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# Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington

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*Abstract.* -In recent years an increasing share of fishery management resources has been committed to alteration of fish habitat with artificial stream structures. We evaluated rates and causes of physical impairment or failure for 161 fish habitat structures in 15 streams in southwest Oregon and southwest Washington, following a flood of a magnitude that recurs every 2-10 years. The incidence of functional impairment and outright failure varied widely among streams; the median failure rate was 18.5% and the median damage rate (impairment plus failure) was 60%. Modes of failure were diverse and bore no simple relationship to structure design. Damage was frequent in low-gradient stream segments and widespread in streams with signs of recent watershed disturbance, high sediment loads, and unstable channels. Comparison of estimated 5-10-year damage rates from 46 projects throughout western Oregon and southwest Washington showed high but variable rates (median, 14%; range, 0- 100%) in regions where peak discharge at 10-year recurrence intervals has exceeded 1.0 $m^3 \cdot s^{-1} \cdot km^{-2}$. Results suggest that commonly prescribed structural modifications often are inappropriate and counterproductive in streams with high or elevated sediment loads, high peak flows, or highly erodible bank materials. Restoration of fourth-order and larger alluvial valley streams, which have the greatest potential for fish production in the Pacific Northwest, will require reestablishment of natural watershed and riparian processes over the long term.

During the past decade, popular demand and financial support for restoration of fish habitats in North American streams have increased dramatically. Restoration or "enhancement" activity in the west has concentrated on direct modification of streams with artificial structures such as log weirs and gabions. Despite numerous pleas for careful scientific evaluation (e.g., Hall and Baker 1982; Reeves and Roelofs 1982; Everest and Sedell 1984; Hall 1984; Klingeman 1984; Platts and Rinne 1985) large and costly projects continue to be planned and implemented by federal and state agencies with little or no analysis of their effectiveness.

During the 1980s, habitat management programs of federal agencies became increasingly dominated by artificial-structure programs. For example, according to the U.S. Bureau of Land Management (1989), even as the number of fishery biologists in the agency dropped by more than half between 1980 and 1987, budgets increased for fish "habitat development" and "project maintenance" -a program dominated by artificial structures. The Bonneville Power Administration spends more than US $5 million annually on stream structures and related projects in Idaho, Oregon, and Washington in attempts to mitigate hydropower impacts on wild fish (Bonneville Power Administration, unpublished data). In fiscal year 1987, the U.S. Forest Service built more than 2,400 fish habitat structures in its Pacific Northwest Region, and the budget for this program far exceeded funds available to protect, monitor, and rehabilitate soil and watershed resources (U.S. Forest Service, unpublished data).

An illustration of the new reliance that resource managers are placing on artificial fish habitats appears in the Siskiyou National Forest Management Plan (USDA 1989), which prescribes structures costing more than $1.7 million over 3 years. In the computer model used to assess the economic effects of activities, Siskiyou National Forest planners assumed, without supporting evidence, a net gain of 3-4 lb (1.4-1.8 kg) of anadromous fish annually for each dollar spent on artificial structures. Logging in riparian areas and a projected influx of many tons of sediment annually caused by new roads and logging were assumed to have no significant adverse effect on fishery values (USDA 1989). The Forest Service assumed that any adverse effects on fish habitat and water quality would be more than compensated by fish habitat created with new artificial structures.

Ongoing evaluation of failures, as well as successes, is necessary to ensure that a program is achieving its objectives without costly mistakes or unintended side effects. The few evaluations of artificial-structure projects in the Pacific Northwest have shown mixed results. Hall and Baker (1982) and Hamilton (1989) summarized published and many unpublished evaluations of the effectiveness of fish habitat modification projects in streams. Although studies of apparently successful projects (e.g., Ward and Slaney 1981; House and Boehne 1986) have been cited widely, Hamilton's review (1989) suggested that studies showing neutral or negative biological effects have been published less frequently than those with favorable results.

Several studies have indicated that structural modifications can be ineffective or damaging. For example, Hamilton (1989) observed reduced trout abundance in a northern California stream reach with artificial boulder structures, compared with an adjacent unaltered reach. A large-scale habitat modification program on Fish Creek in western Oregon produced cost-effective increases in fish production from opening of off-channel ponds, but generally negative or neutral effects from boulder berms and log structures (F. E. Everest et al., U.S. Forest Service Pacific Northwest Research Station, unpublished data). Some structures in Fish Creek were damaged by floods before they measurably affected physical or biological conditions of the stream (Everest et al., unpublished data). In Idaho, C. E. Petrosky and T. B. Holubetz (Idaho Department of Fish and Game, unpublished data) found little evidence that instream structures increased the abundance of juvenile chinook salmon *Oncorhynchus tshawytscha* and steelhead *0. mykiss*, and in one project more than 20% of the structures failed during their first winter. In Big Creek, Utah, Platts and Nelson (1985) found that outside a fenced exclosure, artificial structures were destroyed by livestock trampling and grazing-related streambank erosion. Babcock (1986) reported that nearly three-quarters of the structures in a Colorado project failed or were rendered ineffective by a flood just 2 years after construction. Several of the remaining structures apparently created migration barriers for fishes, a problem also observed in Oregon (C.A.F., personal observation).

For artificial structures to function successfully, they must meet carefully defined objectives specific to target species, life history stage, and prevailing physical factors (Everest and Sedell 1984), and design must be closely tailored to geomorphic and hydraulic conditions (Klingeman 1984). To meet specific biological and economic objectives, most structures employed to date (e.g., wire gabions and log weirs) must remain intact at the installation site for their projected life span. Yet in the Northwest, few projects have been in place long enough for researchers to assess their durability across a range of stream flows. In this paper, we evaluate the incidence and causes of physical damage to artificial stream structures at several projects in Washington and Oregon. A flood of a magnitude that recurs at 2-10-year intervals occurred within the first few years after construction, which provided an opportunity to evaluate how well these projects could be expected to survive and function for their projected life spans. We examine the incidence of structure impairment and failure in relation to design, stream characteristics, and regional hydrologic conditions, and we discuss the implications of structure dysfunction for fish habitat management in the Pacific Northwest.

## Methods

*Study sites.* -In the summer of 1986, we determined the incidence of physical impairment or failure of artificial structure projects on eight streams in southwest Oregon and seven streams in southwest Washington (Figure 1; Table 1). The sample comprised 161 structures built by the state of Oregon's Salmon and Trout Enhancement Program and by the U.S. Forest Service between 1981 and 1985.

