AN ABSTRACT OF THE THESIS OF

Stephen P. Levesque for the degree of Master of Science in Forest Engineering presented on June 19, 1998. Title: Evaluation of Culvert Condition and Road Closure Methods in Southern Southeast Alaska.

Abstract approved: Brian W. Kramer

Brian W. Kramer

Because of their potential for adversely affecting aquatic resources, increased rates of erosion and sedimentation associated with low-volume forest roads have recently gained the attention of land managers in the Pacific Northwest. For example, on the Tongass National Forest in Southeast Alaska, there is an urgent need to explore the interaction of roads with existing hydrologic and geomorphic processes.

The design and maintenance of drainage structures are often of major importance for preventing environmental impacts from forest roads. The primary objective of this study was to evaluate the condition of culverts in order to address current maintenance and road closure strategies within the Ketchikan Area of the Tongass National Forest.

A total of 671 drainage structures associated with 40 road segments were examined during the summer of 1997. The population of corrugated metal pipes consisted of 552 ditch-relief and 119 stream-crossing structures. Culvert condition was evaluated based on changes in the cross-sectional area of the culvert barrel reduced by damage or blockage. Overall, 47% of drainage structures were operating with at lest a 10% reduction in culvert end area. Structural damage was the most frequent reduction mechanism observed (34%),

closely followed by the accumulation of sediment (23%) and woody debris (21%) at the culvert inlet.

There was no significant difference in culvert condition for open and closed roads where culverts have been left in place and native vegetation has been allowed to become established on the road prism. The analysis suggests that landscape characteristics such as topographic location are commonly associated with the observed reductions in culvert end area. Loss of culvert end area appears to trigger a disturbance cascade, often resulting in the diversion of surface water past the culvert inlet and subsequent fluvial erosion.

Master of Science thesis of Stephen P. Levesque presented on June 19, 1998.

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Stephen P. Levesque, Author

Evaluation of Culvert Condition and Road Closure Methods in Southern Southeast Alaska

by

Stephen P. Levesque

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DEDICATION

This thesis is dedicated in memory of my father,

Philip Dodge Levesque.

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EVALUATION OF CULVERT CONDITION AND ROAD CLOSURE METHODS IN SOUTHERN SOUTHEAST ALASKA

INTRODUCTION

Forest roads dissect the rugged, island landscapes of the Tongass National Forest in Southeast Alaska. Though road location, design, and construction practices have certainly improved, there remains a history of past practices and an intense debate over appropriate methods for effective road management. Much of the attention to date has focused on effects related to the interaction of roads and existing hydrologic and geomorphic processes (Hicks et al., 1991; Furniss et al., 1996; Wemple et al., 1996). Understanding the effects of these interactions is critical to the maintenance of natural disturbance regimes and is essential for sustaining freshwater habitats of anadromous and resident salmonids (Resh et al., 1988; Reeves et al., 1995).

Land managers in the Pacific Northwest recognize that stream-crossing and ditch-relief structures commonly represent loci of ongoing and impending impacts to aquatic resources (Furniss et al., 1996). These road-related impacts generally result from the concentration of both runoff generated on road surfaces and intercepted subsurface discharge (Montgomery, 1994). Alterations to local hydrologic regimes are potentially manifested as changes in sediment production, streamflow patterns, and the distribution of fish species (Harr et al., 1975; Beschta, 1978; Fowler et al., 1988). Although road surface and ditch erosion are common geomorphic effects, increased rates of fillslope failure have also been observed (Burroughs, 1984; Krag et al., 1986; Swanson et al., 1987).

Ecologically sound road management strategies need to address natural disturbance processes and minimize hydrologic interactions with road prisms. Where hydrologic pathways are not accounted for through the maintenance of proper road drainage, accelerated rates of hillslope erosion have often been attributed to damaged or plugged culverts (Dyson et al., 1966; Best et al., 1995). For example, restriction of the culvert inlet can lead to surface or gully erosion by water flowing on the road; saturation and catastrophic failure of the road prism; or water continuing down the ditch, to be diverted by the next culvert (Piehl et al., 1988). The connectivity of road and stream networks is another factor to consider. Recent research indicates that roads may extend stream networks and increase routing efficiency (Wemple et al., 1996). Consequences of these effects are difficult to evaluate or accurately predict because they are dependant on site-specific conditions, storm magnitude, fill characteristics, flowpaths, and proximity of a sediment producing event to valuable forest resources (Furniss et al., 1996).

In forested mountainous terrain, culverts are the most common structure employed where roads cross streams and for the maintenance of proper road drainage on hillslopes. Stream-crossing and ditch-relief structures are essential components of the design, operation, and maintenance of forest transportation systems (Donahue and Howard, 1987; Kramer, 1993). To reduce the risk of impacting forest resources, land managers have developed road maintenance and road closure strategies based on the anticipated use of forest roads.

On the Tongass National Forest in Southeast Alaska, the U.S. Forest Service has a legacy of "closed" roads where culverts remain in place and native vegetation has become established on the road prism. These roads are generally assigned a Maintenance Level 1, may be of any type, class, or construction standard, and are managed to prohibit and eliminate traffic. A Maintenance Level 1 category indicates custodial maintenance activities are generally performed to prevent significant damage to adjacent resources. However, while these roads are placed in storage, planned road deterioration may occur. Other situations require that the road be stabilized to preserve the road prism and/or to reduce erosion, then closed between use cycles (U.S.D.A. Forest Service, 1987).

Research conducted in the Pacific Northwest suggests that current road closure or storage methods may not effectively maintain culvert condition and ensure proper road drainage (Burroughs, 1984). Unfortunately, a review of the literature yielded only a few articles describing the condition of culverts on low-volume forest roads (Dyson et al., 1966; Piehl et al., 1988; Best et al., 1995) and no published accounts from Southeast Alaska. Because road related effects are sensitive to local conditions (Reid and Dunne, 1984), it may not be appropriate to assume research conducted in California, Oregon, and Washington is directly applicable to mountainous terrain in Southeast Alaska.

The primary objective for this study was to evaluate and compare the condition of stream-crossing and ditch-relief culverts associated with open and closed roads managed by the U.S.D.A Forest Service in Southeast Alaska. Culvert condition was evaluated based on changes in the cross-sectional area of the culvert barrel reduced by damage or blockage. A secondary objective included an investigation of the mechanisms responsible for any observed reductions in cross-sectional area. In addition, an analysis of design characteristics that optimize culvert performance and reduce potential for diversion or erosion was undertaken.

STUDY AREA

Road systems selected for this study are located within the Ketchikan Area of the Tongass National Forest in Southern Southeast Alaska (Figure 1). The historical pattern of road network development in the Ketchikan Area has been similar to other federal lands of the Pacific Northwest and was closely linked with providing access to valuable timber resources (Wemple, 1994). The extent to which forest roads weave through the landscape has been largely influenced by terrain conditions and the technology available for timber harvest at the time of road design and construction (Figure 2). Currently, the extension and development of road networks to facilitate timber harvest on the Ketchikan Area continues, but at a rate far below historical levels.

The climate and weather of Southeast Alaska is dominated by North Pacific pressure cells that produce strong winds and large amounts of precipitation when they meet the rugged coastline. Average annual precipitation ranges from 229 cm at lower elevations to more than 508 cm at higher elevations, with October generally the wettest month. Much of the landscape of Southeast Alaska has been shaped by glaciation and is characterized by wide U-shaped valleys interspersed with mountain. Soil development is strongly influenced by high levels of rainfall, cool maritime temperatures, and moderately low annual soil temperatures. Organic debris decomposes slowly, resulting in a thick layer of organic matter on the forest floor. This organic layer has an important role in minimizing the

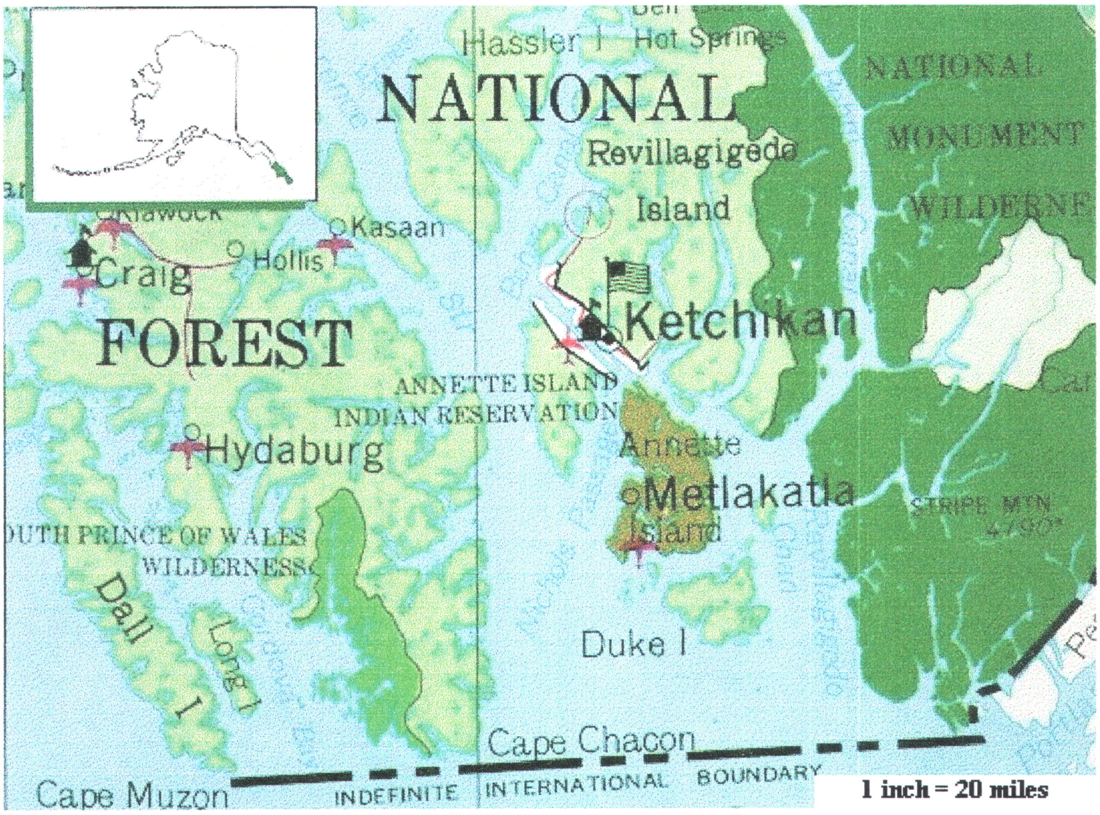


Figure 1. Study area located on the Ketchikan Area of the Tongass National Forest, Southern Southeast Alaska.

