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ESTIMATING STREAMFLOWS ON SMALL FORESTED WATERSHEDS FOR CULVERT AND BRIDGE DESIGN IN OREGON

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INTRODUCTION

Culvert and bridge failures during large storms on forest lands can cause serious environmental and economic damage. In order to avoid these problems, Oregon's Forest Practice Rules require that wherever these structures are used as water crossings, they must be designed to handle flows from large storms (Adams 1984). Specifically, the installations must at least allow for flows from storms having a "25-year frequency"—major storms that occur, on the average, only once every 25 years.

How is the 25-year or greater stormflow estimated for a specific stream crossing? A variety of approaches have been used, many based on simplified calculations (for example, the "Rational Method"—see American Iron and Steel Institute 1983) or local judgment, or both. In some cases, culverts and bridges are grossly under- or over-designed, despite the needless damage or expense that often results. Such approaches continue to be used because they are usually easy to apply and because suitable alternatives have often been unavailable or not widely known.

This Bulletin describes another approach for estimating peak stormflows on small forested watersheds in Oregon. It involves the use of prediction equations based on years of flow data collected on numerous small streams throughout most of the state. The equations should provide reasonable estimates of peak streamflows for specific locations, with a minimum of time and effort.

DEVELOPING THE EQUATIONS

Local streamflow records provide a sound basis for predicting peak flows for culvert and bridge design; such records were assembled from 73 gauged streams in Oregon and 7 in northern California. The 80 stations were selected primarily because (1) they had at least 10 years of flow records, (2) the watersheds were largely forested, and (3) the watersheds and streams were relatively small.

Most of the gauged streams had between 10 and 20 years of flow records, and the records for all of the stations ranged from 10 to 52 years. Watershed area ranged from 0.21 to 10.6 square miles. Only 12 of the watersheds were larger than 5 square miles, and most of these were in eastern Oregon where there were relatively few gauged watersheds. Nine watersheds were less than 50 percent forested, and most others were at least 80 percent so.

Oregon's climate and hydrology are diverse. Peak flows west of the Cascade Range, for example, normally occur in fall or winter when large frontal storms move in from the Pacific Ocean. In eastern Oregon, annual peak flows usually occur during spring snowmelt, although winter frontal and summer convective storms, if extreme, can sometimes produce peak flows.

Records from the 80 stream stations were thus stratified among six hydrologic regions to produce relatively homogeneous databases (Fig. 1). The four regions in western Oregon were previously defined in a similar study (Harris et al. 1979); climate and topography were used to define the two regions in eastern Oregon. A large area of eastern Oregon was left undefined because of the limited number of suitable gauged and forested watersheds, although data from other stations in this area have been used in a related study (Harris and Hubbard 1983).

Annual peak flows for the stations in each of the six regions were evaluated by a chi-square goodness-of-fit test to determine which of

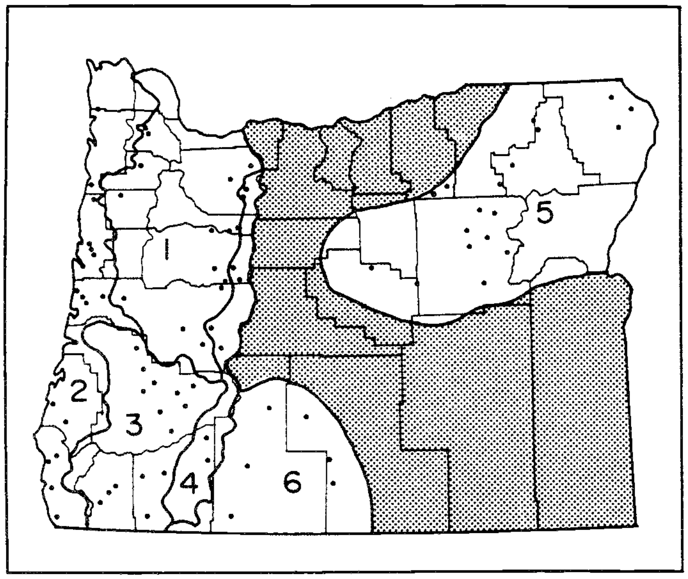

FIGURE 1.

