APPENDIX A: Culvert Sizing procedures for the 100-Year Peak Flow

A. INTRODUCTION

Several methods have been developed for estimating the peak flood discharge that can be expected from small ungaged, wildland watersheds. These procedures are useful for determining the size (diameter) of culvert that should be installed in a stream crossing that is to be constructed or upgraded.

Determining the proper size (diameter) culvert requires: 1) estimating the peak discharge of streamflow which would occur at each stream crossing during the 100-year flood, and then 2) determining the size of culvert which would handle that flow using the Federal Highway Administration (FHWA) culvert capacity nomograph (FHWA, 1965).

A summary of selected methods, with example calculations for flood flow estimating is available from the California Department of Forestry and Fire Protection (CAL FIRE) in an "in-house" document called "Designing Watercourse Crossings for Passage of 100-year Flood Flows, Wood, and Sediment" (Cafferata et al., 2004). The document covers such techniques as the Rational Method, the USGS Magnitude and Frequency Method, and the Flow Transference Method. Each method has its strengths and weaknesses, and relies on field or map measurements, published climatic data, and subjective evaluations of watershed conditions.

Several of the methods require precipitation intensity data which are typically available from the National Oceanic and Atmospheric Administration (NOAA) website: http://dipper.nws.noaa.gov/hdsc/pfds/, or your state's water resource or forestry departments. Rainfall depth-duration frequency data are also available in published map atlases online, or in good public and college libraries. Ask for assistance from the state forest professional with jurisdiction for your area, as foresters are routinely required to perform these calculations.

A description of methodology and an example are provided for the three techniques to estimate the 100-year flood flow (Rational Method, USGS Magnitude and Frequency Method, and Flow Transference Method). It is recommended that two or three different methods be used in an area to compare and verify the results. Field experience can also be used as a check. Just remember, most of us have not been around for a 100-year flood and we naturally tend to underestimate the amount of water that is carried by streams during these extreme events.

B. CULVERT SIZING METHODS (EXAMPLES)

METHOD 1. THE RATIONAL METHOD OF ESTIMATING 100-YEAR FLOOD DISCHARGE

The most commonly used technique for estimating 100-year flood discharges from small ungaged forested watersheds is the Rational Method.

This method is based on the equation:

$$Q_{100} = CIA$$

Where: Q_{100} = predicted peak runoff from a 100-year runoff event (in cubic feet second)

C = runoff coefficient (percent of rainfall that becomes runoff)

I = uniform rate of rainfall intensity (inches/hour)

A = drainage area (in acres)

Assumptions:

1. The 100-year design storm covers the entire basin with uniform constant rainfall intensity until the design discharge at the crossing is achieved.

2. The design watershed characteristics are homogenous.

3. Overland flow. This method is less accurate or predictable as the percent impervious surface area in the watershed decreases.

4. The runoff coefficient (*C*) is constant across the watershed.

5. The 100-year storm event produces the 100-year flood flow.

Advantages:

1. Frequently used and flexible enough to take into account local conditions.

2. Easy to use if local rainfall data is available.

Disadvantages:

1. Flexibility may lead to misuse, or misinterpretation of local conditions.

2. Precipitation factor "*I*" may be difficult to obtain in remote areas.

3. Less accurate for watersheds greater than 200 acres

Information needed:

A = area of watershed (acres)

C = runoff coefficient from Table A-1

H = elevation difference between highest point in watershed and the crossing point (feet)

L = length of channel from the head of the watershed to the crossing point (miles)

I = uniform rate of rainfall intensity. Obtained from precipitation frequency-duration data for local rain gages as shown in Table A-2.

TABLE A-1. Values for Rational Method runoff coefficient (C) values

Soils	Land use or type	C value
Sandy and gravelly soils	Cultivated	0.20
	Pasture	0.15
	Woodland	0.10
Loams and similar soils without impeded horizons	Cultivated	0.40
	Pasture	0.35
	Woodland	0.30
Heavy clay soil or those with a shallow impeding horizon; shallow over bedrock	Cultivated	0.50
	Pasture	0.45
	Woodland	0.40

TABLE A-2. Example of Rainfall Depth Duration Frequency Data for Eureka, California National Weather Service Station (NWS)