South coastal Oregon has intense winter precipitation, flashy streamflow, and very high sediment yields, particularly from heavily logged watersheds. Projects in southwest Oregon were intended to increase spawning habitat for fall chinook salmon by stabilizing gravel and providing cover for adults, and to improve rearing habitat for juvenile chinook salmon, steelhead, and cutthroat trout *Oncorhynchus clarki* by increasing area, depth, and complexity of pools (Johnson 1984; USDA 1989; G. Westfall, Oregon Department of Fish and Wildlife, unpublished data). Structures consisted of lateral log deflectors, cross-stream log weirs, multiple-log structures, and cabled natural debris jams. Benefit-cost projections were based on a life span of 20-25 years for all structures (Johnson 1984; USDA 1989).

In southwest Washington, a region of moderately high sediment yield and high peak flows from winter rain-on-snow, projects were intended to increase pool area for rearing of juvenile salmonids (USDA 1987). Steelhead, brook trout *Salvelinus fontinalis,* and spring chinook salmon occurred in project streams. The structures consisted of log

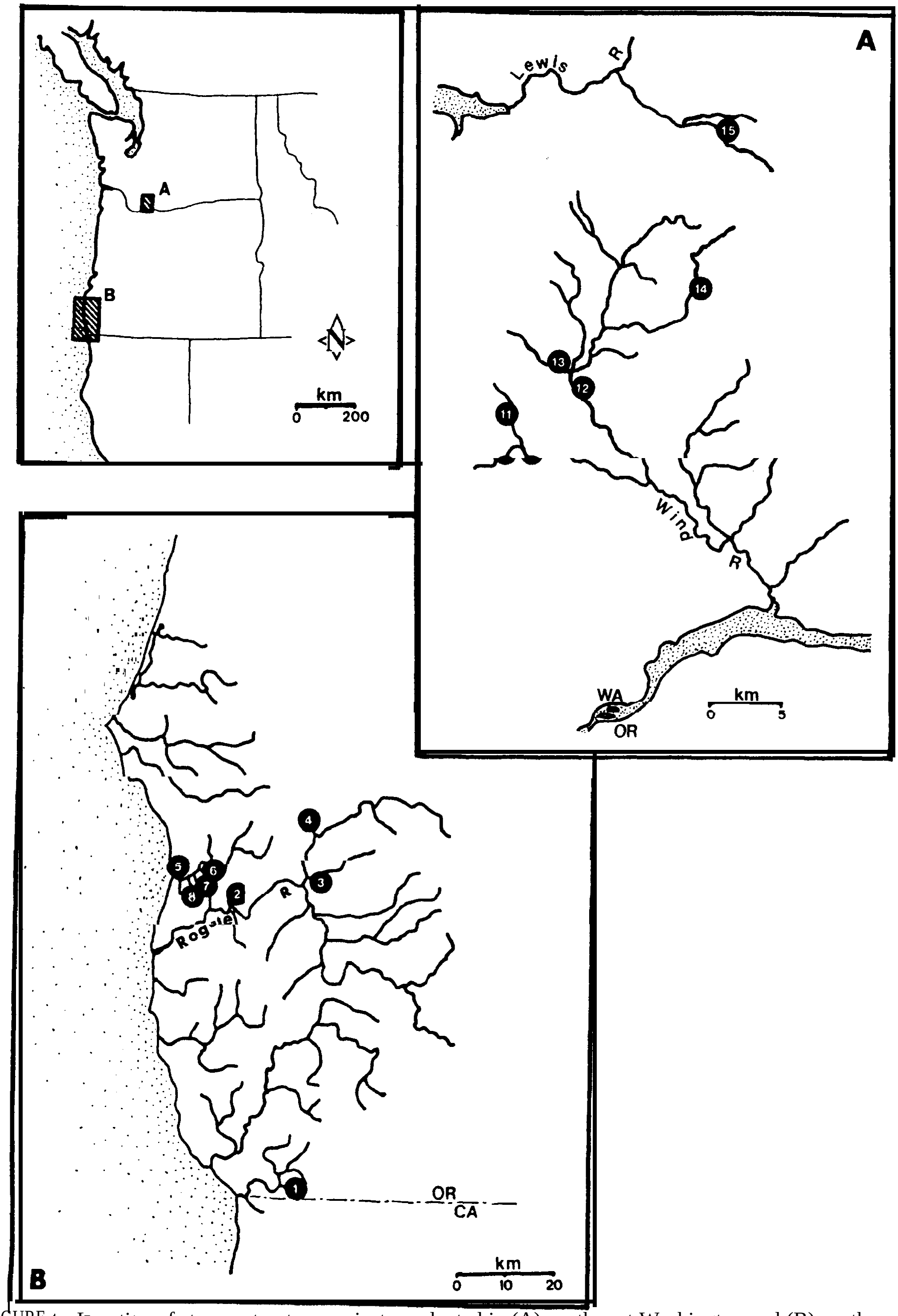


FIGURE 1.—Location of stream structure projects evaluated in (A) southwest Washington and (B) southwest Oregon during 1986. Oregon sites are 1, Bear Creek; 2, Silver Creek; 3, Shasta Costa Creek; 4, Foster Creek 5 Euchre Creek; 6, Crooked Bridge Creek; 7, "Outcrop Creek"; and 8, Boulder Creek. Washington sites are 9, Lower Trout Creek; 10, Layout Creek; 11, Upper Trout Creek; 12, Wind River; 13, Trapper Creek; 14, Falls Creek; and 15, Rush Creek.

TABLE 1.-Physical characteristics of study sites. Valley segment types are large-scale geomorphic units, slightly modified from Frissell and Liss (unpublished) and Cupp (1989). Valley segment codes are: AV = alluvial valley; AFV = alluvial fan-influenced valley; TBV = terrace-bound valley; AC = alluviated canyon; IUH = incised U-shaped valley, high gradient. A slash between two codes means both valley types occurred within the project area.

