Road Construction and Maintenance Furniss, M. J., T. D. Roelofs, and C. S. Yee. "Road construction and maintenance." American Fisheries Society Special Publication 19 (1991): 297-3...

Chapter · January 1990

1 author:

Michael J Furniss
Humboldt State University

Chapter 8

Road Construction and Maintenance

M. J. Furniss, T. D. Roelofs, and C. S. Yee

Forest and rangeland roads can cause serious degradation of salmonid habitats in streams. Numerous studies during the past 25 years have documented the changes that occur in streams as a result of forest and rangeland roads and related effects. Once the mechanisms of these changes are understood, it is possible to design roads that have less harmful effects on stream channels and their biota.

Only recently have steps been taken to minimize the negative effects of roads on streams. In the past, the primary considerations in road planning, construction, and maintenance have been traffic levels and economics, and little concern was expressed for the environmental influences of roads (Gardner 1979).

It should be recognized that only rarely can roads be built that have no negative effects on streams. Roads modify natural drainage networks and accelerate erosion processes. These changes can alter physical processes in streams, leading to changes in streamflow regimes, sediment transport and storage, channel bank and bed configurations, substrate composition, and stability of slopes adjacent to streams. These changes can have important biological consequences, and they can affect all stream ecosystem components. Salmonids require stream habitats that provide food, shelter, spawning substrate, suitable water quality, and access for migration upstream and downstream during their life cycles. Roads can cause direct or indirect changes in streams that affect each of these habitat components.

Many studies have shown how roads affect the physical environment of streams, and how the physical environment of streams affects fish. This research permits the diagnosis of problems and the design of engineering solutions to reduce negative effects.

Effects of Roads on Streams

Roads can affect streams directly by accelerating erosion and sediment loadings, by altering channel morphology, and by changing the runoff characteristics of watersheds. These processes interact to cause secondary changes in channel morphology. All of these changes affect fish habitats.

Accelerated Erosion Rates

Construction of a road network can lead to greatly accelerated erosion rates in a watershed (Haupt 1959; Swanson and Dyrness 1975; Swanston and Swanson 1976; Beschta 1978; Gardner 1979; Reid and Dunne 1984). Increased sedimenta-

Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats
American Fisheries Society Special Publication 19:297–323, 1991

tion in streams following road construction can be dramatic and long-lasting. The sediment contribution per unit area from roads is often much greater than that from all other land management activities combined, including log skidding and yarding (Gibbons and Salo 1973).

Sediment entering streams is delivered chiefly by mass soil movements and surface erosion processes (Swanston 1991, this volume). Failure of stream crossings, diversions of streams by roads, washout of road fills, and accelerated scour at culvert outlets are also important sources of sedimentation in streams within roaded watersheds.

Mass soil movement.—Where forest and rangelands occur on steep terrain, mass soil movement is often the primary mode of erosion and sediment delivery to streams from roads. Four types of mass movement common to western forest lands are described by Swanston (1991): slumps and earthflows, debris avalanches, debris flows, and debris torrents. These processes are differentiated on the basis of speed of travel and shape of the failure surface. Forest and rangeland roads can increase the incidence and severity of each type of mass movement. Several studies in the western Cascade Range in Oregon showed that mass soil movements associated with roads are 30 to more than 300 times greater than in undisturbed forests (Sidle et al. 1985) (Table 8.1).

Construction of roads can increase the frequency of slope failures from several to hundreds of times, depending on such variables as soil type, slope steepness, bedrock type and structure, and presence of subsurface water. Road location is the most important factor because it affects how much all of these variables will contribute to surface failure (H. W. Anderson 1971; Larse 1971; Swanston 1971; Swanston and Swanson 1976; Lyons and Beschta 1983). Mass soil movements triggered by roads can continue for decades after the roads are built.

The most common causes of road-related mass movements are improper placement and construction of road fills, inadequate road maintenance, insufficient culvert sizes, very steep hillslope gradient, placement or sidecast of excess materials, poor road location, removal of slope support by undercutting, and alteration of slope drainage by interception and concentration of surface and subsurface water (Wolf 1982).

Surface erosion.—Surface erosion from roadbed surfaces, drainage ditches, and cut-and-fill surfaces can severely affect streams below the right-of-way (Burns 1970; Brown and Krygier 1971; Larse 1971; Gibbons and Salo 1973; Weaver et al. 1987). In a study on the Clearwater River in Washington, Cederholm et al. (1981) found that the percentage of fine sediment in spawning gravels increased above natural levels when more than 2.5% of basin area was covered by roads. The chief variables in surface erosion are the inherent erodibility of the soil, slope steepness, surface runoff, slope length, and ground cover.

Surface erosion can be the major source of sediment delivered to streams in sensitive terrain, such as areas with soils derived from granite and from highly fractured sedimentary rocks. Surface erosion and piecemeal mass movement from landslide surfaces can prolong sediment delivery to streams after initial landslide events. Such chronic secondary erosion could be as damaging to stream biota as catastrophic or episodic sediment inputs from mass-movement events, because the particles will be finer and they will be delivered over longer time periods.

The
that
and

and
eam
ated
eams

rain,
very
orest
ava-
d on
land
nent.
s soil
an in

veral
ness,
ion is
s will
1971;
nents

roper
suffi-
xcess
, and
e and

tches,
Burns
et al.
(1981)
above
chief
slope

ms in
highly
t from
dslide
iota as
cause
ds.

TABLE 8.1.—Comparative rates of soil mass movement with various land uses, based on landslide inventories over relatively long time periods. (From Sidle et al. 1985.)

				Mass erosion	
Area (source[a])	Land use	Years of record	Number of landslides	Annual rate (m^3/hectare)	Multiple of undisturbed land
H. J. Andrews Forest, Oregon Cascade Range: unstable zone (1)	Forest	25	32	0.87	1.0
	Clear-cuts	25	36	2.45	2.8
	Roads	25	71	26.19	30
Oregon Cascade Range: Alder Creek (2)	Forest	25	7	0.45	1.0
	Clear-cuts	15	18	1.17	2.6
	Roads	15	75	155.65	346
Oregon Cascade Range: Blue River (3)	Forest	34	19	0.37	1.0
	Clear-cuts	22	30	3.22	8.7
	Roads	25	69	16.3	44
Oregon Coast Range: Mapleton area (4)	Forest	15		0.19	1.0
	Clear-cuts	15		0.7	3.7
Oregon Coast Range: Mapleton area, soil type 47 (5)	Forest	15	34	0.28	1.0
	Clear-cuts	10	186	1.13	4.0
	Roads	15	41	34.91	125
Oregon Coast Range: Mapleton area, slideprone soils (5)	Forest	15	42	0.32	1.0
	Clear-cuts	10	317	0.62	1.9
	Roads	15	89	15.85	50
Olympic Peninsula, Washington (6)	Forest	84	25	0.7	1.0
	Clear-cuts	6	0	0	0
	Roads	6	83	117.74	168
Coastal southwest British Columbia (7)	Forest	32	29	0.11	1.0
	Clear-cuts	32	18	0.25	2.3
	Roads	32	11	2.83	26
Idaho Batholith: Pine Creek burn (8)	Forest			0.07[b]	1.0
	Burned[c]	2	9	1.38	20
	Roads[d]	2	9	13.15	188
North Westland, New Zealand (9)	Forest			1.0[e]	1.0
	Clear-cut[f]	3	25	11.8	11.8
	Clear-cut[g]	3	72	40.4	40.4
	Roads[h]	3	32	267	267

[a] Sources: (1) Swanson and Dyrness (1975); (2) Morrison (1975); (3) Marion (1981); (4) Ketcheson and Froelich (1978); (5) Swanson et al. (1977); (6) Fiksdal (1974); (7) O'Loughlin (1972); (8) Gray and Megahan (1981); (9) O'Loughlin and Pearce (1976).

[b] Estimated from Zena Creek data (Megahan and Kidd 1972).

[c] Includes some clear-cut areas.

[d] Assumed that 6% of land area was in the road right-of-way.

[e] Estimated.

[f] Gravel substrate.

[g] Sandstone substrate.

[h] Calculations based on 4% of land area occupied by roads and 25% of observed landslides directly related to roads.

Surface erosion from road networks is usually reduced through time by natural revegetation (Beschta 1978), and it can be controlled by mulching, reseeding, and mechanical slope protection (Dyrness 1970; Megahan 1974; U.S. Environmental Protection Agency 1975; Carr 1980; Carr and Ballard 1980). Reid and Dunne (1984) found that sediment yield from roadbeds increased greatly with the amount of truck traffic. Sediment loss from road surfaces is partially a function of the surface composition and road maintenance.

Other sources.—Other erosional processes can cause accelerated erosion and sediment delivery to streams. Failure of road fills is common in steep terrain, particularly on low-standard roads where road fill is not compacted or woody material is incorporated into the fill.

Where flow restrictions such as culverts are placed in stream channels, the scouring power of streamflow is increased. This can lead to increased channel scour, streambank erosion, and undermining of the crossing structure and fill.

Failure of stream crossings can be a major source of increased sediment loading of streams. When stream crossings fail, they often do so catastrophically, causing extensive local scour and deposition and additional erosion downstream. Stream-crossing failures that divert streamflow onto nonstream areas are particularly damaging and persistent (Weaver et al. 1987).