STREAM GAUGING STATIONS AND REGIONS USED TO DEVELOP PREDICTION EQUATIONS FOR PEAK FLOWS ON SMALL FORESTED WATERSHEDS IN OREGON.

several flood-frequency data distributions best fit the data. None proved superior, so the widely accepted and normally reliable log-Pearson type III distribution was used to calculate the flows with 25-, 50-, and 100-year return intervals for the gauged streams (Kite 1977).

A stepwise regression analysis was then used to develop regional prediction equations relating the calculated peak flows to selected characteristics of the gauged watersheds (McCuen et al. 1977, U.S. Water Resources Council 1981). These characteristics included watershed area, mean watershed elevation, gauge elevation, main channel slope, main channel length, percentage of forest cover, mean annual precipitation, 2-year 24-hour precipitation, mean minimum January temperature, latitude, and longitude. The final equations were selected on the basis of the added contribution of each variable and the mean square error at each step. The average percentage of error was also calculated as the difference between the peak flows determined from the log-Pearson distribution and those predicted from the equation.

THE PREDICTION EQUATIONS

Only a few of the measured watershed characteristics were strongly related to peak streamflows in the six regions (Table 1). Drainage area was the most important variable related to peak flows in all regions, and in three regions it was the only significant variable. Relationships between drainage area and streamflow are intuitively logical and often encountered in conventional approaches to estimating streamflow.

Mean basin elevation was also significant in the prediction equations for the Coast region. Pronounced increases in precipitation with increasing elevation often occur in the region because of the orographic cooling of moist air masses that move in from the Pacific Ocean. Relationships between elevation and streamflow could also be strengthened by the fact that soil depths become shallower at higher elevations.

In the Cascade region, mean annual precipitation was significantly related to peak flows. This is another reasonable relationship, and the resulting prediction equations are statistically among the strongest. The limited number of stations (nine) used to develop the equations, however, suggests that additional data could result in somewhat different equations or additional variables.

Although watershed area was clearly related to peak flows in the Rogue-Umpqua, Klamath, and Blue-Wallowa regions, the resulting equations had relatively low correlation coefficients and high standard errors of estimate. The limited number, distribution, and duration of gauging stations in these regions are likely sources of these weaknesses. The hydrology of these regions and origins of local peak flows may also be less homogeneous and more complex than initially expected.

TABLE 1.

EQUATIONS FOR PREDICTING PEAK FLOWS WITH 25–, 50–, AND 100–YEAR RETURN INTERVALS ON SMALL FORESTED WATERSHEDS IN OREGON.

Region and prediction equation[a]	R^2	Average error (percent)	Range of data used to develop equations[b]
Coast			
$Q_{25} = 6.31\ A^{1.01}\ E^{0.51}$	0.83	26	A: 0.3–2.6 E: 260–2800
$Q_{50} = 7.77\ A^{1.01}\ E^{0.50}$	0.79	26	
$Q_{100} = 8.40\ A^{1.00}\ E^{0.50}$	0.78	26	
Willamette			
$Q_{25} = 156\ A^{0.80}$	0.87	24	A: 0.4–5.2
$Q_{50} = 183\ A^{0.80}$	0.87	24	
$Q_{100} = 212\ A^{0.80}$	0.86	24	
Cascade			
$Q_{25} = 0.032\ A^{0.44}\ P^{1.97}$	0.86	16	A: 0.2–8.0 P: 50–88
$Q_{50} = 0.063\ A^{0.45}\ P^{1.87}$	0.81	22	
$Q_{100} = 0.111\ A^{0.46}\ P^{1.78}$	0.71	27	
Rogue–Umpqua			
$Q_{25} = 163\ A^{0.77}$	0.46	53	A: 0.8–6.4
$Q_{50} = 191\ A^{0.80}$	0.50	49	
$Q_{100} = 221\ A^{0.82}$	0.53	47	
Klamath			
$Q_{25} = 41.9\ A^{0.79}$	0.56	52	A: 1.0–10.6
$Q_{50} = 54.5\ A^{0.77}$	0.59	47	
$Q_{100} = 69.6\ A^{0.75}$	0.61	64	
Blue–Wallowa			
$Q_{25} = 67.6\ A^{0.47}$	0.36	48	A: 0.3–6.9
$Q_{50} = 85.2\ A^{0.48}$	0.35	52	
$Q_{100} = 105\ A^{0.50}$	0.34	56	

[a] Q_T = peak flow (ft^3/s or cfs) of T–year recurrence.
A = drainage area (mi^2).
E = mean basin elevation (ft).
P = mean annual precipitation (in.).

