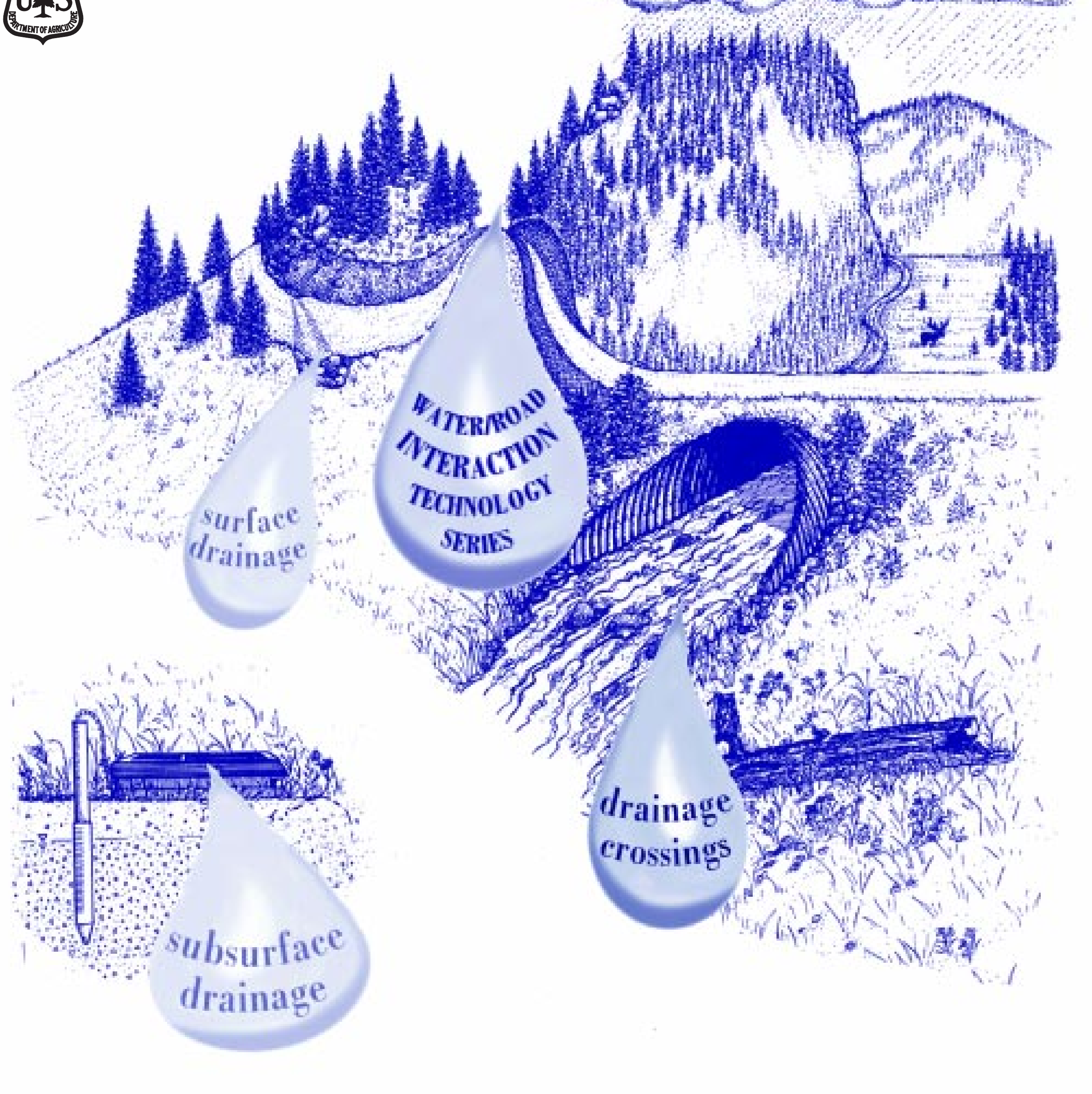
United States
Department of
Agriculture

Forest Service

**Technology &
Development
Program**

7700—Transportation Systems
2500—Watershed and Air Management
September 1998
9877 1806—SDTDC

Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California



Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California

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San Dimas, California

September 1998

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ACKNOWLEDGMENTS

Bruce McCammon and John Rector helped defined the study goals and methods, and provided crucial technical assistance. Beverley Wemple, Gordon Grant, and Fred Swanson helped to frame the primary questions in the context of a broader assessment of flood effects. John Mohney, Chester Novak, and Kim Johannsen participated in the design of this study and conducted portions of the field work. Numerous people at the field offices of the Forest Service and BLM helped immeasurably with logistics and information, which made the study possible. Jeff Moll and Tom Moore of the San Dimas Technology and Development Center provided helpful guidance throughout the project. Natalie Cabrera prepared Figure 11, and Martha Brookes edited the manuscript.

INTRODUCTION

The relation between forest roads and increased rates of erosion and sedimentation into streams is well documented (Reid and Dunne 1984; Bilby et al. 1989; Megahan et al. 1991). Recently, road-stream crossings constructed with culverts have been identified as a significant source of road-derived sediment (Hagans and Weaver 1987; Best et al. 1995; Weaver et al. 1995; Park et al. 1998). Culverted road-stream crossings can cause large inputs of sediment to streams when the hydraulic capacity of the culvert is exceeded, or the culvert inlet is plugged and streamflow overtops the road fill. The result is often erosion of the crossing fill, diversion of streamflow onto the road surface or inboard ditch, or both. Fill-failures and diversions of road-stream crossings have been found to cause 80 percent of fluvial hillslope erosion in some northern California watersheds (Best et al. 1995). In a study examining the sources and magnitude of gully erosion in Redwood National Park, Weaver et al. (1995) found that 90 percent of the measured gully erosion was caused by the diversion of first- and second-order streams as a result of plugged and inadequately sized culverts at road-stream crossings. Although undersized and plugged culverts are often implicated in stream diversions and fill failures at crossings, we are aware of no studies examining the mechanisms of road-stream crossing failures.