Alterations in Channel Morphology

A stream adjusts its geometry to accommodate the water and sediment it carries. When the amount of water or sediment a stream must carry increases, channel geometry must change to accommodate the increase. When channel geometry is artificially changed, such as by a stream crossing, a stream will adjust by altering its geometry upstream or downstream of the change. The nature of the adjustment depends on the original geometry and composition of the channel, how these are changed, and the ability of the channel to reshape itself. Channel adjustments that occur, in order of smallest to largest energy requirements, are changes in channel bed form, channel bed armor, channel width, channel pattern (alignment), and longitudinal profile (Heede 1980).

Hagans et al. (1986) demonstrated that road construction and inadequate maintenance lead to substantial increases in stream-channel drainage densities and channel dimensions. Adjustments can occur quickly, but often continue over many years. The adjustments usually are detrimental to fish habitat. Therefore, road crossings that modify and restrict channel geometry least, such as bridges or low-water crossings, are likely to have the least adverse effects on fish habitat.

Channel morphology is also sensitive to indirect changes resulting from other effects that roads may have on streams. Increases in sediment loading and peak flows cause changes in channel morphology that can be detrimental to fish habitat.

Other Effects of Roads on Streams

Although sedimentation and stream-channel changes are the primary negative effects of roads on streams, roads can adversely affect streams in other ways. These include changes in rainfall–runoff relationships, hillslope drainage, potential for chemical contamination, the amount and type of organic debris in stream channels, and human access to streams and fish populations.

Roads can change the stream hydrograph and affect sediment deposition in streams. Harr et al. (1975) reported an increase in peak flows following road construction. King and Tennyson (1984) found that the hydrologic behaviors of small forested watersheds were altered when as little as 3.9% of the watershed was occupied by roads.

Hauge et al. (1979) discussed several ways that roads can affect hillslope drainage, including changes in infiltration rates, interception and diversion of subsurface flow, changes in the watershed area of small streams, changes in the time distribution of water yield to channels, and changes in the fine (micro) details of drainage. These changes combine to cause a rerouting of hillside drainage that can lead to changes in erosion and the hydrologic behavior of small streams.

Chemicals used to suppress dust, stabilize or deice road surfaces, and fertilize or control roadside vegetation can enter streams directly or can be transported by runoff water or on sediment. Little is known about the effects of these chemicals on stream biota. Furthermore, a chemical-spill hazard exists wherever roads are near streams or road drainage enters streams.

Organic debris from construction clearing and landslides caused by roads can enter and block streams. These materials can cause additional erosion and alteration of channel morphology, and can form migration barriers. However, they can also provide important cover and channel diversity for juvenile fish. Removal of large organic debris at stream crossings can eliminate important components of fish habitat.

Roads allow easier human access to streams, facilitating both legal and illegal fishing. They also give access to biologists for fish habitat and population assessment, and for habitat restoration and enhancement projects. In some cases a road can be a positive contribution to a fisheries management program for a stream, provided the road is located, designed, constructed, and maintained to protect fish and fish habitats.

Effects of Roads on Salmonid Habitats

The habitat requirements of salmonids are reviewed by Bjornn and Reiser (1991, this volume). The particular habitat requirements for each salmonid species vary with the season and life cycle of the fish. All salmonids require access to spawning areas, appropriate substrates for reproduction (including substrates that can support egg incubation, alevin development, and fry emergence), and suitable water quality. Species that rear in streams for months to years before they enter the ocean also require food organisms and shelter or cover. Physical alterations in sediment loading, channel morphology, substrate composition, riparian conditions, and other road-related changes can adversely affect all freshwater stages of these fish: migration, spawning, incubation, emergence, and rearing.

Migration

Improperly designed roads can prevent or interfere with upstream migration of both adult and juvenile salmonids in several ways. Macroinvertebrate movements can also be impaired or prevented by road-related changes to stream channels (Pearce and Watson 1983). Culverts pose the most common migration barriers associated with road networks. Hydraulic characteristics and culvert configuration can impede or prevent fish passage (discussed in detail later in this chapter). Extreme sedimentation from roads can cause streamflow to become subsurface or too shallow for upstream fish movement. Likewise, stream-crossing structures can impede gravel movement in streams, leading to bed aggradation and subsurface flows that block migration. Large landslides or debris avalanches can form temporary dams that prevent fish passage (Pearce and Watson 1983). In very cold climates, large ice buildups at culverts can create barriers to migration.

Spawning

Adult salmonids have exacting habitat requirements for spawning, including requirements for substrate sizes, water depth, and velocity (Bjornn and Reiser 1991). The abundance and quality of spawning substrate can be severely affected by sedimentation. Fine sediment can be deposited in gravel interstices, even in fast-moving streams, because of the lower water velocities within the gravels. If the amount of fine material in the gravel matrix is too great, the gravels may become so cemented or indurated that fish are unable to excavate a redd.

In low-velocity stream reaches, an excess of fine sediment can completely cover suitable spawning gravel, rendering the reach useless for spawning. Excessive sediment loading of streams can also result in channel braiding, increased width:depth ratios, increased incidence and severity of bank erosion, reduced pool volume and frequency, and increased subsurface flow. These changes can result in a reduction in quality and quantity of available spawning habitat.

Gravel extraction for road construction may directly remove suitable spawning substrate. In some cases, gravel removal creates additional spawning areas, but such gravels often are hydraulically unstable. This can attract spawners to gravels that will not stay in place long enough to successfully incubate embryos.

Incubation

Successful incubation of salmonids in stream gravels depends on intragravel water flow to provide oxygen and to remove carbon dioxide and other waste metabolites (Bams 1969). If the gravel interstices are filled with fine sediments, intragravel water flow and gas exchange are reduced and egg development is slowed or halted. Fry emergence is likewise hampered by excessive fine sediments that can trap fry in the gravel (Phillips et al. 1975).

The gravels of redds must be stable throughout the incubation period. Developing embryos can be destroyed by gravel scour resulting from peak flows. Increases in peak flows and sedimentation can increase the incidence of redd destruction by scouring.

Juvenile Rearing

Increased sediment in streams can adversely affect juvenile salmonids in several ways. Most of the food items in the diets of juveniles are macroinvertebrates living in the stream. Large amounts of fine sediment reduce or eliminate much of the suitable substrate for producing macroinvertebrates, thereby limiting the food available to juvenile fish (Cordone and Kelley 1961).

Excessive sediment delivery to streams can modify the stream channel configuration, decreasing the depth and number of pools and reducing the physical

---

space ava
of juvenil
substrates
Riparia
ing shade
stability,
riparian v
from road
large woo
(1987).
Everes
fish produ
are comp
of fish, c
system,
habitats,
lithology

The ba
the phys
ensure th
erosion;
to chann
hillslope
past stre
Four g
roads.

- Kno
cesses, a
patterns
- Avo
possible
usually t
habitat.
- It is
so that
mobilize
costly th
- Min
from str
roads an

Plannin

Larse
minimiz

space available for rearing fish. These changes can also lead to reduced survival of juvenile fish by filling interstitial spaces in the boulder and large cobble substrates where fish reside over the winter.

Riparian vegetation provides important components of rearing habitat, including shade (which often maintains cool water temperatures), food supply, channel stability, and channel structure. Road construction near streams often removes riparian vegetation directly. Mass soil movements and channel changes resulting from roads can also eliminate or damage riparian vegetation. The essential role of large woody riparian debris in salmonid streams was reviewed by Bisson et al. (1987).

Everest et al. (1987a) reviewed the effects of fine sediment on fish habitats and fish production. They demonstrated that the effects of fine sediment on salmonids are complex and depend on many interacting factors, including species and race of fish, duration of freshwater rearing, spawning escapement within a stream system, presence of other fish species, availability of spawning and rearing habitats, stream gradient, channel morphology, sequence of flow events, basin lithology, and history of land use.

How to Prevent or Minimize Damage

The basic strategy to prevent or minimize damage from roads is to understand the physical and biotic conditions that could be affected. Then, planning should ensure that roads are designed, constructed, and maintained to reduce the risks of erosion; that the risk of eroded material entering streams is low; that disturbances to channel morphology will be reduced or eliminated; that the alteration of hillslope drainage patterns will be minimized; and that fish will be able to migrate past stream crossings.

Four general principles should be considered to control erosion resulting from roads.

- Know what the erosional processes are, how roads can affect these processes, and the appropriate measures to prevent or control changes in erosional patterns.
- Avoid building roads in areas with high erosion hazards to the greatest extent possible. Minor changes in location can often prevent major problems. This is usually the single most important consideration in preventing degradation of fish habitat.
- It is almost always less expensive and more effective to design and build roads so that erosion is prevented or minimized than to control sediment once it is mobilized. Remedial measures for major erosional events usually are much more costly than preventing the events in the first place.
- Minimize the effects of roads on streams by keeping road disturbances as far from streams as possible, and by providing buffers of undisturbed land between roads and streams.