Design storm (Return Period)	Maximum precipitation for indicated rainfall duration										
	5 Min	10 Min	15 Min	30 Min	1 Hr	2 Hr	3 Hr	6 Hr	12 Hr	24 Hr	C-Yr
RP 2	0.17	0.25	0.31	0.41	0.55	0.77	0.95	1.34	1.88	2.51	37.88
RP 5	0.23	0.34	0.41	0.55	0.74	1.04	1.28	1.81	2.54	3.38	47.93
RP 10	0.27	0.39	0.48	0.64	0.86	1.21	1.49	2.10	2.95	3.93	53.51
RP 25	0.32	0.46	0.56	0.75	1.00	1.42	1.74	2.45	3.44	4.59	59.83
RP 50	0.35	0.51	0.62	0.82	1.10	1.56	1.92	2.70	3.79	5.06	63.88
RP 100	0.38	0.55	0.67	0.90	1.20	1.70	2.09	2.95	4.13	5.51	67.71
RP 200	0.41	0.59	0.72	0.97	1.30	1.84	2.25	3.18	4.46	5.95	71.30
RP 500	0.45	0.65	0.79	1.06	1.41	2.00	2.46	3.47	4.86	6.49	76.06
RP 1000	0.48	0.69	0.84	1.13	1.51	2.14	2.63	3.70	5.20	6.93	78.94
RP 10000	0.58	0.83	1.01	1.35	1.80	2.55	3.13	4.42	6.21	8.28	88.75

Steps:

1. Select runoff coefficient (*C*) values: Several different publications give a range of "*C*" values for the rational formula, however, the values given in Table A-1 by Rantz (1971) appear to be the most appropriate for the woodlands and forests around Eureka, California.

2. Select a rainfall intensity (*I*) value: In selecting an "*I*" value, two factors are considered: a) the travel time or time of concentration (T_c) for the runoff to reach the crossing, and b) the precipitation conditions for the particular watershed in question.

   a. Time of concentration (T_c) can be calculated using the formula:

   $$T_c = \left[\frac{11.9L^3}{H} \right]^{0.385}$$

   Where: T_c = time of concentration (in hours)
   L = length of channel in miles from the head of the watershed to the crossing point
   H = elevation difference between highest point in the watershed and the crossing point (in feet) (where the culvert is going to be installed).

   (Note: if the value of T_c is calculated as less than 10 minutes, studies suggest you should use a default value of 10 minutes)

   b. Uniform rate of rainfall intensity.

Once the time of concentration has been determined, then that value is used to determine which rainfall duration to use (i.e., if T_c = 1 hour, then use 100-year, 1 hour precipitation duration; if T_c = 4 hours, then use 100-year, 4-hour duration). Rainfall depth duration tables similar to Table A-2 are available for precipitation stations throughout each state. For example, rainfall depth duration frequency data can be obtained from the California Department of Water Resources on-line at ftp://ftp.water.ca.gov/users/dfmhydro/Rainfall%20Dept-Duration-Frequency/. Contact your state's water resources department (or its equivalent) to obtain rainfall depth duration frequency data for your area.

Example: Rational Method used to calculate 100-year design storm

1. Area of example stream crossing watershed (A) = 100 acres.

2. Runoff coefficient (C) = 0.30 (loam woodland soil, from Table A-1)

3. Calculate the time of concentration (T_c)

$$T_c = \left[\frac{11.9L^3}{H} \right]^{0.385}$$

Where,

L = 1.8 mi., H = 200 ft.

$$T_c = \left[\frac{11.9(1.8)^3}{200} \right]^{0.385}$$

= 0.67 inches

According to Table A-2, a value of 0.67 inches corresponds to the 15-minute intensity of a 100-year return period storm event.

4. Calculate the rainfall intensity (I)

$$I = \left(\frac{0.67 \text{ in}}{15 \text{ min}} \right) \times \left(\frac{x \text{ in}}{60 \text{ min}} \right) = 2.68 \text{ in/hr}$$

5. Calculate Q_{100}

$Q_{100} = CIA$
$Q_{100} = (0.3) \times (2.68) \times (100)$
= 80.4 cubic feet per second (cfs)

