As part of a hierarchical approach to classifying watersheds and stream habitats based on geomorphic and geologic criteria, we defined ten classes of fluvial and lacustrine habitats at the scale of valley segments. Valley segments are landscape units which encompass surface waters and the adjacent floodplains and hillslopes with which they interact over time frames of thousands of years. They form a large-scale template that constrains the character of aquatic habitat, controls the effects of disturbances in riparian areas, and mediates responses of streams to upland and upstream events. The regional distribution of valley segment types in southwest Oregon reflects bedrock geology and tectonic history of the landscape. Fluvial segment types differ in stream-adjacent landforms, slope erosion processes, floodplain and valley morphology, channel slope, riparian vegetation, streambank texture, gravel bar morphology, and pool-forming features. Studies that do not carefully account for inherent differences between valley segment types could fail to detect critical changes in stream habitat caused by human disturbance. Alluvial valley and alluviated canyon segment types, which have extensive...
floodplains, low channel slopes, abundant woody debris, and ample gravel beds, are of
greatest direct importance for salmon and other native fishes. Virtually all alluvial valleys
in the study area have been heavily disturbed by logging, agriculture, and residential
development. Alluviated canyon segments located in the few drainage basins where
human activity has been limited probably serve as habitat refugia for the last diverse
assemblages and productive populations of salmon in the region. Alluviated canyons in
extensively-logged basins exhibit increased abundance of large woody debris, fewer
cross-channel debris jams, more extensive bank erosion, reduced pool area and
increased riffle area, shallower ripples, and increased surface concentration of fine
sediments in pools and other habitats, compared to similar segments in lesser-disturbed
basins. These changes in channel morphology and stability appear to be driven by
increased sediment load, caused by logging-related landslides and other erosion
sources. Field studies in Sixes River basin indicated that abundance and diversity of
salmonid fishes declines as maximum stream temperature increases. Changes in
summer distribution of juvenile chinook and coho salmon since 1970 are related to
changes in water temperature. Although some tributaries have cooled, a decline in
rearing distribution in mainstem areas could be caused by long-term loss of channel
complexity and associated coolwater refugia. Analysis of fish habitat structures
constructed by federal and state agencies indicated that failure rates are high. Recovery
of anadromous fish runs in southwest Oregon will require protection of remaining habitat
refugia and reduction of sediment yield from disturbed watersheds.
Cumulative Effects of Land Use on Salmon Habitat in Southwest Oregon Coastal Streams

by
Christopher A. Frissell

A THESIS
submitted to
Oregon State University

In partial fulfillment of the requirements for the degree of
Doctor of Philosophy

Completed April 30, 1992
Commencement June 1992
APPROVED:

Redacted for Privacy

[Signature]

Associate Professor of Fisheries and Wildlife in charge of major

Redacted for Privacy

[Signature]

Head of Department of Fisheries and Wildlife

Redacted for Privacy

[Signature]

Dean of Graduate School

Date thesis is presented April 30, 1992

Typed and Formatted by Christopher A. Frissell
ACKNOWLEDGEMENTS

Bill Liss has provided me with years of steady support and creative spark. Charles Warren and Jim Lichatowich also made this research possible, and I think of them as the grandfather and godfather of this work, respectively. I thank the members of my graduate committee, Fred Swanson, Jim Sedell, Ron Neilson, and Tom Bedell for their assistance and always interesting discussions. Jim Hall has also been an encouraging and helpful influence. Rich Nawa and Joe Ebersole have been dedicated and cherished colleagues. While these individuals deserve credit for anything that's good in this thesis, I take full responsibility for the rest.

Many talented people have assisted on this project in the field and in the lab; their contributions have been crucial. Roughly in chronological order I thank Earl Hubbard, Dan Schively, Eric Leitzinger, Shaun Robertson, and Rodney Garland. Kelley Wildman has provided dedicated and talented administrative support and a cheerful presence I value highly. Most of the best-looking figures were drafted by Bill Gilbert. John Bragg provided photography that has been invaluable in public presentations. Other faculty, researchers, fellow graduate students, and miscellaneous personalities have had major, though indirect, influences on this work. In particular I wish to acknowledge Brendan Hicks, Jeff Dambacher, Bruce Sims, Courtney Cloyd, Gordon Reeves, Gordon Grant, Danny Hagans, Mary Ann Madej, Steve Ralph, Dave Bella, Dan Bottom, Hiram Li, John Bragg, Jim Britell, Mike Anderson, David Bayles, Don Boyd, Bill Bakke, and all the folks at Oak Creek Lab. This list is far from complete, but I have to turn this thesis in tomorrow morning. I thank John Bragg, Eric Cain, Steve Jones, Ted Williams, and Dennis Hayward for bringing our project and its implications to the attention of so many.

I especially thank Dale Hannon for her love and perseverance, and my parents for lots of kind encouragement.

\[ n = 1 \]
\[ \text{d.f.} = 0 \]

\( \odot \) 1991

A patriot must always be ready to defend his country against his government.

--Edward Abbey

Those who fail to learn natural history are condemned to be eaten by it.

--bOB gROSS
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter 1: Overview</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 2: Aquatic Habitat in a Coastal Mountain Landscape:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification and Ecological Significance of Valley Segments</td>
</tr>
<tr>
<td>ABSTRACT</td>
</tr>
<tr>
<td>1. Introduction</td>
</tr>
<tr>
<td>2. Methods</td>
</tr>
<tr>
<td>2.1 Study Area</td>
</tr>
<tr>
<td>2.2 Reconnaissance and Identification of Segment Types</td>
</tr>
<tr>
<td>2.3 Landscape Associations</td>
</tr>
<tr>
<td>2.4 Field Surveys</td>
</tr>
<tr>
<td>2.5 Biological Information</td>
</tr>
<tr>
<td>3. Results</td>
</tr>
<tr>
<td>3.1 Valley Segment Types and Landscape Distribution</td>
</tr>
<tr>
<td>3.2 Valley Slope, Rock Type, and Landscape Development</td>
</tr>
<tr>
<td>3.3 Floodplain and Valley Width</td>
</tr>
<tr>
<td>3.4 Streamside Geomorphic Surfaces and Processes</td>
</tr>
<tr>
<td>3.5 Channel Pattern and Bar Form</td>
</tr>
<tr>
<td>3.6 Streambank Texture</td>
</tr>
<tr>
<td>3.7 Riparian Vegetation and Canopy Cover</td>
</tr>
<tr>
<td>3.8 Biological Significance of Valley Segments</td>
</tr>
<tr>
<td>4. Implications for Landscape Change and Aquatic Fauna</td>
</tr>
<tr>
<td>5. Comparison with Other Classifications</td>
</tr>
</tbody>
</table>
Chapter 3: Interactive Effects of Valley Geomorphology and Logging on
Stream Habitat in South Coastal Oregon.................................78

ABSTRACT.................................................................79

1. Introduction..........................................................80

2. Methods..............................................................82

  2.1 Study Area.........................................................82

  2.2 Study Design.....................................................83

  2.3 Field Methods...................................................86

  2.4 Analysis..........................................................88

3. Results............................................................90

  3.1 Bank Erosion.....................................................90

  3.2 Large Woody Debris............................................93

  3.3 Pool- and Riffle-Forming Features...........................97

  3.4 Pool and Riffle Structure....................................100

  3.5 Depths of Pools and Riffles..................................108

  3.6 Texture of Bed Materials and Instream Cover...............112

4. Discussion........................................................117

ACKNOWLEDGEMENTS.................................................126
## TABLE OF CONTENTS, continued

Chapter 4: Water Temperature and Distribution and Diversity of Salmonid Fishes in Sixes River Basin, Oregon, USA: Changes Since 1965-72

- **ABSTRACT** ........................................................................................................ 128
  - 1. Introduction ................................................................................................. 129
  - 2. Methods ........................................................................................................ 131
    - 2.1 Study Area .............................................................................................. 131
    - 2.2 Historical Data ...................................................................................... 135
    - 2.3 Water Temperature ............................................................................... 136
    - 2.4 Environmental Variation ....................................................................... 138
    - 2.5 Fish Distribution .................................................................................. 139
  - 3. Results .......................................................................................................... 141
    - 3.1 Environmental Conditions .................................................................... 141
    - 3.2 Water Temperature ............................................................................... 143
    - 3.3 Fish Distribution .................................................................................. 148
    - 3.4 Basin-Wide Abundance ......................................................................... 156
    - 3.5 Temperature and Assemblage Diversity ............................................... 158
    - 3.6 Juvenile Behavior and Thermal Heterogeneity ..................................... 163
  - 4. Discussion ..................................................................................................... 165
    - 4.1 Temperature and Fish Assemblages ...................................................... 165
    - 4.2 Physical and Biological Recovery .......................................................... 167
    - 4.3 Habitat Refugia and Persistence of Fish Populations ......................... 170

- **ACKNOWLEDGEMENTS** ............................................................................... 172
TABLE OF CONTENTS, continued

Chapter 5: Incidence and Causes of Physical Failure of Artificial Habitat Structures in Streams of Western Oregon and Washington.............................................................173
ABSTRACT.................................................................................................................174
  1. Introduction........................................................................................................175
  2. Methods............................................................................................................178
    2.1 Study Sites.................................................................................................178
    2.2 Flood Peak Estimation..............................................................................182
    2.3 Definitions................................................................................................183
    2.4 Structural Evaluation................................................................................184
    2.5 Inter-regional Comparisons......................................................................185
  3. Results..............................................................................................................186
    3.1 Damage Rates in Relation to Stream Characteristics...........................186
    3.2 Mode of Damage.......................................................................................191
    3.3 Effect of Structure Type..........................................................................195
    3.4 Inter-regional Patterns..............................................................................198
  4. Discussion.......................................................................................................205
    4.1 Implications for Economic Analyses.....................................................208
    4.2 Implications for Habitat Management...................................................209
ACKNOWLEDGMENTS.........................................................................................211