Culverts are traditionally sized to convey water, which implies that the principal mechanism of failure would be excessive stream discharge relative to the hydraulic capacity of the culvert. In forested watersheds, however, culverts often carry large amounts of sediment and organic debris in addition to water, particularly during peak flows. The relative importance of water, wood, and sediment in triggering road-stream crossing failures has not been adequately studied. Specific engineering techniques do not exist for assessing the hazard presented by debris and sediment, other than the site-specific intuition of designers. Further, design criteria for facilitating the passage of organic debris and sediment through culverts are poorly tested. Effects on downstream aquatic and riparian resources from road-stream crossing failures would be reduced if appropriate designs were incorporated into existing culvert-sizing techniques to facilitate the passage of organic debris and sediment (Figure 1).

Recent regulations for federally managed lands in the Pacific Northwest mandate that road-stream crossings be designed to accommodate at least the 100-year flood, including associated bedload and debris (USDA/USDI 1994). Little is documented about the effects of large storm events on road-stream crossings. Recent flood events in the Pacific Northwest (November 1995; February, November, December 1996) provided an opportunity to examine this topic. The storms produced record peak flows in many California, Oregon, and Washington rivers, with recurrence intervals ranging from 5 to more than 100 years (Table 1). Roads on National Forest and United States Department of the Interior (USDI) Bureau of Land Management (BLM) lands sustained severe damage, with numerous road-stream crossing failures.

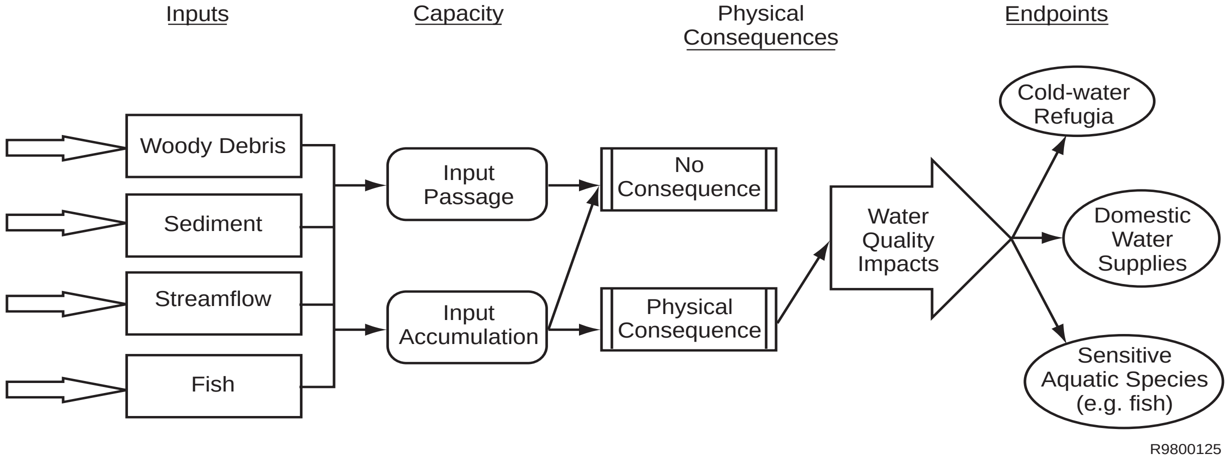

Figure 1—A conceptual model of environmental risk at road-stream crossings. Each component of risk—inputs, capacity, consequences, and endpoints—is relevant to the composite environmental risk of single crossings as well as the cumulative effects of all crossings in a watershed.

Table 1. Estimated peak flows and recurrence intervals for flood events responsible for road-stream crossing failures.

National Forest (Gage Station)	Regional Flood Events (date)	Peak Flow (m^3/s)	Recurrence Interval (years)
Umatilla:			
Mill Creek near Walla Walla	November 1995	58	> 10
	February 1996	180	> 100
Gifford Pinchot:			
Cispus River near Randle	November 1995	728	> 100
	February 1996	1131	> 100
Mt. Hood:			
Hood River at Tucker Bridge	November 1995	385	< 5
	February 1996	660	25
Mt. Hood and Eastern BLM:			
Clackamas River at Estacada	November 1995	1136	> 5
	February 1996	1953	50
Willamette NF:			
South Santiam River	February 1996	898	< 100
below Cascadia	November 1996	638	> 10
Klamath NF:			
Klamath River at Seiad Valley	December 1996	3316	*15

Notes: Estimates were provided by the USGS (Sept. 1997) and are considered provisional and subject to revision.

* Recurrence interval provided by Klamath National Forest is considered provisional and subject to revision.

As part of a flood impact assessment project, the USDA Forest Service and USDI BLM initiated a survey of failed road-stream crossings on public lands in areas of the Coastal, Cascade, Klamath, and Blue Mountain Provinces of the Pacific Northwest. The objectives of the survey were to: identify the mechanisms and on-site consequences of road-stream crossing failure and determine the degree to which specific failures could have been predicted by using watershed-scale screening methods currently under development.

FIELD METHODS

Survey Methodology

The survey was conducted between April 1996 and November 1997 in the Salem District of the USDI BLM and the following National Forests:

- Umatilla (Walla Walla District)
- Gifford Pinchot (Randle District)
- Willamette (Rigdon and Sweethome Districts)
- Mt. Hood (Barlow, Clackamas, Hood River, and Zig Zag Districts)
- Klamath (Oak Knoll and Scott Districts).

The survey focused on areas heavily affected by the flood events. Priority was given to road systems having a high frequency of failed crossings in which evidence of failure and of erosional and depositional consequences was intact. The survey was limited to road-stream crossings that had definable channels; it excluded bridged crossings and cross-drain culverts. Two survey methodologies were used: one sampled all road-stream crossings for a road segment, allowing comparison of the hydraulics and design components of failed and unfailed crossings; the other limited the survey to failed crossings. Failed crossings were surveyed in the Willamette National Forest during the November and December 1996 flood events, providing an opportunity to observe and record actively failing crossings.