METHOD 2. THE USGS MAGNITUDE AND FREQUENCY METHOD FOR ESTIMATING 100-YEAR FLOOD DISCHARGE

The USGS Magnitude and Frequency Method is based on a set empirical equations derived for six regions in the state of California for the 2-, 5-, 10-, 25-, 50-, and 100-year design flood flows. These equations were developed from the precipitation and runoff data collected from more than 700 stream gaging stations in California (USGS, 2012). For the purposes of this handbook, only the set of equations for the 100-year design flood flow are shown below:

$$\text{North Coast } Q_{100} = 48.5A^{0.866}p^{0.556}$$

$$\text{Sierra } Q_{100} = 20.6A^{0.874}p^{1.24}H^{-0.25}$$

$$\text{Desert Region } Q_{100} = 1{,}350A^{0.506}$$

$$\text{Central Coast } Q_{100} = 11.0A^{0.84}p^{0.994}$$

$$\text{South Coast } Q_{100} = 3.28A^{0.891}p^{1.59}$$

$$\text{Lahontan } Q_{100} = 0.713A^{0.731}p^{1.56}$$

Where: Q_{100} = predicted peak runoff from a 100-year storm (cubic feet second)
A = drainage area (square miles)
H = Mean basin elevation (feet)
P = mean annual precipitation (inches/year)

Assumptions:

1. The 100-year design storm uniformly covers large geographic areas.

2. The design watershed characteristics are homogenous.

3. The 100-year storm event produces the 100-year flood flow.

Advantages:

1. Equations are based on a large set of widely distributed gaging locations, including rain on snow events.

2. Easy to use.

3. Mean basin elevation is easy to determine from USGS topographic maps.

4. Mean annual precipitation data are readily available

5. Equations were updated in 2012.

Disadvantages:

1. Generalizes vast geographic areas and can result in over estimation and under-estimation at the local watershed level.

2. Less accurate for watersheds less than 100 acres. The regression equations were based on data for larger watershed areas (>100 acres), and therefore using the regression equations for smaller watersheds would result in extrapolating the Q_{100} estimate below the range of data used to develop the regression equation.

Information needed:

1. A = area of watershed (acres)

2. P = mean annual precipitation (in/year)

3. H = Mean basin elevation (feet).

Example: USGS Magnitude and Frequency Method used to calculate 100-year design storm

1. Geographic area = Sierra Nevada Region (e.g., Mohawk Ravine in Nevada County, California)

2. Area of example stream crossing watershed (A) = 445 acres or 0.7 square miles.

3. Mean annual precipitation (P) = 65 in/year

4. Mean basin elevation (H) = 4,112 feet

5. Calculate Q_{100} for the Sierra Region:

$$Q_{100} = 20.6A^{0.874}p^{1.24}H^{-0.25}$$
$$Q_{100} = 20.6(0.7)^{0.874}65^{1.24}4{,}112^{-0.25}$$
Q_{100} = 334 cubic feet per second (cfs)

METHOD 3. FLOW TRANSFERENCE METHOD FOR ESTIMATING 100-YEAR FLOOD DISCHARGE

The 100-year design flood flow can also be calculated for proposed stream crossings that are located in or nearby a hydrologically similar watershed that has a long-term gaging station. The 100-yr discharge is calculated by adjusting for the difference in drainage area between the gaged station and the ungaged site using the following equation:

$$Q_{100} = Q_{100g}\left(\frac{A_u}{A_g}\right)^b$$

Where: Q_{100u} = peak runoff from a 100-year storm at ungaged site (cubic feet per second)

Q_{100g} = peak runoff from a 100-year storm at gaged site (cubic feet per second)

A_u = drainage area at ungaged site (square miles)

A_g = drainage area at gaged site (square miles)

b = exponent for drainage area from appropriate USGS Magnitude and Frequency equation—for example, the exponent (b) = 0.87 for the North Coast USGS Magnitude and Frequency Method equation (see Method 2 above)

Assumptions:

1. Ungaged and gaged stream sites have the same geomorphic and hydrologic characteristics.

2. Long-term stream gaging data at gaged site.

Advantages:

1. More accurate than other methods if the stream gaging station is nearby and the available stream gaging peak discharge records are accurate (Cafferata et al., 2004)

2. Easy to use.

3. Local data are more likely to reflect the proposed stream crossing site's drainage basin characteristics (e.g., slopes, geology, soils, and climate).

Disadvantages:

1. Less accurate if gaging data record is less than 20 years.

2. Less accurate if used with gaged and ungaged watersheds that are in different locations or have different watershed conditions and characteristics.