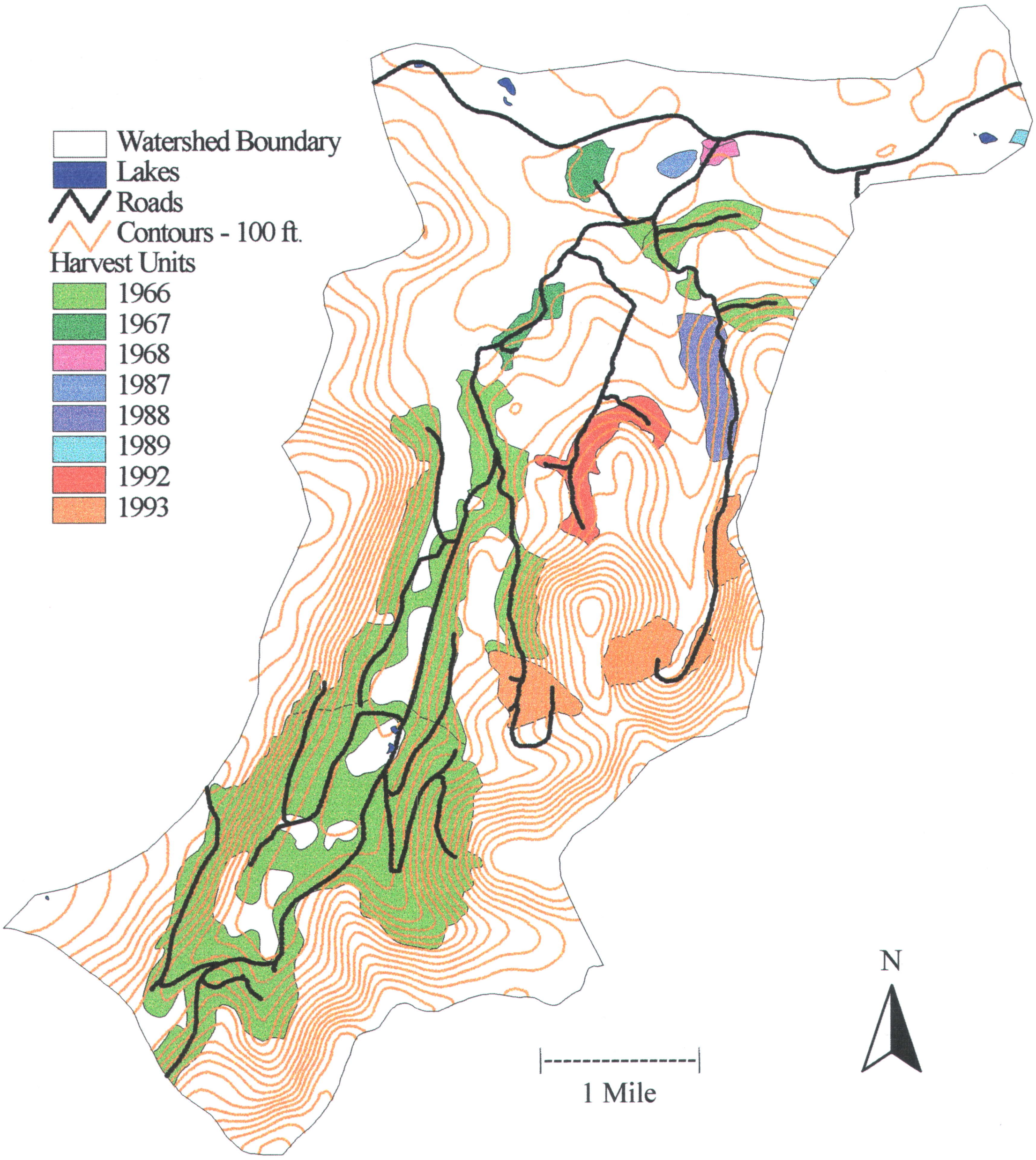


Figure 2. Timber harvest history and road network expansion for the Rio Beaver Watershed, Prince of Wales Island.

exposure and consequent erosion of the underlying mineral soils. Surface erosion and mass wasting are most likely to occur are along streambanks, ravines, and avalanche tracks. Landslides, windthrow, and flooding are the dominant disturbance processes.

METHODS

Five road networks were selected for study within the Ketchikan Area of the Tongass National Forest (Figure 3). The Shoal Cove network is on Revillagegedo Island and Lancaster, Rio Beaver, Sal Creek, and North Thorne are located on the larger Prince of Wales Island. Roads systems selected for study ranged in age from 5 to 30 years. U.S. Forest Service records (i.e., road logs) that delineated individual road segments and culvert locations by milepost were obtained for each road system. This information was used in conjunction with the Ketchikan Area's Geographic Information System (GIS) database to determine topographic location (valley bottom versus hillslope), average road grade (percent slope), and total length (kilometers) for each road segment.

Preliminary field reconnaissance was also required to determine road status. Road segments were considered "closed" if access was restricted by a man-made barrier, bridge removal, or the establishment of vegetation on the road prism. Roads without such restrictions were categorized as "open." Evaluations of culvert condition were restricted to road segments greater than 0.8 km in length. With the exception of Shoal Cove, the entire population of culverts on each road segment was evaluated during the 1997 field season.

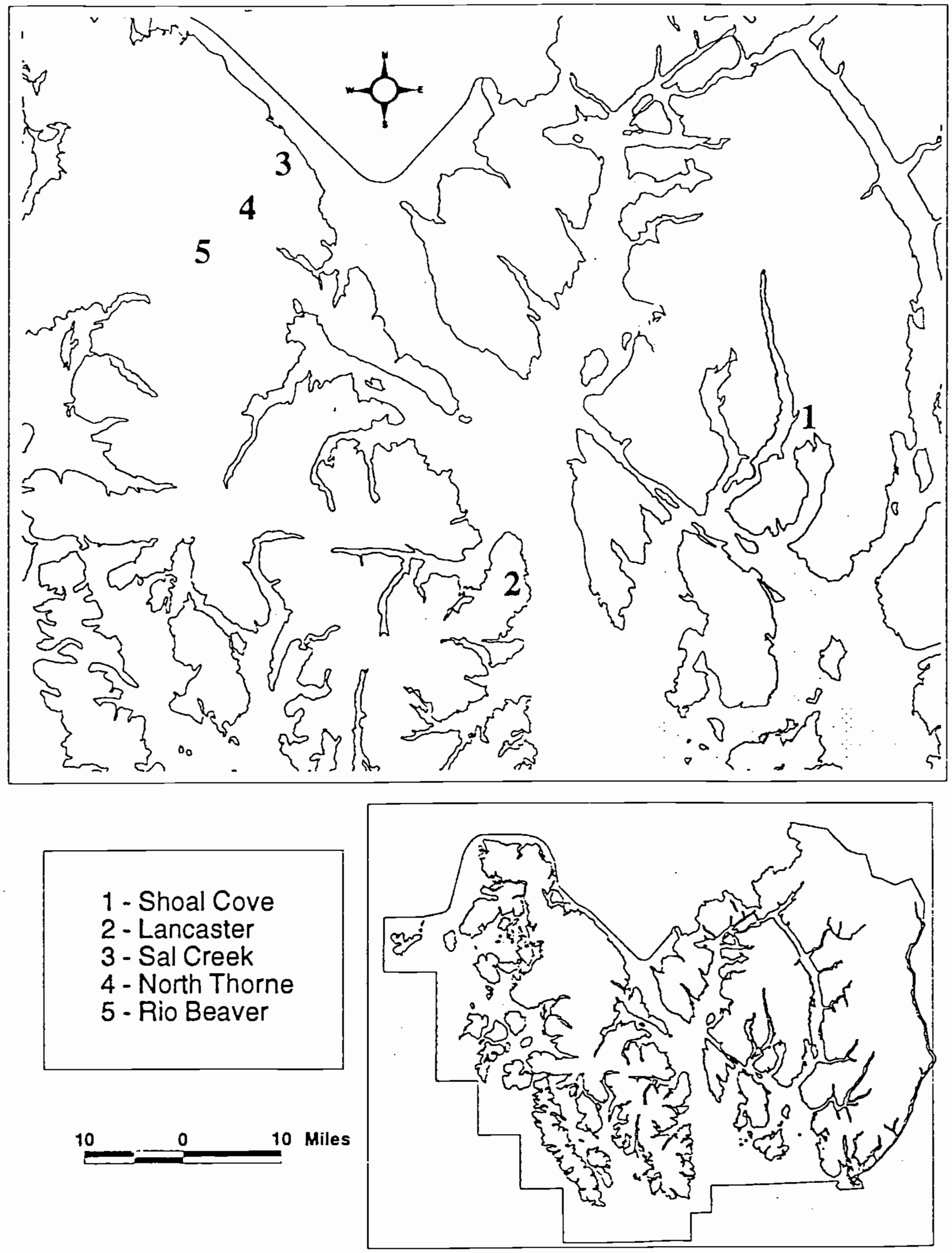


Figure 3. Road systems selected for study on the Ketchikan Area of the Tongass National Forest.