| Stream | Elevation (m) | Drainage area ($km^2$) | Mean channel slope (%) | Mean active channel width (m) | Mean active channel depth (m) | Valley segment type |
|---|---|---|---|---|---|---|
| **Southwest Oregon** | | | | | | |
| Bear Creek | 50 | 22.9 | 2.0 | 10.9 | 0.7 | AC |
| Foster Creek | 60 | 30.6 | 1.5 | 9.6 | 0.8 | TBV |
| Silver Creek | 20 | 25.1 | 1.0 | 8.9 | 0.4 | AFV |
| Shasta Costa Creek | 50 | 46.0 | 1.0 | 18.2 | 0.9 | TBV |
| Euchre Creek | 25 | 51.4 | 1.0 | 30.0 | 1.0 | AV/AFV |
| Crooked Bridge Creek | 25 | 2.7 | 2.5 | 6.0 | 0.7 | AV |
| "Outcrop Creek" | 25 | 1.2 | 4.0 | 5.5 | 0.5 | AFV |
| Boulder Creek | 25 | 5.9 | 2.0 | 12.0 | 0.7 | AFV/AV |
| **Southwest Washington** | | | | | | |
| Rush Creek | 945 | 17.8 | 2.0 | 10.4 | 0.7 | AV |
| Falls Creek | 830 | 24.8 | 6.0 | 8.1 | 0.6 | IUH |
| Layout Creek | 540 | 14.8 | 1.0 | 15.6 | 0.7 | AV |
| Upper Trout Creek | 565 | 10.8 | 2.0 | 9.3 | 0.6 | AV |
| Lower Trout Creek | 535 | 62.7 | 1.0 | 20.0 | 1.0 | AV |
| Wind River | 335 | 632.0 | 1.0 | 31.2 | 1.0 | AV |
| Trapper Creek | 340 | 28.8 | 1.5 | 25.6 | 0.8 | AV |

weirs, diagonal log deflectors, multiple-log structures, cabled natural woody debris jams, and single and clustered boulders.

*Flood peak estimation.* -Because none of the project streams were gauged, we used several methods to estimate recurrence interval of the February 1986 flood, the primary event affecting our study. At that time gauged streams in southwest Oregon experienced an instantaneous peak flow with about a 2-year recurrence interval (Geological Survey Water Resources Data for Washington and Oregon, Water Year 1986; Friday and Miller 1984). However, the 1986 flood was unusual in its duration, causing high flows for several consecutive days. After adjustment for duration, the estimated recurrence interval was 5-7 years based on the estimates of Friday and Miller (1984) for Chetco River near Brookings and South Fork Coquille River at Powers. McGavock et al. (1986) estimated the recurrence interval of the February 1986 flood in gauged southwest Washington streams at 3-5 years.

To assess variation in the February 1986 peak flow among the project streams in southwest Oregon, we surveyed cross sections at the project sites and reconstructed flood crests based on flotsam lines. Using the Manning equation (Richards 1982; Thome and Zevenbergen 1985) with roughness estimated visually (Barnes 1967), we estimated peak flows for each stream. We then estimated flood recurrence intervals (for instantaneous peak flow) following three regional prediction procedures (Harris et al. 1979; Campbell et al. 1982; Andrus et al. 1989). Final estimates for each stream are the averaged results of the three procedures except for two watersheds of less than 5 $km^2$, where only the Andrus et al. (1989) method appeared to provide reasonable estimates. Because estimates of peak discharge often err by as much as 30% (Thome and Zevenbergen 1985), and because predictions of recurrence intervals introduce additional error, these estimates-which varied from slightly less than 2 years to 10 years among the Oregon streams (Table 2)-should be viewed as rough approximations.

*Definitions.* -We classified structures into three categories, depending on their physical condition and function. A structure that had been washed downstream, severely fragmented, or grossly dislocated so it retained little or no contact with the low-flow channel or was otherwise incapable of achieving its intended physical objective (e.g., creating or enlarging a pool) was classified as a "failure." A structure that remained in its original location but, because of alteration to it or the stream channel, no longer functioned in the intended mode or appeared to be at least temporarily ineffective, was classified as "impaired." A structure that had been buried under bed-load deposits was considered impaired. A structure not visibly damaged or

TABLE 2.-Flood magnitude estimates, and rates of damage and failure for fish habitat structures surveyed in 1986. Flood peak is the estimated peak discharge; the estimated recurrence interval is in parentheses. A dash indicates discharge data were not available; recurrence intervals at these sites were estimated from nearby streams or from regional analyses by the U.S. Geological Survey.

| Stream | 1985-1986 flood peak, $m^3/s$ (recurrence interval) | Number of structures | Damage rate (%) | Failure rate (%) |
|---|---|---|---|---|
| **Southwest Oregon** | | | | |
| Bear Creek | 28 (2 years) | 19 | 79 | 32 |
| Foster Creek | 30 (2 years) | 15 | 27 | 7 |
| Silver Creek | 17 (2 years) | 6 | 50 | 17 |
| Shasta Costa Creek | 45 (<2 years) | 18 | 83 | 55 |
| Euchre Creek | 92 (5 years) | 19 | 100 | 95 |
| Crooked Bridge Creek | 12 (10 years) | 6 | 100 | 100 |
| "Outcrop Creek" | 7 (5 years) | 5 | 40 | 40 |
| Boulder Creek | – (5 years) | 5 | 60 | 40 |
| **Southwest Washington** | | | | |
| Rush Creek | – (< 2 years) | 9 | 22 | 11 |
| Falls Creek | – (<2 years) | 6 | 0 | 0 |
| Layout Creek | – (3-5 years) | 9 | 89 | 11 |
| Upper Trout Creek | – (3-5 years) | 19 | 42 | 0 |
| Lower Trout Creek | – (3-5 years) | 5 | 40 | 0 |
| Wind River | – (3-5 years) | 10 | 70 | 0 |
| Trapper Creek | – (3-5 years) | 10 | 60 | 20 |

debilitated was categorized as functioning roughly as intended or "successful."

We defined "damage rate" as the proportion of structures of a project in the failed and impaired categories (structures not successfully meeting physical objectives). "Failure rate" was defined as the proportion of structures of a project in the failure category only (structures lost or completely dysfunctional). Based on the time since installation and the estimated recurrence interval of the February 1986 flood, we assumed these rates reflected the incidence of damage and failure to be expected over a 5-10-year time span.

Obviously, some subjectivity was involved in judgments about impairment and, to a lesser extent, about failure, particularly where the intent of the designer was not immediately clear. We based our determination of whether structures achieved design objectives primarily on the general physical objectives outlined in project plans (e.g., "create new rearing pools"), but criteria varied somewhat depending on structure type. For example, a log weir would be expected to produce a plunge pool, a single boulder was probably intended to create a small scour hole, and a cabled natural debris jam would be expected to stay in place and maintain preexisting pool and cover conditions. Within these limitations, damage rate is a useful indicator of the effective life of a project, maintenance requirements, the importance of unintended side effects, and the likelihood of future failure.

*Structural evaluation.* -As we surveyed a stream, we recorded the location and type of each structure. We measured reach slope with an Abney level, measured width of the active (unvegetated) channel with a meter tape, and measured the depth and surface area of the pool associated with each structure. We recorded processes and events contributing to impairment or failure of the structure, and in some cases we drew a small sketch map. Previous knowledge of structure design and placement at many of the projects helped us reconstruct failure processes, but we avoided speculation where no physical evidence of failure mode remained. Because failed structures sometimes wash away and leave no trace, we undoubtedly underestimated the number of structures originally present in some projects, making our estimates of failure rates conservative. We recorded information on streambank materials and riparian landforms in the field, and we compared these data with topographic maps to classify stream segments following C.A.F. and W. Liss (Oregon State University, unpublished data) and Cupp (1989). We calculated failure and impairment rates for each structure type and each stream, and we compared them with stream-specific data on flood flow magnitude, mean channel width, slope, drainage area, and stream segment type (Table 1).

