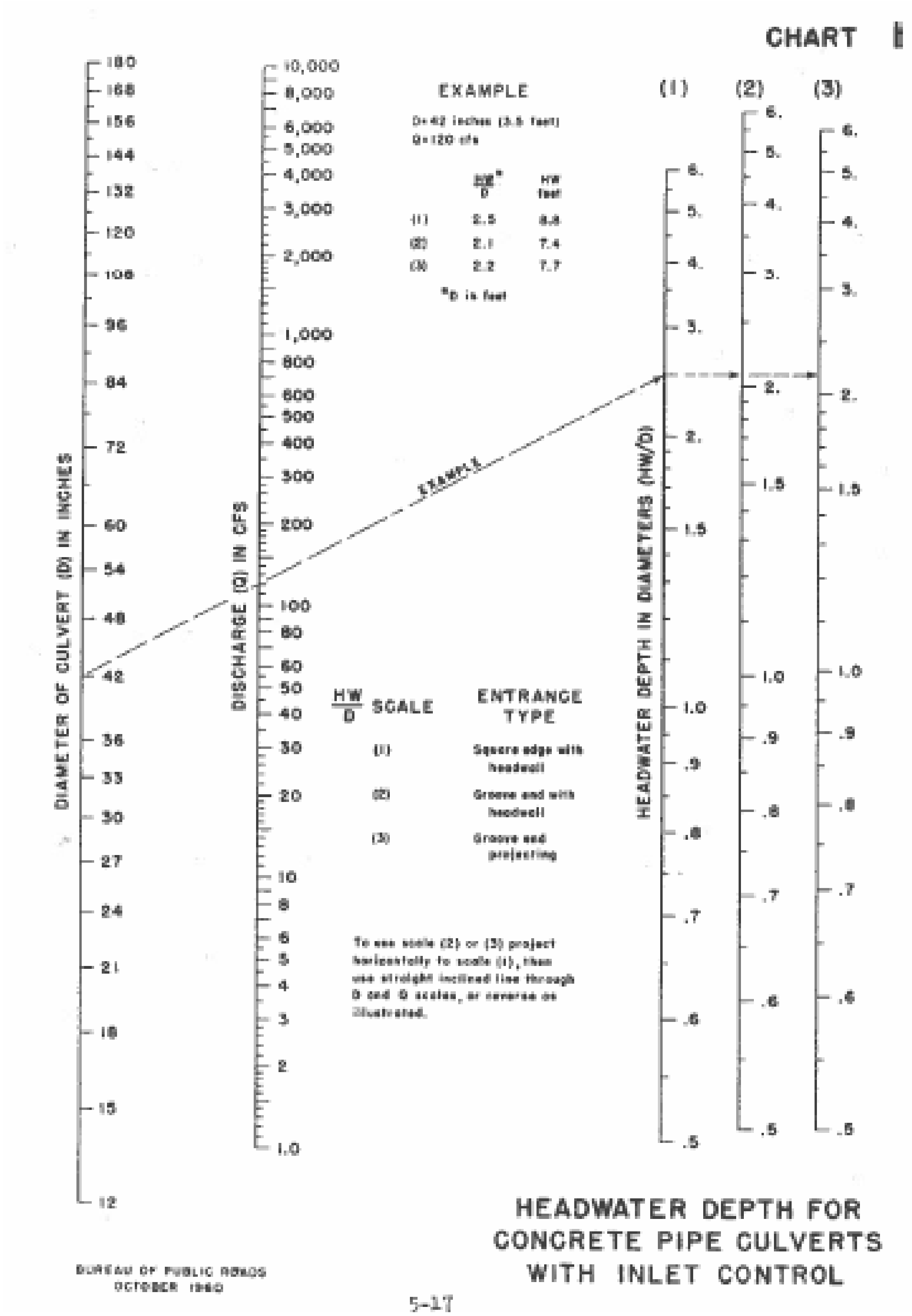
$$\text{New diameter} = 2\left(\sqrt{0.6736\,m^2/\pi}\right) = 0.9261\ m$$

Culvert area is decreased by 16.6%.

New area has a diameter 8% smaller than original diameter.

Final culvert design diameter needs to be increased by 8% to account for the area lost to riverbed material.