BIBLIOGRAPHY...................................................................................................212
<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Location of the study area, the quadrangles where extensive map survey of streams was conducted, and field study basins in southwest Oregon</td>
<td>12</td>
</tr>
<tr>
<td>2. Ten valley segment types identified in southwest Oregon</td>
<td>22</td>
</tr>
<tr>
<td>3. Broad-scale distribution of valley segment types of lakes and fourth-order or larger streams across the study area</td>
<td>28</td>
</tr>
<tr>
<td>4. Maps of valley segments in Sixes River (a) and Euchre Creek (b) basins</td>
<td>31</td>
</tr>
<tr>
<td>5. Valley slope as a function of Strahler stream order for third-order and larger channels in four fluvial segment types</td>
<td>37</td>
</tr>
<tr>
<td>6. Downstream gradient in channel, floodplain, and valley width, and geomorphic conditions in three valley segments of Edson Creek, tributary to Sixes River</td>
<td>43</td>
</tr>
<tr>
<td>7. Simple ordination of valley segments by field measurements of ratio of active channel width to floodplain width and mean channel slope</td>
<td>46</td>
</tr>
<tr>
<td>8. Mean frequency distribution of channel-adjacent geomorphic surfaces in field surveys</td>
<td>48</td>
</tr>
<tr>
<td>9. Mean linear frequency and estimated volume of sediment contributed to streams from riparian hillslopes, based on field surveys</td>
<td>51</td>
</tr>
<tr>
<td>10. Frequency distribution of channel pattern and bar form of five segment types, based on field surveys</td>
<td>55</td>
</tr>
<tr>
<td>11. Texture of bank materials in five valley segment types, measured as percent of transects in which particle size class was first or second most abundant in streambank exposures</td>
<td>60</td>
</tr>
<tr>
<td>12. Relative abundance of tree species in riparian canopy and percent canopy cover of four segment types</td>
<td>63</td>
</tr>
<tr>
<td>13. Conceptual model of cumulative effects of natural and human-caused erosion and sedimentation in southwest Oregon drainage basins</td>
<td>72</td>
</tr>
<tr>
<td>14. Proportion of stream banks that showed evidence of recent or active erosion, plotted against cumulative area of the drainage basin logged since 1940</td>
<td>92</td>
</tr>
<tr>
<td>15. Correlation between drainage basin size and wetted area in pools at low flow</td>
<td>104</td>
</tr>
<tr>
<td>16. Relationship between channel slope and the proportion of total wetted area comprised by pools, alluviated canyon valley segments only</td>
<td>107</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>17</td>
<td>Mean depth of riffles as a function of drainage basin area, alluviated canyons only</td>
</tr>
<tr>
<td>18</td>
<td>Effect of valley segment type on bed material size distribution in five classes of low flow habitats</td>
</tr>
<tr>
<td>19</td>
<td>Abundance of fine sediment on the bed surface in habitats located in alluviated canyon valley segments</td>
</tr>
<tr>
<td>20</td>
<td>Location of water temperature and air temperature stations, 1987-89</td>
</tr>
<tr>
<td>21</td>
<td>Maximum water temperature by seasonal time period beginning May 5 and ending Sept. 25</td>
</tr>
<tr>
<td>22</td>
<td>Longitudinal profile of maximum temperature during late July to early August of 1970 and 1989</td>
</tr>
<tr>
<td>23</td>
<td>Maps of the number of salmonid age classes and species present in Sixes River during late summer in 1987-90 and the distribution and abundance by species and age class</td>
</tr>
<tr>
<td>24</td>
<td>Salmonid diversity as measured by the number of species and age classes present, in relation to maximum water temperature</td>
</tr>
<tr>
<td>25</td>
<td>Abundance of salmonids in relation to maximum water temperature in segments of Sixes River during 1987-90</td>
</tr>
<tr>
<td>26</td>
<td>Location of stream structure projects evaluated in southwest Oregon and southwest Washington during 1986</td>
</tr>
<tr>
<td>27</td>
<td>Failure and damage rates of projects in southwest Oregon and southwest Washington in relation to active channel width</td>
</tr>
<tr>
<td>28</td>
<td>Failure and impairment rates of structures classified by design</td>
</tr>
<tr>
<td>29</td>
<td>Box plots of 10-y peak flow standardized by drainage area for streams in six regions of western Oregon</td>
</tr>
<tr>
<td>30</td>
<td>Relation between rates of failure and damage of projects and regional median 10-y-recurrence interval peak flow standardized by drainage area</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>24. Species and age class diversity relative to maximum temperature</td>
<td>159</td>
</tr>
<tr>
<td>25. Observed fish density relative to maximum temperature</td>
<td>161</td>
</tr>
<tr>
<td>26. Location of structure projects evaluated</td>
<td>179</td>
</tr>
<tr>
<td>27. Incidence of failure (A) and damage (B) relative to active channel width</td>
<td>188</td>
</tr>
<tr>
<td>28. Failure and impairment rate by structure type</td>
<td>196</td>
</tr>
<tr>
<td>29. 10-year recurrence interval peak flow by region</td>
<td>201</td>
</tr>
<tr>
<td>30. Rate of failure and damage relative to peak flow</td>
<td>203</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Characteristics of the field study sites</td>
<td>16</td>
</tr>
<tr>
<td>2. Key characteristics of ten valley segment classes in southwest Oregon</td>
<td>25</td>
</tr>
<tr>
<td>3. Percent of each valley segment type located within indicated geologic map unit</td>
<td>29</td>
</tr>
<tr>
<td>4. Regression parameters and their 95 percent confidence intervals for the regression of log, valley slope on Strahler stream order, in four valley segment types</td>
<td>29</td>
</tr>
<tr>
<td>5. Translation key for valley segment classifications for southwest Oregon from this paper and nearest comparable stream segment or reach types from classifications by Cupp (1999), Rosgen (1985 et seq.), Marion et al. (1987), and Gregory et al. (1990)</td>
<td>75</td>
</tr>
<tr>
<td>6. Study sites in Curry County, southwest Oregon</td>
<td>85</td>
</tr>
<tr>
<td>7. Linear frequency, spatial arrangement, and size of accumulations of large woody debris in the study streams</td>
<td>94</td>
</tr>
<tr>
<td>8. Mean percent of pool habitats in each valley segment type associated with each of seven morphogenetic features</td>
<td>98</td>
</tr>
<tr>
<td>9. Pool- and riffle-level composition of habitats in the study segments</td>
<td>101</td>
</tr>
<tr>
<td>10. Distribution of cover types in main channel pools of fluvial valley segment types, measured as median percent area of habitat occupied by cover element</td>
<td>118</td>
</tr>
<tr>
<td>11. Temperature station locations and physical data</td>
<td>137</td>
</tr>
<tr>
<td>12. Changes in interannual mean water temperature maxima between the year intervals 1965-72 and 1987-89</td>
<td>144</td>
</tr>
<tr>
<td>13. Change in summer distribution of juvenile coho and chinook salmon in upper, middle, and lower Sixes River basin</td>
<td>154</td>
</tr>
<tr>
<td>14. Available habitat and crude estimates of total abundance of juvenile salmonids by species/age class in upper, middle, and lower sections of Sixes River basin in midsummer of 1987-89</td>
<td>157</td>
</tr>
<tr>
<td>15. Physical characteristics of study sites</td>
<td>181</td>
</tr>
<tr>
<td>16. Flood magnitude estimates and rates of total damage and failure for fish habitat structure projects surveyed in 1986</td>
<td>187</td>
</tr>
<tr>
<td>17. Percent of structures in each project for which there was evidence that the indicated process contributed to failure or impairment</td>
<td>192</td>
</tr>
</tbody>
</table>
LIST OF TABLES, continued

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>18. Rates of physical failure and damage reported for projects in western Oregon surveyed by other agencies</td>
<td>199</td>
</tr>
<tr>
<td>19. Unit discharge of ten-year recurrence interval peak flow of selected Oregon streams having greater than 20 years of record, drainage area exceeding 100 km² but less than 2500 km², and no significant influence of reservoir regulation</td>
<td>200</td>
</tr>
</tbody>
</table>
CONTRIBUTIONS OF COAUTHORS

This thesis consists of four manuscripts summarizing work completed over a six-year period. The research often involved close collaboration among the coauthors, particularly in the planning and accomplishment of field work. The principle author did most of the data analysis, writing, and final editing of the material contained in this thesis, and should be held solely responsible for any errors or exaggerations of fact. The particular contributions of coauthors to papers in this thesis are summarized below.

R.K. Nawa-- Involved in all phases of field work and some aspects of quality control and analysis of data; closely collaborated in developing objectives, field study design and methods, and management implications; reviewed and edited the manuscripts several times.

W.J. Liss-- Principal Investigator of project, handled most aspects of funding and administrative arrangements; participated in setting study objectives and theoretical perspective; reviewed and edited manuscripts.

J.L. Ebersole-- Assisted in field work and development of field methods; reviewed and edited manuscript.
Cumulative Effects of Land Use on Salmon Habitat in Southwest Oregon Coastal Streams

Chapter 1

Overview
Overview

The primary theme of this dissertation is that drainage basins exert pervasive control of the stream habitats and biota embedded within them. This is a refrain long-developed by Warren (1979) and others before him, but one which unfortunately has been widely neglected in environmental research, planning, and management. It is a confounding assumption from the standpoint of the mechanistic world view, for to the extent that the organization and response of a system is dependent on its context in space and time, no two ecosystems or habitats are alike. The conduct of the rather mechanistic pursuit I will here call "standard resource science" rests on the existence of replicate systems, on the ability of such replicates to exhibit independent responses, and to a large extent upon the principle that natural and cultural process-response systems are fundamentally reversible. In the realm of ecology and resource management, we have much evidence that none of these three notions is reasonable.

The decline of the Pacific salmon during this century is a tragic and resonant illustration of the failure of the European paradigm of resource science and management. The story of the salmon dramatically underscores the inadequacy of the assumptions of the prevailing paradigms of resource management and science. Each population of salmon is unique, in that it homes to and is intricately adapted to the peculiar combination of circumstances in its natal stream and the associated rearing environment. Even if such populations were similar enough that they were functionally
interchangeable, an idea which a century of experience in salmon culture has consummately refuted, they are unique by virtue of their location and the timing of their life history events. In ecological and human terms, the importance and singularity of the salmon is defined by the very habitat it animates.

Finally, there is little evidence that the depletion of the salmon and its ecosystem is reversible, at least under the cultural norms and environmental conditions that have prevailed since the virtual destruction of the aboriginal civilization. Perhaps the best-fit model of the salmon decline is one of unremitting, incremental loss of habitat and biotic diversity for the century or so that European man has been a major force in their environment. Arthur McEvoy has documented this story eloquently (McEvoy 1986), and strikingly recounts how the once-rich cultural diversity of salmon fisheries--aboriginal and later Eurasian--has suffered the same fate as the natural system upon which it depends.

We can find hope, however, in small places. A few salmon populations have demonstrated remarkable capacity for either explosive growth or slow and steady rebound if their habitat is intact and artificial impediments to their survival are removed. There is widespread and growing interest in not just the protection of salmon ecosystems, but their restoration. And perhaps even as a consequence of the descent of the wild salmon's importance as simple raw material for the region's economy, its value as a cultural icon and symbol of environmental quality is becoming rediscovered, recognized, and celebrated.

Science is complicit in the loss of the salmon and the environmental destruction it signifies. Scientists have not just tacitly accepted, but actively courted the demands that economic and political forces have thrust upon them: that in questions about the management of ecosystems, the burden of proof lies with those who would ensure their protection, rather than those who would risk them through resource exploitation.
Following in step with the expectations of policymakers, most scientists have proceeded to apply the unrealistic premises of the highly mechanistic paradigm in their research, and have generally failed to demonstrate that human activities have damaged ecosystems, even as those ecosystems were disappearing beneath them (McEvoy 1986).

In this dissertation I focus on the fate of salmon and their habitat in the watersheds of southwest Oregon. The following chapters examine one approach to understand and articulate the complex network of habitats and cascade of processes that constitute the stream and its watershed. The challenge of such research is to determine how activities occurring over large expanses of land and long spans of time can affect the aquatic habitat downslope and downstream. The approach taken is a hierarchical one, where close attention is paid to scale and the contingent constraints imposed by nested environments. My goal in this thesis is to further a "non-standard" scientific path, one more coherent with what we know to be fundamental principles of ecosystemic and cultural behavior, while avoiding being perceived as wholly bizarre or unrealistic by the guardians of the prevailing paradigm. I am not particularly satisfied with the result. The social challenge of bridging contradictory world views and the scientific and technological subcultures they pervade has been a far more daunting charge than gaining understanding of the natural world. Here is the message that keeps filtering back from the front lines: this work is but a small step where great strides are needed.
Aquatic Habitat in a Coastal Mountain Landscape:  
Classification and Ecological Significance  
of Valley Segments

Christopher A. Frissell  
William J. Liss  
Richard K. Nawa

Oak Creek Laboratory of Biology  
Department of Fisheries and Wildlife  
104 Nash Hall  
Oregon State University  
Corvallis, Oregon 97331
ABSTRACT

In the Klamath Mountains of southwest Oregon we describe ten classes of fluvial, lacustrine, and estuarine habitats that differ in fundamental geologic, geomorphic, and ecological properties. Valley segment classes encompass stream channels and the adjacent floodplain and riparian lands with which channels directly interact over time periods of thousands of years. Valley segments form a large-scale template controlling the effects on aquatic habitat of disturbances in riparian areas and mediating the response of streams to upstream and upslope disturbances in their drainage basins. The regional distribution of valley segment types is controlled by lithology and tectonic history. Fluvial segment types differ in stream-adjacent landforms, slope erosion processes, floodplain and valley floor width, channel slope, riparian vegetation, texture of streambank deposits, gravel bar morphology, and pool-forming features. By virtue of their geomorphology and downstream location, alluvial segment types are the most widely impacted and most sensitive to the cumulative effects of basin-wide disturbance. Such low-gradient segments with active floodplains are of greatest ecological importance for salmon and other native fishes, many species of which are in serious decline. This classification provides a systematic methodology for large-scale mapping of stream and riparian habitats, and analysis, prediction, and monitoring of the effects of landscape change on aquatic ecosystems. We believe this kind of approach will be necessary for effective protection and recovery of threatened fishes and other aquatic biota.
1. Introduction

Landscapes along tectonically active continental margins, such as the west coast of North America, are marked by short, very steep gradients from the mountain crest to the sea, and abundant, periodically intense rainfall. These conditions drive extreme rates of transfer of material and energy from upland to lowland areas via colluvial, fluvial, chemical, and biological processes (Hewitt 1972, Muhs et al. 1987). In steep, humid regions, stream systems serve as the primary pathways for this seaward flux. Natural and anthropogenic disturbances originating high in the watershed are rapidly and efficiently transferred, transformed, and sometimes amplified downslope and downstream. Therefore, coastal mountain streams, although biologically productive, offer highly dynamic, physically challenging habitats for aquatic organisms.