*Interregional comparisons.* -To set our results in broader context, we compared our summary data with unpublished information on other projects constructed during 1981-1985 by the U.S. Forest Service (B. Higgins and H. Forsgren, Mount

Hood National Forest, unpublished data; D. Hohler, Mount Hood National Forest, unpublished data) and the Bureau of Land Management (House et al. 1989). Although our impairment and failure estimates often were somewhat greater than those of agency biologists responsible for the projects, we believe these data are comparable as a rough approximation of regional patterns. Because most of the projects had experienced a flood of between 5- and 25-year recurrence intervals during the 2-8 years they had been in place, we used the data to approximate average failure and impairment rates (Appendix 1).

Because climatic and geomorphic conditions in western Oregon are diverse, we grouped the data for all projects into five regions defined by geology, topography, elevation, climate, and streamflow patterns. We examined streamflow statistics for gauged streams in each region (Friday and Miller 1984) and used these to characterize regional peaks for flood flows (Appendix 2).

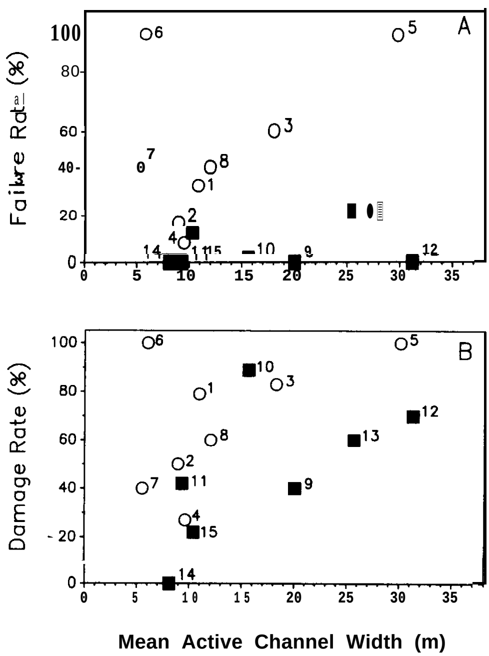


**FIGURE** 2.-(A) Failure and (B) damage rates of projects in southwest Oregon (open circles) and southwest Washington (solid squares) in relation to active channel width. Stream numeric codes are given in Figure 1. Damage rate includes both failed and impaired structures.

## Results

### *Damage Rates in Relation to Stream Characteristics*

The incidence of structure failure and damage varied widely among streams (Table 2). Overall, failure rates were higher in southwest Oregon streams (median, 40%; mean, 48%; range, 7-100%) than in southwest Washington streams (median, 0%; mean, 6%; range, 0-20%). Rates of overall damage were less disparate but appeared to be higher in southwest Oregon (median, 70%; mean, 67%; range, 27-100%) than in southwest Washington (median, 42%; mean, 46%; range, O-89%).

Rates of damage were higher in larger and wider streams (Figure 2B). Projects in streams with active channel widths wider than 15 m had a median damage rate of 79% (range, 50-l00; N = 6) whereas those with active channels narrower than 15 m were highly variable and had a median damage rate of 50% (range = 0-100; N = 9). Southwest Oregon data suggested a roughly linear increase in failure rate with stream width (Figure 2A). In southwest Washington, failure rate apparently was not correlated with stream width, although impairment and therefore damage rate were correlated with stream size. There was no clear relationship between drainage basin area and failure or damage rates. Because climatic and hydrologic characteristics of individual streams vary within a region, active channel width is a better site-specific, integrated measure of streamflow and associated hydraulic stresses than is basin area. Channel width is influenced by bank material erodibility (Schumm 1960; Richards 1982), which also affects structure performance (see Mode of Failure).

Although Hamilton (1989) concluded that projects in high-gradient streams had higher failure rates than those in gently sloping streams, we found no evidence to support this generalization in our study streams. In southwest Washington the incidence of damage actually increased as slope decreased (regression analysis, $P < 0.04$, $r = -0.79$), largely because structures became buried in low-gradient reaches. In southwest Oregon, damage rate did not vary significantly with slope, nor did failure rate in either region. However, high-gradient streams were not well represented in our sample; only three projects were in stream reaches exceeding 2% slope. Regression of failure and damage rates against an index of stream power, defined as the product of channel slope and mean active channel depth, were similar to regressions based on channel slope alone.

Neither failure nor overall damage rates appeared to be strongly related to the estimated absolute or relative magnitude of the flood peak experienced by projects during 1986. There was little difference in median or range of failure rates between one group of projects subjected to peak flows of a 2-year recurrence interval and another group subjected to 5-10-year peak flows. Falls Creek was the only project for which no damage or failure was recorded, perhaps because this high-elevation stream (830 m) did not experience a large rain-on-snow peak flow in 1986.

The correlation between active channel width and slope (regression analysis, $P < 0.01$, $r = -0.68$), and the relationships among these variables and drainage area, discharge, and bed and bank texture, make simple, univariate explanations of damage patterns difficult. There was no obvious overall relationship between failure or damage rates and valley segment type, a broad classification that accounts for covariation of numerous geomorphic variables (Frissell et al. 1986). In general, however, there appeared to be a trend of more extensive damage in wide, low-gradient reaches in alluvial valleys and alluvial fans, which are susceptible to bed-load accumulation and bank erosion when the drainage catchment has been disturbed by logging or large natural landslides. Additionally, some projects in terrace-bound valley or alluviated canyon segment types (comparatively narrow channels with restricted floodplains) in southwest Oregon had high failure rates which, based on field evidence, appeared to result from the scouring effects of high-energy, sediment-charged flood flows.

### *Mode of Damage*

Processes that damaged structures included design- or material-related phenomena, such as failure of cables and anchoring devices, and a wide variety of processes that produce changes in the immediate environment of structures, such as bank erosion and bed-load deposition (Table 3). In some cases, such channel changes appeared to be largely a direct but unanticipated hydraulic consequence of placement of the structures themselves (e.g., bank erosion at the lateral margins of log weirs; see Cherry and Beschta 1989). In most instances, however, the channel changes that damaged structures appeared to be driven primarily by watershed-scale phenomena, such as active landslides or road failures upstream that caused massive bed-load deposition in the project area. Many structures exhibited evidence of multiple, and sometimes interacting, modes of damage.