Appendix 3



Inlet Control nomograph for Concrete Pipe Culverts (Bureau of Public Roads, 1961)

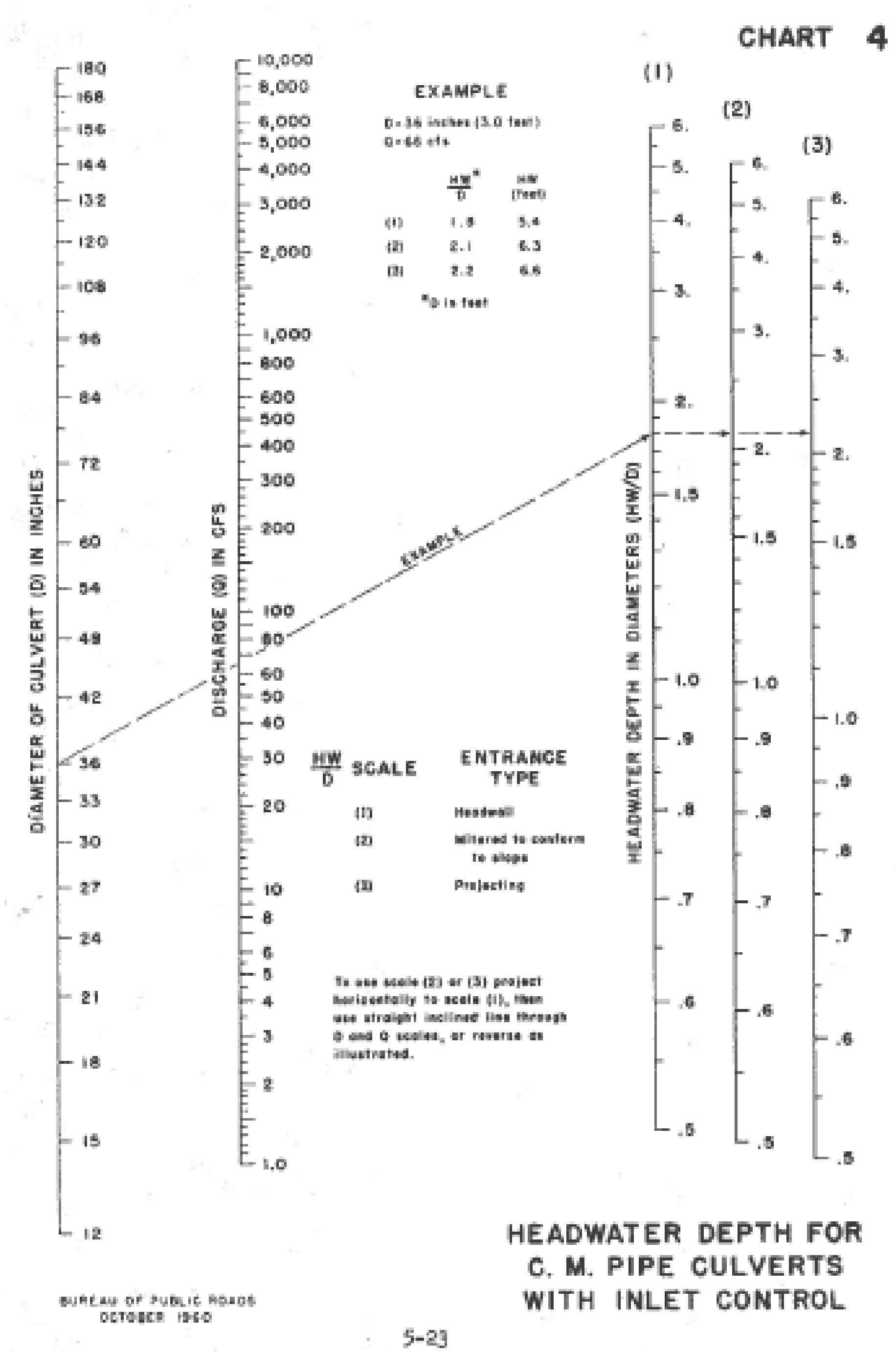


Figure 15 - Inlet Control nomograph for Corrugated Metal Culverts (Bureau of Public Roads, 1961)