Data Collection

Inventory methods and a data form were developed to collect stream crossing information. The data form was incorporated by the BLM in developing expanded inventory methods for the BLM Salem District. Data collected for the study included fill dimensions, culvert diameter and slope, inlet type, rustline width, channel width and slope, and potential diversion distance and receiving feature. Additional information recorded at failed sites included the primary failure mechanism, erosional and depositional consequences, and actual diversion distance and receiving feature.

Defining Road-Stream Crossing Failure

To provide a controlled and hydraulically definable condition that constituted "failure," road-stream crossing failure was defined as a discharge that exceeds a ratio of headwater depth to culvert diameter greater than 1 (HW/D>1).

Investigating the Primary Mechanism of Failure

Field observations were used to determine the primary mechanism or mechanisms of road-stream crossing failure. The primary mechanism of failure was defined as the process that initiated the series of events leading to failure of the crossing. We distinguished four different mechanisms that initiated road-stream crossing failures (Table 2), but distinguishing between wood and sediment slugs relied primarily on stratigraphic interpretations that proved to be difficult at several sites. Thus, a fifth category combining wood and sediment (WD/Sed) was created. Figures 2, 3, 4, and 5 provide examples of evidence used to determine failure initiating mechanisms and local consequences.

Table 2. Road-stream crossing failure mechanisms and evidence for field determinations.

Failure mechanism	Visible evidence	Difficulty in discerning
Debris flow	• Channel scoured to bedrock • Poorly sorted deposits, often mixed with large, woody debris • Scour marks or high water marks on banks and vegetation, or both	Easy—Debris flow evidence was typically well preserved and extensive.
Woody debris lodgment	• One or more pieces lodged across culvert inlet • Deposition of fine sediments (up to small pebbles) in inlet basins, often moderately sorted and thinly bedded (< 2 cm thick).	Easy to difficult—Often debris plugging was followed by sediment accumulation burying the debris at the inlet. Stratification, sorting, and grain-size distribution were useful clues. Also, if the buried culvert was suitably configured, a flashlight shone in from the outlet could indicate the plugging mechanism. Where excavation had occurred and debris flows could be excluded, however, the mechanism was considered wood and sediment.
Sediment "slug"	• Rapid delivery of sediment to the inlet, with deposition above the crown of the culvert or above crown elevation in the inlet basin • Adjacent hillslope failure delivering material a short distance to the inlet • Lack of evidence of woody debris plugging or debris torrent • Unsorted or poorly sorted deposits	Easy to difficult—Rapid, catastrophic delivery of sediment buried the inlet. Although the particle sizes delivered to the inlet were capable of fluvial transport through the culvert, rapid delivery overwhelmed the transport capacity. See woody debris notes for problems distinguishing between wood and sediment.
Hydraulic exceedence	• High-water debris accumulations • Draping of fine sediments within the ponded area • Inlet not plugged with debris	Moderate to difficult—Hydraulic exceedence required careful examination of the inlet basin. Debris deposits at the high-water line and fine-sediment deposits were often of limited extent and were rapidly covered with vegetation. Where fill erosion and/or diversion evidence existed, hydraulic exceedence was arrived at by a process of elimination. Hydraulic exceedence, through ponding, may have contributed to or triggered other mechanisms (for example, woody debris rafts, fill saturation), but this could not be field verified.

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Figure 2—Woody-debris plugging often results in burial of the inlet, suggesting sediment plugging as the cause. However, upon excavation several pieces of wood were discovered here, lodged across the inlet, indicating that woody debris initiated the plug.

R9800127

Figure 3—Debris flows were relatively easy to identify. Evidence consisted of either evacuated channels upstream of the crossing or, as in this photo, large, poorly stratified deposits where the flow was impounded against the road fill.

R9800128

Figure 4—Hydraulic exceedence was often difficult to determine. At this site, evidence consisted of a debris line near the center of the photo and removal of litter in the bottom half of the photo. Snow cover during flooding and surveys resulted in different evidence than would have occurred without snow cover. Evidence was rapidly obscured by litter-fall, new growth, and additional rainfall.

R9800129

Figure 5—Consequences of failure are usually simpler to characterize than mechanism of failure. Here, diversion of stream flow out of the natural channel and onto the road surface and ditch produced erosional consequences much greater than if the flows had flowed over the road surface and re-entered the natural channel near the culvert outlet. *[Photo courtesy of R. Ettner, Siskiyou National Forest.]*

Modeling Hydraulic Capacity

A spreadsheet template, designed by Six Rivers National Forest, was used to identify undersized and high-risk stream crossings. The template uses an empirical equation developed by Piehl et al. (1988), combined with regional flood-estimation equations to estimate the following:

- The hydraulic capacity of a given culvert for water-surface elevations equal to the pipe diameter (d) and the height of the fill (f)
- The probability (expressed as recurrence interval, in years) of streamflows that would overtop the culvert inlet, T_d, and fill prism, T_f, based on the computed hydraulic capacity of each culvert.

The template was applied to the stream-crossing survey data to answer the following questions:

- Are the T_d, failure rate, and the failure mechanism related?
- Are hydraulic-based models useful in predicting road-stream crossing failure?

RESULTS

Figure 6 shows the results, sorted by hydraulic capacity, failure mechanism, and local consequences.

Failure Mechanisms

Sediment slugs (36 percent) and debris torrents (26 percent) were the most common failure mechanisms we observed (Figures 2 and 3). Sediment slugs were commonly the result of rapid deposition of colluvium from an upstream landslide or cutbank failure. Debris torrents were often initiated by a pulse of sediment and organic material entering the stream from a channel streambank or hillslope failure.