At Shoal Cove, a subset of the road system (representing 50% of the total) was evaluated. Ditch-relief and stream-crossing culverts were characterized by diameter (cm), length (m), grade (%), spacing (m), skew angle (°), and rustline width (cm). Culvert diameter was measured at the inlet of the pipe and recorded in centimeters while length was measured to the nearest tenth of a meter.

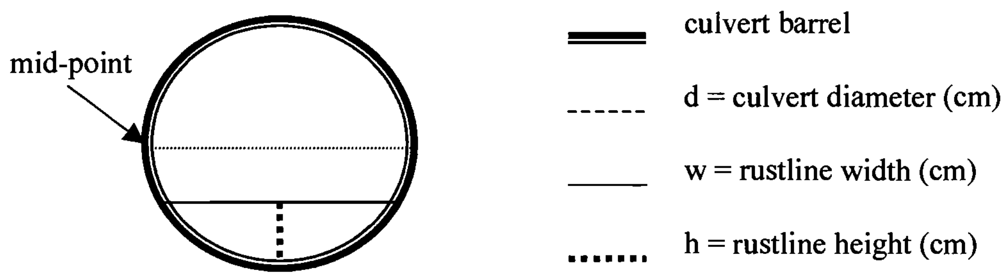
Inlet and outlet elevation measurements were obtained with a stadia road and hand level. Culvert slope then calculated from the difference in elevations and culvert length. Spacing was calculated by dividing the number of drainage structures (ditch-relief and stream-crossing) per segment by the total road segment length.

A compass was used to determine the skew angle at which culverts intersected the road prism. As the skew angle decreases, flowing water must turn sharply to enter the culvert inlet, resulting in greater potential for diversion water past an inlet and the accumulation of woody debris or sediment (Piehl, 1988). Where culverts are installed perpendicular to the road prism their efficiency to pass water, sediment, or woody debris through the inlet is likely at a minimum.

Peak width of the rustline was measured one culvert diameter in from the outlet of the culvert. Rustlines generally develop in galvanized steel culverts after a few years in response to moisture and water chemistry. For most installations, flows corresponding to the dimensions of the rustline are roughly equated to winter base flows. In assessing the risk of crossing failure, Furniss et al. (1996) have observed that the relationship between the rustline height and culvert diameter may be a good indicator of hydraulically undersized drainage structures. Simplified equations were developed from Pyles (1998) to calculate rustline height from the rustline width measurements obtained in the field. Two equations were required to account for rustlines measured below and above the mid-point or spring-line of the culvert barrel (Figure 4).

Visual estimates were used to determine the percent cross-sectional culvert end area lost due to damage or blockage. Where restriction of the barrel exceeded 10%, one of the following potential failure mechanisms: structural damage, sediment accumulation, woody debris blockage, or the accumulation of unstable fillslope or cutslope material was assigned.

Presence or absence of diversion at the culvert inlet was assessed for each drainage structure. "Diversion" was defined as the redirection of surface water past a culvert inlet. Thus, the flow of water into a culvert installation for proper routing through the road prism is less likely to occur, particularly during larger storms. Where diversion was observed at a culvert inlet, an attempt was made to identify either the road surface or the drainage ditch as the receiving feature. In cases where evidence of diversion was observed but the receiving feature could not be clearly defined, the presence of diversion potential was recorded.
The identification of sediment sources was not a direct objective of this study, however, the presence of fluvial erosion was recorded if observed at culvert inlets. No attempt was made to quantify the volume of material eroded from the road surface or associated ditch.



(a)

$$h = (d/2) - \sqrt{(d/2)^2 - (w/2)^2}$$

(b)

$$h = (d/2) + \sqrt{(d/2)^2 - (w/2)^2}$$

Figure 4. Rustline height equations used to account for rustline width measurements taken (a) below and (b) above the mid-point of the culvert barrel.

RESULTS AND DISCUSSION

A total of 671 drainage structures associated with 40 road segments were evaluated during the summer of 1997. Although not distributed evenly throughout the five road systems, the 105.7 total road kilometers consisted of nearly equal lengths of hillslope and valley bottom categories (Table 1 and Figure 5). The population of corrugated metal pipes consisted of 552 ditch-relief and 119 stream-crossing structures. The frequency of culvert diameters is dominated by 46 and 61 cm (18 and 24 in) ditch-relief culverts; the smaller population of stream-crossing culverts accounts for half of the 89 cm (36 in) diameter class and all the culverts 122 cm (48 in) in diameter and greater (Figure 6).

Culvert Condition Associated with Open and Closed Forest Roads

The majority of culverts inventoried (59%) were located on "closed" roads that accounted for half the total kilometers of road surveyed (Table 1). Road management regimes and closure methods varied for each road system (Figure 7).

Culvert condition was evaluated by expressing restrictions to the cross-sectional end area of the culvert barrel as a percent of the original cross-sectional end area. For each road segment and culvert diameter class, the number of culverts with end area reductions of at least 10% and 25%, was identified. Nearly, half the population of sampled culverts was operating at or below 90% of original culvert end area (Figure 8).

Inferential statistics were employed to test the hypothesis that current road closure methods would result in a lower percentage of culverts operating at optimal

Table 1. Drainage structures inventoried on the Ketchikan Area of the Tongass National Forest by topographic location and road status.

		Road Status		
Topographic Location	Parameter	Closed	Open	Totals
Hillslope	Road length (km)	24.8	27.4	52.2
	Ditch-relief culverts	182	136	318
	Stream-crossing culverts	15	25	40
	Bridges or log culverts	1	0	1
Valley Bottom	Road length (km)	28.8	24.7	53.5
	Ditch-relief culverts	144	90	234
	Stream-crossing culverts	35	44	79
	Bridges or log culverts	9	12	21
Totals	Road length (km)	53.6	52.1	105.7
	Ditch-relief culverts	326	226	552
	Stream-crossing culverts	50	69	119
	Bridges or log culverts	10	12	22
Grand Totals	Drainage structures	386	307	693
	Corrugated metal pipes	376	295	671

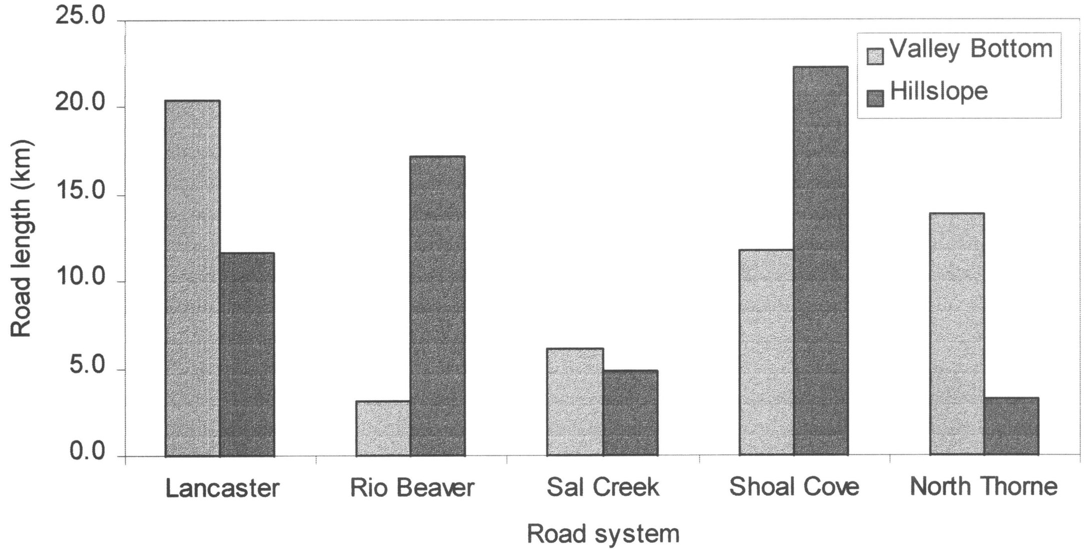
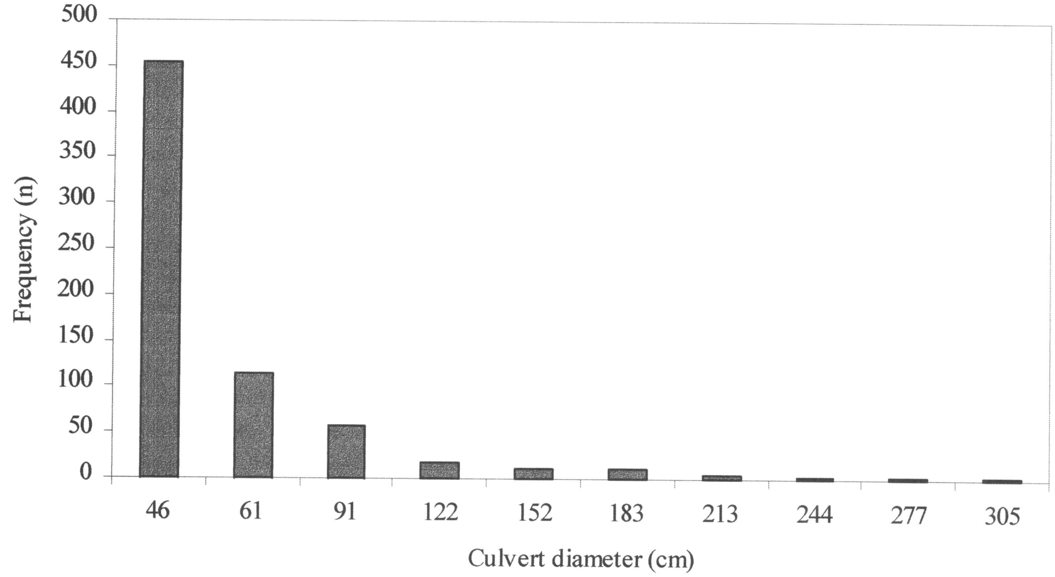