Planning and Reconnaissance

Larse (1971) pointed out that the most important steps that can be taken to minimize the impacts of roads on streams usually occur during planning, recon-

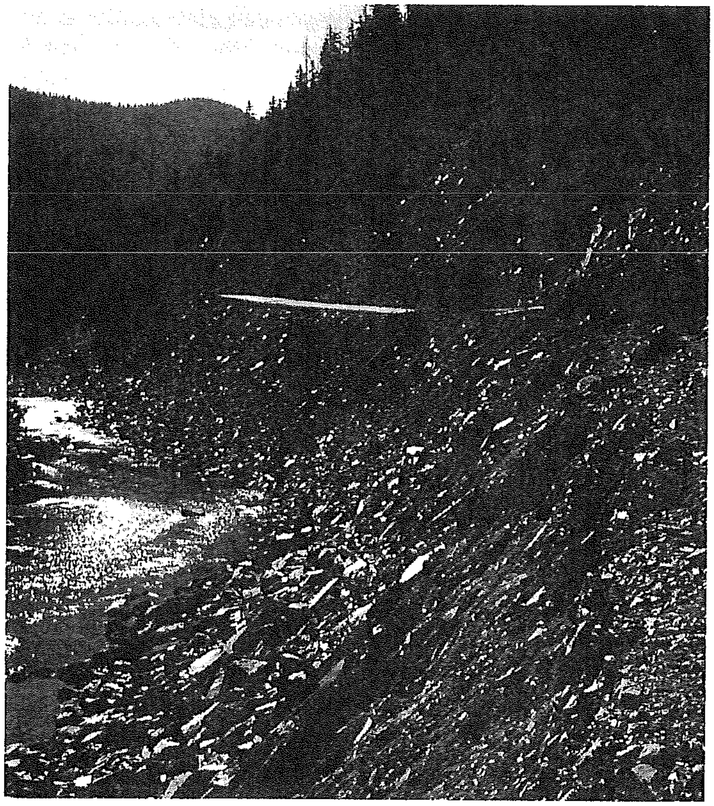

FIGURE 8.1.—Roads built near watercourses often have severe adverse effects on fish habitats. Sediments eroded from exposed and disturbed ground by rain, runoff, or streamflow move directly into stream habitats.

naissance, and route selection rather than during or after construction. Many problems can be eliminated or reduced by including on the planning team specialists such as geologists, soil scientists, hydrologists, and biologists, along with engineers. Key environmental problems and constraints are easily overlooked when routes are located and roads are designed by one person.

The following guidelines will help reduce adverse effects of roads on streams.

- Conduct long-range transportation planning for large areas to ensure that roads will serve future needs. This will result in less total road distance, roads built to appropriate standards, reduced costs of development, and fewer effects on streams.
- Use adaptable road standards to avoid sensitive areas. The prevailing planning philosophy should be to *fit the road to the landscape*. Rigid design standards, especially when limits on grade are inflexible, can severely restrict options for location, and often result in roads that pass through areas with high erosion hazards. Short grades of 14–22% can be practical for low-volume roads, and they can make it possible to avoid landslides or other sensitive areas.

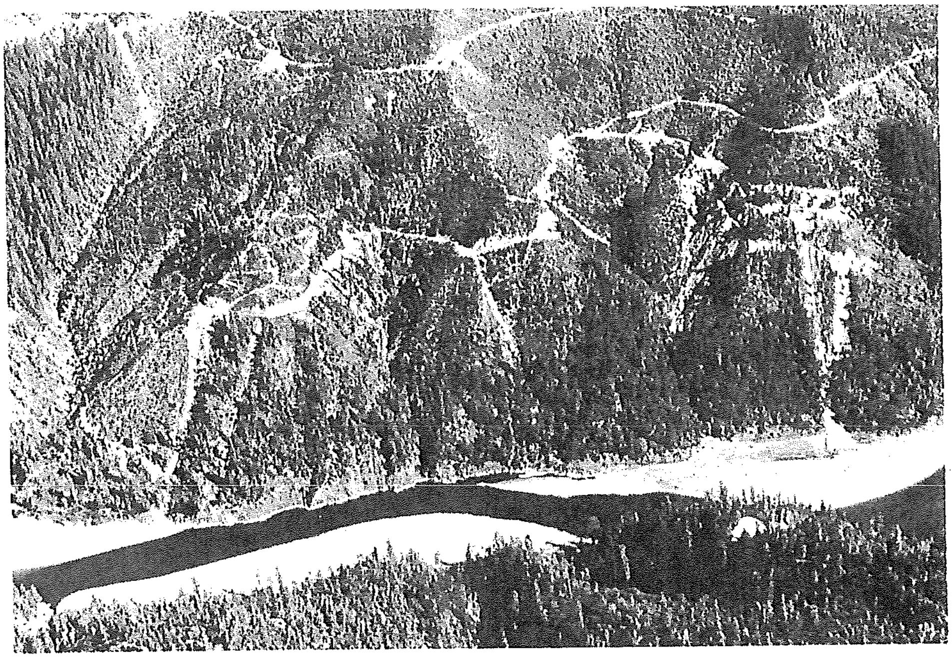

FIGURE 8.2.—Steep slopes close to waterways are high-risk locations for roads because they usually are the most erosion-prone areas in a watershed. Sediments eroded here are readily delivered to fish habitats.

- Avoid midslope locations in favor of higher, flatter areas. Ridgetop roads usually have the least effect on streams.
- Locate ridgetop roads to avoid headwalls at the source of tributary drainages. Headwall areas also are very prone to landslides (Weaver et al. 1987).
- Do not locate roads within the inner valley gorge (the oversteepened slopes adjacent to streams). These areas have the highest incidence of landsliding of any portion of an upland watershed (Wolfe 1982) (Figures 8.1, 8.2).
- Avoid slopes that show signs of excessive wetness, such as springs or water-loving vegetation.
- Avoid slopes where sidecast material could enter streams, or plan to end-haul excess material.
- Avoid slopes where large cuts and fills would be required.
- Locate roads to minimize roadway drainage area and to avoid modifying the natural drainage areas of small streams.
- Locate valley-bottom roads to provide a buffer strip of natural vegetation between the road and stream.
- Locate roads to take advantage of natural log-landing areas, such as flatter, higher, drier, and more stable terrain with good access to the timber to be removed. Good landing locations can also reduce the amount of necessary roading.
- Minimize the number of stream crossings consistent with the above considerations.

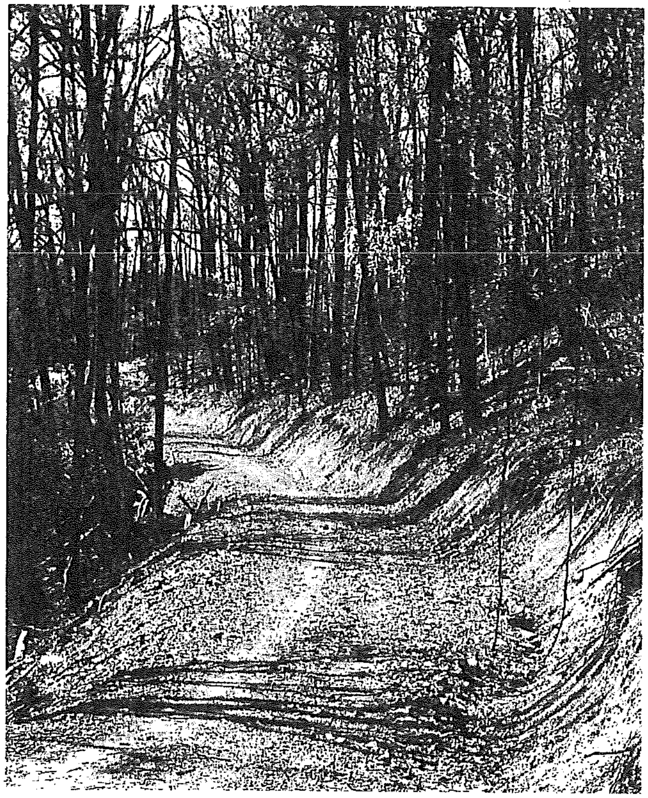

FIGURE 8.3.—A low-impact road fitted to the landscape with a narrow roadbed, narrow clearing limits, small cuts and fills, and outslope drainage. There is no inboard ditch to concentrate the erosive power of running water.

- Locate stream crossings to minimize channel changes and the amount of excavation or fill needed at the crossing.

Design

The following guidelines for road design will help minimize adverse effects on salmonid habitats.

- Use the minimum design standards practical with respect to road width, radius, and gradient (Figure 8.3).
- Minimize excavation with a balanced earthwork design wherever possible. Bench or terrace and drain natural slopes to provide a sound foundation for embankments.
- Design cut slopes to be as steep as practical. Some sloughing and bank failure is usually an acceptable trade-off for the reduced initial excavation required.
- Determine the type and extent of fish habitat before selecting criteria for drainage structure design. Bridges and arch culverts are preferred for streams with migratory fish. Where culverts are used, the gradient should be less than 1%, the culvert should be placed at or below the original streambed elevation, and

narrow
ditch to

ount of

ects on

width,

ossible.
tion for

k failure
red.
eria for
streams
han 1%,
on, and

FIGURE 8.4.—Stream crossings pose the greatest risk to fish habitats of any road feature. When culverts are plugged by debris or overtopped by high flows, road damage, channel realignment, and severe sedimentation often result. The capacity of the culvert shown here was exceeded during a heavy storm, and a large slug of sediment was rapidly delivered to fish habitats downstream. Water was not diverted down the road, however. Roads should be constructed so they will not divert streams; where existing roads have the potential to do so, creation of a simple dip or "failure point" will prevent the catastrophic effects that can result from a diversion.

water depth and velocity at both low and high flows should be integrated into the design (discussed in detail later in this chapter).