Southwest Oregon projects suffered damage from a wide variety of processes, ranging from failure of anchoring devices and structural breakage indicative of high hydrodynamic stress, to burial and channel shifting indicative of high rates of bed-load transport and deposition. In comparison,

TABLE 3.-Percentage of structures in each project for which there was evidence that the indicated process contributed to failure or impairment. Because many structures exhibited multiple-failure modes, percentages across rows do not necessarily sum to 100. Modes of damage are arranged from high-energy, scour-related processes at left to low-energy, deposition-related processes at right.

| Stream | Log breakage | Anchor bolt failure | Cable failure | Logs stranded out of channel | Bed scour undermined structure | Bank erosion | Anchor tree washout | Bar or channel shift | Burial by bed load | Unknown |
|---|---|---|---|---|---|---|---|---|---|---|
| **Southwest Oregon** | | | | | | | | | | |
| Bear Creek | 0 | 21 | 21 | 0 | 16 | 16 | 0 | 0 | 5 | 0 |
| Silver Creek | 0 | 0 | 17 | 0 | 0 | 17 | 0 | 0 | 33 | 0 |
| Shasta Costa Creek | 6 | 11 | 17 | 22 | 0 | 11 | 17 | 6 | 0 | 0 |
| Foster Creek | 0 | 0 | 7 | 0 | 7 | 7 | 0 | 0 | 13 | 0 |
| Euchre Creek | 0 | 0 | 0 | 0 | 0 | 16 | 0 | 16 | 0 | 89 |
| Crooked Bridge Creek | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| "Outcrop Creek' | 0 | 0 | 0 | 20 | 0 | 20 | 0 | 0 | 0 | 20 |
| Boulder Creek | 0 | 0 | 0 | 0 | 20 | 20 | 0 | 0 | 0 | 40 |
| **Southwest Washington** | | | | | | | | | | |
| Layout Creek | 0 | 0 | 0 | 0 | 4 | 6 | 0 | 11 | 11 | 0 |
| Upper Trout Creek | 0 | 0 | 0 | 0 | 80 | 0 | 0 | 20 | 20 | 20 |
| Lower Trout Creek | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 0 |
| Wind River | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 80 | 0 |
| Trapper Creek | 0 | 0 | 10 | 0 | 10 | 0 | 0 | 20 | 20 | 10 |
| Falls Creek | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rush Creek | 0 | 0 | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

fewer failure modes were observed in southwest Washington projects, and these were mostly indicative of changes in erosion and deposition in low-gradient reaches. For example, a series of boulder placements in Wind River, expected to scour pools within a long riffle, instead triggered deposition of a large midchannel gravel bar that isolated the structures from the low-flow channel.

At numerous sites, structures caused inadvertent physical effects that we judged to be adverse rather than beneficial. Adverse effects for which we found evidence included (1) accelerated bank erosion at log weirs, (2) direct damage to gravel bars and riparian vegetation by heavy equipment, (3) felling of key streamside trees to provide sources of materials, causing loss of shade and bank stability, (4) flood rip-out of riparian trees used to anchor log structures, (5) aggradation of gravel bars or silt and sand deposits (see also Platts and Nelson 1985) which caused shallowing and loss of microhabitat diversity in preexisting natural pools, and (6) torrents of bed load and debris triggered by collapse of structures during the flood. Eggs and fry of fish that spawned in the gravel above log weirs, as well as juvenile fishes wintering in and near the structures, may have been killed when the structures failed and washed out. Fragments of epoxy or resins used to anchor structures were very common in many pools, and there is evidence that these materials can be toxic to fishes (Fontaine and Merrit 1988). Frayed cables and sheets of ripped out geotextile or chain-link anchoring material at damaged structures created obvious aesthetic liabilities. Furthermore, repairs may have exacerbated initial damage. Riprap, which was used extensively to repair bank erosion associated with log weirs, may adversely affect stream habitat over the long term (Richards 1982; Sedell and Frogatt 1984; Bravard et al. 1986; Li et al. 1984; Knudsen and Dilley 1987).

## *Effect of Structure Type*

Of the eight structure designs for which we had sufficient sample size, only two-cabled natural woody debris and individual boulder placements-were not impaired or did not fail in more than half the cases (Figure 3). All log weir designs had high rates of impairment or failure, and one type, the downstream-V weir, failed or was impaired in every instance. Boulder structures had lower failure rates than log weirs. Previous studies have shown low failure rates for boulder structures in streams of less than 2% gradient but higher failure rates in steeper streams (Hamilton 1989). Although many boulders had been almost completely buried in place by bed-load deposits, we classified these as impairments rather than failures, because they might someday be reexcavated by the stream.

To some extent, failure and impairment rates

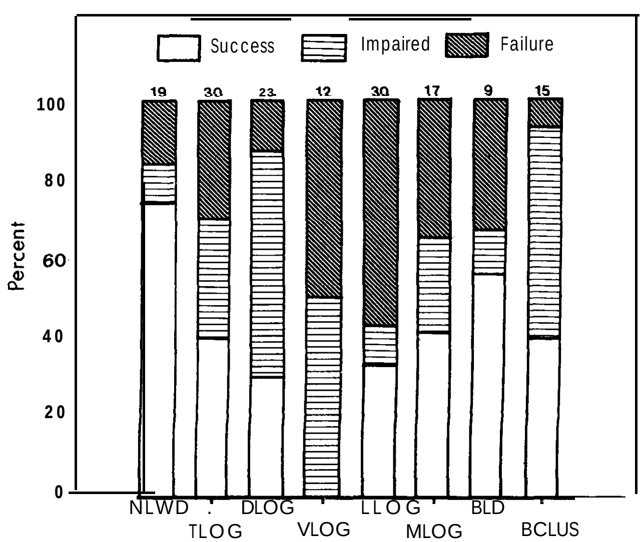


FIGURE 3. -Failure and impairment rates of structures classified by design. Number at top of each bar indicates the number of structures in the sample. NLWD = cabled natural large woody debris or jam; TLOG = transverse log weir; DLOG = diagonal log weir; VLOG = downstream-V log weir; LLOG = lateral log deflector; MLOG = multiple-log structure; BLD = individually placed boulders; BCLUS = clustered boulders.

presented in Figure 3 are biased because not all designs were represented in all streams. For example, the higher success rate of boulder projects is partly related to their concentration in relatively stable southwest Washington streams where damage to structures of all types was small.

*Interregional Comparisons*

When we compared our results with data from other regions in western Oregon (Appendix 1), we found that the projects we studied had higher-than-average rates of impairment and failure. However, the projects we evaluated were in regions with intense winter precipitation and substantially higher peak discharge than most other regions (Figure 4; Appendix 2). There was a positive relationship between impairment and failure rates and peak flows. Streams in regions characterized by 10-year-recurrence peak flows exceeding 1 $m^3 \cdot s^{-1} \cdot km^{-2}$ had high but variable rates of damage (range, 0-100%; median, 46%) and failure (range, 0-100%; median, 14%) (Figure 5).