Figure 5. Kilometers of valley bottom and hillslope locations by road system.

(a)



(b)

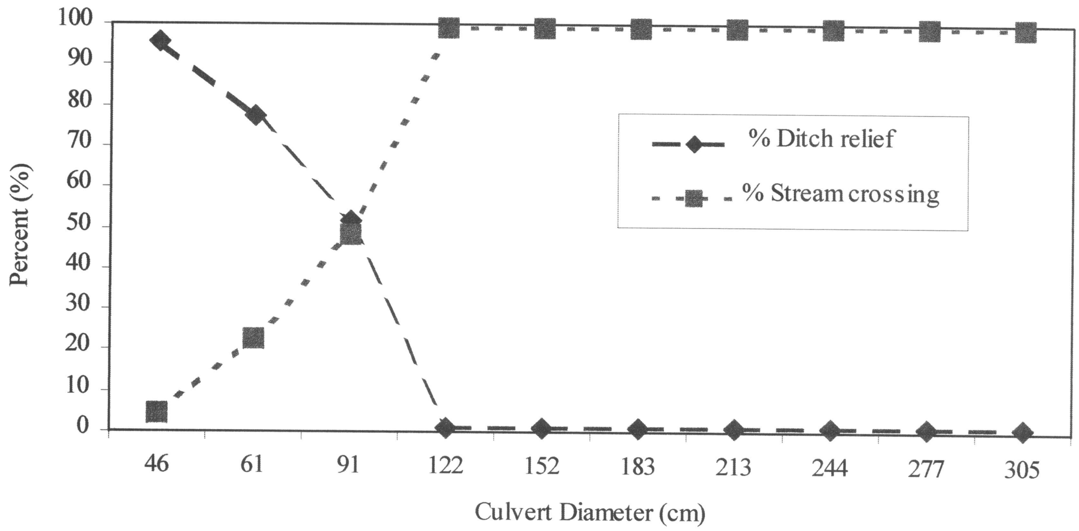


Figure 6. (a) Culvert frequency for all culverts (n=671) and (b) relative frequency of ditch-relief (n=552) and stream-crossing culverts (n=119), by diameter class.

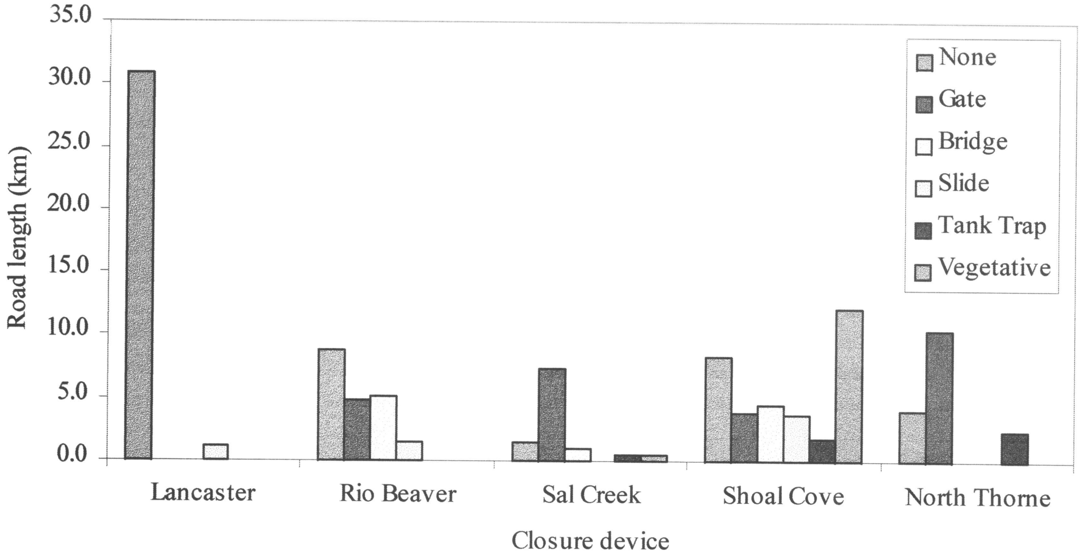


Figure 7. Road status and closure devices by road system

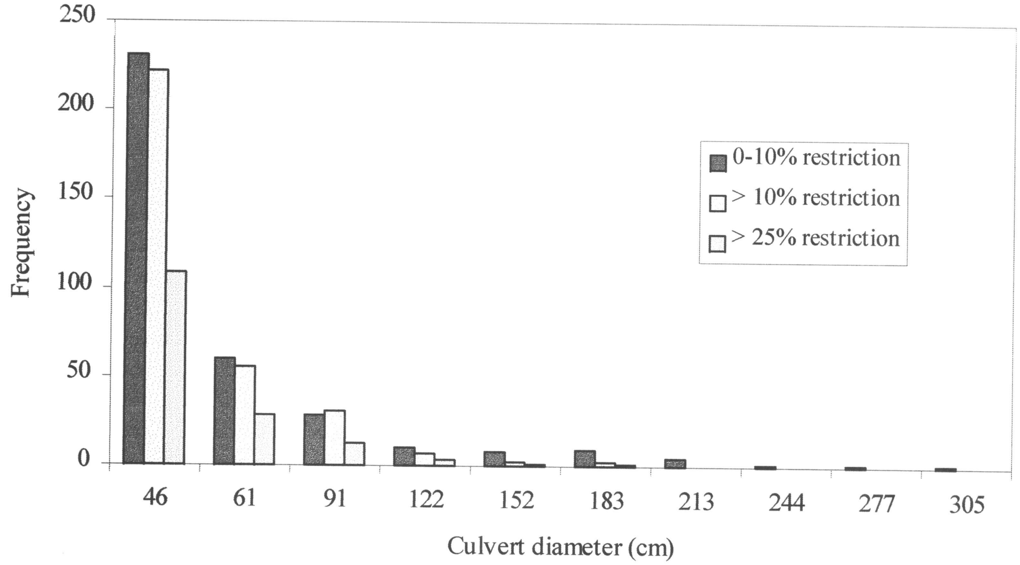


Figure 8. Condition of ditch-relief and stream-crossing culverts expressed as a function of culvert end area restrictions.

relative to those associated with open roads. Two sample t-tests conducted on the road segment data did not detect a significant difference between culvert condition for open and closed roads at the 95% confidence level. Additional t-tests also failed to detect a significant difference (p-value < 0.05) between the percentage of ditch-relief and stream-crossing culverts with observed reductions in end area for valley bottom and hillslope roads.

Further statistical testing of the road segment data was conducted with the aid of step-wise logistic regression. This analysis method was selected because the binomial response variable allows the model to account for variation in the numbers of culverts sampled on each road segment (Hosmer and Lemeshow, 1989). The response variable used for the regression model was the number of culverts per segment operating with at least a 10% reduction in the cross-sectional area of the culvert barrel. Explanatory variables included road status (i.e., open or closed), topographic location (i.e., valley bottom or hillslope), road grade, culvert spacing, and stream density. Topographic location was the only significant variable at the 95% confidence level. The model estimates that the number of culverts with reductions in cross-sectional area is 1.8 times greater for hillslope than valley bottom roads (95% confidence interval from 1.3 to 2.4).

$$\ln Y = \underset{(0.12)}{-0.43} + \underset{(0.16)}{0.59} * X_1$$

Y = number of culverts per segment with a 10% reduction in end area
X_1 = topographic location, where 1 = hillslope
P-value < 0.01
n = 40 road segments
Note: standard errors displayed in parentheses