The fish fauna of north Pacific coastal streams is generally species-poor. However, abundant populations of Pacific salmon (Oncorhynchus spp.) are widely distributed and culturally and economically valued. The watersheds providing freshwater habitat for these fishes also support a burgeoning array of land uses, including logging, agriculture, mining, urbanization and industrial development. Many species of Pacific salmon have suffered serious decline and local extinction in recent decades, particularly in the southern portion of their ranges (Konkel and McIntyre 1987, Moyle and Williams 1990, Nehlsen et al. 1991). Most of these losses are associated with damage or
destruction of freshwater habitats (Nehlsen et al. 1991, Frissell submitted). However, the complex causal relationships between logging and other human modifications of the landscape and deterioration of aquatic habitats are poorly understood, in part due to inherent variation among watersheds in different geologic and climatic regions (Swanston 1991, Hicks et al. 1991a) and among streams in different geomorphic settings (Chamberlin et al. 1991).

To date, research and management of aquatic ecosystems in the coastal zone have focused on direct, lateral linkages between riparian areas and immediately adjacent aquatic habitats. However, because habitats within aquatic ecosystems are also tightly coupled in the longitudinal or downstream dimension (Vannote et al. 1979), there is clearly a need for landscape-level conceptual and methodological tools to understand and predict the cumulative, downstream-propagating impacts of land use on aquatic habitats within whole drainage basins. This requires a conceptual framework for interpretation of linkages between terrestrial and aquatic environments. It also requires a means of classifying landscape "patches" that both reflects key land-water linkages, and discriminates spatial units at a level of resolution appropriate for mapping and analysis of large drainage basins. In an earlier paper we described a hierarchical conceptual framework for understanding the structure and function of watersheds and stream systems, including general criteria for classification of stream habitats at a range of spatio-temporal scales (Frissell et al. 1986). In this paper we describe a specific classification scheme which resolves watersheds and streams into units at the scale of valley segments.

Valley or stream segments, defined in Frissell et al. (1986), are hundreds of meters to kilometers in length and persist as geomorphic units over time scales of thousands of years. Valley segment types differ geomorphically and ecologically in ways that constrain the potential morphology and dynamics of stream channels and
aquatic habitat at smaller scales (Frissell et al. 1986), and largely determine the suite of physical and biotic processes linking terrestrial and aquatic systems (Hynes 1975, Decamp 1984, Swanson et al. 1988). The variables most useful for such a classification reflect the diverse geomorphic origins of valley segments, and identify long-term constraints on aquatic habitats and their potential response to changes in the watershed (Warren 1979, Frissell et al. 1986). For valley segments these variables include channel slope, bedrock geology, sideslope and floodplain morphology, soil properties, and potential natural vegetation (Frissell et al. 1986).

Various investigators have suggested comparable typological schemes for stream segments or reaches in mountainous areas (e.g., Platts 1979, Rosgen 1985, Marion et al. 1987, Harris 1988, Cupp 1989a, 1989b). Although the potential advantages of such classifications have been frequently acknowledged (Warren 1979, Lotspeich and Platts 1982, Mosley 1987, Hicks et al. 1991, Naiman et al. 1992), so far those who have attempted to evaluate their actual utility in research and management report mixed success (e.g., Platts 1979, Mosley 1987, Bryant et al. 1991, Ralph et al. 1991, MacDonald et al. 1991). Unfortunately few of these reports have appeared in the peer-reviewed literature. Most are limited in geographic scope (as may be appropriate), and none address the particular conditions of the Klamath Mountains region of coastal Oregon and California, where the crisis of collapse and endangerment of fish populations is particularly acute. This paper describes a classification of valley segments designed to assess the geographic distribution and physiography of aquatic habitats, to define their relationship to terrestrial landscape features, and to predict their response to human disturbance of drainage basins in southwest Oregon. Elsewhere we apply the classification in field studies of the effects of logging on channel morphology and aquatic habitat (Frissell et al. 1992b).
2. Methods

2.1 Study Area

The study area (Fig. 1) is broadly defined as the coastal river basins within the Klamath Mountains physiographic province of southwest Oregon (Franklin and Dyrness 1976). The area comprises steep, highly dissected mountains descending to short river valleys and a very narrow, discontinuous coastal plain. The region is largely forested with diverse, patchy stands of conifers and hardwoods. Common tree species include Douglas-fir (Pseudotsuga menziesii), Port-Orford-cedar (Chamaecyparis lawsoniana), western hemlock (Tsuga heterophylla), red alder (Alnus rubra), bigleaf maple (Acer macrophyllum), California bay laurel (Umbellularia californica), willow (Salix spp.), tanoak (Lithocarpus densifloras), and Pacific madrone (Arbutus menziesii). Clear-cut logging has been widely practiced since about 1955. The few low-lying areas along the coast have been largely cleared for agricultural and residential development, mostly prior to 1940 (Frissell and Liss 1986). The study area supported large indigenous runs of salmon, steelhead, and trout (Oncorhynchus spp.) that have dramatically declined in recent decades (Nicholas and Hankin 1988, Nehlsen et al. 1991, Frissell submitted).

Steep slopes and river canyons have developed on highly heterogeneous geologic formations in a tectonically active landscape (Kelsey 1990), sometimes referred to as the Klamath Knot (Wallace 1983). These formations include large areas of metamorphosed and faulted and sheared rocks of sedimentary, volcanic, and plutonic origin (Beaulieu and Hughes 1976, Ramp et al. 1977). Very steep slopes on competent rocks are prone to shallow, rapid landsliding, whereas deep soils formed over incompetent rocks are subject to deep-seated slump-earthflows, block slides, rapid soil creep, and gully erosion (Beaulieu and Hughes 1976, Swanston 1979, Sonneville et al.)
Figure 1. Location of the study area, the quadrangles where extensive map survey of streams was conducted (stippled), and field study basins (diagonally shaded) in southwest Oregon. Number codes as in Table 1. Symbols indicate basin geology: square for highly sheared, Jurassic age metasedimentary rocks (Otter Point Formation); upward-pointing triangle for massive, Cretaceous-age sandstone and conglomerate (Rocky Point and Humbug Mountain Formations); circle for basins comprised of a complex of Jurassic age schist (Colebrook Schist), Otter Point Formation metasediment and Cretaceous sedimentary rocks; and downward-pointing triangle for massive, Jurassic-age greywacke sandstone (Dothan Formation).

Intense winter rainstorms produce flashy, high-magnitude peak flows, followed by extremely low streamflow during the dry period between July and October (Friday and Miller 1984). Accelerated erosion and sedimentation associated with floods and logging have caused widespread aggradation, widening, and destabilization of channels since 1955, disturbing forest vegetation along low-gradient reaches of the many of the region's rivers (Kelsey 1980, Lisle 1981, Frissell and Liss 1986).

2.2 Reconnaissance and Identification of Segment Types

Following review of existing literature and topographic and geologic maps, we conducted field reconnaissance, including mapping of landforms and channel features, reconstruction of vegetation and land use history, and survey of cross sections along selected streams. These observations allowed us to relate patterns on maps and aerial photographs to site-specific field conditions. Based on the apparent role of geologic and geomorphic features in constraining key geomorphic and ecological processes (e.g., erosion, sediment transport, composition and succession of vegetation, and input and retention of boulders and large wood in streams) we subjectively identified major valley segment classes, discernible using topographic maps or field data. For the purposes of mapping and analysis in this paper, we did not discriminate geomorphically
distinct units of less than 100 m in length as valley segments, but rather treated them as
inclusions within larger units. The final typology is the outcome of a years-long, iterative
process of field description, map and airphoto investigations, development of conceptual
hypotheses to explain the causal bases of differences among sites, and sorting, lumping,
splitting, or rejection of provisional categories.

2.3 Landscape Associations

Once we defined a satisfactory classification, we used 1:62,000-scale
topographic and geologic maps to develop a provisional map of segment types across
all the basins of the study area. This analysis was intended as a rapid and approximate
assessment at a regional scale of the spatial distribution of valley segment types. In this
coarse-resolution mapping we aggregated competent bedrock canyons with colluvial
canyons, and alluvial-fan-influenced valleys with alluvial valleys, since more detailed work
using larger-scale maps, aerial photographs, or field work is often necessary to
adequately distinguish these classes.

To assess the correspondence between geomorphically-defined valley segments
and aspects of the drainage basin including position within the drainage network (i.e.,
stream size), geology, and channel slope, we mapped valley segments in the Sixes
River, Euchre Creek, and portions of Elk River and Floras Lake basins in detail. This
area is representative of the northern half of the study region. The sample
encompassed valley segments of Strahler order four or larger based on U.S. Geological
Survey 1:24,000- scale topographic quadrangles (Fig. 1) (Cape Blanco, Sixes, Mt. Butler,
Floras Lake, and the western one-third of Langlois quadrangles). In this survey we
identified and classified valleys based strictly on topographic criteria, primarily side slope
steepness and form and topographic expression of valley floor surfaces. We then measured the downstream slope of the valley floor from the topographic map and determined bedrock geology from geologic maps (Beaulieu and Hughes 1976, Ramp et al. 1977, DOGAMI 1982). As an index of stream size we determined stream order following Strahler (1952), using contour crenulation on the topographic maps to delineate headwater, ephemeral-flow channels as first-order streams (Gregory 1966). We compared frequency distributions of these factors among segment types, and assessed differences between segment types using linear regression and analysis of variance. Because we gained considerable field experience in this portion of the regional study area, we were able to develop detailed and field-verified maps of valley segments in several basins, two of which are included in this paper.

2.4 Field Surveys

In summer of 1989 we conducted field inventories to assist in validation of map-based valley segment classification and to compare stream habitat conditions among valley segment types. We designed the field study to accommodate four important sources of variation: valley segment type, geology of the drainage basin, land use history of the basin, and basin size (Table 1). These factors interact to affect habitat conditions and response of habitat to natural or human disturbance (Frissell et al. 1986). Based on evidence that low-gradient, alluvial segment classes provided much of the habitat critical for native fishes in the area, and that these habitats were likely the most sensitive to basin-wide disturbance, we selected 19 study streams that included major alluvial valley, alluvial fan, alluviated canyon, or terrace-bound-valley segments (Fig. 1).
Table 1. Characteristics of the field study sites. Site codes refer to Fig. 1. Segment type codes as in Table 2. In parentheses is number of discrete segments surveyed if more than one. Basin Geology is generalized, refers to dominant rock type as follows: Jop = Otter Point Formation, Jurassic metamorphics; Krh = Rocky Peak and Humbug Mountain Formations, Cretaceous sedimentary rocks; Jc/Krh = Complex of Colebrook schist and Otter Point metasedimentary rocks, with Cretaceous sedimentary rocks in headwaters; Jd = Dothan Formation, Jurassic greywacke sandstones. Land Use codes: OG/M = predominantly old-growth and mature forest; SG/CC = predominantly second-growth and clear-cut forest; AG = areas of agricultural land use occur at lower elevations.

<table>
<thead>
<tr>
<th>Number</th>
<th>Stream Code</th>
<th>Valley Segment Types</th>
<th>Drainage Basin Data</th>
<th>Study Site Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Edson Cr</td>
<td>AV(2), BRC</td>
<td>Jop</td>
<td>28.1 SG/CC, AG</td>
</tr>
<tr>
<td>2</td>
<td>Big Cr</td>
<td>CC(2), AC</td>
<td>Jop</td>
<td>3.9 OG/M</td>
</tr>
<tr>
<td>3</td>
<td>Upper Sixes R</td>
<td>TBV</td>
<td>Jp/Krh</td>
<td>98.6 SG/CC, AG</td>
</tr>
<tr>
<td>4</td>
<td>Little Dry Cr</td>
<td>AC, CC</td>
<td>Krh</td>
<td>3.4 SG/CC</td>
</tr>
<tr>
<td>5</td>
<td>Dry Cr</td>
<td>AV, AC</td>
<td>Krh</td>
<td>41.7 OG/M, AG</td>
</tr>
<tr>
<td>6</td>
<td>Rock Cr</td>
<td>AV, AC</td>
<td>Krh</td>
<td>3.4 SG/CC</td>
</tr>
<tr>
<td>7</td>
<td>Anvil Cr</td>
<td>AC, BRC</td>
<td>Krh</td>
<td>7.2 OG/M</td>
</tr>
<tr>
<td>8</td>
<td>Chismore Fk</td>
<td>of Euchre Cr</td>
<td>AC</td>
<td>5.4 SG/CC</td>
</tr>
<tr>
<td>9,10,11</td>
<td>Euchre Cr</td>
<td>AV, AFV (2), AC</td>
<td>Jc/Krh</td>
<td>65.0 SG/CC, AG</td>
</tr>
<tr>
<td>12</td>
<td>Cedar Cr</td>
<td>AV</td>
<td>Jop</td>
<td>23.4 SG/CC, AG</td>
</tr>
<tr>
<td>13</td>
<td>Lobster Cr</td>
<td>AV, CC</td>
<td>Jc/Krh</td>
<td>144.8 SG/CC</td>
</tr>
<tr>
<td>14</td>
<td>Quosatana Cr</td>
<td>AC</td>
<td>Jc/Krh</td>
<td>65.9 OG/M</td>
</tr>
<tr>
<td>15</td>
<td>Indian Cr</td>
<td>AV</td>
<td>Jop</td>
<td>9.6 SG/CC, AG</td>
</tr>
<tr>
<td>16</td>
<td>Deep Cr</td>
<td>AV, AC</td>
<td>Jop</td>
<td>9.2 SG/CC</td>
</tr>
<tr>
<td>17</td>
<td>Jack Cr</td>
<td>AV (2)</td>
<td>Jd</td>
<td>22.1 SG/CC, AG</td>
</tr>
<tr>
<td>18</td>
<td>Wheeler Cr</td>
<td>AC, BRC, CC</td>
<td>Jd</td>
<td>18.0 SG/CC</td>
</tr>
<tr>
<td>19</td>
<td>E.Fk Winchuck R</td>
<td>AC, CC</td>
<td>Jd</td>
<td>58.8 OG/M</td>
</tr>
</tbody>
</table>

*Elevation measured at downstream end of survey section, to nearest 5 m.*
The study basins can be grouped into four major geologic associations, adapted from Beaulieu and Hughes (1976): largely incompetent metamorphic rocks of Jurassic age (Otter Point Formation, Jop and Jov); Jurassic age, incompetent schist with competent sedimentary rocks in the headwaters (Colebrook schist and Cretaceous sedimentary rocks, Jc/Krh); largely competent, Dothan Formation sandstone of Jurassic age (Jd); and competent, massive Cretaceous conglomerate and sandstone (Krh).

We surveyed several bedrock canyons and colluvial canyons adjacent to the alluviated segments, but our sample size for these categories is relatively small. In addition, we surveyed just one terrace-bound-valley segment, and two alluvial-fan-influenced valleys (Table 1). We did not conduct field surveys in estuaries or lakes, since they comprise a very small part of the study area, are easily discriminated from other segment types, and would require different sampling techniques.

Field surveys, conducted during summer and fall of 1989, included systematic transect samples at intervals of 50, 100 or 200 m (increasing with increasing stream width), from downstream to upstream. At each transect point, we measured width of the active, unvegetated channel, width of active floodplains (surfaces showing evidence of inundation, scour, or deposition from floods of recent decades), and width of the valley floor, including alluvial fan and terrace surfaces above the active floodplain. Channel slope was measured with a hand-held Abney level. Texture of soils exposed in each streambank was described semiquantitatively by ranking the following size classes in terms of their volumetric abundance in the deposit (median axis length range in parentheses): bedrock (massive), large boulders (>100 cm), small boulders (26-100 cm), cobbles (6-25 cm), gravel (0.8-6 cm), fine gravel (2-8 mm), sand (0.06-2 mm, gritty consistency), silt (0.008-0.06 mm, greasy consistency), and clay (<0.008 mm, sticky consistency). We classified the riparian vegetation structure at the transect as grassland, brush, clear cut plantation (<10 y old), second-growth forest (>10 y old),
mature forest (trees 75-200 y old with few snags or downed logs), and old growth forest (some trees >200 y old, with numerous snags and downed logs). Riparian tree species were ranked by their relative contribution to canopy over and adjacent to the channel at the transect site. We visually estimated total canopy cover in terms of percent of the low-flow channel shaded by vegetation.

Channel pattern of the 50-m reach centered on the transect was classified based on Richards (1982) as straight, sinuous, meandering, anabranching (multiple channels with vegetated islands), or braided (multiple sub-channel threads across a continuous, unvegetated channel surface). This classification indicates increasing sinuosity, lateral complexity, and width of channels.

Between transect points, we recorded the occurrence of erosion sources, tributaries, debris jams, and stream-adjacent landforms within each reach. Following Varnes (1958) and Swanston (1979), we classified erosion sources as debris avalanches, streamside debris slides, debris flows from tributary sources, slump-earthflows, or gullies. We recorded only the erosion sources that, based on vegetation growth, had occurred or been active during the five years prior to the survey. The minimum volume of sediment delivered to the channel was roughly estimated by measuring the size of the evacuated erosion scar, or in the case of debris flow deposits, estimating the volume of the depositional fan or lobe. Our objective was to roughly estimate the quantity of material transferred from hillslope or tributary to valley floor locations by various processes.

At each debris jam, erosion feature, tributary, and transect site we identified the right- and left-bank landforms adjacent to the active channel. We classified landforms or geomorphic surfaces, adapted from Balster and Parsons (1966) and Parsons (1978), as follows: steep, competent hillslopes (>60% even, unbroken slope, shallow rocky or skeletal soils, or rock cliff face), moderate competent slopes (15-59% even slope,
moderate to deep, fine-textured soils), colluvial complex slopes (variable hummocky or broken slope, unstable, deep, heterogeneous soils), rock-floored strath terraces (alluvium veneer over exposed bedrock, silty or sandy soils), alluvial terraces (high, flat or very gently sloping surface entirely of alluvial origin, silty or sandy soils), floodplain (lower, flat surface of alluvial origin; silty, sandy, or gravelly deposits), and alluvial-colluvial fans (gently sloping, cone-shaped, heterogeneous deposits at tributary mouths).

Between transects we also counted gravel bars and classified them as transverse, mid-channel, side, point, or diagonal in form, following Richards (1982). Bar form reflects sediment size, transport processes, and sorting of bed materials, and the relative abundance of different kinds of gravel bars is correlated with channel pattern and bed stability (Richards 1982).

2.5 Biological Information

We used information on spawning and juvenile rearing distribution of anadromous fish in Sixes River and Elk River (Reimers 1971; Stein et al. 1972; Reimers and Concannon 1977; Burck and Reimers 1978; Gordon Reeves, U.S. Forest Service, Pacific Northwest Research Station, Corvallis, Oregon, unpublished data; Oregon Department of Fish and Wildlife, unpublished data), coupled with data from our own field studies in Sixes River and Euchre Creek (Frissell et al. 1992c; Nawa and Frissell, unpublished data) to qualitatively assess how key native fishes use segment types during their freshwater life history.
3. Results

3.1 Valley Segment Types and Landscape Distribution

We identified six classes of fluvial valleys, three lacustrine valley types, and one estuarine type (Fig. 2, Table 2). These categories can be readily recognized in the field, and most of these types can be discriminated using topographic maps of 1:62,500 or larger scale. Accuracy can be improved if field data or detailed maps of surface geology or soils are available. Table 3 indicates that strong associations exist between geologic map units and segment types.

The study area can be broadly divided into subregions having different spatial associations of valley segments (Fig. 3). Certain segment types, primarily alluvial valleys, terrace-bound-valleys, and the three types of lakes, are highly clustered within the study area. This distribution relates closely to geology and tectonic history. Most of the region is dominated by a mosaic of narrow, canyon segment types interspersed with slightly wider alluviated canyons.

Colluvial canyons are associated with sheared or faulted schist, siltstones, ultramafic rocks, or faulted sandstones vulnerable to deep-seated creep, slumps, and earthflows (Kelsey 1988). Competent bedrock canyons are incised in thickly bedded, unsheared sandstones; highly metamorphosed, indurated siltstones of the Galice Formation; and hard, metavolcanic or intrusive, granitic rock masses (Fig. 4, Table 3). Bedrock canyons also occur locally within other, less competent rock formations, commonly corresponding with unmapped intrusions or isolated, massive blocks within otherwise highly sheared formations. Chi-square analyses of the data in Table 3 indicate that colluvial canyons occur more frequently and bedrock canyons less frequently than would be expected by chance (\( P < 0.0001 \)) within the highly sheared Otter Point
Figure 2. Ten valley segment types identified in southwest Oregon. For each type, figure shows a generalized oblique view, and paired topographic and geomorphic surface maps for a type locality, for which a legal description is provided. Type localities were selected for representativeness, availability of field data, and ease of public access. Scale varies as indicated on topographic maps, contour interval is 12.2 m (40 ft). For fluvial segment types we provide typical cross sections from field surveys indicating vegetation, soil morphology, and location and width of active channels, and floodplains of approximate 5-10-year and 100-year inundation frequency. Legends for geomorphic maps and cross-sections are inset. Table 2 provides verbal description and criteria for identification.
FIGURE 2

A. COMPETENT BEDROCK CANYON

B. COLLUVIAL CANYON

C. ALLUVIATED CANYON
TERRACE-BOUND VALLEY

ALLUVIAL VALLEY

ALLUVIAL-FAN-INFLUENCED VALLEY

Figure 2
GLACIAL LAKE
Babyfoot Lake (Chetco R.) SWNE sec. 3 T38S R9W

SLUMP LAKE
Frog Lake (Saunders Cr., Rogue R.) SEMW sec. 36 T36S R14W

DUNE LAKE
Croft Lake, Mud Lake (New R.) SWSW sec. 11 T30S R15W

ESTUARY
Sixes River estuary SESE sec. 36, T31S R16W

Figure 2
<table>
<thead>
<tr>
<th>Valley segment type</th>
<th>Valley slope</th>
<th>Floodplain width</th>
<th>Valley Channel width</th>
<th>Channel pattern</th>
<th>Landscape position</th>
<th>Geomorphic surfaces and soils</th>
<th>Dominant Geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial valley (AV)</td>
<td>&lt;3%, mean 1%</td>
<td>&gt;2X ACW</td>
<td>&gt;2X ACW</td>
<td>Meandering or sinuous</td>
<td>Mostly near coast, some in tectonic or landslide-dammed basins in headwaters; 10-100 m elevation</td>
<td>Broad, continuous floodplains, local alluvial or marine terraces, local contact with marginal hillslopes</td>
<td>Quaternary alluvium</td>
</tr>
<tr>
<td>Alluvial-fan-influenced valley (AFV)</td>
<td>&lt;2%, mean 0.7%</td>
<td>&gt;3X ACW</td>
<td>&gt;3X ACW</td>
<td>Anastomosed, relatively unstable</td>
<td>Where tributary depositional fans encroach on alluvial valley mainstem, &lt;50 m elevation</td>
<td>Heterogeneous alluvial fan deposits, gravel, sand, and silt; complex floodplain surfaces, relict channels and wetlands</td>
<td>Quaternary alluvium</td>
</tr>
<tr>
<td>Terrace-bound valley (TBV)</td>
<td>&lt;2%, mean 1%</td>
<td>&lt;2X ACW</td>
<td>&gt;2X ACW</td>
<td>Meandering or sinuous, stable</td>
<td>Uplifted, flat valleys floored by competent sandstone strata, 10-100 m elevation</td>
<td>Uplifted, bedrock-floored strath terraces, local hillslope contact; channel floor and banks are bedrock or consolidated alluvium</td>
<td>Quaternary fluvial terraces, Tertiary sedimentary rocks, Dothan formation metasediments</td>
</tr>
<tr>
<td>Alluviated canyon (AC)</td>
<td>&lt;7%, mean 1%</td>
<td>1.2-2X ACW</td>
<td>1.2-2X ACW</td>
<td>Sinuous or straight</td>
<td>Transition zone between steep, headwater canyons and alluvial valleys, or as isolated flats within mountain canyons, 10-500 m elevation</td>
<td>Narrow, discontinuous floodplains, bounded by colluvial complex or competent hillslopes</td>
<td>All formations, especially at faults, shear zones, contacts, paleolandslides</td>
</tr>
<tr>
<td>Colluvial canyon (CC)</td>
<td>1-20%, mean 5%</td>
<td>=ACW</td>
<td>=ACW</td>
<td>Straight</td>
<td>Steep, narrow canyons in headwater and mid-basin areas, 10-800 m elevation</td>
<td>Angular boulders, cobbles in deep, fine-textured matrix of colluvium; at least one side slope shows paleolandslide, creep-earthflow, slump, blockslide, debris slide features (colluvial complex)</td>
<td>Incompetent rocks in fault or shear zones, paleolandslides, or where colluvial deposits occur along toeslopes</td>
</tr>
<tr>
<td>Competent bedrock canyon (BRC)</td>
<td>0.5-20%, mean 2%</td>
<td>=ACW</td>
<td>=ACW</td>
<td>Straight</td>
<td>Steep, narrow canyons in headwater and mid-basin areas, 10-800 m elevation</td>
<td>Bounded both sides by steep, competent hillslopes with shallow skeletal or sandy soils, locally talus</td>
<td>Competent rocks, various formations</td>
</tr>
</tbody>
</table>
Table 2. Continued.

<table>
<thead>
<tr>
<th>Valley segment type</th>
<th>Valley slope</th>
<th>Floodplain width&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Valley width&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Channel pattern</th>
<th>Landscape position</th>
<th>Geomorphic surfaces and soils</th>
<th>Dominant Geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacial lake (GL)</td>
<td>Level</td>
<td>--</td>
<td>--</td>
<td>Poned</td>
<td>Glaciated cirque basins and troughs, ridgelines and peaks &gt;750 m elevation</td>
<td>Glacial moraines, periglacial colluvium, talus, and steep, glacially scoured competent hillslopes</td>
<td>Quaternary glacial deposits within various rock formations of high Klamath peaks</td>
</tr>
<tr>
<td>Slump lake (SL)</td>
<td>Level</td>
<td>--</td>
<td>--</td>
<td>Poned</td>
<td>Small basins or saddles in headwaters, 300-800 m elevation</td>
<td>Colluvial complex slopes predominantly large slump-earthflow features</td>
<td>In shear zones of Jurassic age metasediments and serpentine masses; or where Tertiary sediments overlie sheared older rocks</td>
</tr>
<tr>
<td>Dune lake and wetland complex (DL)</td>
<td>Level</td>
<td>--</td>
<td>--</td>
<td>Poned</td>
<td>Coastal margins with active or stabilized dunes, &lt;10 m elevation</td>
<td>Sandy beach, dune, and marine terrace deposits, with silt and sand alluvial and lacustrine deposits on extensive floodplains and alluvial terraces</td>
<td>Quaternary alluvium, beach and dune deposits, Quaternary marine and fluvial terraces</td>
</tr>
<tr>
<td>Estuary and estuarine wetlands (EST)</td>
<td>Tidally variable</td>
<td>--</td>
<td>--</td>
<td>Poned, or braided at low tide</td>
<td>Mouths of rivers and major streams, at sea level</td>
<td>Sandy beach and dune lands, silty and sandy floodplains, sandy alluvial and marine terraces adjacent</td>
<td>Active beach and dune lands, Quaternary alluvium, fluvial and marine terraces</td>
</tr>
</tbody>
</table>

<sup>a</sup> Includes width of active channel; ACW = mean active channel width of segment; for fluvial segments only.

<sup>b</sup> Includes width of active channel, floodplain, and alluvial fans and terraces forming valley fill.
Figure 3. Broad-scale distribution of valley segment types of lakes and fourth-order or larger streams across the study area. In this map alluvial fan-influenced valleys are not differentiated from alluvial valleys, and colluvial canyons are not discriminated from competent bedrock canyons, due to limitations of map interpretation and field verification at this scale. Some short (<200 m) alluviated canyon segments also do not appear. Letter codes indicate geomorphic subregions defined by their diversity of valley segment types.  

a: Klamath Uplands, the regional matrix of dissected, mountainous terrain composed of narrow canyons and isolated alluviated canyons.

b: Langlois Plain, coastal lowlands with dune-formed lakes and wetlands.

c: Cape Blanco Shelf, uplifted coastal plain with alluvial valleys and estuaries dissecting marine terraces.

d: Powers Valley, interior basin with terrace-bound valleys incised in Tertiary-age sedimentary rocks.

e: Agness shear zone, slump-formed lakes on highly sheared and faulted metasedimentary rocks.

f: Ophir-Pistol shelf, narrow coastal benches with alluvial valleys and estuaries, local marine terraces and small dunes.

g: Klamath-Siskiyou peaks, high-elevation uplands with glacially-formed lake basins.

h: Franciscan terraces, terrace-bound-valleys incised in uplifted strath terraces of Dothan or Franciscan sandstones.

i: Del Norte shelf, northern end of a series of subsident coastal benches extending south into California, associated with broad alluvial valleys and sand-formed estuaries or large lagoons.
ALLUVIAL VALLEYS & ALLUVIAL-FAN-INFLUENCED VALLEYS
TERRACE-BOUND VALLEYS
ALLUVIATED CANYONS
COLLUVIAL AND COMPETENT BEDROCK CANYONS
FRESHWATER LAKES AND ASSOCIATED WETLAND COMPLEXES
ESTUARIES AND ASSOCIATED WETLAND COMPLEXES

Figure 3
Table 3. Percent of each valley segment type located primarily within indicated geologic map unit.

<table>
<thead>
<tr>
<th>Valley segment type</th>
<th>Quaternary</th>
<th>Tertiary</th>
<th>Cretaceous</th>
<th>Jurassic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alluvium</td>
<td>Sandstones</td>
<td>Conglomerate,</td>
<td>Otter Point</td>
</tr>
<tr>
<td></td>
<td>and fluvial</td>
<td>and Siltstones,</td>
<td>and siltstone</td>
<td>meta-sedimentary</td>
</tr>
<tr>
<td>Alluvial valleys (17)</td>
<td>76.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alluvial-fan-influenced valleys (1)</td>
<td>100.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Terrace-bound valleys (1)</td>
<td>100.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alluviated canyons (33)</td>
<td>0</td>
<td>0</td>
<td>6.1</td>
<td>51.5</td>
</tr>
<tr>
<td>Colluvial canyons (178)</td>
<td>0</td>
<td>0</td>
<td>7.9</td>
<td>32.6</td>
</tr>
<tr>
<td>Competent bedrock canyons (55)</td>
<td>0</td>
<td>0</td>
<td>7.3</td>
<td>87.3</td>
</tr>
<tr>
<td>Dune lakes (4)</td>
<td>25.0</td>
<td>75.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Estuaries (6)</td>
<td>66.7</td>
<td>33.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>All segment types combined</td>
<td>6.5</td>
<td>2.7</td>
<td>6.8</td>
<td>41.8</td>
</tr>
</tbody>
</table>

a Sample from selected portions of northwest quarter of study area (see text).
b In parentheses is number of segments sampled in category.
Figure 4. Maps of valley segments in Sixes River (a) and Euchre Creek (b) basins. Bedrock geology (sources cited in text) is indicated to show relationships between geology and valley geomorphology. Fourth-order and larger streams and lakes are shown. Segment classification in these basins is about 90 percent field verified.
BEACH AND DUNE SAND
QUaternary Alluvium
QUaternary Alluvial Terraces
QUaternary Marine Terraces
Tertiary Sedimentary Rocks (Flournoy and Lookingglass Formations)
Cretaceous Sedimentary Rocks (Running Mountain Conglomerate, Rocky Peak Formation)
Jurassic Shales (Galice Formation)
Jurassic Metasedimentary Rocks (Otter Point Formation)
Jurassic Schist (Colebrook Schist)
Jurassic Metavolcanics
Jurassic Granitic Intrusives (Pease Peak Diorite)
Serpentine and Peridotite Masses
Definite Fault
Approximate Fault
Thrust Fault

Figure 4
metasedimentary rock formation. Conversely, bedrock canyons are more frequent and colluvial canyons less frequent within areas of the more competent Cretaceous sedimentary rocks (Chi-square test, P < 0.0001). Hillslopes in both types of canyon typically assume the convex form of an inner gorge, indicating a tectonically rejuvenated landscape (Kelsey 1988).

Alluviated canyons have developed where faulted or sheared, incompetent hillslopes have allowed limited valley floor widening and landslide-caused constrictions or tectonic deformation have encouraged fluvial deposition (McHugh 1987, Kelsey 1988, Swanson et al. 1990). Alluviated canyons are not strongly associated with any particular geologic map unit (Table 3). Alluviated canyons are distinguished in the field and on detailed topographic maps by narrow, often discontinuous floodplains of Recent alluvium, but due to their small size these deposits are rarely delineated on geologic maps. Since Table 2 is derived from geologic maps, the geologic aspects of alluviated canyons and colluvial canyons appear very similar. It seems likely that colluvial and alluviated canyons are closely associated in geomorphic origin, and perhaps evolutionary transitions between them are common over a time frame of tens or hundreds of thousands of years: large-scale slope failure occurs, the debris is subsequently excavated by fluvial processes, and another cycle of failure is initiated. Fault movement or other tectonically-driven landscape deformation may be the initial trigger for many of these large landslide features.

Alluvial valleys primarily encompass coastal plains and river mouths where river canyons have been filled with Quaternary alluvium (Fig. 3, Fig. 4), probably during interglacial periods of high sea level (Beaulieu and Hughes 1976) or as a result of local tectonic subsidence (Kelsey 1988). Most of the alluvial valleys include extensive high terraces, as well as active floodplains, and are commonly bordered by colluvial complex slopes. These slopes contain relict landslide features that were probably extensively
active prior to valley filling (Late Pleistocene or early Holocene?), but today fail primarily
where they are undercut by the outside edge of a stream meander.

We have identified only a few alluvial-fan-influenced valleys in the study area.
They occur where tributaries draining highly unstable colluvial hillslopes join a mainstem
channel on a broad valley floor. The formation over centuries of a large fan of alluvial
and debris flow deposits at the tributary mouth creates highly unstable, complex channel
and groundwater networks in the tributary, and sometimes also in the main stream
adjacent to and upstream from the fan.

Terrace-bound valleys are common in two areas, one in the northeastern portion
of the study area in association with Tertiary-age sedimentary deposits (Fig. 3, Fig. 4a),
and a second along the southern coastal margin (extending south into northwestern
California) in association with fluvial terraces overlying Dothan or Franciscan formation
sandstones (Fig. 3). Terrace-bound valleys have sinuous or meandering channels
incised into broad, bedrock-floored strath terraces. These gently-sloping, entrenched
channels may have formed partly as a result of the unusual susceptibility of certain
bedded sandstones to fluvial corrosion of the channel floor (Ashley et al. 1988), but likely
have developed in response to late Pleistocene or Holocene uplift of pre-existing alluvial
valleys (Muhs et al. 1987, Kelsey 1988).

Lacustrine segment types are highly clustered in space (Fig. 3), and the pattern
reflects their diverse geomorphic origins. Dune-formed lakes and associated wetland
complexes occur at sea level on the widest coastal plain, near Cape Blanco. They are
associated with Holocene beach sands and dunes, uplifted marine terraces of
Pleistocene age (Kelsey 1990), and alluvial deposits at river mouths. A second group of
small lakes and bogs-- sag ponds formed in depressions within slump and earthflow
landforms-- is scattered in uplands on sheared sedimentary, metasedimentary, and
ultramafic rocks of the central portion of the study area. The third lacustrine type
encompasses of high-altitude, glacial-origin lakes near ridgetops in the Kalmiopsis Wilderness. Small, sand-bedded, interannually unstable estuaries occur at the mouths of larger basins in the study area, formed by the interaction of seasonally transported beach sands, fluvial deposits, and associated dune sets (Clifton et al. 1973).

Table 3 provides some indication of the relative extent of different valley segment types in the region as a whole. About 60 percent of the valley segments surveyed in this portion of the study area were colluvial canyons, about 20 percent were competent bedrock canyons, and 11 percent were alluviated canyons. Alluvial valleys, alluvial-fan-influenced valleys, and lakes and estuaries comprised the remaining 9 percent. In general, low-gradient, alluviated canyons or alluvial segment types rich in floodplains, which harbor much of the region’s fish diversity, encompass less than 20 percent of its stream valleys.

3.2 Valley Slope, Rock Type, and Landscape Development

Valley floor slope, as measured on topographic maps, varies by valley segment type. In general, valley slopes were lowest in alluvial valleys, slightly greater in alluviated canyons, much greater in bedrock canyons, and greatest in colluvial canyons. These differences are partly a function of whether segments tend to be located high or low in the drainage network. More importantly, downstream changes in valley slope differed among segment types (Fig. 5), and irregularities in downstream profiles were associated with the sequence of valley segment types present. We speculate these differences reflect different geomorphic processes controlling the evolution of river valleys.

For a given stream order, valley slope declined more rapidly downstream in competent bedrock canyons than in colluvial canyons and other segment types (Fig. 5,
Figure 5. Valley slope as a function of Strahler stream order for third-order and larger channels in four fluvial segment types. Note that y-axis scale varies. Curves are predicted means based on regression of $\log_e$ slope on order. Data derived from 1:24,000-scale topographic maps.
Figure 5
Table 4. Regression parameters and their 95 percent confidence intervals for the regression of loge valley slope on Strahler stream order, in four valley segment types.

<table>
<thead>
<tr>
<th>Segment Type</th>
<th>R²</th>
<th>P-value</th>
<th>Predicted Min.</th>
<th>Predicted Max.</th>
<th>95% C.I.</th>
<th>95% C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial Valleys</td>
<td>0.345</td>
<td>0.013</td>
<td>-0.47</td>
<td>-0.11</td>
<td>-0.82</td>
<td>-0.82</td>
</tr>
<tr>
<td>Alluviated Canyons</td>
<td>0.505</td>
<td>0.000</td>
<td>-0.46</td>
<td>-0.29</td>
<td>-0.63</td>
<td>-0.63</td>
</tr>
<tr>
<td>Colluvial Canyons</td>
<td>0.433</td>
<td>0.000</td>
<td>-0.62</td>
<td>-0.52</td>
<td>-0.73</td>
<td>-0.73</td>
</tr>
<tr>
<td>Competent Bedrock</td>
<td>0.707</td>
<td>0.000</td>
<td>-0.88</td>
<td>0.93</td>
<td>-1.09</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Slope

v-intercept
Table 4); in other words, competent bedrock canyons were relatively steeper than other segment types in low-order, headwater streams, but relatively low in gradient among higher-order, mainstem rivers. This could reflect an ability of larger streams to carve graded profiles through competent rocks where deep gorges can develop without collapsing, while small, headwater streams lack the power to incise into hard rock and thus are only slightly less steep than adjacent competent hillslopes. By contrast, colluvial canyons are frequently re-loaded with coarse sediment as oversteepened hillslopes fall into the channel, preventing even higher-order streams with high stream power from reaching a graded state. As watersheds develop over periods of thousands of years, colluvial canyons can be viewed as the primary zones of rapid erosion, bedrock canyons primarily function as stable transport zones, and alluvial valleys serve as zones of deposition and storage of alluvium.

Geology and valley slope are correlated with the valley shape variables we used to classify segments in this analysis, and segment type accounted for most of the variation among streams in valley slope. However, we wanted to determine the extent to which bedrock geology influences variation in valley and channel slope within segment types. For example, bedrock geology could affect the long-term development and present-day state of competent bedrock canyons and colluvial canyons in much different ways, because the geomorphic processes linking hillslopes to stream channels differ dramatically between the two canyon types. By regressing the log-transformed slope against stream order, then performing one-way ANOVA on the residuals classified by channel-adjacent bedrock type, we could assess whether for a given segment type there were any consistent deviations from the mean channel slope/stream order relationship that could be explained by differences in bedrock geology of side-slopes. Only for colluvial canyons did we detect significant variation among residuals associated with geology ($P < 0.001$). Among colluvial canyons, streams passing through Colebrook
schist had the lowest slopes, those in Cretaceous sediments and Otter Point
metamorphic rocks had intermediate slopes, and streams in Galice formation shales and
Tertiary sedimentary rocks were steepest.

Colluvial canyons, therefore, appear to be more sensitive to variation in bedrock
geology than are other valley segment types. We speculate that in colluvial canyons,
where over a time frame of centuries channels are frequently loaded from hillslope
failures, valley slope is a function of particle size and resistance of the material delivered
(Hack 1957, Milne 1982). Valley slopes are therefore lowest for rock types delivering
primarily small rock fragments (Cretaceous sediments) or clasts that are rapidly broken
down in the fluvial environment (e.g., Colebrook schist). Valley slopes are steeper in
less friable, less sheared (e.g., Tertiary sediments), or more highly metamorphosed (e.g.,
Galice formation) rocks where large, hard clasts are delivered. Geology and clast size
makes less difference in other segment types, where delivery rates of hillslope material
are low relative to transport capacity (competent bedrock canyons) or channel form is
largely determined by deposition and reworking of alluvium (alluvial valleys, alluviated
canyons).

Alternatively, one could hypothesize a tectonic explanation for differences in
valley slope among colluvial canyons in this actively uplifting landscape (Kelsey 1988,
Kelsey 1990). Within the sample area, for example, the rate of uplift in the area
dominated by Tertiary sediments and Galice shales could, by coincidence, have
exceeded that in the area with other rock types, steepening stream channels there.
However, the close intermingling of Tertiary sediments and Galice shales (having steep-
floored colluvial canyons) with Cretaceous sedimentary rocks (with relatively gently-
sloping canyon floors) in the precipitous, dramatically uplifted southern portion of the
sample area (Fig. 4) argues against a purely tectonic explanation for the differences in
valley slope seen among different rock types. Over time periods of millenia, differential
uplift undoubtedly has influenced valley form and channel profiles in the study area, but any such effects appear to be mediated or overwhelmed by large-scale hillslope processes partly determined by pre-existing valley and channel floor geology. The secondary geomorphic processes of landscape development, triggered by faulting, shearing, and failure of valley slopes, may obscure the direct effects of tectonic deformation on stream networks.

Because geologic mappers use geomorphic cues to interpret boundaries of their map units, and lithology and tectonic history exert strong control over the geomorphic processes and the development of landforms, geomorphic and geologic data derived from maps should not be considered strictly independent. Our interpretations of causal mechanisms, therefore, are not conclusive. However, the analysis does confirm that in the study area, as elsewhere in mountainous regions (e.g., Hack 1957, Keller and Tally 1979, Kelsey 1988), valley structure largely reflects the underlying geology.

3.3 Floodplain and Valley Width

A longitudinal view of three valley segments in Edson Creek illustrates covariation among valley and floodplain width, geology, geomorphic surfaces, and pool-forming channel features in the channel (Fig. 6). Floodplains widen as the stream passes through less competent rock formations, emerging from a narrow bedrock canyon into a transitional, rather narrow alluvial valley, then finally a wide alluvial valley. The influence of hillslope landforms decreases downstream, and pool-forming roughness elements shift from bedrock and boulders in the bedrock canyon to large wood, tree roots, and eroding cutbanks in the alluvial valley.

Field data verified and clarified the differences in valley floor slope and floodplain
Figure 6. Downstream gradient in channel, floodplain, and valley width, and geologic and geomorphic conditions in three valley segments of Edson Creek, tributary to Sixes River. Floodplain width includes active channel, and valley width includes width of floodplain and active channel. AV1 is a wide alluvial valley with extensive terraces and a meandering channel pattern. AV2 is a narrower alluvial valley, lacking high terraces and having a sinuous channel pattern. BRC is a bedrock-walled canyon, with very sparse, discontinuous floodplains and a straight channel pattern. Valley structure reflects geologic properties of the watershed, as indicated. Inset bar chart depicts relative frequency of geomorphic surfaces along the channel margin; SS = steep competent hillslopes, CC = colluvial complex slopes, ST = strath terraces, AF = alluvial fans, FP = floodplains. Pie diagrams show relative frequency of pool-forming features; BR = bedrock, B = boulders, LWD = large woody debris, TRC = tree roots and eroding cutbanks.
Figure 6

- Metasedimentary rocks, shear zone
- Faulted metamorphic rocks
- Metavolcanic rocks
width that we used to classify valley segments from topographic maps. A bivariate plot of field measurements of the ratio of active channel width to floodplain width (a scaling factor for stream size) against channel slope provides a simple ordination in which segment types can be seen as rough clusters (Fig. 7). Valley width and valley slope are in general inversely correlated (Richards 1982, Harris 1988, Kelsey 1988), and field measurements of valley or channel slope closely approximated valley slope measured from topographic maps. Canyon types are not easily differentiated from each other on this plot, because they are discriminated largely based on the stability of stream-adjacent hillslopes, rather than morphometric variables. It is likely that with the addition of more observations, overlap would increase between segment types in this ordination space, but it is unlikely that the centroids of the clusters would change much. Field data on this plot cover much of the range of geologic conditions in the study region.

3.4 Streamside Geomorphic Surfaces and Processes

Field data confirmed that frequency distributions of stream-adjacent geomorphic surfaces differed significantly among segment types (Fig. 8). Steep slopes dominated bedrock canyons, where they were about three times more abundant than in all other segment types (one-way ANOVA, $P < 0.001$). Stable slopes of moderate steepness were rare in the study area; we recorded them only in two alluviated canyon segments. Predictably, colluvial complex slopes dominated colluvial canyon segments, where they were 2-3 times more abundant than in any other segment type (ANOVA, $P < 0.001$). Colluvial complex slopes are surfaces with deep regolith having poorly developed soil profiles, including active or metastable slump-earthflows and blockslides, creep-prone
Figure 7. Simple ordination of valley segments by field measurements of ratio of active channel width to floodplain width and mean channel slope. Dashed lines define clusters by segment type.
Figure 7
Figure 8. Mean frequency distribution of channel-adjacent geomorphic surfaces in field surveys. Data for upper and lower Big Creek colluvial canyons are aggregated to compensate for small sample size. In parentheses is number of segments in sample.
hillslopes with remnant landslide morphology, or toeslope accumulations of colluvium derived from numerous, smaller up-slope failures. Bedrock-floored strath terraces and terraces of unconsolidated alluvium occurred as scattered, remnant surfaces.

Of the streams where we conducted field surveys, terraces occurred as continuous features only along the terrace-bound valley segment. Likewise, small depositional fans of colluvial and alluvial origin occurred at low frequency in nearly all segment types, being widespread only in the alluvial-fan-influenced valley of Euchre Creek. Floodplains were about twice as frequent in alluvial valleys as in alluviated canyons (ANOVA, P<0.001), and were occasionally present but infrequent in bedrock and colluvial canyons. Floodplains in alluvial valleys and alluvial-fan-influenced valleys were broad and continuous, whereas those in alluviated canyons and the terrace-bound valley were narrow and often disjunct. In narrow canyons floodplains occurred as very small, isolated features associated with large boulders, bedrock outcrops, or woody debris jams.

Processes of slope erosion differed substantially among segment types (Fig. 9). Most slope erosion adjacent to the study reaches occurred as mass failure, with occasional instances of gully erosion of tributaries and valley floor surfaces. Alluvial valleys and the terrace-bound valley had relatively low incidence of slope erosion, as might be expected given their infrequent contact with hillslope surfaces. Slope failures were very frequent, however, along alluviated canyons, where large, translational, streamside debris slides were common along colluvial complex slopes.

Alluviated canyons appear to be especially vulnerable to secondary effects triggered by aggradation and widening of stream channels following increased sediment delivery from upstream sources. Aggradation reduces channel stability and forces the stream laterally against unstable toeslopes, triggering streamside slides (Hagans et al. 1986). The frequency and persistence of streamside landslides in alluviated canyons
Figure 9. Mean linear frequency (left) and estimated volume (right) of sediment contributed to streams from riparian hillslopes, based on field surveys. Number below vertical axis is total distance surveyed.
may be further increased by the direct effects of roads or logging, for example, by loss of root strength following vegetation removal. Deforestation and increased groundwater can accelerate creep of colluvial complex slopes (Swanston 1979, Swanston et al. 1988), resulting in progressive slope deformation that triggers landslides in stream-adjacent, steepened toeslope areas of colluvial canyons and alluviated canyons. Streamside debris slides were the most frequent erosion source in both alluviated and colluvial canyons, but they delivered far greater volume in colluvial canyons (Fig. 10). For example, a single very large slump-blockslide, activated along the toe of a Forest Service clear cut in 1986, delivered more than 50,000 m$^3$ of sediment to the surveyed section of Wheeler Creek, dwarfing all other sediment sources. We have observed several other very large, active slump-earthflows and blockslides along streams in southwest Oregon, and indeed such failures are the primary process shaping inner gorge topography in colluvial canyons (Kelsey 1988). By contrast, slope failures in competent bedrock canyons are more frequent but much smaller. They are dominated by rockslides and shallow debris avalanches, rather than the deep-seated failures prevalent in colluvial canyons and along the colluvial complex slopes adjacent to alluviated canyons.

It is clear that improved understanding of the causes and effects of landslides will be critical for predicting the cumulative effects of human activities in this landscape. The valley segment types we describe markedly differ in slope-channel linkages, so this classification should prove useful in this task. The frequency of debris avalanches, debris slides, and other relatively shallow erosion processes in the Klamath Mountains is clearly increased by roads and logging of steep slopes (Amaranthus et al. 1985, Hagans et al. 1986, McHugh 1987). Very large landslides such as the Wheeler Creek feature remain problematic, for despite apparent spatial and temporal associations between logging and their movement, the causal mechanisms of failure are poorly understood.
However, a considerable portion of the Klamath mountains landscape has the potential for such large failures, and the impact of a single such event on a stream system may far outweigh and outlast the combined effects of numerous smaller erosion sources.

3.5 Channel Pattern and Bar Form

Channel pattern differs predictably among valley segment types (Fig. 10, top). Channel pattern is related to valley slope and to constraints imposed by hillslopes, and it reflects sediment load relative to transport capacity, and the processes by which streams route sediment from upslope and upstream sources (Richards 1982). Straight reaches dominate competent bedrock canyons, where channels are highly constrained by hillslopes. Straight and sinuous reaches are about equally common in colluvial canyons (although their sinuosity is imposed by sideslopes, rather than being formed by channel bends on a valley floor). Short braided reaches occur where landslide deposits create coarse lag deposits in the channel and backwater effects at high flow.

Alluviated canyons are more diverse in channel pattern, but predominantly sinuous, with local straight and braided reaches. Braided reaches occur at recent landslide deposits and large debris jams. The existence of a floodplain also allows development of local anabranching reaches in alluviated canyons. Anabranches usually develop from diversion of flood waters by large debris jams, and often contain cool, spring- or tributary-fed habitats in summer. These secondary channels also provide critical shelter for fishes and other organisms during high flows in winter (Brown and Hartman 1988).

Alluvial valleys are dominated by sinuous reaches, but where valley slopes are gentle they also contain fully meandering reaches. Surprisingly, we recorded no
Figure 10. Frequency distribution of channel pattern and bar form of five segment types, based on field surveys. In parentheses is number of valley segments in sample.
Figure 10
anabranching reaches in the alluvial valleys we surveyed. This is likely a result of extensive human disturbance in this valley type, as complexly anabranching channels can be readily observed in historic aerial photographs of many of these valleys, and we found numerous relict channels in the field. Many anabranches are derived from meander cutoffs, so that a long-term trend of channel straightening associated with increased sediment load (Lisle 1982, Lyons and Beschta 1983, Hagans et al. 1986) may drive a trend toward channel simplification. Deforestation from agriculture and logging, log drives (Sedell et al. 1991) (e.g., splash damming occurred on Sixes River in the 1930's), and channelization and bank stabilization projects not only damage secondary channels directly but also eliminate the processes that allow complex anabranches to develop and persist (Sedell and Frogatt 1984, Amoros et al. 1987, Chamberlin et al. 1991). With the loss of anabranching channels comes diminishment of critical habitat such as winter shelter and summer thermal refugia required by anadromous fish.

Although we did not quantify channel pattern in alluvial-fan-influenced valleys, field observations indicate they are dominated by sinuous and anabranching reaches. The development of comparatively unstable anabranches is fostered by cyclic formation of large debris dams, sediment deposition, and consequent channel avulsion on or near alluvial fans. Most large alluvial fans in the region are more heavily impacted by deforestation and channelization than are our study sites in middle Euchre Creek, resulting in more simplified straight or sinuous channels. However, because topographic and sedimentological conditions in the vicinity of alluvial fans favor more frequent channel switching and anabranch development, this valley type may maintain more complex channels in the face of human disturbance than do alluvial valleys.

Channel pattern in terrace-bound valleys is typically sinuous or meandering. However, these are not free meanders, as they are deeply entrenched in the valley floor, so that rapid migration or development of anabranches are largely precluded. Because
their channels are less complex and skirted by erosion-resistant bedrock or saprolitic material along terrace margins, streams in terrace-bound valleys appear to be generally less sensitive to upstream disturbance than are alluvial valleys. Most terraces in southwest Oregon are bedrock-floored and therefore resistant to lateral erosion. However, where terraces are comprised of unconsolidated materials (e.g., fluvially graded landslide deposits, glacial valley fill), they are subject to bank failure and streamside landslides, particularly if channels are destabilized from upstream sediment sources or terrace scarps are deforested. Terrace-bound valleys are sensitive to channel degradation and widening which can eliminate or reduce the inundation frequency of floodplains. When large wood is removed from the channel, rapid entrenchment ensues. Re-establishment of debris jams, beaver dams, and other sources of channel complexity in degraded terrace-bound valleys could be difficult or impossible in the absence of major pulses of very large woody material from the riparian zone or tributaries.

Correlated with differences in channel pattern is variation in bar form (Figure 10, bottom). Colluvial and competent bedrock canyons were dominated by transverse bars, mid-channel bars, and side bars. These bar forms are often associated with stable hydraulic obstructions like large boulders or bedrock outcrops, and they tend to be comprised bed materials of coarse gravel to small boulder size. Mid-channel bars are characteristic of braided reaches. Channels in alluviated canyons contained a wider range of bar forms, dominated by side bars. Point bars and diagonal bars, typical of more sinuous, low-gradient channels and formed of sand- and gravel-size materials, were more abundant in alluvial valleys and the terrace bound valley.
3.6 Streambank Texture

Because segment types differ in geomorphic surfaces and rock type, texture of materials in the streambank varies accordingly. Field data (Fig. 11) indicate that boulders and bedrock dominated most streambanks in colluvial and competent bedrock canyons. About one-third of the banks in colluvial canyons, where the stream abutted fine-textured colluvium or small floodplain benches, contained large amounts of cobble and gravel. Alluviated canyons had very diverse streambanks, with those adjacent to hillslopes dominated by boulders and bedrock outcrops, others along floodplains dominated by cobble, gravel, or sand. Sand and silt were more abundant in alluvial valleys where the channel bisected wide, low floodplains formed by frequent overbank deposition of fines in ponded flood waters. More locally, streambanks formed in active channel and flood berm deposits of alluvial valleys were coarser deposits dominated by cobble and gravel. The terrace-bound valley of Sixes River had a bimodal distribution of streambank texture, with banks along narrow, inset floodplains dominated by sand and silt, alternating with bedrock-dominated banks adjacent to uplifted strath terraces.

Because bank erodibility is a function of silt and sand content of nonconsolidated materials (Schumm 1960, Richards 1982) it seems likely that alluvial valleys are more vulnerable to bank erosion than are other segment types. Textural differences between deposits derived from different geologic parent materials could further influence the resistance of banks to erosive forces, and also affect the rate at which riparian vegetation recolonizes and stabilizes flood-disturbed valley surfaces. Our field observations indicated that drainage basin geology affected the texture of floodplain deposits and stream banks. For example, silt and clay dominated the fine fraction in basins draining Otter Point metasedimentary rocks, whereas sand more frequently dominated the fine fraction in basins draining Colebrook schist and especially
Figure 11. Texture of bank materials in five valley segment types, measured as percent of transects in which particle size class was first or second most abundant in streambank exposures. In parentheses is number of segments in sample.
Bedrock

- Large boulders (>1.0 m)
- Boulders (25-100 cm)
- Cobble (6-25 cm)
- Gravel (0.8-6.0 cm)
- Fine gravel (2-8 mm)
- Sand (0.06-2.00 mm)
- Silt (0.008-0.06 mm)
- Clay (<0.008 mm)

Alluvial Valleys (9)

- Terraced bound Valley (1)

Alluviated Canyons (13)

Colluvial Canyons (5)

Competent Bedrock Canyons (3)

**Percent of Banks Dominated by Particle Size Class**

Figure 11
Cretaceous sedimentary rocks. This would make channels in the latter two formations especially prone to bank erosion. A more intensive sampling method than our semi-quantitative procedure would be necessary to detect such subtle variations in texture.

3.7 Riparian Vegetation and Canopy Cover

Tree species composition of riparian forests differed among segment types, with conifer species more important in canyon and alluviated canyon segments than in alluvial valleys (Fig. 12). Three hardwood species—red alder, bigleaf maple, and California bay laurel—dominated stands along all nearly all the streams surveyed. California bay laurel (also known as Oregon myrtle) is particularly significant ecologically in that its ability to establish by root sprouting from fallen boles and drifted logs enables it to rapidly colonize and stabilize flood-stripped surfaces. Many floodplains in the area are dominated by nearly monotypic, mature stands of this species. A fourth hardwood, willow, was common only on active floodplains in alluvial valleys and alluvial-fan-influenced valleys.

Conifer abundance and tree species diversity was greatest in canyon and alluviated canyon segment types where hillslopes more frequently impinging on channel margins. However, we observed decayed conifer stumps, dead snags, and scattered individuals of several conifer species in alluvial valleys, indicating that human activities have affected forest composition. Because of their accessibility, these flatter, low-elevation valley segments have been subject to selective logging of conifers (particularly Port-Orford-cedar, western red-cedar, and later Douglas-fir) since before the turn of the century. Further, introduction in recent decades of an exotic, water-bourne fungal disease, spread by logging, to these watersheds has caused extensive mortality of Port-
Figure 12. Relative abundance of tree species in riparian canopy and percent canopy cover of four segment types. Abundance is measured as percent of segments surveyed in which species was among the four most important taxa in overstory. In parentheses is number of segments in sample. Too few transects were measured to report reliable data for alluvial-fan-influenced valleys and terrace-bound valleys.
Red alder
Big leaf maple
California bay laurel
Willow
Vine maple
Douglas-fir
Western hemlock
Grand fir
Port-Orford-cedar

Alluvial Valleys (9)
Alluviated Canyons (13)
Colluvial Canyons (5)
Competent Bedrock Canyons (3)

Relative Abundance in Canopy

Figure 12
Orford-cedar (Zobel et al. 1985). Compared to Douglas-fir, Port-Orford-cedar is a more successful invader of hardwood-dominated riparian stands, and may play a critical role in the successional establishment of mixed conifer and hardwood stands in riparian areas. The exotic pathogen and logging have nearly eliminated this species from floodplains in alluvial valleys, where they historically were abundant. The loss of Port-Orford cedar may be critical given its apparent role in vegetation succession, as well as its large size, decay resistance, and long residence time, which confer disproportionate ecological value to fallen logs of this species in streams and on floodplain surfaces.

Canopy cover over the stream channel varied widely, decreasing from an average of about 60 percent in streams with active channel width of <10 m to 20 percent where channel width exceeded 30 m. When the effect of stream size was taken into account by regressing canopy cover against channel width ($P < 0.001, R^2 = 0.664$), analysis of the residuals suggested that alluvial valleys had more open canopies and alluviated canyons somewhat more dense canopies than other segment types (one-way ANOVA on residuals, $P < 0.05$). Two alluvial valleys with older riparian forest (selectively logged >50 y ago) approached the overall average canopy condition for all segment types combined, whereas many alluvial valleys that had been logged in recent decades had 20-30 percent less cover than the overall average. This pattern may result from the elimination of older, taller conifers such as Port-Orford cedar and Douglas-fir and their replacement by willow and red alder on logged and flood-disturbed floodplains. Within other segment types, we were able to discern no consistent effect of logging or vegetation successional state on canopy cover.