[b] Equations should be used only with data in this range.

USING THE EQUATIONS

Several important points should be kept in mind when using the prediction equations in Table 1. The first is that the data for the watershed of interest should fall within the range of values used to develop the prediction equation (last column in Table 1). Estimated peak flows derived from values outside these ranges are, at best, of questionable reliability. Similarly, the equations should be used only for watersheds that are predominantly forested and have natural flow regimes. Other equations are available for larger or non-forested watersheds (Harris et al. 1979, Harris and Hubbard 1983).

Watershed data entered into the equations should originate from consistent and accurate procedures like those used in the study. Reliable and detailed aerial photos and topographic maps should be used with a planimeter or suitably scaled overlay grid to determine watershed area. Mean basin elevation can be accurately estimated with a grid by averaging the elevations at each intersection, provided that the selected grid spacing gives at least 25 intersections within the basin boundary. For the Cascade region, mean annual precipitation on a watershed should be obtained from isohyetal maps used in the study (Oregon Water Resources Board 1958, 1959, 1961, 1971, U.S. Weather Bureau 1964a). A portion of a similar map is reproduced in Appendix 1.

The summary statistics in Table 1 suggest that the reliability of estimated peak flows will vary according to the equation used. Because most of the basic flow records extended fewer than 20 years, the equations for 25-year return-interval flows should be more reliable than those for 50-year flows. Furthermore, most records from gauging stations included the effects of the unusually large 1964 storm (considered an event with a 50- to 100-year return interval), and the inclusion of the latter may cause the 25- and 50-year flows to be somewhat overestimated.

The regression analysis indicates that most confidence can be placed in the prediction equations for the Willamette, Coast, and Cascade regions. Although the equations for the other regions would be expected to be less reliable, their foundation in actual data still provides a distinct advantage over rules of thumb or outdated empirical approaches for estimating peak flows.

Because of the limited site-specific data used in the equations, it is always important to inspect the area for any unusual watershed characteristics that could prompt an adjustment of the predicted peak flow. For example, a predicted peak flow might be adjusted upward for a watershed with unusually shallow soils. On the other hand, a stream draining a relatively level, swampy area might justify a decrease in the estimated flow. The average percentages of error (Table 1) can provide a reasonable indication of how much a predicted value might be raised or lowered, although expert help may be needed to maximize the accuracy and confidence of such judgments.

Additional details and discussions on the development and use of the prediction equations can be found elsewhere (Campbell et al. 1982, Campbell and Sidle 1984). These references should be particularly useful for refining and improving the equations as more streamflow data become available.

CULVERT SIZING

Before using the equations to predict peak flows (Table 1) for culvert sizing, you must ask an important question, i.e., during the expected life of a culvert, what chance of a peak flow greater than the design flow are you willing to accept? Or more specifically, if you have a drainage structure that has an expected life of 25 years, what probability of exceeding the design flow are you willing to accept over this period? Your answer to this question will have a great effect upon the size of culvert that you ultimately select.

For example, if culverts for a given road system are designed to handle a 25-year flow, nearly 65 percent of them would be expected to experience a flow larger than a 25-year event sometime within the next 25 years; half of them would be expected to experience a flow greater than a 25-year event within 17 years. However, if a 30 percent risk of exceeding the design flow over the 25-year period is what you would accept, then the culverts should be designed for about a 71-year peak flow.

The return period associated with a specific expected life and risk of exceeding a given design flow can be calculated from the following equation:

$$T_r = \frac{1}{1 - (1 - p)^{1/n}}$$

where

T_r = return period of design flow

p = probability or risk of exceeding the specified design flow over the expected life of the culvert

n = expected life of the culvert.

The level of risk you select depends on a wide range of factors. These might include the potential for downstream damage should failure occur, the importance of the road to the overall transportation system, construction standards for fill material, expected maintenance, etc. Once you decide what level of risk is acceptable, then the prediction equations in Table 1 provide a means of calculating a specific design flow.

In many cases (depending on the level of risk specified), the design flow will need to be interpolated from the results of the equations in Table 1. For example, assume you would like to find the size of culvert needed to handle a 71-year flow (based on a 25-year expected life and a 30 percent risk of exceeding the design flow during that period) for a 130-acre (0.20 square mile) watershed in the Oregon Cascade Range. Assume further that the watershed annually receives an average of 56 inches of precipitation. Inserting these values into the appropriate equations (Table 1) gives

$$Q_{25} = 0.032(0.20)^{0.44} (56)^{1.97} = 44 \text{ cfs}$$

$$Q_{50} = 0.063(0.20)^{0.45} (56)^{1.87} = 57 \text{ cfs}$$

$$Q_{100} = 0.111(0.20)^{0.46} (56)^{1.78} = 68 \text{ cfs}$$

These calculated flows are then graphed (Appendix 2); the 71-year peak flow of 63 cfs is found on the graph. This flow is then used with the nomograph in Appendix 3 to determine culvert sizing. In this example, a 48-inch-diameter culvert is needed (assuming a headwater depth, in culvert diameters, of 1.0) to handle a 71-year flow. This design provides a 70 percent chance that the culvert will not have its capacity exceeded during its expected life of 25 years. Of course, if another level of risk is specified or the headwater depth is altered, a different pipe size may be needed. For example, had you accepted a design based on the 25-year peak flow for this stream (along with its 65 percent chance of exceeding the design flow in 25 years), a 42-inch pipe would have been adequate.

As described, the risk of exceeding the design flow is an important consideration during the design of road drainage structures. Similarly, for many forest streams, the appropriate headwater depth to be used will also have a major effect upon culvert sizing. For example, many forest streams carry floatable organic debris that can partially block a culvert inlet. Even small blockages can cause large reductions in the hydraulic efficiency of the inlet. Using a headwater depth of less than 1.0 (e.g., 0.7 to 0.9) during the design procedures in order to allow for improved passage of floatable organic debris at high flows provides an extra level of protection. Regular and emergency inspection and maintenance programs can also be invaluable for avoiding major problems (Adams 1983).

Finally, where large (greater than 72 in.) or non-round pipes are needed or other extreme conditions exist, expert engineering assistance should be sought. Professional help with culvert design and installation may also be needed to ensure resource protection and legal compliance on fish-bearing streams.

CONCLUSIONS

Adequately designed culverts and bridges can help avoid damaging and costly failures during large storms on forest lands. The equations presented here should provide reasonable estimates of 25-, 50-, and 100-year flows to guide these designs on small forest watersheds in Oregon. Watershed data entered into the equations should be carefully collected, and only those data that fall within the range of values used to develop the equations should be used. Predicted peak flows can be adjusted upward or downward when warranted by local conditions revealed by an on-site inspection or by a change in the acceptable risk of exceeding the design flow of a structure.

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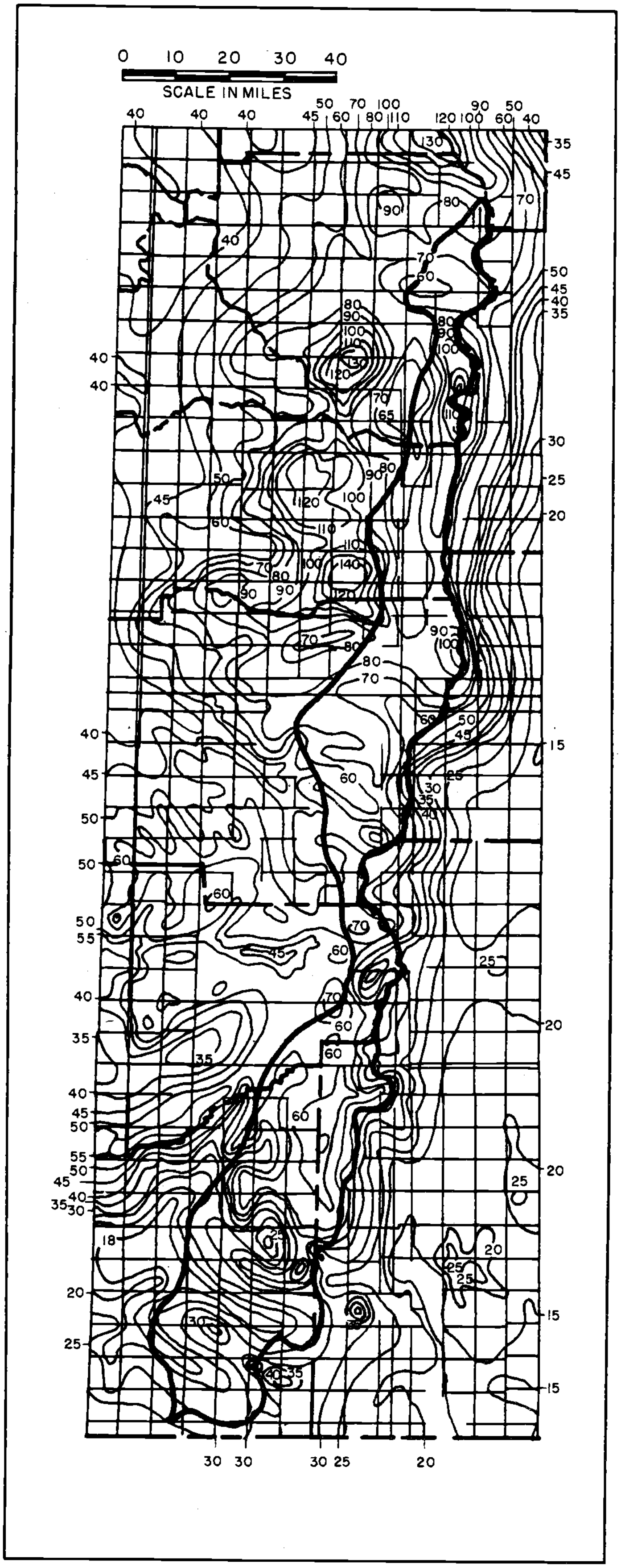
British/Metric Conversion