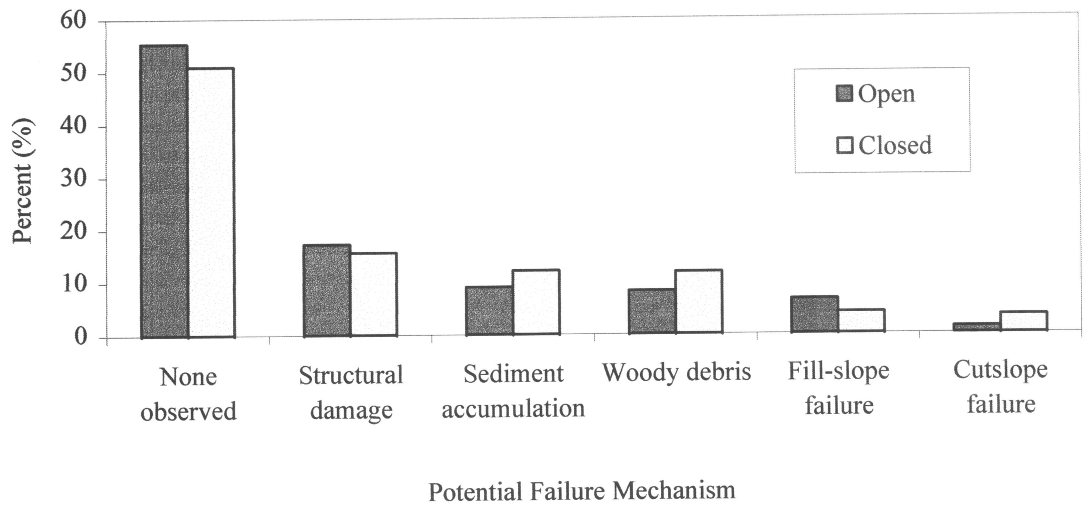
Results of both analyses suggest there is no detectable difference in culvert condition, expressed as a reduction in cross-sectional area, between open and closed roads. Closer inspection of the data reveals that while 49% of the culverts sampled on closed roads were operating with less than 90% of their original areas, open roads did not fare much better with 45% of those culverts in a similar state.

Frequency of Culvert End Area Reduction Mechanisms

To investigate potential mechanisms responsible for observed reductions in cross-sectional end area, the population of 46 and 61 centimeter culverts was selected for analysis. Large sample size and common function make this group ideal for study. Out of the 566 culverts included in this population, 299 were operating with more than 90% of their original cross-sectional end area. On the remaining 267 culverts, structural damage was the most frequent reduction mechanism observed (34%), closely followed by the accumulation of sediment (23%) and woody debris (21%). Blockage resulting from unstable fillslope and cutslope material made up a relatively small fraction of the observed mechanisms (10% and 6% respectively). Beaver activity attributed to six of the observed reduction mechanisms.

Field observations led to speculation that the effects of vegetative road closure would be reflected in changes to the relative frequency of culvert end area reduction mechanisms (Figure 9a). It was hypothesized that the establishment of vegetation onto the road prism and a lack of maintenance would increase the number of culverts with

(a)



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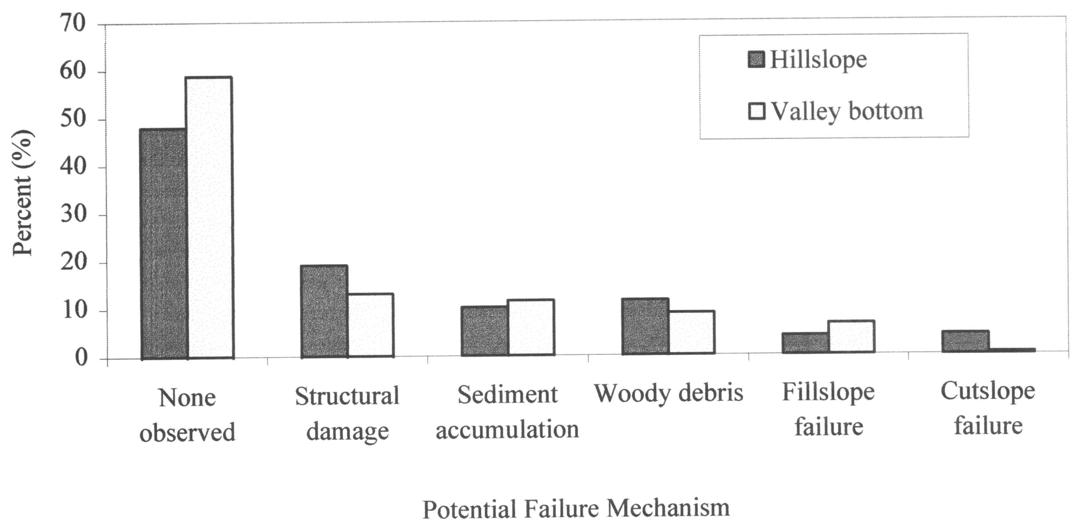

Figure 9. Relative frequency of culvert end area reduction mechanisms for (a) road status and (b) topographic position.

restrictions due to the accumulation of sediment and woody debris. However, Chi square tests performed to determine if the distribution of restriction mechanisms was influenced by road status were not significant (Table 2a). Additional Chi square tests conducted to evaluate the effects of topographic location were significant (Table 2b.). The Chi square values suggest a shift in the relative frequency of reduction mechanisms for hillslope and valley bottom roads, primarily due to the variation in observed cutslope failures between valley bottom and hillslope roads (Figure 9b).

Design Characteristics and Culvert Performance

To avoid failure, ditch-relief and stream-crossing culverts must successfully pass water, organic debris and sediment. Ensuring that this occurs requires an effective road design and maintenance strategy that recognizes and manages local interactions. In an effort to further describe the effects and design factors associated with culvert restriction, multiple logistic regression was used to analyze the population of 46 and 61 cm culverts. To determine whether observed reductions in culvert end area could be explained using field measurements, explanatory variables included in the analysis were road status, topographic location, road grade, culvert slope, skew angle, rustline height to diameter ratio, and culvert length. For culverts operating with less than 90% of their original end area, topographic location and the ratio of rustline height to culvert diameter were significant at the 95% confidence level. The model indicates that the odds of a 10% reduction in culvert end area

Table 2. Chi square results testing the relative frequency of culvert end area reduction mechanisms for (a) road status and (b) topographic position.

(a)

		Potential Failure Mechanisms					
	Road Status	None Observed	Structural Damage	Sediment Accumulation	Woody Debris	Fillslope Failure	Cutslope Failure
X^2 value	Open	0.29	0.14	0.70	1.00	0.98	1.53
	Closed	0.22	0.10	0.53	0.76	0.74	1.16

$$P (X^2_6 > 8.15) < 0.23$$

(b)

		Potential Failure Mechanisms					
	Topographic Position	None Observed	Structural Damage	Sediment Accumulation	Woody Debris	Fillslope Failure	Cutslope Failure
X^2 value	Valley Bottom	1.42	1.43	0.11	0.45	0.84	3.95
	Hillslope	1.66	1.67	0.12	0.52	0.98	4.61

$$P (X^2_6 > 17.77) < 0.01$$

were 1.8 times greater for hillslope than for valley bottom roads (95% confidence interval from 1.3 to 2.6). The results also provide evidence that the ratio of rustline height to culvert diameter may be a good indicator of culvert efficiency. Where the rustline height to diameter ratio was greater than 0.25, the odds of a 10% loss in culvert end area increased 1.9 times (95% confidence interval from 1.3 to 2.9). In severe cases, where the rustline height was equal to half the culvert diameter, the odds nearly quadrupled (3.8, 95% confidence interval from 1.7 to 8.4).

$$\ln Y = \underset{(0.16)}{-0.69} + \underset{(0.17)}{0.61} * X_1 + \underset{(0.81)}{2.67} * X_2$$

Y = probability of a 10% reduction in culvert end area, %
X_1 = topographic location, where 1 = hillslope
X_2 = rustline height to diameter ratio, cm/cm
P-values < 0.01
n = 566 culverts (46 and 61 cm diameter)
Note: standard errors displayed in parentheses

Analysis of landscape and road design characteristics was repeated for the population of culverts operating with less than 75% of original end area. The final model provided statistical evidence that road grade and the ratio of rustline height to culvert diameter were significant factors. Based on these analyses, the odds of a 25% loss in end area are increased 1.4 times for each 5% increase in road grade (95% confidence interval from 1.1 to 1.6). In other words, the risk of a severe flow restriction is increased for culverts installed on steeper sections of the road prism. Similar to the previous model, greater rustline height to diameter ratios are strongly associated with reductions in culvert end area. Ratios of 0.25 and 0.50 were estimated to increase the odds of a 25% loss in culvert end area 2.1 and 4.6 times respectively (95% confidence intervals from 14 to 3.2 and 2.1 to 10.2).

$$\underset{}{\ln Y} = \underset{(0.21)}{-1.93} + \underset{(0.02)}{0.07} * X_1 + \underset{(0.82)}{3.06} * X_2$$

Y = probability of a 25% reduction in culvert end area, %
X_1 = road grade, %
X_2 = rustline height to diameter ratio, cm/cm
P-values < 0.01
n = 566 culverts (46 and 61 cm diameter)
Note: standard errors displayed in parentheses

Consequences of Reduced Culvert End Area

The risk to aquatic resources increases as surface water becomes diverted from a stream channel or ditch and is allowed to interact with the road prism. Research conducted in Northern California has shown that diversion was responsible for 80% of the observed road-related fluvial erosion (Best et al., 1995). In this study, evidence of diversion past the inlet was observed at 15% of the 46 and 61 centimeter culverts evaluated. For this sub-population of 85 culverts, the most frequent receiving feature was the ensuing ditch (47%) while diversion of surface water onto the road prism was not as common (15%). Diversion potential was noted for the remaining 38% of culverts where evidence of diversion was observed but a single receiving feature could not be clearly identified.