Information needed:

1. A_u = drainage area at ungaged site (square miles)

2. A_g = drainage area at gaged site (square miles)

3. b = exponent for drainage area from appropriate USGS Magnitude and Frequency Method equation

Example: Flow Transference Method used to calculate 100-year design storm

1. Geographic area = North Coast (e.g., unnamed tributary in North Coast)

2. Q_{100u} = 14,000 cfs

3. Area of example gaged stream crossing watershed (A_g) = 54,000 acres or 84.4 square miles.

4. Area of example ungaged stream crossing watershed (A_u) = 300 acres or 0.47 square miles.

5. b = 0.87 – area exponent from the North Coast USGS Magnitude and Frequency equation

6. Calculate Q_{100}:

$$Q_{100} = Q_{100g}\left(\frac{A_u}{A_g}\right)^b$$

$$Q_{100} = 14{,}000 \text{ cfs} \left(\frac{0.47 \text{ sq mi}}{84.4 \text{ sq mi}}\right)^{0.87}$$

Q_{100} = 153 cubic feet per second (cfs)

C. SIZING CULVERTS USING THE FEDERAL HIGHWAY ADMINISTRATION CULVERT CAPACITY NOMOGRAPH

The Federal Highway Administration (FHWA) Culvert Capacity Nomograph is commonly used throughout the U.S. as a tool to determine the recommended culvert diameter based on calculated design stream flow and headwater depth (headwall/diameter) ratio (Figure A-1).

Once the 100-year design flood flow is determined using one or more of the methods stated previously, the steps to determine the adequate culvert size are very straight forward:

1. Determine the culvert "entrance type" from the three types illustrated in Figure A-1. Typically, most rural roads have culverts with "projecting" (barrel shaped) inlets. Other

choices include mitered or beveled inlets and culverts with headwalls.

2. Determine the "Headwater Depth Ratio" for the proposed stream crossing. The "Headwater Depth Ratio" is the ratio *HD/D* where *HD* is the headwall depth from the height of the fill where water would begin to spill out of the crossing (this could be the low point in the fill or an adjacent road ditch) to the bottom of the culvert invert (culvert bottom), and *D* is the diameter or rise of the culvert inlet. It is not recommended to design a stream crossing culvert with a *HW/D* ratio greater than 1, even though the fill may be considerably higher and a large pond could be physically accommodated.[1]

3. To size a projecting inlet culvert, place a straight edge connecting the "Headwater Depth" ratio of 1 on the "Projecting Inlet" scale at (far right scale of the nomograph) through the 100-year design flood discharge calculated for the proposed stream crossing site (see middle scale on diagram for "Discharge (*Q*) in cfs."

4. Read off the needed culvert diameter on the left scale of the nomograph.

5. For example, a stream with Q_{100} = 200 cfs, designed with a projecting inlet culvert with Headwater Depth ratio = 1 would require a 72 in diameter pipe.

1 Current recommended design standards are for culverts to accommodate a "Headwater Depth" ratio of 1, where the culvert is assumed to be over capacity if the water depth rises above the top of the culvert inlet (*HW/D* = 1). This is a conservative and protective design recommendation. Technically, most stream crossing fills have room for standing water higher, sometimes a lot higher, than the top of the culvert, but relying on high headwalls to accommodate peak flows and standing water is a risky proposition that can lead to increased risk of overtopping and crossing failure. Because most culvert plugging and exceedance is attributable to culvert plugging with woody debris and sediment, proposed *HW/D* design ratios are now proposed to be less than 1 (See Section "D" below for "Headwater Depth" suggestions for accommodating or accounting for woody debris and sediment).

D. SIZING CULVERTS TO ACCOMMODATE THE 100-YEAR DESIGN FLOOD FLOW, WOODY DEBRIS AND SEDIMENT

Typically culverts are sized to only accommodate the 100-year design flood flow. Some landowners and land managers desire to design stream crossing culverts to accommodate expected sediment and organic debris in transport in addition to meeting the requirements for passing 100-year peak flows. This is especially important in unconfined and confined stream channels that transport a lot of woody debris and sediment during flood flows.

One proposed methodology for accomplishing this includes designing culvert size based on 0.67 headwall-to-culvert diameter ratio (*HW/D*), instead of the 1.0 *HW/D* that is typically applied (Cafferata et al., 2004). This often results in culverts that are 12 in. diameter larger than would be required to pass the 100-year peak flood flow. Another method to reduce the potential for culvert plugging by sediment and organic debris is to size culverts based on bankfull channel width, either by using oval or arch culverts, or by employing oversized round culverts that match or exceed mean bankfull channel width (Flanagan and Furniss, 2003). This is often employed when designing embedded culverts for fish passage (NMFS, 2001). A third method to account for plugging potential (and which PWA generally employs) is to apply secondary treatments, such as flared inlets or trash barriers, at culverted stream crossings judged to have a higher than normal likelihood of culvert plugging.