- Control scouring at culvert outlets with energy dissipators such as heavy rock riprap, weirs, or gabions, consistent with fish passage considerations.
- Design drainage structures to accommodate peak streamflow based on at least a 50-year-interval flood (100-year flood for large permanent bridges and major culverts), and give consideration to the possibility that bed load and debris will restrict the flow capacity of the structure. The risk of failure can be calculated by

$$F=1-(1-1/t)^n;$$

F is the chance of failure during the design life, t is the flood recurrence interval, and n is the design life of the road or structure. For example, a culvert sized for a 50-year flood has a 33% chance of failure during a 20-year design life. Campbell and Sidle (1984) described methods for predicting peak flows and sizing culverts for small watersheds. Keep in mind that, whatever the design life, any crossing structure has a virtually 100% chance of failing over its installation life if it is not removed after the road is abandoned.

- At stream crossings, avoid channel-width changes and protect embankments with riprap, masonry headwalls, or other retaining structures. Align culverts with the natural course and gradient of the stream. Debris that floats during high

FIGURE 8.5.—If road drainage becomes concentrated, it must be discharged into places that can handle the flow without accelerated erosion. When the natural drainage of small streams is changed and concentrated flow is discharged into nondrainage areas, severe gullying and landslides can result.

streamflow can plug or restrict flow at culverts, causing severe changes in road embankments, streambanks, or channels (Figure 8.4). Trash racks can reduce culvert plugging, but can easily become barriers to fish passage. Avoid the need for trash racks by designing culverts to pass debris downstream.

- Wherever possible, disperse drainage rather than concentrating it, except in streams. Always strive to keep water flowing where it would naturally flow.
- Avoid the discharge of large amounts of concentrated runoff onto nondrainage areas (Figure 8.5).
- Do not change natural drainage areas by means of culvert or waterbar placement.
- Surface forest and rangeland roads wherever practical to control erosion and to maintain the surface drainage configuration under expected traffic conditions. Design road surfaces to remain stable and erosion-resistant during the wettest period of use. Control access on roads intended for dry-season use only.
- Use outslope drainage wherever feasible to disperse runoff. This results in the least potential for erosion and does not require as wide a road (no ditchline).

General
grades a
Inslopin
Cross-d
which c
• Wh
frequen
enter st
prone t
sensitiv
• Wh
flume tc
the outl
• Pro
erosion
erosion-
and Bal
• Kee
streams
• Dev
stream
the ope
most ea
• Wh
reduce
• Des
out of t
with de
• Fie
certain
critical
been de

Constr

A cha
possible
of the a
severe
followin
habitats

• Sch
Consult
when e
streamf
• Ens
even if

to places
: of small
s, severe

in road
ı reduce
:he need

xcept in
low.
ıto non-

vaterbar

sion and
nditions.
: wettest
,.
lts in the
.tchline).

Generally, outslope drainage works well where sideslopes are greater than 20% and grades are less than about 12%, and where surface configuration can be maintained. Insloping with frequent cross-drainage is appropriate on roads with steeper grades. Cross-drainage on outsloped roads should be considered as a backup to outsloping, which can become ineffective under some traffic and surfacing conditions.

- Where inslope-and-ditch drainage is used, relieve the ditchline of drainage at frequent intervals onto areas that will not erode excessively or cause sediment to enter streams. Special care must be taken to avoid discharging drainage onto areas prone to gullying, slumping, or landsliding. Ditches along steep grades and in sensitive areas should be lined with rock to control ditchline erosion.
- When discharging drainage onto a long, erodible fill, use a discharge pipe or flume to convey the drainage to the bottom of the fill. Place energy dissipators at the outlet.
- Provide for vegetative or mechanical stabilization in areas where cut-and-fill erosion will cause sediment delivery to streams. Several publications describe erosion-control measures for cut-and-fill surfaces (Patric 1976; Carr 1980; Carr and Ballard 1980; Rothwell 1983; Swift 1986).
- Keep approaches to streams as close to right angles as possible to minimize streamside disturbances.
- Develop a specific plan for stream-crossing construction that addresses stream diversion, disturbance limits, equipment limitations, erosion control, and the operational time period when disturbances caused by construction can be most easily limited.
- Where necessary, use retaining walls with properly designed drainage to reduce excavation, contain bank material, and prevent stream encroachment.
- Design and construct stream crossings so that they will not divert streamflow out of the channel and down the road alignment if the culvert should fail or plug with debris (Figure 8.6) (Weaver et al. 1987).
- Field-check the designs before the plan drawings are complete to make certain that the design fits the terrain, that drainage needs have been met, that all critical slope conditions have been identified, and that appropriate solutions have been designed for all problem areas.

Construction

A challenge to the road builder is to construct the designed facility with the least possible disturbance of the right-of-way and without damage to or contamination of the adjacent landscape and streams. Poor construction practices can lead to severe erosion problems, toxic spills, and other water-quality problems. The following construction practices will help reduce adverse effects on salmonid habitats.

- Schedule construction during noncritical times for the local fish populations. Consult a fisheries biologist for this information. For example, avoid construction when eggs or alevins are in the gravels downstream, and do not restrict or block streamflow when adult fish are migrating upstream.
- Ensure that erosion-control measures are completed prior to rainy weather, even if construction is incomplete.

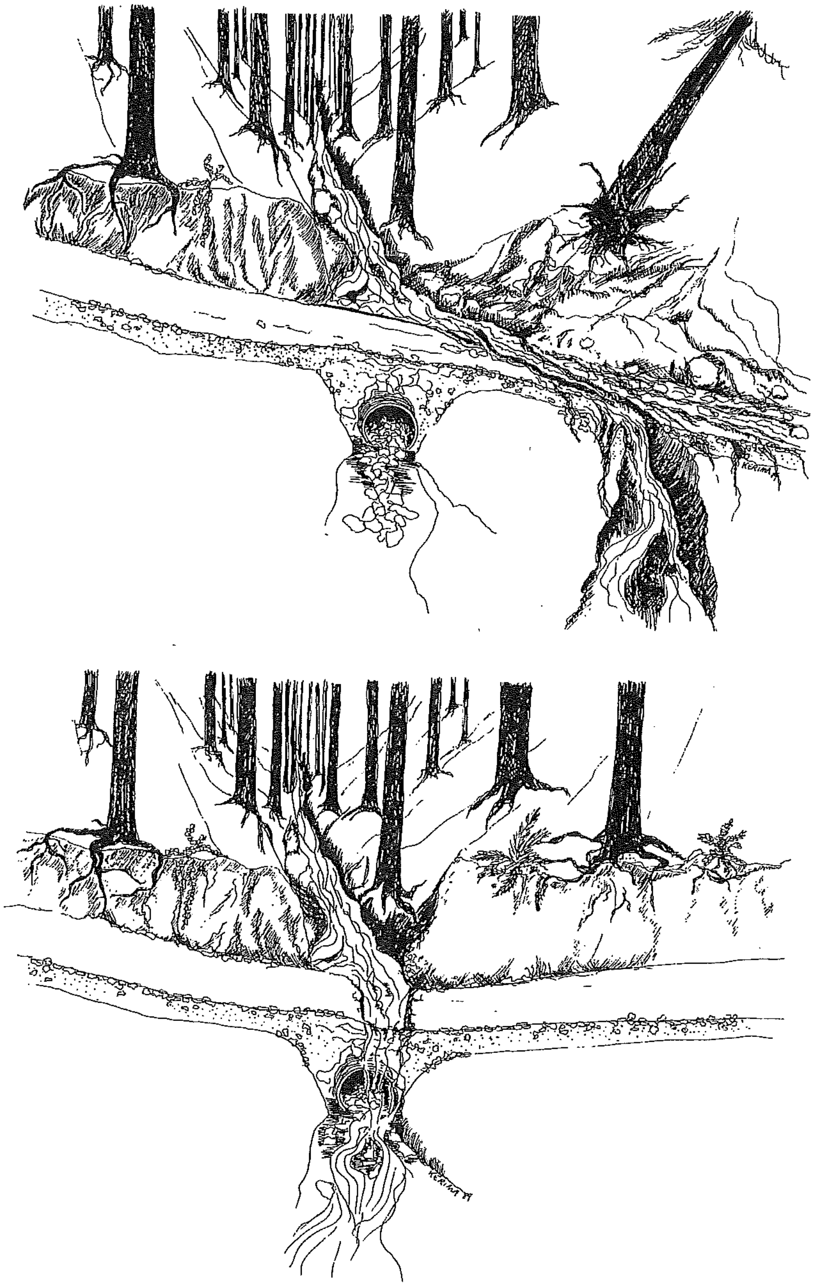

FIGURE 8.6.—Stream crossings can be considered dams that are designed to fail. The risk of failure is substantial for most crossings, so *how* they fail is of critical importance. In the upper sketch, the crossing has failed and the road grade has diverted the stream down the road, resulting in severe erosion and downstream sedimentation; such damage to aquatic habitats can persist for many years once begun. Stream diversions are easy to prevent, however, as illustrated by the lower sketch, in which the road grade was such that a crossing failure only caused the loss of some road fill.