Multiple logistic regression models were tested to determine if characteristics of the culvert or road prism were associated with the presence of diversion and/or fluvial erosion at the culvert inlet. Variables analyzed were (1) percent loss of culvert end area, (2) road status, (3) topographic location, (4) road grade, (5) culvert slope, (6) skew angle and (7) rustline height to culvert diameter ratio. Interaction terms were used to describe how two variables might jointly influence the mean response. With the presence or absence of diversion as the response variable, the odds of diversion were estimated to be 1.4 times greater for each 10% reduction in cross-sectional area (95% confidence interval from 1.3 to 1.5).

$$\ln Y = \underset{(0.18)}{-2.54} + \underset{(0.01)}{0.03} * X_1$$

Y = odds of diversion at culvert inlet
X_1 = reduction in culvert end area,%
P-value < 0.01
n = 566 culverts (46 and 61 cm diameter)
Note: standard errors displayed in parentheses

As hypothesized, the presence of surface erosion at culvert inlets was significantly associated with the presence of diversion. The odds of fluvial erosion were estimated to be 2.2 times greater for installations where evidence of the diversion of surface water was observed at culvert inlets (95% confidence interval from 1.4 to 4.0). Interaction terms also included in the regression model are difficult to interpret but the results indicate that a combination of steep road grades and low skew angles increase the odds of surface erosion.

$$\ln Y = -1.78 + 0.81 * X_1 - 0.01 * X_2 * X_3$$
$$\quad\quad (0.15) \quad (0.30) \quad\quad (0.001)$$

Y = odds of fluvial erosion at culvert inlet
X_1 = diversion, where 1 = presence
P-value < 0.01
X_2 = culvert skew angle, ^{0}
X_3 = road grade, %
P-value < 0.02
n = 566 culverts (46 and 61 cm diameter)
Note: standard errors displayed in parentheses

CONCLUSIONS

Results of this study in Southern Southeast Alaska suggest that culvert condition is not directly influenced by current road closure or storage strategies. Although the analysis suggests that road closure and the establishment of native vegetation onto the road prism is effective at maintaining culvert condition, it is important to recognize that the performance of culverts associated with the open roads used for comparison was far from ideal. Nearly half the drainage structures sampled on open roads were operating with less than 90% of their original end area. It is clear that existing maintenance activities on open roads are not resulting optimal culvert performance. Furthermore, it is likely that much of the observed reductions in culvert end area occurred prior to road closures. A significant increase in culvert performance on both open and closed roads could be readily achieved by expanding existing maintenance regimes to include hand-cleaning of culvert inlets.

Analysis of potential culvert failure mechanisms indicates that open and closed roads respond similarly to local hydrologic and geomorphic processes. Observed accumulations of woody debris and sediment resulting in reduced culvert end area could easily be corrected through the initiation of more thorough maintenance practices. In addition, the level of structural damage to culvert inlets and outlets may also be reduced with greater attention focused on the effects that harvesting operations and road grading practices can have on culvert condition (Piehl et al., 1988).

It is apparent that landscape characteristics such as topographic location are important factors associated with the observed reductions in culvert end area. Loss of culvert end area appears to trigger a “disturbance cascade”, resulting in the diversion of water and subsequent fluvial erosion of the road prism. These results generally concur with research conducted elsewhere in the Pacific Northwest that has documented the potential for hillslope roads to intercept surface and subsurface flows, potentially affecting geomorphic and hydrologic regimes (Montgomery, 1994; Wemple, 1994).

Rustline height to diameter ratios may be valuable indicators of culvert performance. Although rustlines may be effected on a site-specific basis by culvert gradient and water chemistry, the increased risk of culvert end area reduction associated with rustline height to diameter ratios greater than 0.25 is noteworthy. Evaluation of rustlines may also aid in the identification of sites where the initiation of disturbance cascades are likely to occur.

This research has shown that the condition of culverts on low-volume Forest Service roads in Southeast Alaska warrants further study. It is uncertain to what extent these results can be extrapolated to other areas of the Tongass National Forest, however, it is clear that current maintenance and road closure practices are not resulting in optimal culvert performance. Additional research focusing on the effects of restrictions in culvert end area would aid greatly in the assessment of risk to aquatic resources. The shot-rock road construction techniques common to this study area appear to be relatively resistant to fluvial erosion and mass wasting, suggesting the loss of culvert end area and subsequent diversion may not pose the same risk as observed in other portions of the Pacific Northwest.

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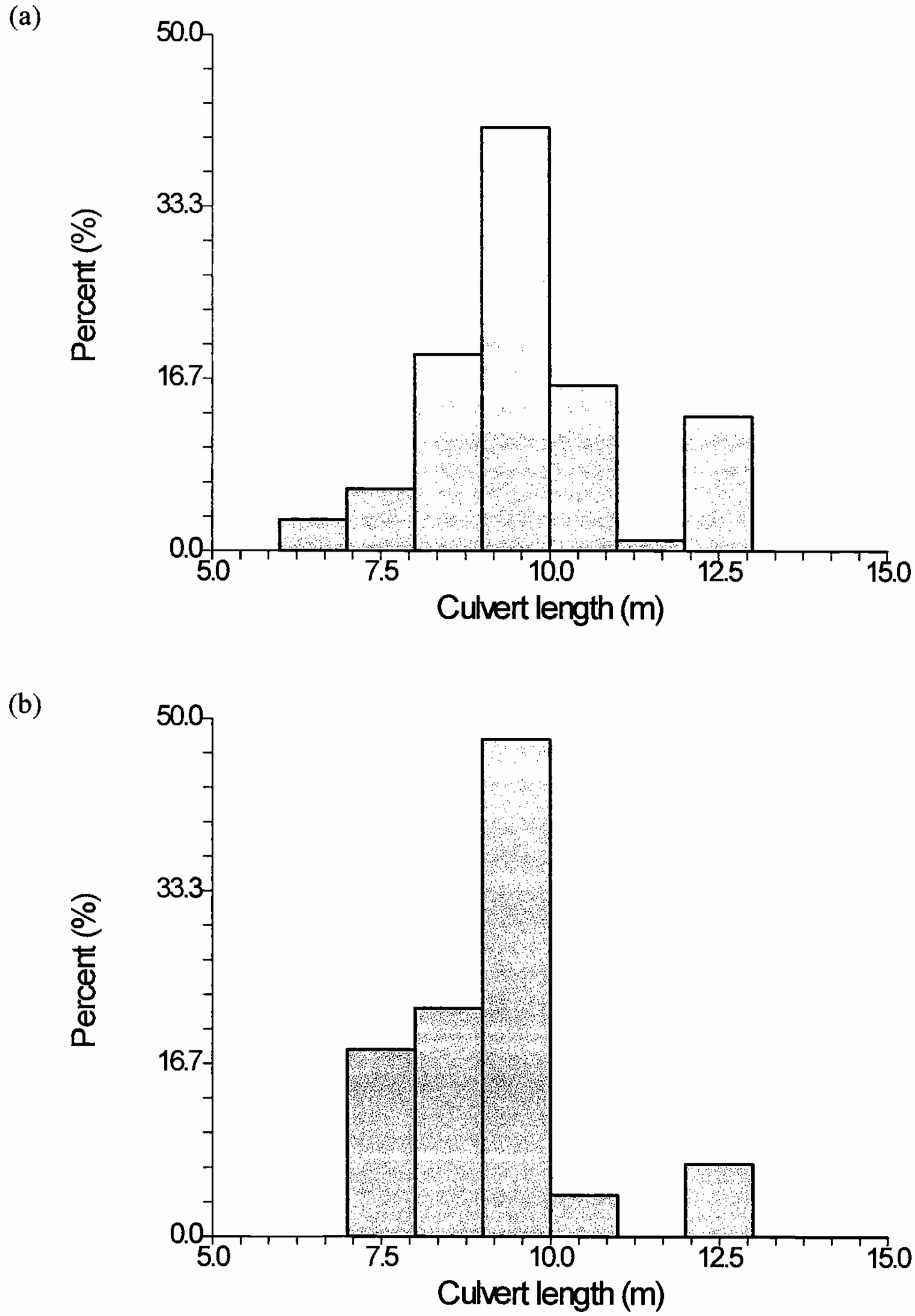
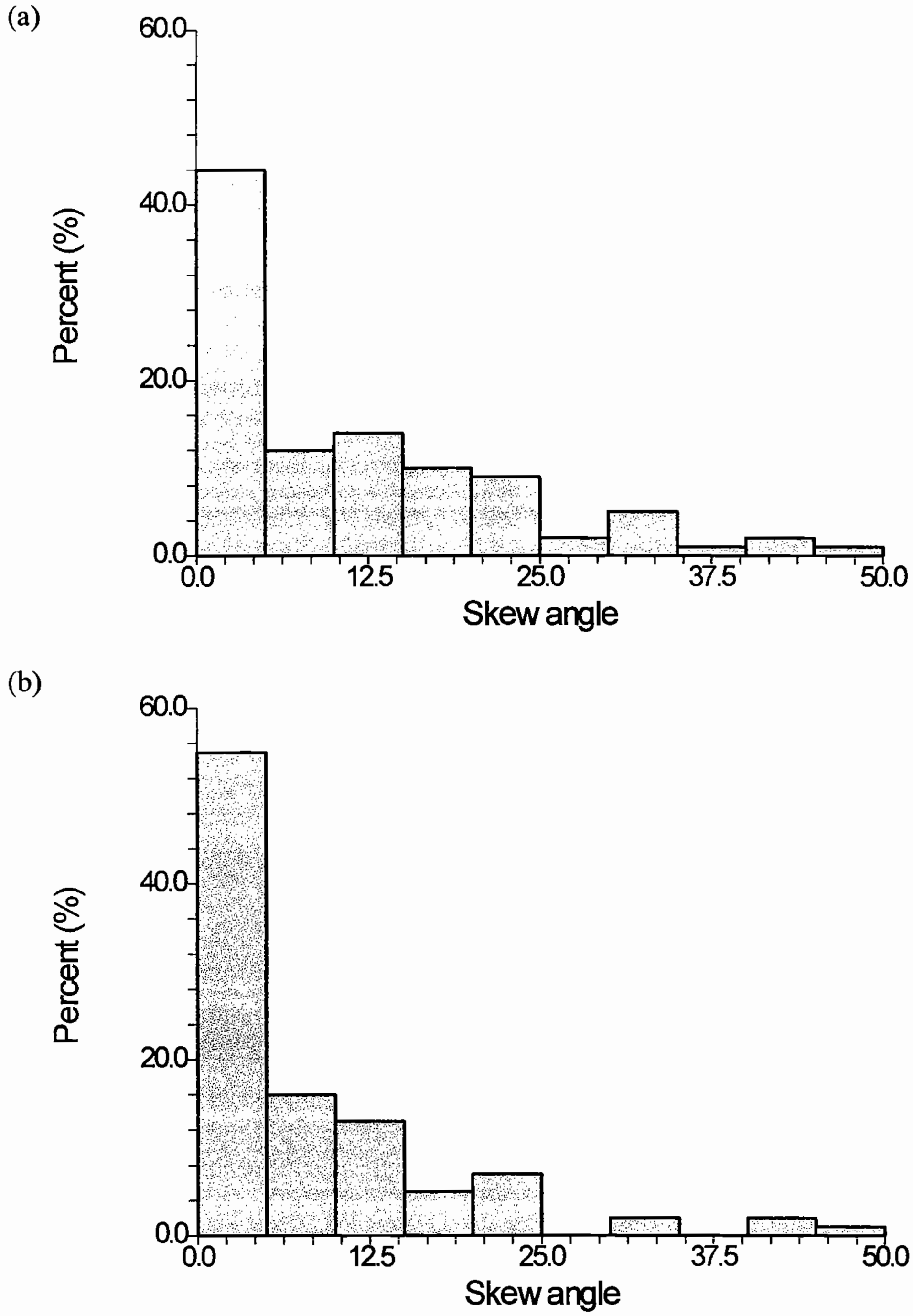
APPENDIX