Woody-debris failures usually resulted from multiple pieces of wood lodging across the inlet of the culvert, trapping sediment upstream and plugging the inlet. Small pieces of wood appeared to be just as likely to initiate plugging as were large pieces (Flanagan, in preparation). Of the measured woody debris initiating culvert plugging, 23 percent (n = 13) were shorter than the diameter of the culvert they plugged. Failure from exceeding hydraulic capacity was infrequent (9 percent of the failures).

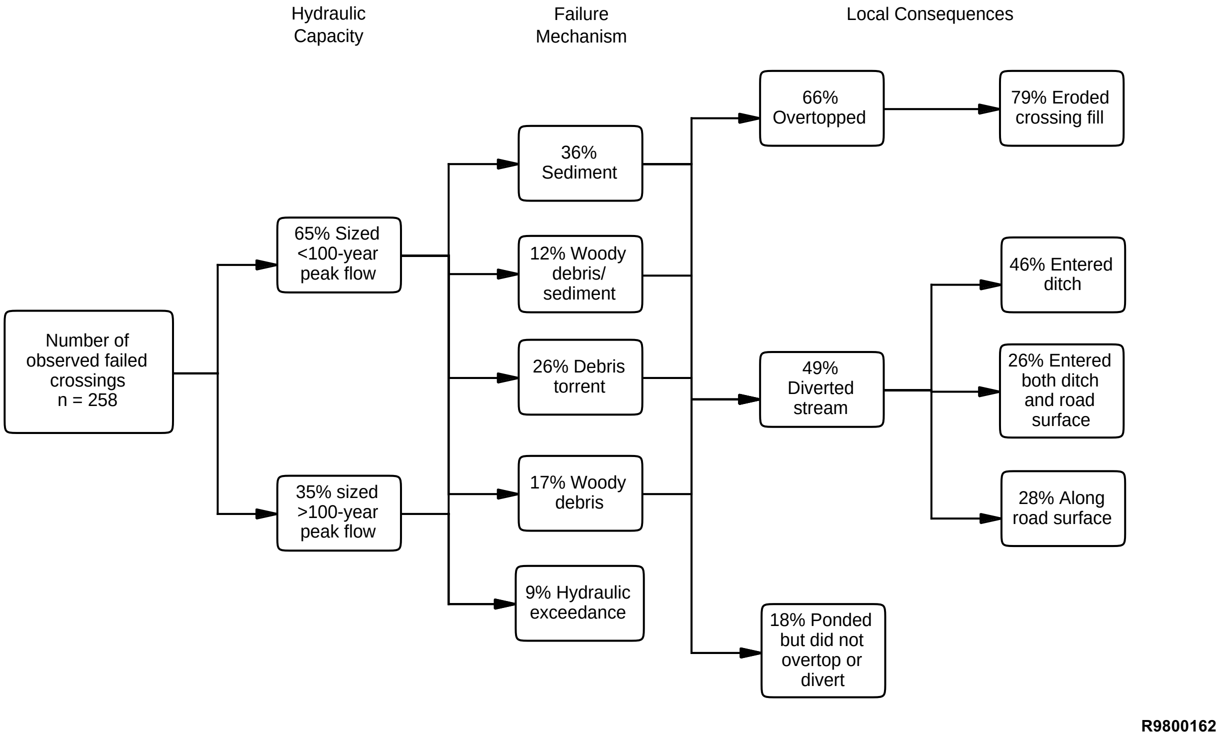

Figure 6—Results sorted by hydraulic capacity, falure mechanism, and local consequences

Failure Mechanism by Region

The leading mechanisms of failure observed in the Cascade Region were debris torrents (30 percent), followed by sediment slugs (25 percent), and woody debris (23 percent) (see Figure 3). Crossing failures were most commonly found in mid-slope road sections. These areas have high road-stream crossing densities and are characterized by steep, unstable slopes susceptible to mass wasting. Sediment slugs were the principal mechanism for failure in the Blue Mountains (68 percent), Coast Range (39 percent), and the Klamath Mountains (40 percent). For the Blue Mountains, the preponderance of sediment-slug failures can be attributed to fractured basalts found in the area, which tend to slump from steep roadside cutslopes and hillslopes, rapidly filling inlet basins and overwhelming the capacity of the culvert to pass sediment. Figure 7 shows the distribution of the failure mechanisms.

Fill Erosion

Road-stream crossing fill eroded, either progressively or catastrophically, at 79 percent of the sites where streamflow overtopped the road (n = 171) (Figure 8). Progressive erosion often led to head-cutting of the downstream fill slope, while catastrophic erosion, analogous to a “dambreak” flood, resulted in loss of a large proportion of the fill. At several sites, rapid stream aggradation associated with sediment slugs filled the inlet basin, depositing material on the road surface and resulting in net deposition and little or no fill erosion. Material was deposited onto the road surface, the crossing fill, or both at 15 percent of the sites (n = 92) commonly associated with sediment slug and debris-torrent failures.