FIGUR
bly lead:

- Re
stream
- Lo
contain
equipm
- Re
design
benefici
and gre
- Lo
dation a
- Lo
- Us
streams
- Do

Mainte

Regu
and co
all roa
conside
constru
costs.
deterio

FIGURE 8.7.—Incorporation of woody debris into road fill and sidecast material inevitably leads to mass failure and surface erosion.

- Remove earth material and debris from streambanks so they cannot enter the stream later.
- Locate fuel storage areas well away from streams, and construct dikes to contain the largest possible spill. Leaks of motor oil and hydraulic fluids from heavy equipment should be monitored and controlled to prevent water contamination.
- Restrict gravel-removal operations to areas above the high-water level of the design flood. Coordinate gravel removal with a fisheries biologist. Sometimes beneficial changes can be made, but only when the fluvial system is understood and great care is taken.
- Locate and construct water withdrawal points to prevent streambank degradation and sedimentation.
- Locate road-building camps away from streams and manage wastes properly.
- Use spill-control planning and practice to keep construction toxicants out of streams.
- Do not incorporate woody or vegetative material into road fills (Figure 8.7).

Maintenance

Regular maintenance is required to keep roads in good condition and to identify and correct problems promptly. Preventive maintenance should be practiced on *all* roads, not just actively used roads. Maintenance requirements should be considered during planning and design. The higher initial costs of designing and constructing roads that weather well can be amortized by lower maintenance costs. The following practices will help reduce the adverse effects of road deterioration on salmonid habitats.

- Do not leave berms along the outboard edge of roads, unless an outboard berm was specifically designed to be a part of the road and low-energy drainage is provided for. The creation of outboard berms during road grading is a common mistake, and frequently turns low-impact roads into high-impact, chronic sediment producers.
- Grade and shape roads to conserve existing surface material. Road grading and shaping should maintain, not destroy, the design drainage of the road, unless modification is necessary to improve drainage problems that were not anticipated during the design phase.
- Inspect ditches and culverts frequently, and clean them out when necessary. Do not over-clean them, however, because excessive cleaning of ditches causes unnecessary sedimentation.
- When blading and shaping roads, do not sidecast excess material onto the fill. Periodic sidecasting can prevent fill stabilization and promote erosion.
- Do not use herbicides where they might contaminate streams, such as on areas near streams or in ditchlines that discharge into streams.
- Apply oil, other dust-abatement additives, and stabilization chemicals so they do not enter streams. Subsequent transport of these substances into water courses should be evaluated (Norris et al. 1991, this volume).
- Promptly remove debris that obstructs drainage systems.
- Close unsurfaced roads during the wet season, particularly those that can directly contribute sediment to streams.
- Close and reclaim unneeded roads. They should be put into shape to be stable and drain properly without maintenance. This usually requires earthwork for removing culverts or ''dishing out'' crossings that have high diversion potentials, and shaping the road for long-term stability (Figure 8.8; Eubanks 1980; Weaver et al. 1987). Where high-value fisheries are at risk from abandoned roads, more extensive obliteration and reclamation of roads should be considered.

Roads and Fish Migration

Forest and rangeland roads frequently cross streams. All crossings must be engineered to allow the efficient passage of water under the road. When the streams support fish, a means for their passage must be incorporated as well.

In western streams, anadromous salmonids migrate upstream and downstream during their life cycles, usually over long distances. Many resident salmonids and other fish also move extensively upstream and downstream to seek food, shelter, better water quality, and spawning areas.

Road crossings can be barriers to migration, usually because of outfall barriers, excessive water velocity, insufficient water depth in culverts, disorienting turbulent flow patterns, lack of resting pools below culverts, or a combination of these conditions (Figure 8.9).

The incorporation of fish-passage facilities at stream crossings should be based on assessments of the life-cycle requirements of fish species, of habitat quality, and of the accessibility of sites to fish. Natural barriers downstream or immediately upstream from the site may eliminate the need to provide fish-passage facilities. Usually, a knowledgeable fisheries biologist must be consulted to assess the habitat.

outboard
·ainage is
common
ınic sedi-

l grading
.d, unless
ıticipated

ecessary.
es causes

to the fill.

ıch as on

ls so they
·r courses

that can

be stable
ıwork for
ıotentials,
Weaver et
ıds, more

must be
When the
ıs well.
wnstream
onids and
l, shelter,

l barriers,
ing turbu-
n of these

l be based
ıt quality,
r immedi-
h-passage
l to assess

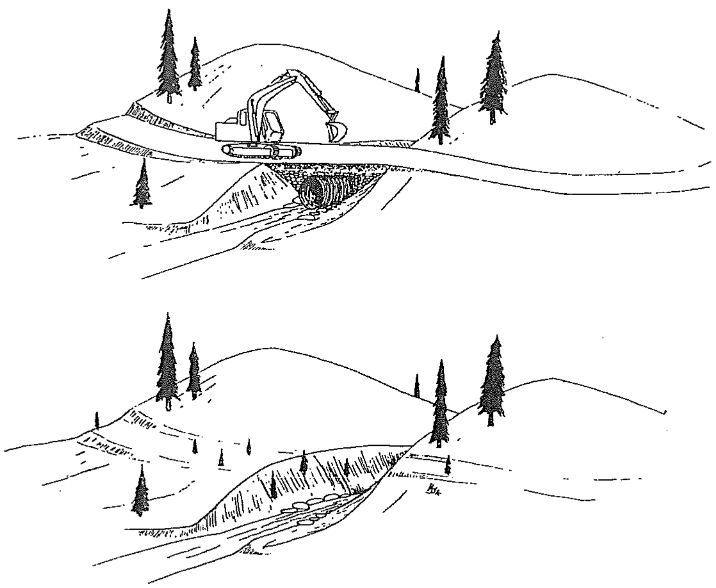

FIGURE 8.8.—When a road is abandoned, most future erosion can be prevented if roads are backfilled, stream crossings are removed, stream channels are reconstructed to stable configurations, and all bare surfaces are revegetated. Severe erosion is almost inevitable if stream crossings are left in place along abandoned roads.

Typical stream crossings involve bridges or culverts. Bridges are preferred because they usually cause less modification of stream channels than do culverts, and they are often the best way to assure fish passage. Building bridges on low-volume forest and rangeland roads is often uneconomical, however, and less-costly culverts are used. Culverts are by far the most common type of crossing device and the most likely to cause barriers to fish migration.

Low-water crossings are sometimes used where transportation requirements are seasonal and stream channel and slope configurations are suitable. Low-water crossings with concrete sills or grade-control structures can be barriers during low-flow conditions, but this can be easily mitigated in design. Low-water crossings are preferable to culverts for fish passage because high-flow migration is unimpaired and low-water migration is easy to provide for.

Consideration of fish passage during planning and design of road stream crossings can greatly reduce or eliminate the barrier effects that crossing structures can have. In many situations, structures must be designed with fish passage as the primary engineering requirement.

Where culverts are deemed necessary for stream crossings, the road designer should be aware of factors that affect the fish, and of the choices among crossing locations and structures. Close coordination between fishery biologists and engineers is critical, especially during planning stages.

The first consideration is whether or not the stream to be crossed is used by migrating fish. If not, the design problem is reduced to one of adequate discharge capacity. If the stream is used by fish that migrate at any time during their life cycles, the designer must know which species use the stream, when they migrate,

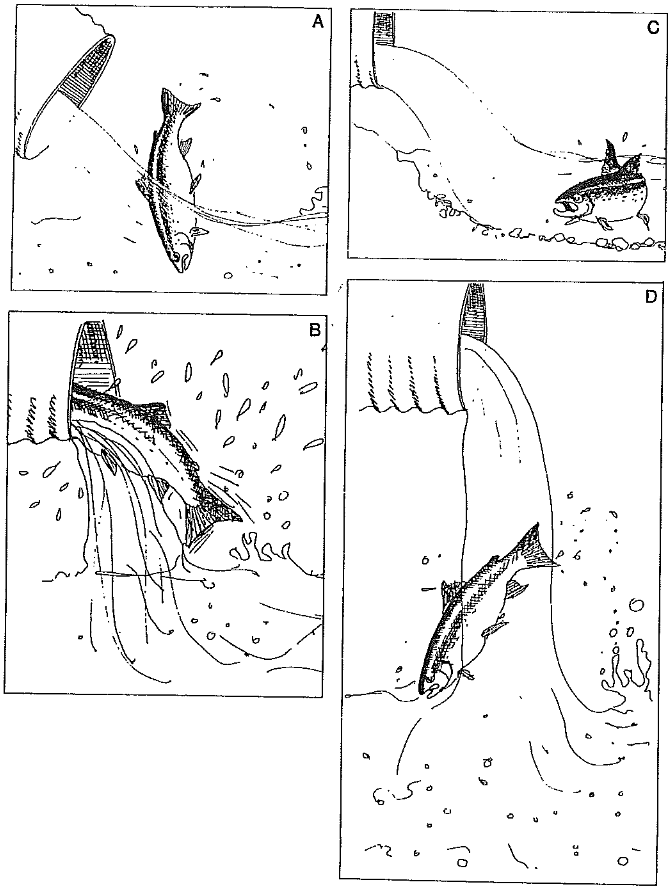

FIGURE 8.9.—Culvert conditions that block fish passage: (A) water velocity too great; (B) water depth in culvert too shallow; (C) no resting pool below culvert; (D) jump too high. (After Evans and Johnston 1980.)

and what their swimming capabilities are. Facilities for fish passage must be based on the swimming abilities of the least-capable migrating fish in the stream, not the champion swimmers.