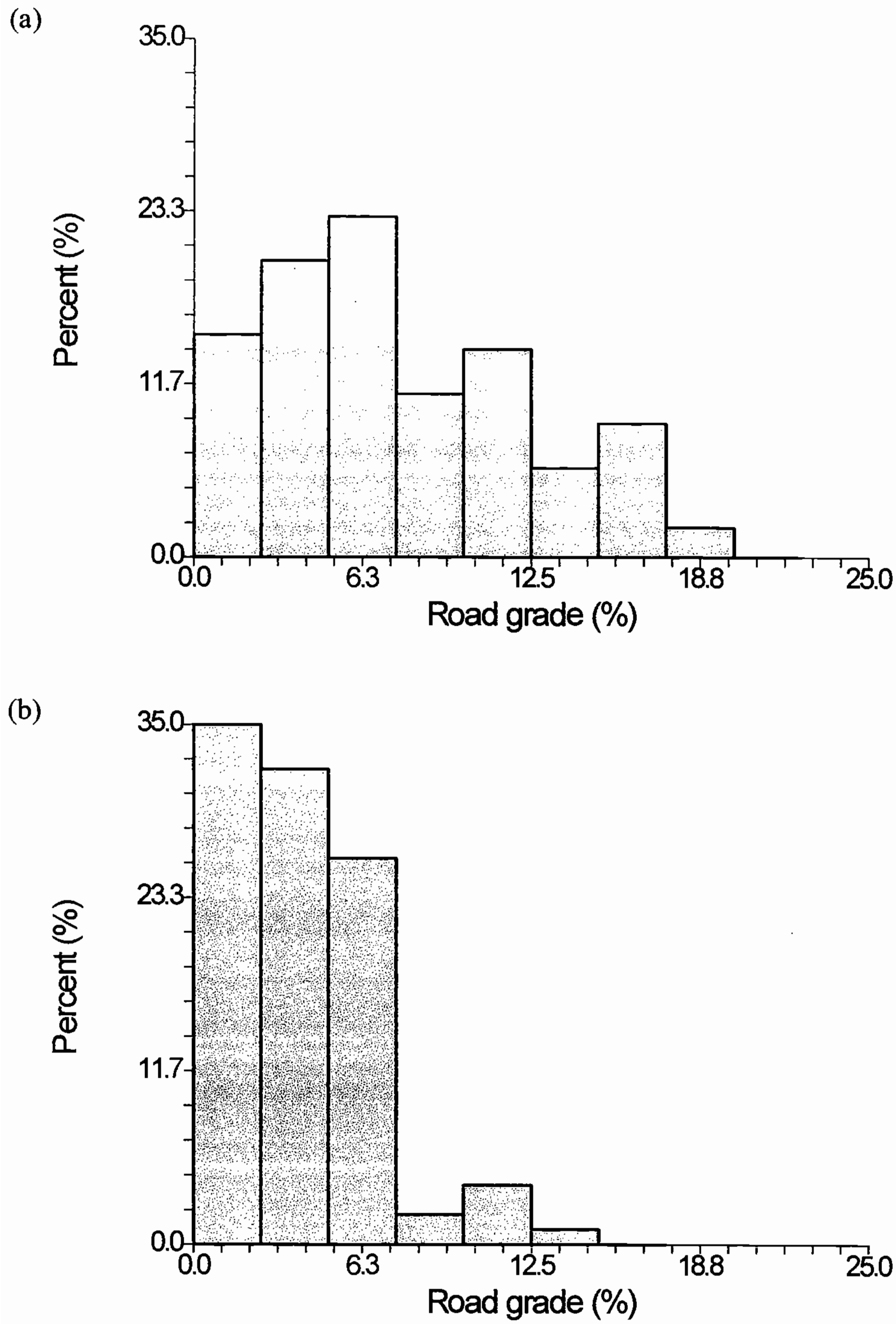
Frequency Distributions



Culvert length frequency distributions for (a) hillslope (n=304) and (b) valley bottom (n=262) locations.

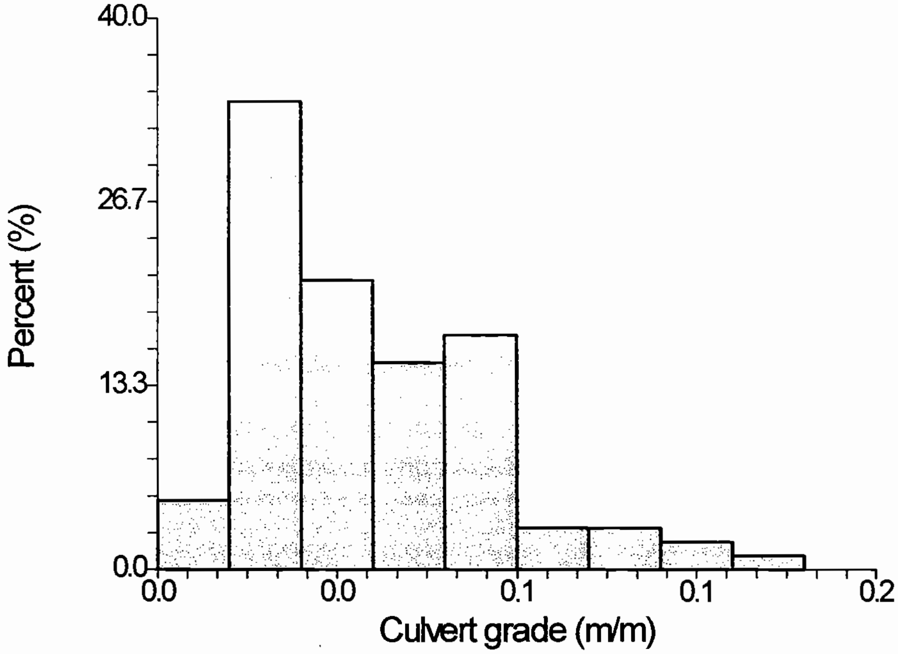


Skew angle frequency distributions for (a) hillslope (n=304) and (b) valley bottom (n=262) locations.