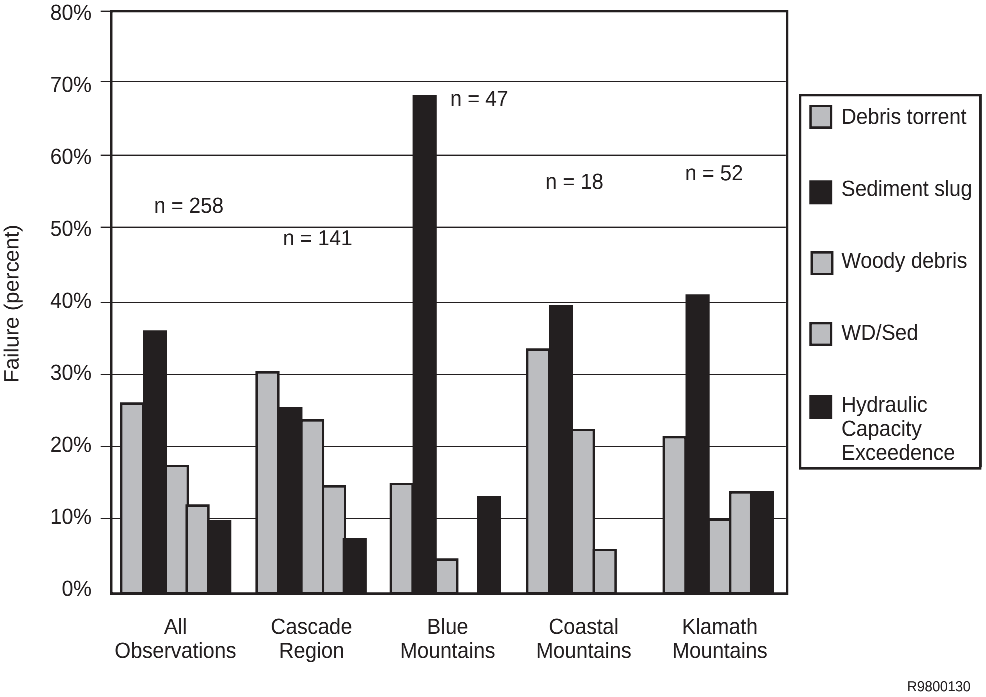

Figure 7—Distribution of failure mechanisms for physiographic regions in Oregon and Washington and the Klamath Mountains in California.

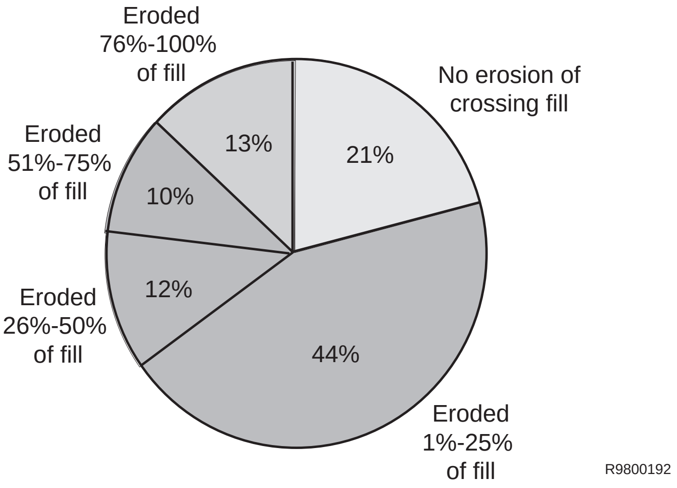

Figure 8—Proportion of road-stream crossing fill eroded where streamflow overtopped the road (n=171).

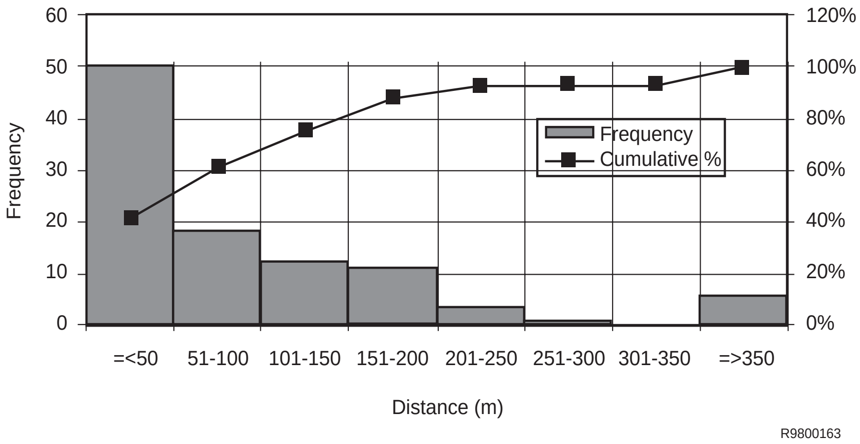

Figure 9—Observed diversion distances at failed stream crossings (n=104).

Diversion

Streamflow was diverted out of its natural channel at 48 percent of failed road-stream crossings (n = 258); 69 percent of both failed and unfailed crossings showed the potential to divert (n = 304). The average observed diversion distance was 109 m, with 90 percent of diversions traveling 200 m or less (see Figure 5). Diversion distance was influenced by the spacing of cross drains and stream crossings, shape and slope of the road, and the inboard ditch configuration.

The routing and receiving features are important factors in determining the consequences of stream diversion. Most roads surveyed were insloped, with inboard ditches leading to cross drains or road-stream crossings. Diverted streamflow was routed along the inboard ditch, road surface, or often both. Diversion out of the ditch and onto the road surface was often the result of runoff forced out of the inboard ditch, through ditch deposition, failed cross-drains, sharp bends on steep roads, cutslope failure into the ditch, road outsloping, and exceedence of the ditch's hydraulic capacity. Fifty-three percent of diverted streamflows entered adjacent cross-drains or road-stream crossings; the remaining 47 percent either flowed across the road and onto the hillslope or infiltrated the road fill (n = 103). Figure 9 shows the distribution of observed diversion distances.

In the study areas, 50 percent of observed diversions left the originating catchment and contributed runoff to adjacent catchments. Diversion of runoff and debris to adjacent crossings often caused the receiving crossings to fail, creating a cascading series of failures. Cascading failures of up to seven cross-drains and road-stream crossings were observed in the field. The net effect of cascading failures included increased diversion distance, transfer of runoff to adjacent catchments, road-surface and fill erosion, hillslope gullying, and mass movement.

Diversion resulted in both erosional and depositional consequences. The most common erosional feature observed from diversion was gullying of the road surface, fill, and hillslopes below the road. Deposition on the road and inboard ditch from diversion, commonly associated with debris torrent and sediment slug plugging (n = 92), was found at 31 percent of the sites.