The regions with highest peak flows include the north Coast Range and south Coast Range-Klamath Mountains in Oregon, which are very steep areas with intense rainfall and frequent rain-on-snow events, and the Columbia Cascades, part of the Cascade Range immediately north and south of the Columbia River subject to severe and frequent winter storms that funnel through the Columbia Gorge either from coastal or interior areas. The south Coast Range-Klamath Mountains region, which had the highest incidence of damage to structures, has mean 10-year peak flows in excess of 2.0 $m^3 \cdot s^{-1} \cdot km^{-2}$. Projects in other parts of western Oregon experienced much lower peak flows and had lower rates of damage (range, 0-67%; median, 12%) and only limited incidence of failure (range, 0-35%; median, 0.5%) (Figure 5).

We had limited data for Oregon streams in the north Coast Range. We expect that when more projects are evaluated, many will be found to suffer high failure and impairment rates because of the region's high peak flows and high frequency of long-runout debris flows (our unpublished data). However, the abundance of clays and the lower proportion of fine sands and silt in soils of this region may render streambanks more resistant to erosion than those of Oregon's south Coast Range, thereby moderating failure rates.

Our experience indicates that sediment yield might be positively correlated and channel stability negatively correlated with regional peak flow. Undoubtedly, these patterns reflect relationships among many aspects of geology, precipitation, soils, and hydrologic and geomorphic processes that are of critical importance to habitat management, from both an ecological and an engineering standpoint. The data for the south Coast Range-Klamath Mountains region of Oregon probably represent conditions in much of northwest California as well.

## Discussion

Artificial stream structures suffered widespread damage in most of the streams we surveyed in

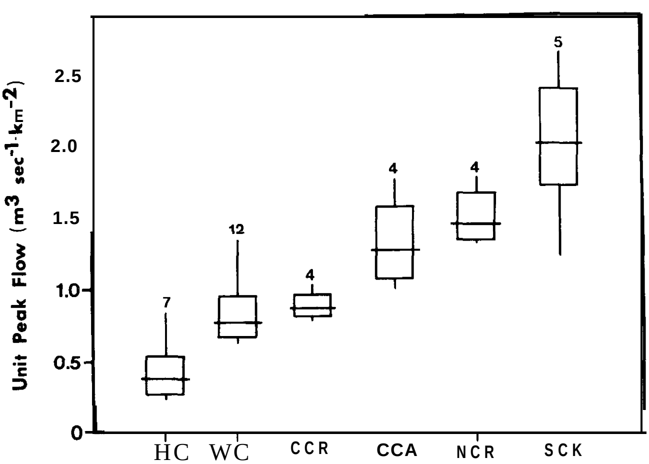


FIGURE 4.- Box plots of 10-year peak flows standardized by drainage area for streams in six regions of western Oregon. Horizontal bar is the median, box is the interquartile range, and vertical line is the data range. Number is the sample size. HC = High Cascades; WC = western Cascades; CCR = central Coast Range; CCA = Columbia Cascades; NCR = north Coast Range; and SCK = south Coast Range-Klamath Mountains.

southwest Oregon and southwest Washington. Rather unpredictable damage rates and the wide range of causes of failure indicate that complex, multiscale interactions between watershed conditions, fluvial processes, and structure design determine the physical success or failure of individual structures and projects. Because streams in these two regions have intense floods, high bed-load yields, and often unstable channels, artificial structures are highly vulnerable to damage.

The wide range of failure modes indicates that simple changes in structure design or materials are unlikely to overcome the problem of high damage rates. Overall, processes of failure and impairment were dominated by changes in channel morphology that, apparently, had not been anticipated by project designers. These changes often were related to dynamic conditions in the watershed or riparian zone, particularly as they affected sediment load, streambank stability, and hydrology. Failure of internal structure or materials- the dominant concern of most biologists and hydrologists who build these projects-appears to be a far less important cause of damage than are watershed-driven aspects of channel dynamics.

We sampled only a subset of the projects present in southwest Oregon and southwest Washington in 1986, but we believe our results are representative of other nearby projects. For example, we observed complete failure of structures in Deep Creek, a tributary of Pistol River in southwest Oregon, caused by sediment-laden flood pulses that originated from large landslides in recent clearcuts. We did not survey Deep Creek and several other projects in detail because repairs were already well under way before we were able to inspect the sites.

Few simple rules about design of artificial structures have emerged from our study, but we can offer some general guidelines for stream restoration programs. Structure designs that failed least often were those that minimally modified the preexisting channel, such as cabling intended to stabilize natural accumulations of woody debris. Elaborate log weirs and other artificial structures, which (if they stay in place) cause immediate and more obvious changes in channel morphology and hydraulics, were subject to high rates of damage. In large, low-gradient streams, configuration of the valley and large-scale roughness elements such as major channel bends exert primary control of the location and morphology of pools and riffles (Lisle 1986), and sediment yield and peak flows strongly constrain channel stability and streambed dynamics. Smaller-scale structures such as log weirs can work effectively only within limits imposed by these larger-scale processes and patterns. Our observations suggest that, at least in southwest Washington and southwest Oregon, it is unrealistic to expect the installation of new artificial structures to stabilize channels; the opposite result may be as likely.

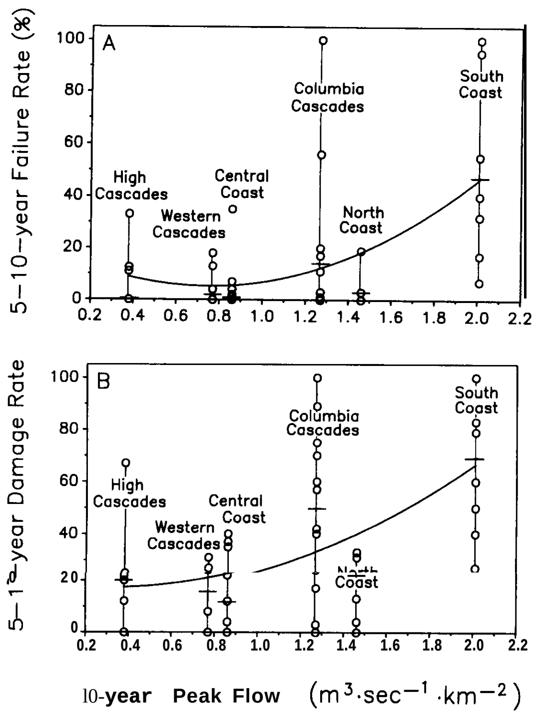


FIGURE 5. -Relation between rates of (A) failure and (B) overall damage of projects and regional median 10-year-recurrence peak flows standardized by drainage area. Each point represents one or more projects (full data are in Appendix 1). Horizontal bars indicate regional medians. Curves are second-order regressions fitted to indicate trend, and are not necessarily statistically significant. Southwest Washington projects from Table 2 are classified as Columbia Cascades region except for Rush Creek and Falls Creek in the High Cascades. Southwest Oregon projects from Table 2 constitute the sample for the south Coast Range-Klamath Mountains region.