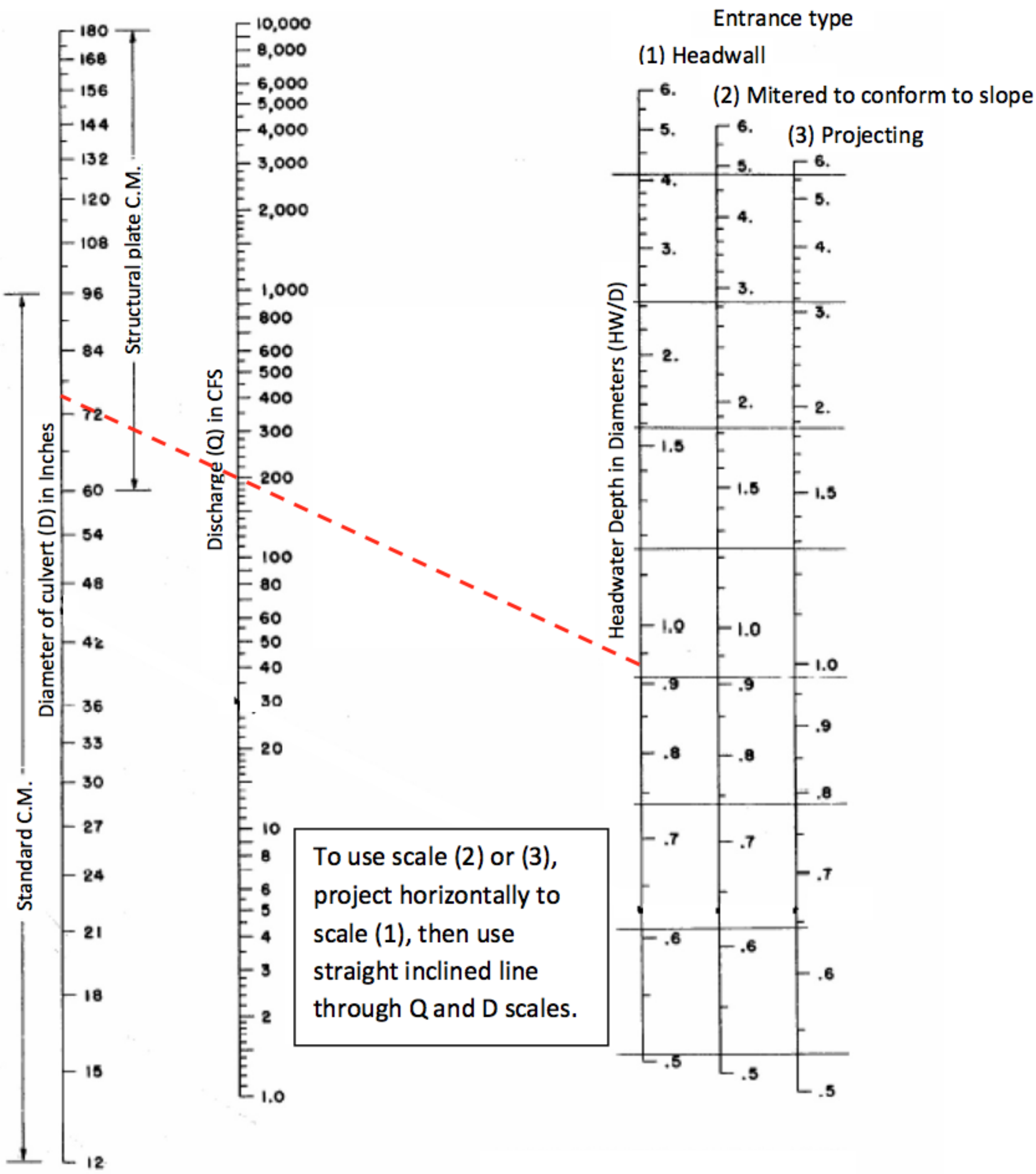

FIGURE A-1. *FHWA Culvert Capacity Inlet Control Nomograph.*

E. REFERENCES

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NOTES: