CULVERT FLOW IN SMALL DRAINAGES IN MONTANE TROPICAL FORESTS: OBSERVATIONS FROM THE LUQUILLO EXPERIMENTAL FOREST OF PUERTO RICO

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ABSTRACT: This paper describes the hydraulics of unsubmerged flow for 5 culverts in the Luquillo Experimental Forest of Puerto Rico. A general equation based on empirical data is presented to estimate culvert discharge during unsubmerged conditions. Larger culverts are needed in humid tropical montane areas than in humid temperate watersheds and are usually appropriate only for drainages less than 1 km^2. However, since culvert size is an exponential function of flow frequency, the cost of designing for 25-year flows is not appreciably greater than the costs associated with culverts based on 10-year flows.
KEY TERMS: Montane tropical forests; culverts; open-channel hydraulics.

INTRODUCTION

Culverts are conduits that convey streamflow under roadways and other obstructions. Because their hydraulics are well understood, culverts can also be used as weirs to obtain accurate discharge measurements (U.S. Federal Highway Administration, 1985). Their use is especially appropriate for watershed studies in wet tropical montane environments where annual peak discharges can overtop standard weirs and financial resources are usually unavailable for the design and installation of custom weirs.

When culverts are used for discharge measurements, concise knowledge of stage-discharge relationships during unsubmerged flow is required. However, most culvert relationships are designed to estimate the maximum allowable discharge and are based on submerged or nearly submerged flow regimes. This paper details the hydraulics of unsubmerged flow for 5 culverts in the Luquillo Experimental Forest (LEF) of Puerto Rico that have been adapted for the measurement of discharge. In addition, design criteria for selecting culverts are discussed.

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STUDY AREA

The present study was conducted on three experimental watersheds in the Bisley sector of the LEF of Puerto Rico (Lat.18°18'N. Long.65°50' W.). The physiography and land-use history of the area have been described elsewhere (Scatena, 1989). In general, these 6.3 to 10-ha watersheds drain a mature secondary forest in a subtropical wet forest life zone. Average annual rainfall typically ranges between 3500 and 4500 mm. Streams draining into the culverts have steep gradient, incised, boulder lined channels.

The five circular culverts studied here pass beneath the same gravel-bedded road and are within 250 m of each other (Table 1). Two of the culverts (1 and 2) are on separate streams while 3 culverts (3-1, 3-2, and 3-3) are parallel to each other on a third stream. All of the culverts are constructed of concrete and have cast-in-place headwalls and outlets. Each culvert has a projecting entrance and an elevated outlet that discharges into a concrete and boulder lined plunge pool. Because of the elevated outlets, the culverts flow with unsubmerged outlets at all but very extreme discharges.

Table 1. Characterické of Bisley Culverts, Luquillo Experimental Forest, P.R.

Culvert	Entrance Diameter (m)	Length (m)	Invert Elevation (m)
1	0.91	7.23	262
2	0.91	8.67	267
3-1	1.25	11.71	266
3-2	1.25	11.64	266
3-3	1.30	11.73	266

The channel thalweg at the invert is below the baselevel for all five culverts. For culverts 1 and 2, sidewalls have been constructed to confine the flow and act as settling basins for bedload sediment and organic debris. These basins are cleaned periodically and not only function to keep the culvert control section clear but also act as traps of bedload material.

METHODS

Velocity measurements were made with Price-type pigmy meters in areas of steady, uniform flow at or within the culvert entrance. Each discharge measurement used in the analysis was an average of three, one minute measurements. Flow depth and width were measured with a carpenters ruler.

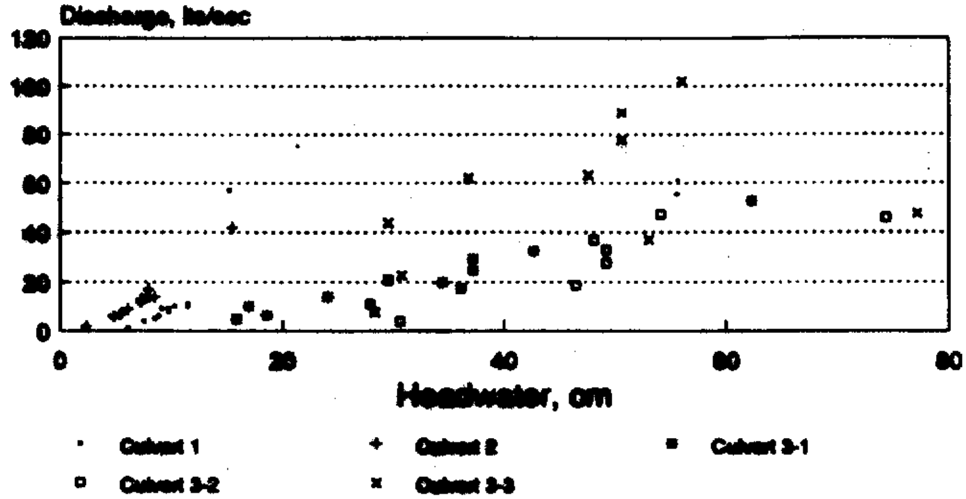

Figure 1. Headwater-discharge relationships for Bisley culverts, Luquillo Mountains, Puerto Rico.

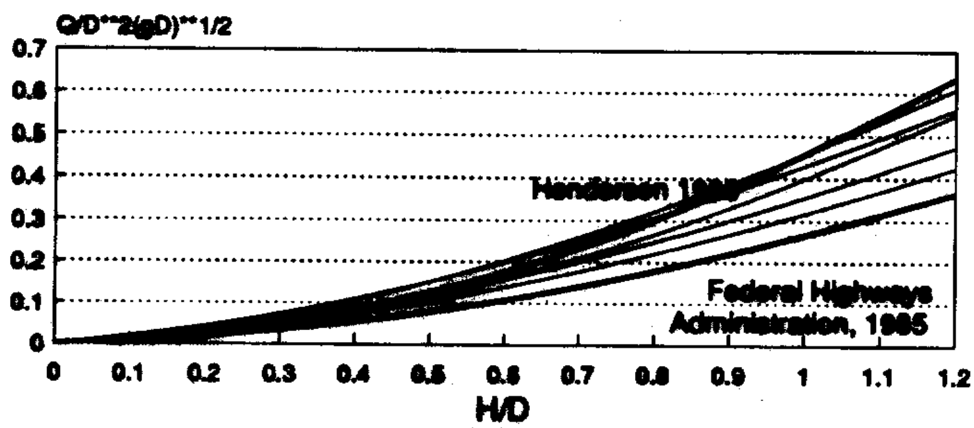

Figure 2. Dimensionless performance curves for Bisley culverts, Luquillo Mountains, Puerto Rico.

Small streams in the study area that drain basins with similar geologic conditions have similar flow frequencies (Fig 3). Regression analysis of Log-Pearson Type III frequency curve values for 2, 10, 25, and 100-year peak discharges indicates that drainage area and annual precipitation were the only charactericts that were significant in predicting peak discharge (Lopez et al., 1979). Peak discharge estimated by the recommended regional equations (Lopez et al., 1979) solved for a mean annual precipitation of 4000 mm is slightly larger than the average values computed from Log-Pearson Type III analysis of 6 streams draining the Luquillo Experimental Forest (Quinones et al., 1984).

The culvert sizes for a given discharge computed from equation 3 are similiar to those estimated by standard culvert tables (Table 3). In general, size increases rapidly for design periods greater than 40 years or drainage areas larger than 1 km^2 (Fig 4). Since circular culverts are rarely built larger than 3.0 m in diameter, they are only appropriate in this region for drainages smaller than 1 km^2. Larger drainages will require pipe-arch or bridge type openings.

Based on the design criterion of HW/D = 1 for 10-year flow peaks, a 3.1 m culvert is needed for a 50 ha forested drainage area. However, for 25-year peaks, a 3.4 m culvert is needed. Generally, selecting a culvert on the basis of 25-year rather than 10-year peaks will not greatly increase total cost and should be done whenever possible.

Table 3. Culvert size (m) for various 40 ha (100 ac) forested watersheds. 1: Based on Helvey and Kochenderfer (1988) and assumes 2% slope, HW/D = 1, and unsubmerged outlet. 2: Based on eq 3. of this study. 3: Based on tables in Douglass (1974) computed from Hydraulic Engineering Circulars No. 5 and No. 10.

Recurrence Interval (yr)	Fernow W.Va.1	Leading Ridge Pa.:1	Hubbard Brook N.H.:1	Luquillo P.R.: 2	Luquillo P.R.: 3
10	0.66	0.71	0.86	2.9	2.3
20	0.71	0.81	1.02	3.1	>2.5
50	0.86	1.02	1.22	3.5	

The size of culverts needed to pass a flow of a given frequency is larger in the Luquillo mountains than for small forested watersheds in humid temperate climates (Table 3). Considering the high intensity rainfall associated with tropical storms, these increases in culvert size are reasonable.

CONCLUSIONS

During unsubmerged flow conditions, water level measurements in culverts can provide accurate estimates of stream discharge for small watershed studies. However, these culverts should have inlet controlled flow at all expected discharges, and individual stage-discharge relationships should be developed for both submerged and unsubmerged flow conditions. A general equation (eq. 3) is presented to estimate culvert discharge based on $HW/D < 1$. The equation is consistent with published experimental and theoretical work and can be used to estimate culvert size needed to pass flows of given return frequencies.

In general, larger culverts are needed in tropical wet montane areas compared to humid temperate watersheds. However, since culvert size is an exponential function of flow frequency and increases rapidly for return periods greater than 25 years, the cost of designing for 25-year flows is not appreciably larger than the costs of designing for 10-year peak flows.

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