Hydraulic Capacity

Each survey site containing a circular corrugated metal pipe and a drainage area definable on a 7.5-minute topographic map was run through the hydraulic assessment template to determine the hydraulic capacity of the culvert in terms of a peak-flow recurrence interval. Discharge was estimated for a headwater depth equal to pipe diameter (HW/D = 1). The recurrence interval of the discharge, T_d, was interpolated by using regional flood-prediction equations. When the recurrence interval was greater than 100 years, T_d was extrapolated with an upper limit set at 250 years.

The recurrence interval for failed pipes was compared with the primary failure mechanism (Table 3). Computed culvert hydraulic capacity correlated well with failure by hydraulic exceedence; was weakly correlated with failure by woody debris plugging; and was not correlated with failure by sediment slugs or debris torrents. Table 3 suggests that sizing for flow reduces the chance of hydraulic failure, and from woody debris to a lesser extent, but does not effectively reduce the risk of failure from sediment and debris torrents.

Similar to the observations of Piehl et al. (1988), we found that T_d was distributed bimodally for both failed and unfailed culverts (see Figure 10). The median of T_d in the Cascade Region was greater than 250 years for unfailed crossings but only 26 years for failed crossings. Failures caused by debris torrents were suspected of being unrelated to culvert size. If we neglect debris-torrent failures, the median T_d for failed crossings is only 18 years. The relative frequency distribution in Figure 10 suggests that culverts in the Cascades sized for less than the 25-year peak flow have a higher probability of failure than those sized for greater than the 250-year peak flow. Stream crossings in the Blue Mountains exhibited the opposite trend, with the median of T_d for unfailed crossings less than that of failed crossings. The hydraulic assessment template was not useful as a screening tool in the Klamath National Forest study area because a majority of the sites, both failed and unfailed, had T_d values less than the 25-year peak flow. The survey size in the Coast Range was insufficient for the analysis of the T_d distribution.

Table 3—Computed probabilities of capacity exceedence and failure frequency by mechanism.

T_d	Hydraulic capacity exceedence	Debris torrents	Sediment slugs	Woody debris
T_d less than 100-year.	70 %	47 %	51 %	59 %
T_d greater than 100-year.	30 %	53 %	49 %	41 %

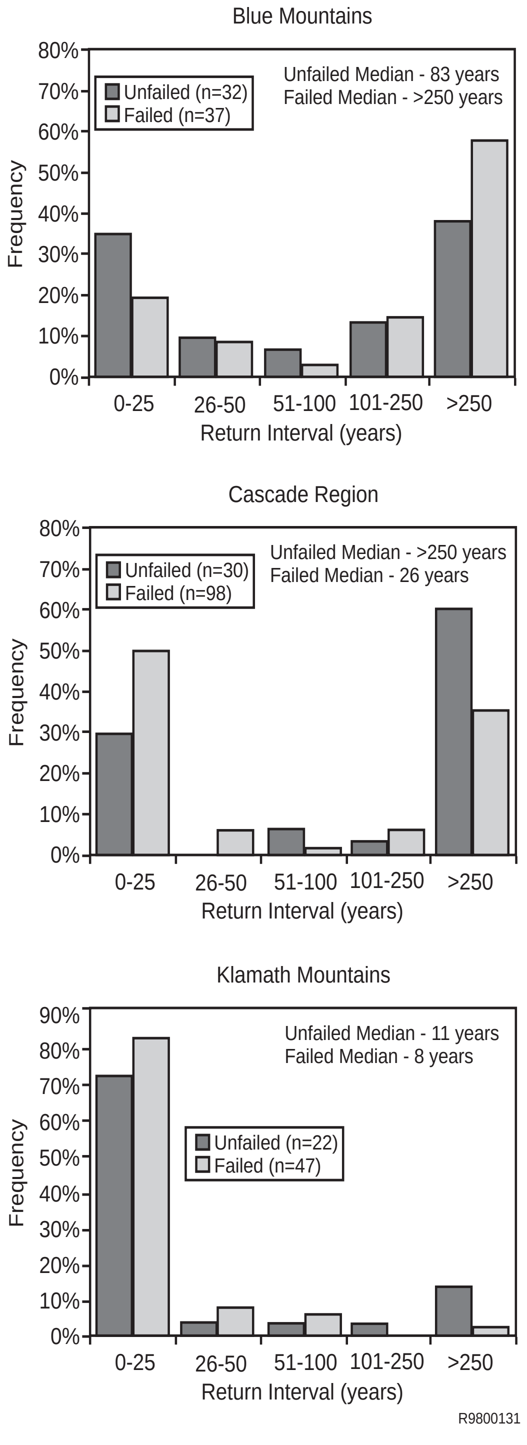

Figure 10—The relative frequency of the probability of exceeding culvert hydraulic capacity, expressed as peak flow recurrence interval, Td, for failed and unfailed stream crossings in the Blue Mountains, Cascade Region, and Klamath Mountains. Within the Cascade Region, failed culverts were more frequently sized for less than the 25-year peak flow (at HW/D = 1), while the majority of unfailed culverts were sized for greater than the 250-year peak flow (at HW/D = 1). The opposite relationship was found for the Blue Mountains.

DISCUSSION

Hydraulic exceedence was not a major failure mechanism at forest road-stream crossings for large flood events. Culverts for stream crossings must be sized to pass both water and other watershed products associated with the design flow. Stream-channel characteristics, and upslope and downslope conditions, should be considered when new culverts are sized or the risk of failure at existing stream crossings is assessed.

The size and intensity of storm events appear to influence the distribution of failure types. A large event will initiate more debris torrents and transport increased sizes and volumes of culvert-plugging material (Sidle and Swanston 1981). Thus, with larger storm events, we would expect to see a higher proportion of failures driven by debris flows, sediment slugs, and large woody debris. In smaller storm events, less upslope material is transported, the proportion of exceedence of hydraulic capacity will be higher, and small woody debris failures will be more frequent. This appears to be the case in the Willamette National Forest, which had lower intensity storms than did the other surveyed management units (Table 1), and experienced a higher proportion of hydraulic-capacity exceedence and woody debris plugging failures.