For fish to overcome obstacles in their migration, the following conditions are necessary.

- A resting–jumping pool must be present immediately below the obstacle. This allows the fish to conserve energy and build up swimming speed to overcome the obstacle.
- Individual jumps must not be too high. For adult trout, a single vertical jump should be no higher than 0.3 m, and individual jumps in series should be 0.15 m high or less. A good working assumption is that adult salmon and steelhead can negotiate single jumps of 0.6–0.9 m or a series of 0.3-m-high jumps.
- Water depth through the culvert must be adequate for swimming. A minimum water depth of 0.15 m for trout and 0.3 m for salmon and steelhead is necessary.

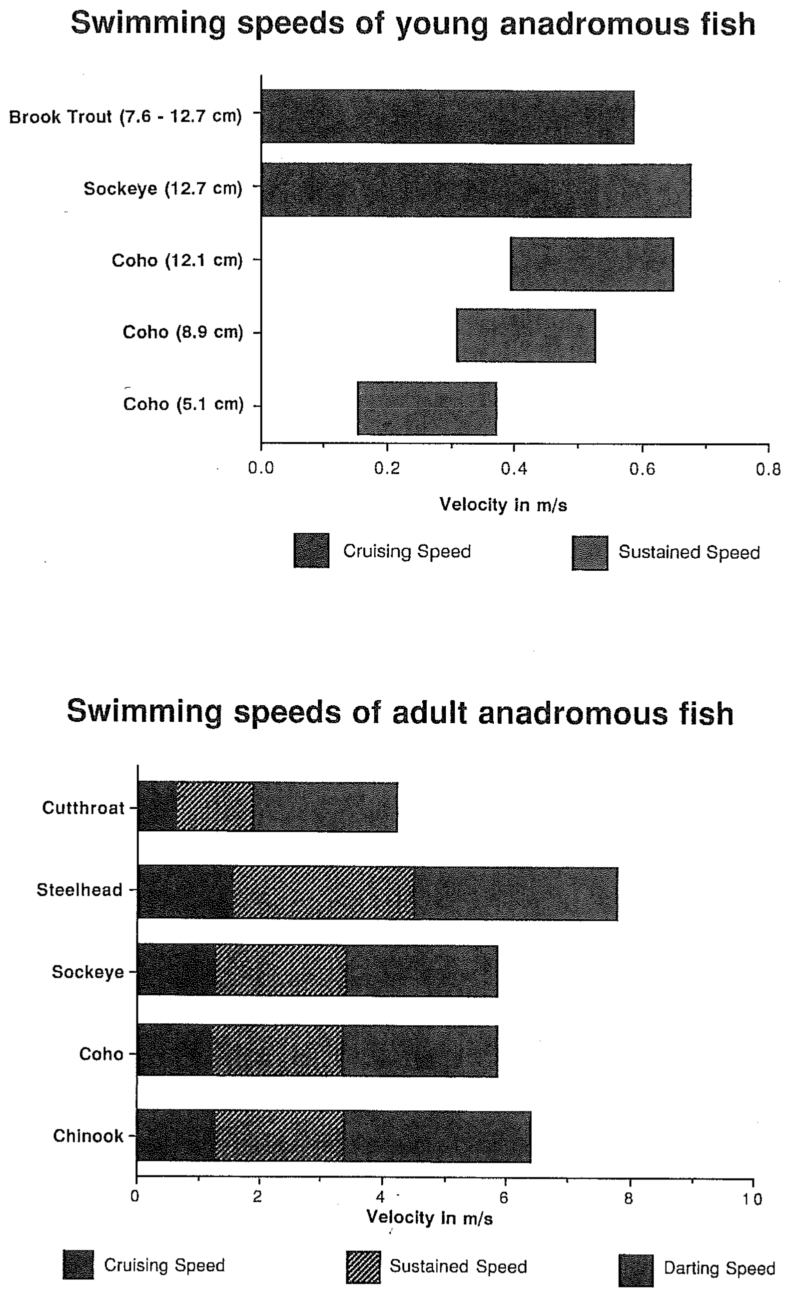

FIGURE 8.10.—Swimming speeds of young and adult anadromous trout and salmon.

- The water velocity in the culvert must not exceed the maximum sustained swimming ability of the migrating species for which passage is designed. Figure 8.10 shows the swimming speeds of adult and juvenile anadromous fish.
- Resting areas must be provided en route wherever the swimming distance through a difficult obstacle exceeds 15–30 m.

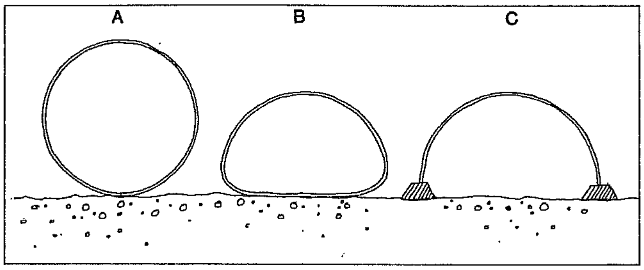

FIGURE 8.11.—Types of metal culverts used on western forest and rangeland roads: (A) corrugated-round; (B) corrugated pipe-arch; (C) structural plate-arch with concrete footings.

- A resting pool at the upstream end of a difficult obstacle is necessary so that exhausted fish are not swept downstream.

The choice of crossing location is very important in terms of both sedimentation effects and fish passage. For fish passage, preferred locations are those that do not cause large increases in velocity and have no abrupt changes in gradient or alignment of the channel. Reaches with uniform alignment, good bank stability, and uniform gentle gradients are the easiest to cross with provisions for fish passage.

Types of Culverts

Three types of metal culverts are commonly used for western forest and rangeland roads. They are classified by shape and are either standard corrugated-round, standard corrugated pipe-arch, or structural plate-arch (Figure 8.11). The first two may be prefabricated, as is usual for the smaller sizes (up to 1.5 m in diameter), or they may be of multiplate design. Structural plate-arch culverts are always of multiplate design because they are so large and are usually fabricated on site.

The structural plate-arch set in concrete footings (Figure 8.11C) is the most desirable culvert type for fish because the natural streambed is left mostly unchanged. Little narrowing of the flow occurs at either end of the culvert and there is no significant change in water velocity. Where concrete footings are not practical, split, wide-flanged, buried steel footings have been used successfully in their place. Many fisheries biologists believe that the structural plate-arch is the only acceptable culvert type where fish passage is required (Evans and Johnston 1980).

Pipe-arch culverts (Figure 8.11B) are less desirable than the structural plate-arch, but they can usually be installed to allow fish passage. Fabricated in smaller sizes, they can be used in smaller, lower fills where structural steel arches would not fit. Wherever pipe arches are used, the gradient must be kept below 1% to minimize water velocities. During periods of low flow, the water in culverts with this shape can be spread so thinly across the bottom that fish passage is impossible. Baffles may be needed to increase the flow depth through the pipe arch (baffle systems are discussed in detail later).

Although the standard corrugated-round culvert (Figure 8.11A) is the type most commonly used in western forest and rangeland roads, it is the least desirable for

FIGURE 8.12.—Culverts installed above the grade of a stream can be a barrier to upstream fish migration. The culvert shown here is impassable to salmon and steelhead.

fish passage. The width constriction from stream channel to culvert is usually severe and the gradient of the pipe must be at or near 0% to keep water velocities within an acceptable range for fish passage. This type of culvert is also the most likely to be installed with its outfall above the tailwater elevation, producing an outfall barrier (Figure 8.12). Elevated outfalls must be avoided or mitigated.

Culvert crossings have been installed in thousands of streams with little or no thought to their effects on fish populations. A single poorly installed culvert can eliminate the fish population of an entire stream system. Poor culvert design and location can still be ranked among the most devastating problems for fish habitats on western forests and rangelands.

Following are some important considerations for culvert installation.

- Installation of round culverts should be avoided where fish passage is necessary. Install either open-arch culverts or bridges, especially if culverts longer than 30 m are required or where the stream gradient is steep (>2%).
- The two most important considerations for fish passage through culverts are maximum acceptable water velocity and minimum acceptable water depth for the migrating species.
- The diameter of culverts must be adequate to pass maximum flows and the expected debris. Washing out of culverts and their earth fills damages the road and is a source of sedimentation. Channel-bank stability upstream and downstream of culverts should be provided for. Road crossings alter the hydraulics of streams above and below the crossing for considerable distances, sometimes making banks more susceptible to erosion. Severe erosion can alter the configuration of

the stream and crossing, and can eliminate the design components that provide for fish passage.