Within the study areas, the stream habitats most important for fish, and most in need of restoration, are those least amenable to structural modification with existing technology. We observed the highest rates of failure and impairment in streams draining watersheds severely damaged by roads, logging, and landslides. Projects with the highest failure rates in southwest Washington were in alluvial deposition areas of Trapper Creek and Layout Creek, in valley segments prone to natural instability, that has been aggravated by removal of natural woody debris and logging of riparian vegetation. Deposition of bed-load sediments in wide, low-gradient alluvial valley segments and the erosion of streambanks and shifting of channels associated with this deposition were the most common causes of damage to structures in our study streams.

Low-gradient alluvial valleys are also the most critical of stream habitats for spawning and rearing of chinook salmon, coho salmon *Oncorhynchus kisutch,* and steelhead (Reimers 1971; Stein et al. 1972; Leider et al. 1986; Lichatowich 1989; our unpublished data). Sediment accumulation in alluvial valley streams can cause numerous adverse effects: loss of pools, destabilization of woody debris, frequent channel shifting and abandonment, increased fine sediments and increased scour of spawning gravel, channel widening, and increased summer stream temperature because of loss of shade (e.g., Lisle 1982; Hagans et al. 1986; Everest et al. 1987). The dominance of sand and gravel in streambanks of alluvial valleys and in alluvial fans makes them highly susceptible to erosion, particularly when riparian vegetation- the roots, stems, and foliage of which help stabilize riparian soils-has been removed by logging, grazing, floods, or builders of artificial structures.

It may take decades or centuries for low-gradient channels in alluvial valleys to recover from downstream-propagating impacts of bed-load accumulation (Lisle 1981; Madej 1984; Hagans et al. 1986). Such recovery proceeds only after sediment yield from the watershed declines to natural levels, which has not yet occurred in many southwest Oregon basins. These basins continue to suffer impacts from failing roads, high erosion rates along streams in second-growth forests, increased logging on steep, highly erodible federal lands (Frissell and Nawa 1989), and repeated short-rotation logging on private lands where there is little regulatory protection for unstable slopes and headwater stream channels (Bottom et al. 1985). Reestablishment of mature riparian forests to stabilize streambanks and floodplain surfaces is also needed for recovery of channel morphology (Lisle 1981).

## *Implications for Economic Analyses*

Existing environmental and economic analyses assume life spans of 20-25 years for artificial structures in south coastal Oregon (Johnson 1984; USDA 1989). This means that the average life span or half-life for all structures (not the maximum life span) must approach 20 years. More than half the structures should survive much longer than 20 years. Our data indicate that a flood of less than a l0-year recurrence interval caused failure rates often exceeding 50%. Given that the probability of occurrence of a 10-year or greater flood within the first decade after installation is about 0.65, and that within the first 20 years it is about 0.88, a majority of projects in southwest Oregon probably will experience failure rates exceeding 50% before they are 20 years old.

Larger floods might have more severe effects. The probability of at least one 20-year flood occurring within any 20-year period is 0.64, and the probability of a flood of a 50-year or greater recurrence interval within 20 years is 0.33 -significant enough to be factored into half-life calculations that would be necessary to accurately estimate average life span for projects. Considering these factors, we estimate that the average half-life (the time elapsed when 50% of the structures are destroyed) of projects is less than 10 years in southwest Oregon and 15 years or less in southwest Washington.

It is unlikely that most stream structure projects in southwest Oregon and southwest Washington would appear cost-effective if planners used realistic estimates of project life, maintenance costs, and adverse side effects. The high rates of impairment we observed indicate structural damage and wear that, if not repaired, greatly increase the risk of failure during subsequent years. The repair of flood damage that is necessary to reduce future failures of structures imposes a heavy maintenance burden, the costs of which are seldom factored into the economic analyses used to justify such projects. Unintended adverse effects, or “negative benefits,” are also neglected in most benefit-cost analyses of artificial structures. Where projects have high impairment rates, there is a high likelihood of net damage rather than benefit to fish and water quality; such risks should be explicitly addressed in project plans and disclosed in environmental analyses.

## *Implications for Habitat Management*

Despite the rather high incidence of physical failure and damage, and despite the lack of demonstrated biological success of surviving structures in the study areas, an inflexible cookbook approach continues to dominate the analysis, planning, and budgeting processes within agencies responsible for fish habitat management in the region.

Currently, most habitat projects in the Pacific Northwest seem to rest on the assumption that the problem is simply a lack of woody debris, and that the solution is to add standard devices such as log weirs, with each new structure creating an incremental improvement of habitat and a known poundage of new fish. However, the widespread loss of woody debris and habitat diversity in Pacific Northwest streams is symptomatic of a complex of ecological problems driven by changes in riparian forests, channelization, and basin-scale erosion and sedimentation (Bisson et al. 1987; Elmore and Beschta 1987; Hicks et al. 1991). Events such as sediment-laden floods and debris flows often reshape channel morphology and fish habitat many kilometers downstream from their origin Benda 1990).

Restoration programs in the regions we studied should follow a hierarchical strategy that emphasizes (1) prevention of slope erosion, channelization, and inappropriate floodplain development, especially in previously unimpacted habitat refugia; (2) rehabilitation of failing roads, active landslides, and other sediment sources; and (3) reforestation of floodplains and unstable slopes (Lisle 1982; Overton 1984; Reichard 1984; Weaver et al. 1987). Unless these larger-scale concerns are dealt with first, direct structural modifications of channels are unlikely to succeed.

Our results point to the general need to consider physical (as well as biological) phenomena in regional and watershed-scale contexts when stream restoration projects are planned. In the long run, evaluation and planning of stream modification projects could greatly benefit from application of a hierarchical classification system comparable to those proposed for land systems by Warren (1979) and Lotspeich and Platts (1982) and for streams by Platts (1979) and Frissell et al. (1986). Such an approach could provide a conceptual framework for ordering, analyzing, and predicting complex aspects of system behavior across different scales of space and time; it would do so by setting local, site-specific concerns in the context of large-scale dynamics of the system (Frissell et al. 1986).