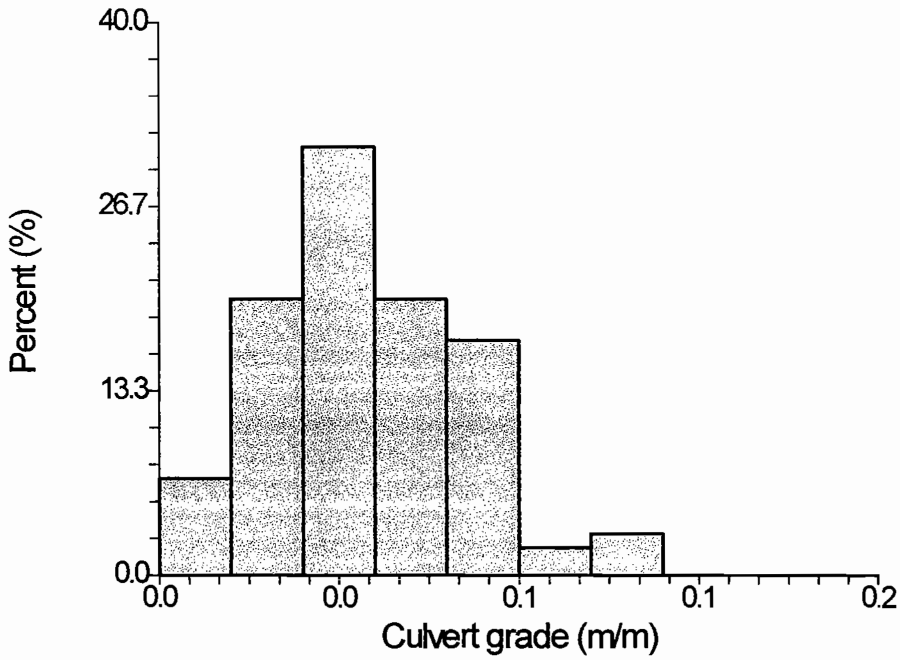


Road grade frequency distributions for (a) hillslope (n=304) and (b) valley bottom (n=262) locations.

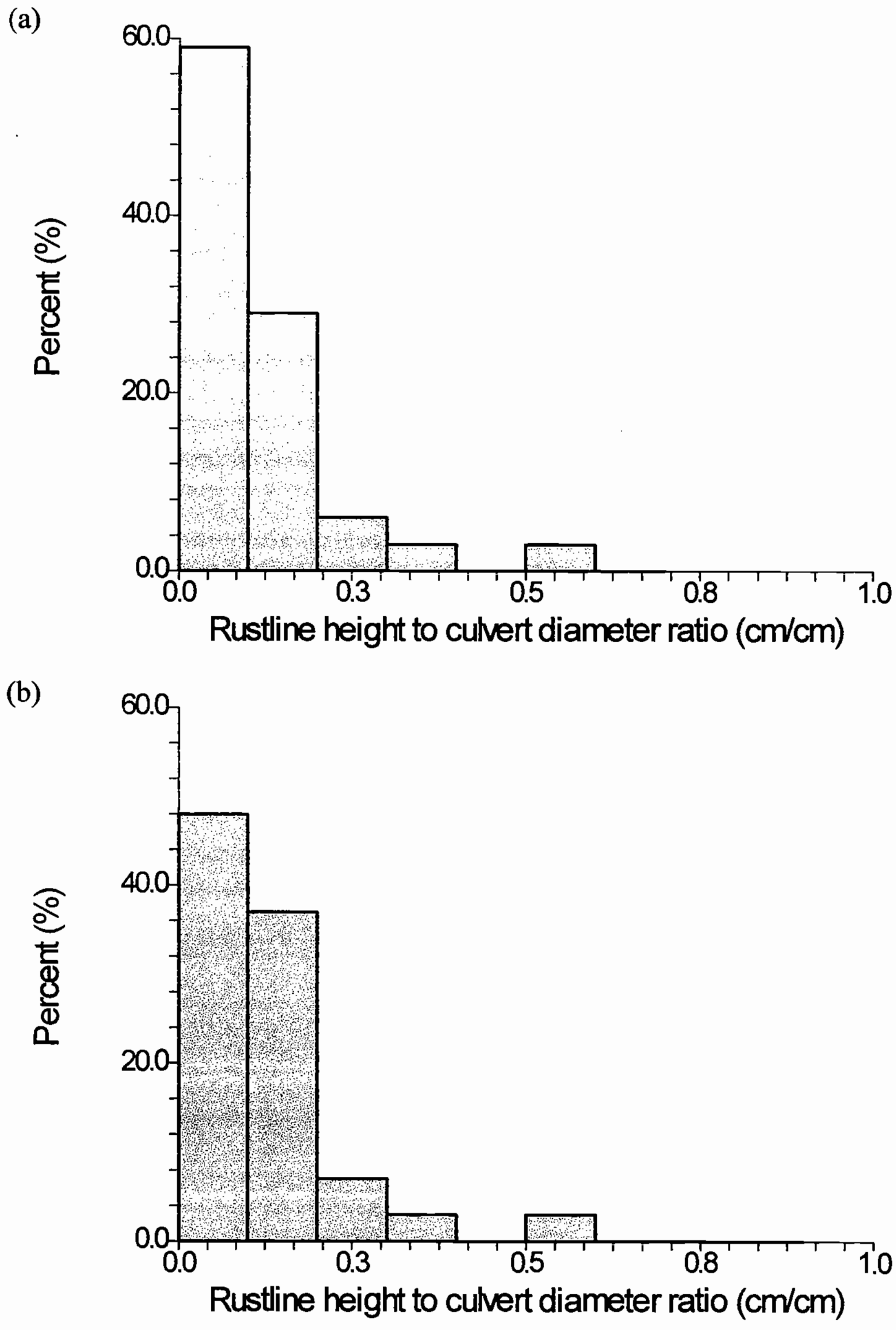
(a)



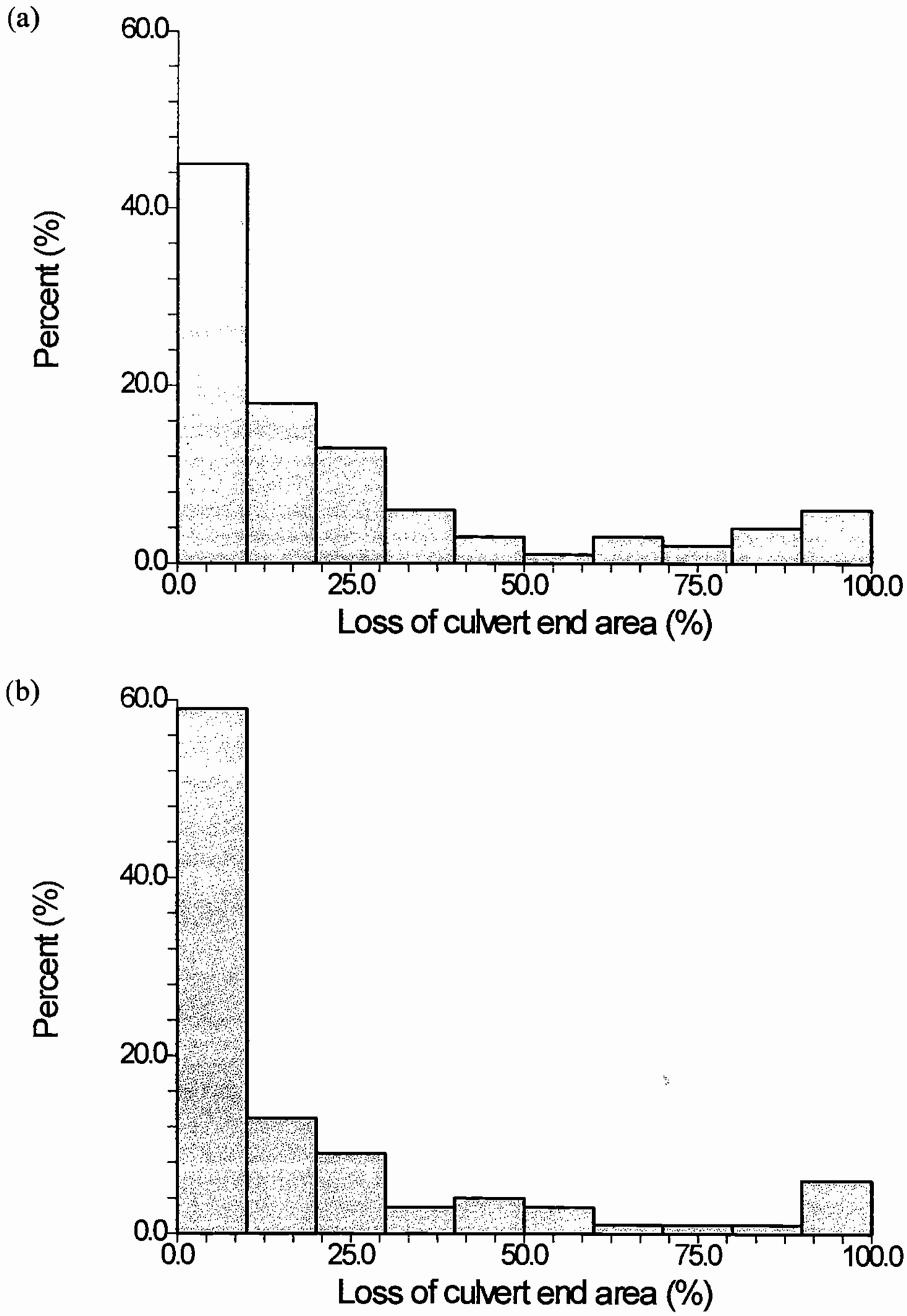
(b)



Culvert grade frequency distributions for (a) hillslope (n=304) and (b) valley bottom (n=262) locations.



Rustline height to culvert diameter ratio frequency distributions for (a) hillslope (n=304) and (b) valley bottom (n=262) locations.



Percent loss of culvert end area frequency distributions for (a) hillslope (n=304) and (b) valley bottom (n=262) locations.