1 inch (in.) = 2.54 centimeters (cm)
1 foot (ft) = 30.48 cm
1 square mile (mi^2) = 2.59 square kilometers (km^2)
1 cubic foot/second (ft^3/s or cfs) = 0.028 cubic meters/second (m^3/s)

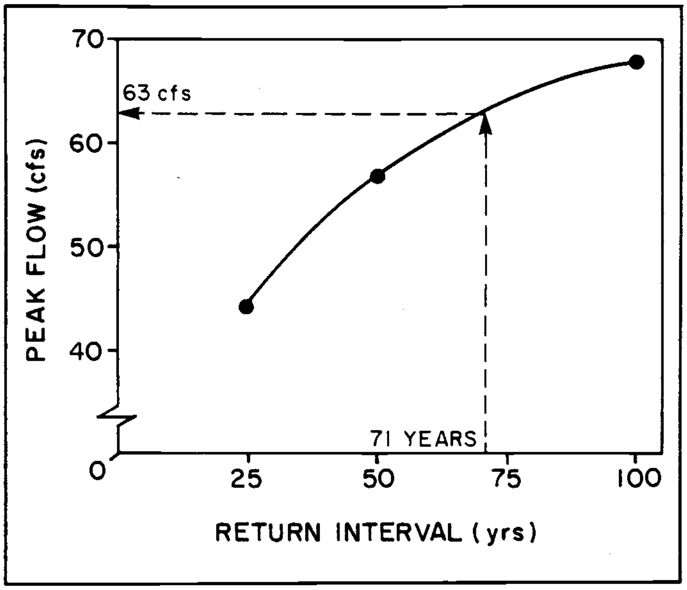
APPENDIX 1



APPENDIX 1

Mean annual precipitation (inches) for Cascade Region. (Adapted from U.S. Weather Bureau 1964b.) See Figure 1 for general location.