- A single large culvert is better than several small ones because it is less likely to become plugged and it carries water at lower velocities.
- The entire length of round culverts should be placed slightly below normal stream grade, at a slope near 0%, to reduce fish passage problems.
- Any structure for fish passage must function through the range of flows during which fish migration occurs. Streams used by salmonids fluctuate widely and have occasional high peak flows. An acceptable practice in culvert design has been to not require conditions suitable for fish passage during the 5% of the year when the flows are the greatest (Evans and Johnston 1980). Fish do not normally migrate during peak flows, so little or no disruption of migration occurs. This practice often results in substantial savings in construction costs. The objective should be to ensure fish passage during all but the highest flows.
- Installations that would require baffling for fish passage should be avoided; a bridge, a low-water crossing, a pipe-arch culvert, a larger culvert, a reduced gradient, or another solution should be used instead. Baffles normally require additional maintenance and occasionally cause debris accumulations. Baffles are sometimes necessary when high water velocities are unavoidable or when fish-passage problems must be corrected at existing culverts.
- Where culverts are installed in stream sections with steep gradients, it is important to create or improve resting pools, cover, and bank protection along the stream above and below the culvert. Maintaining a stable stream bottom through the culvert-influenced area is essential.

Water Velocity in Culverts

The swimming abilities of salmonids increase with the size of the fish. Hence, the species and life history stages that must navigate the culvert determine the allowable maximum water velocity. The swimming abilities of salmonids are not adequately defined, but general information has recently become available. Figure 8.10 shows maximum, sustained, and average swimming velocities for common salmonids in the west.

Metsker (1970) pointed out that the culvert velocity a fish can overcome varies not only with fish size but also with the distance between resting pools above and below the culvert. The Oregon State Game Commission (1971) recommended maximum water velocities of 2.4 m/s for adult salmon and steelhead and 1.2 m/s for trout. The recommended velocities in Oregon, however, were for round culverts up to 30.5 m long. Water velocities in longer culverts should not exceed 1.8 m/s for adult salmon and steelhead or 0.9 m/s for trout.

To aid road designers in estimating the water velocities through culverts, both the Oregon State Game Commission (1971) and the U.S. Forest Service (Evans and Johnston 1980) have produced velocity curves based on Manning's equation for open-channel flow (Chow 1959). The Oregon State Game Commission curves are only for round culverts that range in diameter from 0.6 to 2.1 m. Gradients range from 0.25 to 5.0%. Figure 8.13 is an example of the Oregon velocity curves for a 1.8-m culvert. Fish passage through culverts normally occurs between a minimum depth of 7.6 cm and a maximum depth of two-thirds the pipe diameter; the Oregon curves cover only these depths.

FIGU
flowing
. . ., 59

The
than th
m), fo
(2.1 ×
both v
diamet
a meta
Salm
gradier
carry
velocit
crossin
design,
becaus
Culv
lower-
increa
to the
water
both p
Man
princip
best in
Fisher

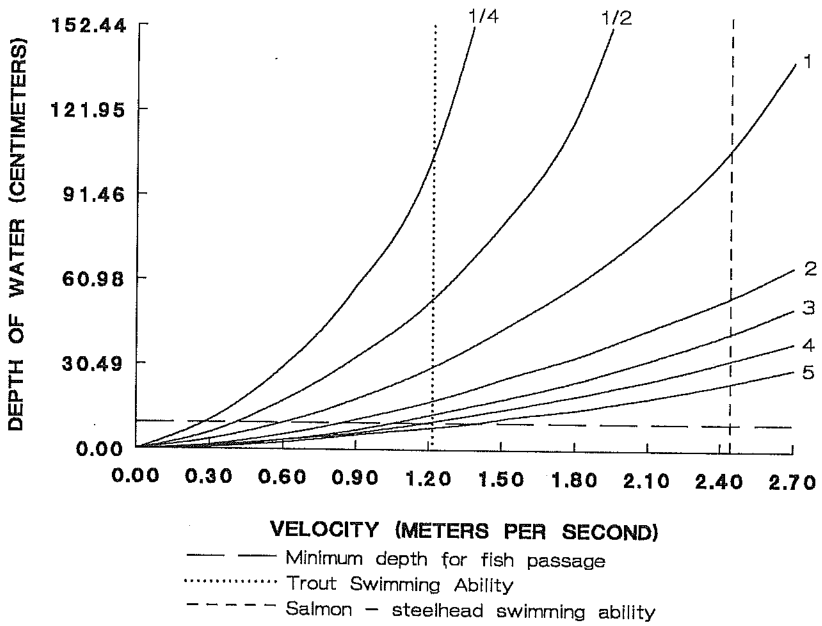

FIGURE 8.13.—Depth–velocity curves (Oregon State Game Commission 1971) for water flowing through a round, 1.8-m-diameter culvert. Curves represent gradients of 0.25, 0.5, . . ., 5%.

The U.S. Forest Service velocity curves are more detailed and comprehensive than the Oregon curves. Velocity curves are provided for round culverts (0.9–3.0 m), for concrete box culverts (0.7–3.0 m), and for corrugated metal pipe-arches (2.1 × 1.5 m to 5.1 × 3.1 m, span × rise). The U.S. Forest Service curves yield both velocity and depth of flow for any given discharge, culvert gradient, and diameter. Figure 8.14 illustrates the format of the U.S. Forest Service curves for a metal pipe-arch.

Salmonid spawning streams in the west are often mountain streams with steep gradients. Even culverts placed on the same grade as the original streambed may carry water at velocities greater than migrating fish can overcome. To control velocity in such situations, installation of baffles may be necessary. For new stream crossings, adequate water depth for fish passage should be integral to the structure design, and should not rely on baffles. Where existing crossings block migration because of inadequate water depth, baffles can be used to increase depth.

Culvert baffles are structures that impede water flow to produce pockets of lower-velocity flow in the culvert, where fish can rest momentarily, or that increase the overall depth of the flow. Impeding water flow in culverts is contrary to the primary engineering purpose of the culvert, which is to efficiently pass water under the road. The biologist and the engineer must work together to solve both problems simultaneously.

Many different baffle designs are available; little is known about their hydraulic principles, however, and additional applied research in this area is necessary. The best information on baffle design can be found in a Washington Department of Fisheries report by McKinley and Webb (1956). The principles in this report are

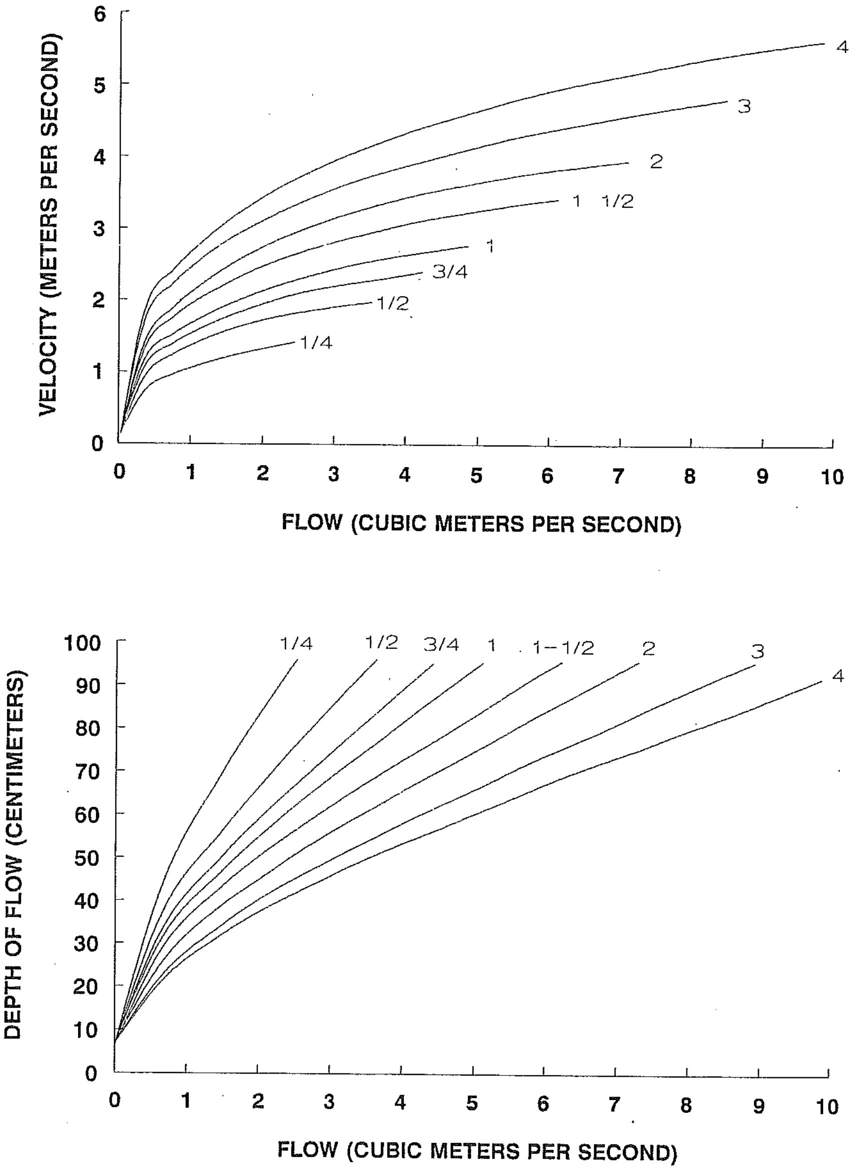

FIGURE 8.14.—Velocity–flow and depth–flow curves (U.S. Forest Service) for water flowing through a 2.1-m × 1.6-m metal pipe-arch. Curves represent gradients of 0.25, 0.5, . . ., 4%. (After Evans and Johnston 1980.)

sufficiently sound to be used as present guidelines, pending results of further research.