The diversion of streams was a common, high-impact, and avoidable effect of road-stream crossing failure. Although the amount of erosion from diversions was not measured in this study, our observations clearly indicated that erosion and sedimentation effects from failures that diverted streams were much greater than for failures that did not divert streams. Similar observations were reported by Park et al. (1998), based on field assessment of flood damage on the Siskiyou National Forest: They reported that "…diversions increased sediment delivery 2 to 3 times over sediment that is delivered if the water is not diverted and erodes only the road fill at the crossing." They also reported that "Diversion of otherwise small streams resulted in some of the most extensive damage features." Stream diversion represents a large and usually avoidable effect of stream-crossing failure.

The consequences of stream-crossing failure appear to be easy to predict accurately. For the sites studied, the local physical consequences of crossing failure could have been predicted prior to failure. Simple inventory of crossings for fill volume and diversion potential would characterize the potential consequences of failure and indicate the priority opportunities for upgrading crossings to reduce potential consequences.

Calculated peak flow vs. culvert hydraulic capacity did not predict stream-crossing failure for large flood events in the areas studied. We believe that, because stream-crossing failure in Pacific Northwest forested watersheds is caused predominantly by accumulations of sediment and debris at the inlet, hydraulic models are not reliable predictors of crossing failure. The loading of sediment and woody debris is difficult to predict and subject to the stochastic nature of landsliding, streambank erosion, treefall, and other processes that contribute these materials. We might be able to anticipate which crossings are more likely to fail—based on upslope/upstream geomorphology, crossing inlet configuration, and hydraulic models—but we expect that actual failures will remain difficult to predict.

Accumulation of headwater (water level above the top of the culvert) at culvert inlets will increase plugging hazard by retarding the passage of floating debris and by decreasing streamflow velocity and the capacity for sediment transport. Ponding at the inlet basin led to the accumulation or "rafting" of woody debris. When the inlet was re-exposed, it was instantly faced with an interlocking raft of wood exceeding the capacity of the inlet, therefore resulting in plugging (Figure 11a).

The behavior of sediment and debris at culvert inlets was crucial to stream-crossing performance. Crossings that presented the least change to channel cross-section, longitudinal profile, channel width, and alignment were most likely to pass sediment and debris (Figure 11b, c, d).

Our observations suggest that:

- Increases in channel width immediately upstream of the culvert inlet promoted accumulation of both woody debris and sediment at the inlet. In widened channels, woody debris can rotate and present larger effective widths to the culvert inlet, increasing the likelihood of lodgment, and resulting in reduction or plugging of the inlet. Narrow channels are more likely to present woody debris to the culvert inlet oriented with the flows and the culvert, and thus more effectively entrain and move sediment through the culvert. (Figure 11b). Wider channels also result in flows that have less hydraulic shear stress and sediment-transport capacity per unit of channel width. Because the culvert inlet width is fixed, the effective sediment-transport capacity at the inlet is reduced where channels widen immediately upstream.

- Culverts set at substantially lower gradient than the natural channel will tend to retard sediment transport and promote plugging. Often the crossing creates a depositional reach in a channel that otherwise efficiently transports its sediment loads (Figure 11c).

- Where culverts are not aligned with the channel, stream energy losses and reorientation of entrained floating debris are likely, leading to sediment deposition and lodging of woody debris at the inlet (Figure 11d).

- Larger rocks are often moved downstream by progressive undermining and rolling. When large rocks encounter the edge of a culvert, undermining ceases and rocks can lodge, leading to plugging by sediment and debris (Figure 11e). Flared metal end-sections that have a well-bedded apron seem to be effective in reducing or eliminating this effect.

IMPLICATIONS FOR ROAD-STREAM CROSSING PRACTICES

The implications of this study for both designing and maintaining road-stream crossings can be divided into: **(1) increasing crossing capacity** and **(2) decreasing the consequences** of exceedence.

Increasing Capacity

Passing watershed products through culverts, particularly sediment and woody debris, should be emphasized for designing and maintaining wildland road-stream crossings. Designs that act to accumulate sediment and debris at inlet basins are usually not suitable in wildland environments where maintenance is infrequent and maintenance during storms is usually impractical or impossible.

Rigorous numerical techniques are available to size culverts to allow passage of water and fish. Such techniques are not generally available to size culverts for woody debris and sediment capacity. The following considerations are important to sizing for woody debris and sediment:

- **Size culverts hydraulically for an allowable headwater of HW/D<1.** Some designers use HW/D = 0.5 or 0.67. We believe this criterion is prudent in any situations where woody debris and sediment must be passed (Figure 11a).

- **Culverts as wide, or nearly as wide, as the stream channel minimize the cross-sectional change in the channel and are least likely to plug.** For small streams, matching the culvert diameter to the channel width is a practical approach (Figure 11b). For larger streams, this approach may be cost-prohibitive and other inlet-configuration measures can be used to mitigate the narrowing of the channel cross-section caused by the culvert. Culverts should be set on the same or greater gradient as the natural stream channel to avoid accumulation of sediment at the inlet (Figure 11c).

- **Culverts should be oriented with the natural channel, and present no angular deviation from the natural channel planform.** At the inlet approach, the channel should be narrow and confined and have a regular cross-section with well-defined non-meandering thalweg so that streamflow has a consistent velocity profile, and high enough energy to facilitate the passage of sediment and woody debris (Figure 11). The common practice of widening the inlet basin during maintenance promotes accumulation of sediment and adverse orientation of woody debris.

- **Vegetation at the margins of the stream-channel approach to the inlet usually acts to confine the channel and keep it aligned and its banks stable.** This orientation is desirable for passing sediment and debris. The common practice of removing streamside vegetation along the inlet approach channel, presumably to reduce the hazard of debris plugging, is counterproductive and should be avoided in most situations.