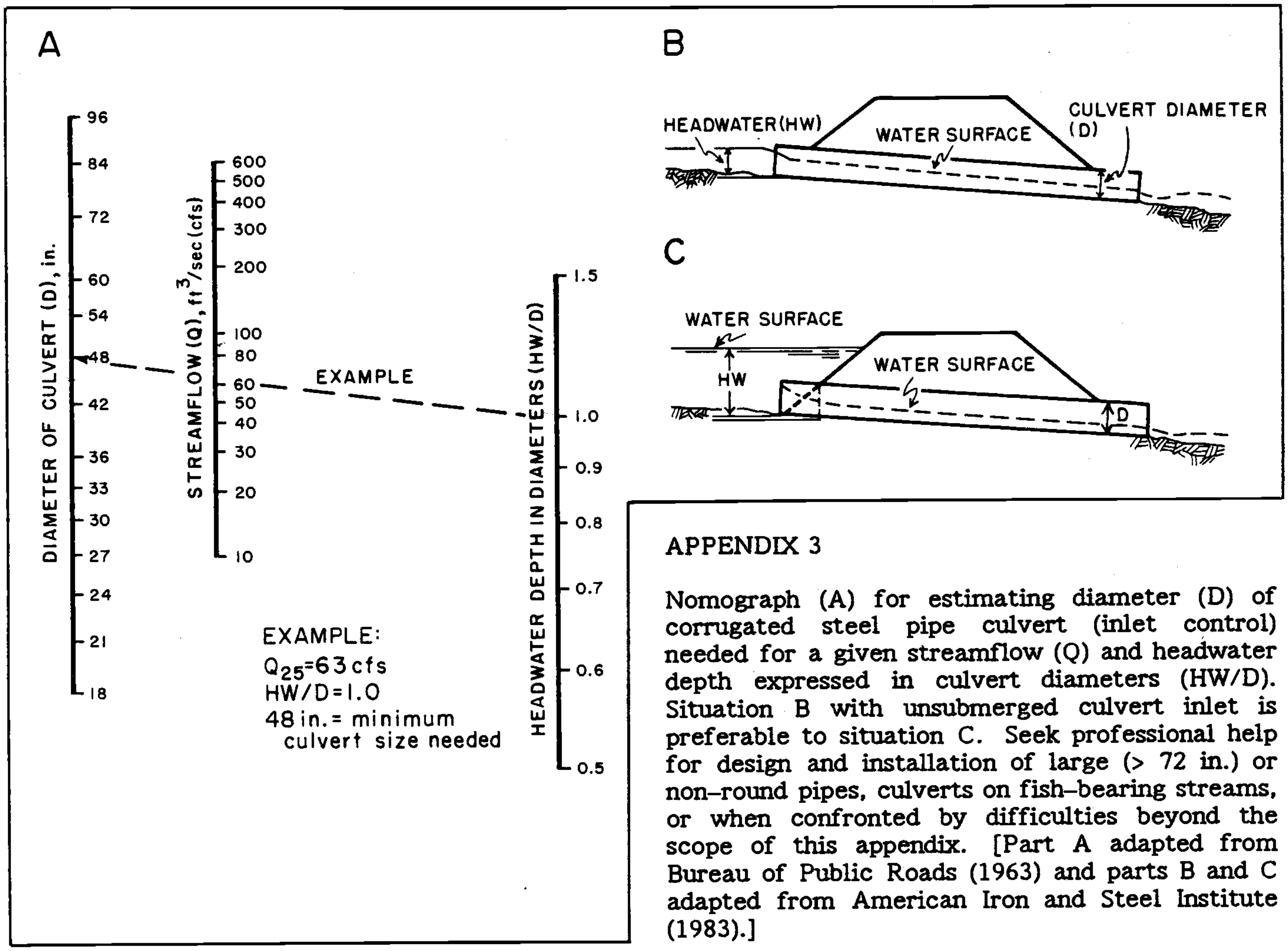
APPENDIX 2



APPENDIX 2

Relationship between peak streamflow and return interval for example described in text.

APPENDIX 3



APPENDIX 3

Nomograph (A) for estimating diameter (D) of corrugated steel pipe culvert (inlet control) needed for a given streamflow (Q) and headwater depth expressed in culvert diameters (HW/D). Situation B with unsubmerged culvert inlet is preferable to situation C. Seek professional help for design and installation of large (> 72 in.) or non-round pipes, culverts on fish-bearing streams, or when confronted by difficulties beyond the scope of this appendix. [Part A adapted from Bureau of Public Roads (1963) and parts B and C adapted from American Iron and Steel Institute (1983).]

ADAMS, P.W., A.J. CAMPBELL, R.C. SIDLE, R.L. BESCHTA, and H.A. FROEHLICH. 1986. ESTIMATING STREAMFLOWS ON SMALL FORESTED WATERSHEDS FOR CULVERT AND BRIDGE DESIGN IN OREGON. Forest Research Laboratory, Oregon State University, Corvallis. Research Bulletin 55. 8 p.

Streamflow records were combined with basic watershed data from 80 small forested basins to develop equations for predicting peak flows in Oregon. Area of drainage basin was most strongly and consistently related to streamflows, while mean basin elevation and mean annual precipitation were also related to flows in areas of western Oregon. The equations can be used with these and other site-specific data and risk assumptions to help design adequate culverts and bridges.

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