A few general principles apply to the use of baffles in culverts.

- Wherever possible, fish passage problems should be solved without baffles, preferably through use of bridges, low-water crossings, arch culverts, or round

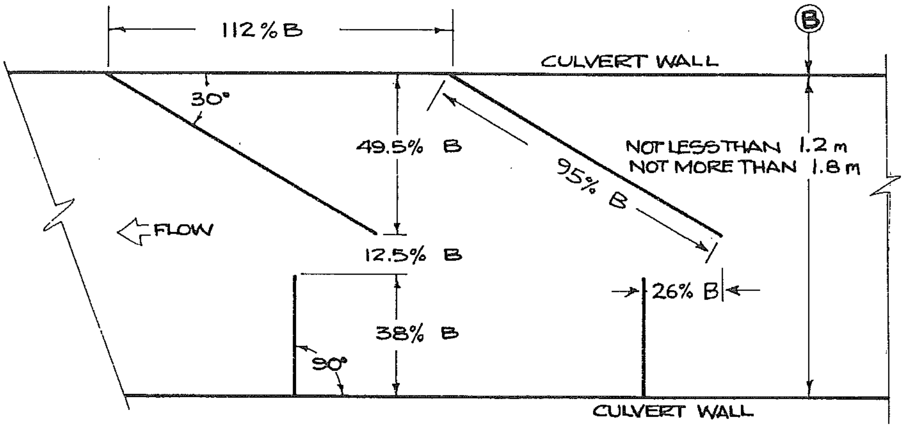

FIGURE 8.15.—Baffle design recommended by the U.S. Forest Service for culverts. Dimensions are scaled (as percentages) to culvert width (B), which can range from 1.2 to 1.8 m. (After Evans and Johnston 1980.)

culverts of adequate size and configuration. Culverts should be installed at or below streambed level such that water velocity is low.

- If higher velocities, extensive distance, or inadequate depth are unavoidable in a round- or box-culvert installation, baffles will be necessary. Baffles and the quieter waters they create allow fish to swim in short spurts through high-velocity water and to enter rest areas parallel to the higher-velocity flow.
- A large, single culvert provides better fish passage than do several smaller ones. Where multiple units are required in parallel, only one must be baffled to pass fish. Selection of the culvert for baffling is based on the route most likely to attract fish. At such installations, low flows should be diverted through the baffled culvert only.
- Large culverts, particularly the box type, can be divided so that baffles are placed in one side only.
- The baffle design illustrated in Figure 8.15 is recommended for use by the California Region of the U.S. Forest Service for solving excessive velocity problems (Evans and Johnston 1980). This design is adaptable to installations of various sizes; dimensions are given as percentages of the total width of the baffled section. Baffles should be at least 0.3 m high and 12.7–15.2 cm wide.
- Passage of water through the culvert will be somewhat impaired by baffle structures. Most culvert designs incorporate large safety factors, so the pipe diameter is considerably larger than is needed for the discharge conditions. Although the actual impairment of discharge capacity due to baffles is relatively small, a larger pipe may be necessary or a lesser safety factor must be tolerated.
- Construction materials for baffles may be wood, metal, or concrete, depending on the local situation. Concrete baffles can be precast and drilled or grouted into place. Metal baffles are usually bolted onto the culvert floor through metal plates, which give added strength.

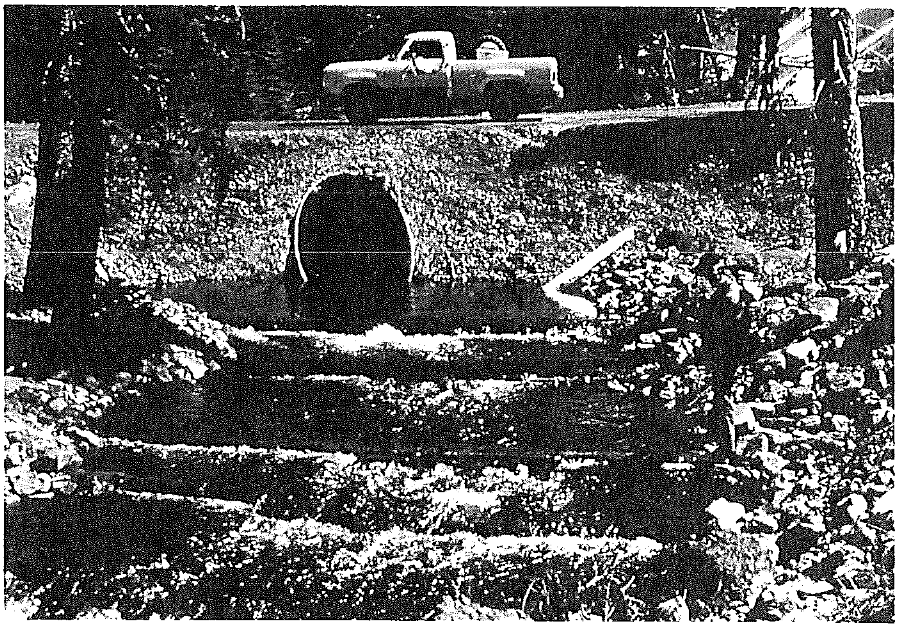

FIGURE 8.16.—Series of low-head dams that prevent a road culvert from being an outflow barrier to upstream fish migration.

- Most baffle designs work best when water flow just overtops the baffle elements. With greater water depth, baffle effectiveness is inversely proportional to the depth of water over them (Gebhards and Fisher 1972).
- Solving fish-passage problems during design and construction of new crossings is substantially less expensive than modifying existing culverts.

Culvert Outfall Barriers

Culverts can be insurmountable barriers to migrating fish when the outlet of the culvert is so far above the tailwater that fish cannot enter the pipe. This condition is termed an outfall barrier (Figures 8.9D, 8.12). When new culverts are to be installed on streams with migrating fish, every attempt should be made to avoid constructing outfall barriers. Putting a new culvert outlet below the tailwater elevation is sometimes not possible, and many existing culverts form outfall barriers.

One way to correct an outfall barrier is to provide for one or a series of low-head dams below the culvert outfall (Figure 8.16). These dams may be nothing more than hand-placed rock "reefs," wire-basket gabions filled with local rock, or concrete sills. These downstream dams raise the tailwater elevation and flood the culvert. Access by fish is not only enhanced, but water velocity in the culvert is decreased. The downstream dams should not create outfall barriers themselves and should therefore be limited to about 0.3 m in height.

For dams of greater heights, there must be a pass-through notch in the center. Because the back-flooding decreases velocity and hence discharge, a culvert of larger diameter may be necessary to handle peak flows when downstream dams

---

are used
low-hea
In sor
the culv
tions in
because
multiple
stacked
well as

Structur

The u
western
howevei
downstr
Althoug
debris-l
streams
be desig
To c
structur
Passing
inlet, an
adds to
debris c
will be l

Fores
habitats
integrat
guidelin
correcti
engineei
maintair

are used. Furthermore, it may be necessary to armor the downstream sides of the low-head dams to prevent scouring by the cataracts formed.

In some streams, the range of flows is so great that it is impossible not to have the culvert outlet above the tailwater at some time. Also, where severe fluctuations in flow require large culverts, fish passage may be impeded during low flows because of shallow flow over the broad culvert bottom. In such cases, stacked- or multiple-culvert installations can be used to provide fish passage. Placing the stacked culverts at different elevations assures adequate discharge capacity as well as fish passage over a wider range of flows.

Structures for Debris Control

The use of debris-control structures, such as trash or debris racks, is growing in western forest and rangelands due to the high cost of failed crossings. Trash racks, however, are detrimental to fish passage. The same freshets that often bring debris downstream are those in which many fish can move up to spawning areas. Although the protected culvert may not be a velocity or outfall barrier, a debris-laden trash rack can be impassable to fish. Debris-catching structures on streams used by migrating fish should therefore be avoided, and crossings should be designed to transmit debris downstream.

To compensate for the loss of culvert protection from a debris-catching structure, the culvert should be large enough to allow debris to pass through it. Passing debris through the culvert is a valid alternative to intercepting it above the inlet, and should not be overlooked. Of course, increasing the culvert diameter adds to its cost and sometimes may be impractical. On the other hand, when debris can be passed through the structure without clogging it, maintenance costs will be lower than when debris is intercepted and must be removed.

Summary

Forest and rangeland roads can have substantial adverse effects on salmonid habitats. These effects can be greatly reduced if the protection of fish habitat is integrated into the planning, design, construction, and maintenance of roads. The guidelines presented in this chapter for erosion control and for preventing or correcting fish migration barriers can be used by interdisciplinary teams of engineers, biologists, and earth scientists to plan and manage forest roads to maintain fish runs and habitats.

Influences of
Forest and Rangeland Management
on Salmonid Fishes and Their Habitats

Edited by

William R. Meehan

U.S. Department of Agriculture
Forest Service

American Fisheries Society Special Publication 19

Bethesda, Maryland, USA
1991