If a hierarchical and contextual approach were used to plan and implement fish habitat restoration programs, many of the costly failures we observed undoubtedly could be avoided, and resources could be directed to effectively treat the primary causes of habitat problems: sedimentation from eroding roads and logged slopes, and logging, grazing, channelization, and urbanization in riparian areas and floodplains.

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**Appendixes follow**

## Appendix 1: Failure and Damage for Other Oregon Projects

TABLE A 1.1. -The following rates of physical failure and damage were reported for projects in western Oregon surveyed by other agencies. N = number of structures in the project. Data sources are indicated as follows: (a) = B. Higgins and H. Forsgren, Mount Hood National Forest, unpublished data; (b) = D, Hohler, Mount Hood National Forest, unpublished data; (c) = House et al. (1989).

| Project | N | Failure rate (%) | Damage rate (%) |
|---|---|---|---|
| **High Cascades** | | | |
| Lake Branch (a) | 24 | 12.5 | 25 |
| Rock Creek (a) | 83 | 0 | 12 |
| Buck Creek (a) | 10 | 0 | 0 |
| Clear Branch (a) | 15 | 0 | 20 |
| Robinhood Creek (a) | 12 | **33** | **67** |
| **Western Cascades** | | | |
| Fish Creek (b) | 252 | 4 | 31 |
| Pansy Creek (a) | 11 | 13 | 27 |
| Cooper Creek (a) | 9 | 0 | 0 |
| Oak Grove Creek (a) | 79 | 0 | 0 |
| Pinhead Creek (a) | 17 | 18 | 24 |
| Fall Creek (a) | 12 | 0 | **8** |
| **Central Coast Range** | | | |
| East Fork Lobster Creek (198 1) (c) | 45 | 0 | 4 |
| Tobe Creek (1982) (c) | 20 | 0 | 0 |
| Upper Lobster Creek (1982) (c) | 9 | 0 | 0 |
| South Fork Lobster Creek (1982) (c) | 65 | 35 | 35 |
| Little Lobster Creek (1986) (c) | 142 | 2 | 4 |
| J Line Creek (198 7) (c) | 30 | 4 | 12 |
| Lobster Creek (1987) (c) | 37 | 7 | 37 |
| Upper Lobster Creek (1987) (c) | 14 | 1 | 40 |
| East Fork Lobster Creek (1987) (c) | 11 | 0 | 22 |
| **North Coast Range** | | | |
| East Beaver Creek (1983) (c) | 32 | 0 | 0 |
| Upper Nestucca River (1984) (c) | 148 | 3 | 33 |
| Little Elk Creek (1986) (c) | 92 | 4 | 15 |
| Middle Nestucca River (1987) (c) | 42 | 19 | 31 |
| Upper Elk Creek (1987) (c) | **77** | **0** | **4** |
| **Columbia Cascades** | | | |
| South Fork Salmon River (a) | 34 | 3 | 24 |
| Kool Creek (a) | 6 | 17 | 17 |
| Clear Creek (a) | 16 | 56 | 75 |
| Clear Fork Sandy River (a) | 10 | 100 | 100 |
| Still Creek (a) | 264 | 1 | 3 |
| Ramsey Creek (a) | 7 | 0 | 57 |

## Appendix 2: 10-Year Peak Flows for Oregon Streams

TABLE A2.1.-The unit discharges ($m^3 \cdot s^{-1} \cdot km^{-2}$) for the following Oregon streams represent peak flows at 10-year recurrence intervals ($Q_{10}$). The streams were selected because they have (1) more than 20 years of records, (2) drainage areas exceeding 100 $km^2$ but less than 2,500 $km^2$, and (3) no significant influence of reservoir regulation. Data are from Friday and Miller (1984). Some stations with records starting about 1957 or later were excluded because of bias of large floods in the 1960s and 1970s. For stations with flow regulation at present, data are for the pre-dam period only.

| Station | Elevation (m) | Unit $Q_{10}$ |
|---|---|---|
| **High Cascades** | | |
| Salmon River near Government Camp | 1,050 | 0.83 |
| Salmon River below Linney Creek | 760 | 0.54 |
| Clackamas River at Big Bottom | 620 | 0.48 |
| Squaw Creek near Sisters | 1,060 | 0.27 |
| Red Blanket Creek near Prospect | 845 | 0.33 |
| Middle Fork Rogue River near Prospect | 800 | 0.38 |
| Rogue River above Bybee Creek | 1,055 | 0.25 |
| Median | | 0.38 |
| **Western Cascades** | | |
| Clackamas River above Three Lynx Creek | 335 | 0.69 |
| Breitenbush River above Canyon Creek | 480 | 1.12 |
| North Santiam River below Boulder Creek | 485 | 0.74 |
| South Santiam River below Cascadia | 230 | 1.32 |
| Calapooya River at Holley | 160 | 1.03 |
| Mohawk River near Springfield | 135 | 0.63 |
| South Fork McKenzie River above Cougar Reservoir | 520 | 0.66 |
| Salmon Creek near Oakridge | 445 | 0.67 |
| North Fork Middle Fork Willamette River near Oakridge | 315 | 0.65 |
| Hills Creek above Hills Creek Reservoir | 500 | 0.79 |
| Middle Fork Willamette River above Salt Creek | 370 | 0.79 |
| Elk Creek near Trail | 445 | 0.87 |
| Median | | 0.77 |
| **Central Coast Range** | | |
| Yaquina River near Chitwood | 15 | 0.78 |
| Alsea River near Tidewater | 15 | 1.03 |
| Siuslaw River near Mapleton | 10 | 0.89 |
| North Fork Siuslaw River near Minerva | 10 | 0.84 |
| Median | | 0.86 |
| **Columbia Cascades** | | |
| West Fork Hood River near Dee | 245 | 1.38 |
| Little Sandy River near Bull Run | 220 | 1.77 |
| Sandy River near Marmot | 220 | 1.14 |
| Salmon River at Welches | 410 | 1.00 |
| Median | | 1.27 |
| **North Coast Range** | | |
| Wilson River near Tillamook | 20 | 1.78 |
| Trask River near Tillamook | 20 | 1.33 |
| Nestucca River near Beaver | 15 | 1.33 |
| Siletz River at Siletz | 30 | 1.56 |
| Median | | 1.46 |
| **South Coast Range-Klamath Mountains** | | |
| South Fork Coquille River at Powers | 60 | 1.72 |
| East Fork Illinois River near Takilma | 540 | 2.01 |
| West Fork Illinois River below Rock Creek | 460 | 2.39 |
| Sucker Creek near Holland | 540 | 1.22 |
| Chetco River at Brookings | 15 | 2.64 |
| Median | | 2.01 |