Minimizing Consequences

Although we probably cannot reliably predict the real probability of crossing failure, we can accurately predict the local physical consequences. Where risk assessment is done for a set of existing crossings, such as for a watershed, basic inventory and assessment should focus on the consequences of failure. When assessments include the probability of failure as well, it should be given less weight than consequences in determining risk and setting priorities for improvements to reduce adverse effects on water quality and aquatic habitat.

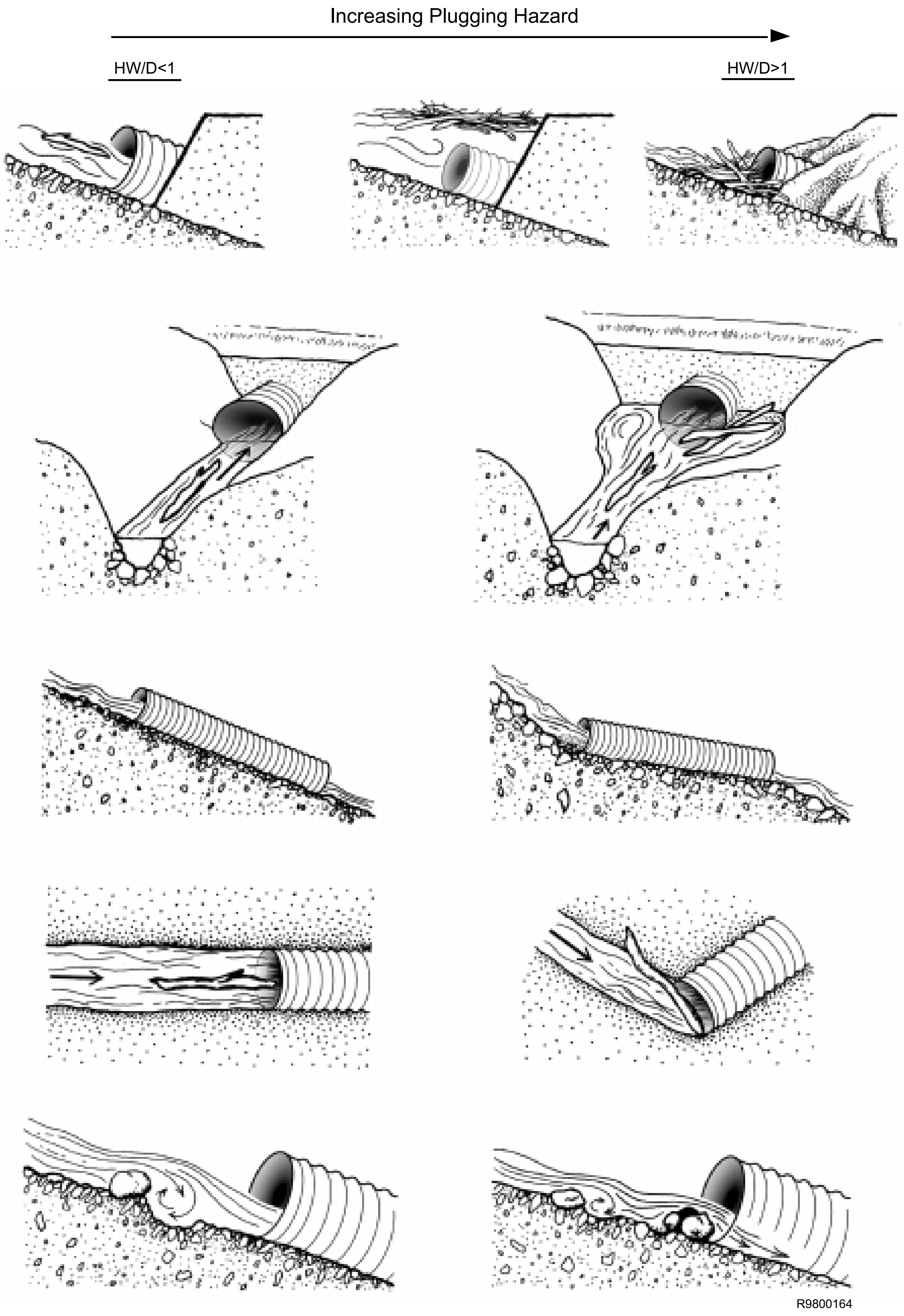

Figure 11—Illustrations of increasing plugging hazard.

Designing all stream crossings to withstand very large storm events is impractical or impossible. Because we cannot reliably predict which crossings will fail, all crossings should be expected to fail and should be designed to minimize the consequences. Ways of reaching this goal include:

- **Design for the smallest fill possible.** The smaller the fill, the less material can be eroded. Where low-water fords are feasible, they present the least consequence (usually zero) of exceedence and should be used.

- **Construct fills with coarse material.** Coarse materials, such as gravel or rock resist erosion more than fine materials do. Designs that include the maximum allowable amount of coarse material may reduce the erosional consequences of a crossing failure. Coarse material eroded from fills is usually less damaging to aquatic habitats than are finer sediments.

- **Consider the erosion mechanism associated with fill failure during design and specification of compaction.** Compacted fills are less susceptible than loose fills to catastrophic, rapid “dam-break” failures. Compacted fills typically gully out progressively upon exceedence, while poorly compacted fills are more likely to fail quickly and catastrophically. Streams are more capable of transporting increments of sediment from gullying than when sediment is rapidly introduced from a catastrophic fill failure. Thus the downstream consequences of failure can be much less where fills are well compacted.

- **Avoid stream diversion. Diversion of streams at overtopped crossings and plugged cross-drains is a major source of preventable effects.** Diversion can be prevented by locating and designing crossings to ensure that streamflow that overtops a crossing fill cannot leave its channel. For existing roads, diversion-prevention dips or other structures can be inexpensively constructed to “storm-proof” crossings that have diversion potential (Furniss et al. 1997).

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