In individual cases, geomorphic processes and the indirect effects of land use exerted strong control over riparian vegetation in the study streams. Colluvial canyons had quite variable overstory development, and two of four had very low canopy cover (<30 percent), apparently caused by frequent or recent landslide disturbance (in one
case, combined with logging) which hinders the establishment of a continuous canopy of mature trees. Lower Edson Creek also had very low canopy cover (about 18 percent). The lack of shade in Edson Creek appears to result largely from recent streambed aggradation, and destruction of stream-adjacent trees by bank erosion. Port-Orford-cedar root disease has contributed to the loss of overstory. Damage to the riparian forest of Edson Creek illustrates that simply leaving buffer zones of vegetation along major streams cannot compensate for the downstream erosional and pathological effects that originate from logged headwater areas.

Our data were not sufficient to discern any direct effect of stream-adjacent or basin bedrock geology on canopy cover. However, observations throughout the study area indicate that vegetation recovery following logging is faster on the fine-textured soils over Colebrook schist and Otter Point metasedimentary rocks than on the coarse-textured or skeletal soils common over Cretaceous sedimentary rocks, Pearse Peak diorite, and steeper slopes within the Dothan sandstones. Due to unusual chemical and physical soil conditions in serpentine areas, many never develop a closed canopy (Franklin and Dyrness 1973). However, these differences are somewhat moderated in riparian areas, where soil and air moistures are higher and fire may be less frequent or less intense.

3.8 Biological Significance of Valley Segments

Spawning of salmon and steelhead in southern Oregon coastal rivers occurs almost exclusively in segments we classified as alluviated canyons, terrace-bound valleys, and alluvial valleys (Reimers 1971, Burck and Reimers 1978, Frissell and Nawa unpublished data). In these valley segments, large, stable expanses of well-sorted
gravel and cobble are available, and the presence of floodplains allows overbank flow, partially buffering the channel from the scouring and depositional effects of floods. In competent bedrock and colluvial canyons, suitable spawning gravel is patchy and large floods are not attenuated by floodplains. Salmon seldom spawn in alluvial fan-influenced valleys, perhaps because eggs and fry have a high risk of mortality in the highly unstable, anastomosing and braided channels, forcing strong natural selection against spawning in these segments (Nawa and Frissell, unpublished data). Other than in Elk River (where logging has been relatively limited), few alluvial valleys of southern Oregon coastal rivers support more than scattered spawning by chinook salmon today. Based on accounts of long-time local residents and biologists, these stream types were heavily used by chinook and probably chum salmon for spawning earlier in the century. We believe these populations have been decimated in part by aggradation and loss of channel stability, following logging-related increases in sediment load (Frissell and Liss 1986; see also Scrivener and Brownlee 1989, Holtby and Scrivener 1989).

Spatial variation in summer rearing of juvenile salmonids in river basins of the study area appears to be strongly controlled by maximum water temperature, although stream size is also important (Stein et al. 1972, Frissell et al. 1992b). In Sixes River basin, density and diversity of species and age classes declined with increasing water temperature. However, after regressing diversity against water temperature, one-way ANOVA of the residuals indicated that for a given temperature regime, total fish species diversity (excepting benthic taxa that were not sampled, e.g., Cottus spp. and lampreys) was related to segment type ($P<0.10$). For a given temperature, diversity was lowest in colluvial canyons and bedrock canyons, intermediate in alluviated canyons, and highest in alluvial valleys and terrace-bound valleys. The differences between segment types were largely due to the presence of largescale suckers (Catostomus macrocheilus) and threespine sticklebacks (Gasterosteus aculeatus) in alluvial valleys and terrace-bound
valleys, and frequent co-occurrence of cutthroat trout (*Oncorhynchus clarki*), juvenile steelhead (*O. mykiss*), chinook salmon fry (*O. tshawytscha*), and coho salmon fry (*O. kisutch*) in tributary alluviated canyons of major tributaries. Evidence from Elk River (G. Reeves, U.S. Forest Service, Pacific Northwest Research Station, Corvallis, Oregon, unpublished data) indicates that alluviated canyons are used heavily during summer by juvenile steelhead, chinook salmon, coho salmon, and possibly cutthroat trout.

4. Implications for Landscape Change and Aquatic Fauna

Alluvial valleys, alluviated canyons, and terrace-bound-valleys are heavily used by fish, perhaps because they contain a diversity of in-channel and floodplain habitats meeting the spawning and rearing requirements of most species during all seasons. The importance of these low-gradient, floodplain-rich valley segments for fish habitat is critical given their inherent sensitivity to increased sediment loads and channel aggradation associated with logging and landslides. Of these segment types, terrace-bound valleys appear to be the most resistant to the adverse effects of increased sediment yield, probably because of the erosion resistance conferred by bedrock banks along the toes of uplifted terraces. Unfortunately, terrace-bound valleys are not widely distributed in the study area (Fig. 3, Table 2). The dependency of native fishes on aquatic habitats that are limited in distribution and highly vulnerable to both direct and indirect, cumulative effects of land use activities can help explain why salmon populations in most streams in southwest Oregon have collapsed since extensive logging of unstable, steeper slopes in their drainage basins (Frissell and Liss 1986).

Human activities may fragment and damage aquatic habitats more rapidly and
intensively than they affect terrestrial habitats. Although the landscape of southwest Oregon is naturally vulnerable to catastrophic disturbance such as fire and large landslides, the continuing, widespread decline of several Pacific salmon and trout species suggests that human activities have artificially accelerated the rate of disturbance. Research on landscape dynamics in alluvial river valleys of Europe has stressed the reversibility of agricultural impacts on floodplains, as opposed to the largely irreversible effects of urbanization and engineering of channels for navigation and flood control (Amoros et al. 1987, Decamp et al. 1988). In southwest Oregon, urban and industrial effects are very limited. Although cultivation and grazing have affected many low-elevation alluvial river valleys, diminishment of these activities in recent decades has resulted in afforestation of many cleared lands. Afforestation of cleared floodplains and terraces occurs over a time period of a few decades, but the large-scale changes in erosion, sediment transport, and channel morphology caused by logging and logging roads on steep, upland slopes may not be reversible except over a time frame of a century or longer (Madej 1984, Hagans et al. 1986). For example, lower Sixes River, which dramatically widened following a massive landslide in the late 1800's (Diller 1903), has remained wide and shallow to the present day (Frissell unpublished data).

Logging affects a large (>75 percent) and growing portion of the landscape, and virtually all low-elevation alluvial valleys have been impacted by adjacent and upstream logging. In Fig. 13 we conceptualize how the intensity and the spatial dispersion of disturbance have been modified by humans. Historically, alluvial valleys of mainstem streams have been the most productive habitats for species like chinook, coho, and chum salmon. We speculate these valley segments, located low in the drainage network, are partly buffered from the effects of natural disturbances in headwater areas. Alluviated canyons in tributaries, by comparison, are closer to and more directly vulnerable to the effects of landslides, debris flows, and sediment pulses.
Under natural conditions, disturbance like fire and landslides were localized; although these events undoubtedly had severe effects on certain tributary habitats and their populations, their effects on downstream alluvial valleys might have been attenuated by distance and time. Large fish populations in mainstem alluvial valleys were likely more stable and less sensitive than smaller, tributary populations to variations in habitat quality. Furthermore, habitats and fish populations in alluviated canyons of other, unimpacted tributaries could help sustain populations in the basin as a whole. Over decades or centuries, each major basin could be viewed as a mosaic of connected salmon populations, anchored by a large population in the mainstem.

Logging affects watersheds in southwest Oregon differently than does natural wildfire. Based on vegetation patterns visible on early aerial photographs, major fires were patchy and a single episode rarely affected more than 25 percent of a large drainage basin. Furthermore, riparian areas were often buffered from fire. The preponderance of old-growth trees and fire-sensitive species like Port-Orford-cedar and Sitka spruce in unlogged riparian areas suggests that under natural conditions fire frequency and intensity were lower on valley floor, toeslope, and channel headwall surfaces than on adjacent slopes and ridgetops. By contrast, during this century riparian areas along larger streams have been the foci of human activities. Alluvial valleys at lower elevations have been hard-hit by both logging and agriculture.

Aside from spatial pattern and rate of disturbance, logging and wildfire differ in several important ways. Abundant large woody debris usually remains after fire. Many trees and shrubs survive fire, so that complete stand mortality is rare. Woody material and live trees help stabilize eroding slopes and channels and facilitate vegetative recovery. By contrast, clear-cut logging involves removal of nearly all large boles. Furthermore, roads, absent in natural burns, are a major and persistent cause of erosion in logged areas. Despite the likelihood that fire suppression has reduced natural
disturbance frequency since early in the century (Agee 1991), this has not compensated for intense and widespread artificial disturbance in ever-expanding, logged areas.

Logging activities, when carried out at present rates, can accelerate the rate of landsliding over a comparatively large portion of the landscape, so that proportionally more tributaries are affected by sedimentation and loss of channel stability (Fig. 13). With logging rotations of 30 to 80 years, large portions of drainage basins are again deforested and made vulnerable to erosion before aquatic habitat and fish populations have recovered from the previous episode of disturbance. Further, the increased rate of erosion basin-wide has contributed to chronic damage of habitat in downstream alluvial valleys, leading to depression and eventual elimination of mainstem-spawning populations of salmon. As roads and logging penetrate the last headwater forests on federal lands, the few remaining islands of undamaged aquatic habitat in tributaries are likely to be damaged before habitats at lower elevations have recovered.

The net result of extensive landscape disturbance is a native fish fauna whose populations have become fragmented as they have declined progressively in an upstream direction (Fig. 13). Isolated alluvial canyons located in tributary streams that drain unlogged, roadless areas, all on federal forest lands, now appear to serve as refugia for many of the last viable fish populations in the region. Because of their location and small size, populations in these refugia are vulnerable to loss from natural disturbance. Nevertheless, current management plans of federal agencies call for rapid, intensive logging of most of these areas, increasing the likelihood of extinction of depressed and fragmented fish populations. In response, some scientists have recently proposed protection of such watershed refugia as a necessary first step toward maintaining aquatic biodiversity and restoring native Pacific salmon populations (Frissell 1991, Johnson et al. 1991). There is a clear need for research focusing on the significance of watershed-scale refugia for sustaining aquatic biodiversity.
Figure 13. Conceptual model of cumulative effects of natural and human-caused erosion and sedimentation in southwest Oregon drainage basins (See text). Rectangles are alluviated canyon and alluvial valley segments, narrow lines in stream network are canyons, and symbols denote disturbance sources. Dashed arrows indicate sediment transfer, shading indicates habitat quality as shown in legend. Area of pie diagram is proportional to total run size, patterned sections indicate relative abundance of three salmon species. Model can represent a time series of a single basin, as shown, or to a spatial comparison of basins having different management histories.
Figure 13

Natural Landslide
Human-caused Landslide
Riparian Deforestation
Productive Habitat
Moderately Impaired
Severely Damaged

1850
1920
1990

Chinook
Coho
Chum
5. Comparison with Other Classifications

Some of our classes appear similar to those of Cupp (1989b), Rosgen (1985), and other schemes. Cupp adapted his system for Washington streams based on our early work in southwest Oregon (Frissell et al. 1986, Cupp 1989a, 1989b). However, there are important differences between some of Cupp’s classes and our own, due both to geographic variation and different emphases in approach. Cupp emphasizes valley cross-sectional form and de-emphasizes geomorphic surfaces and soil textural differences. One theme of this paper has been the importance of geomorphic surfaces, slope processes, and texture of channel-adjacent deposits in interpreting and predicting the habitat conditions and potential response to disturbance of streams in different valley types. In concept our approach to valley segment classification is perhaps most closely allied with that of Platts (1979), in that it stresses terrestrial control of aquatic systems.

In most cases our segment classes can be differentiated reliably by an experienced specialist using topographic maps at the scale 1:62,500 or 1:24,000, stereo airphotos, or field data. Cupp (1989b) provides a comprehensive operational description of the procedures used to classify valley segments from maps. The classifications of Cupp (1989b) and Marion et al. (1987) appear to be conceived at the same level of resolution and with similar objectives as our valley segments. Gregory et al.’s (1991) scheme is applied at a similar scale, but is far more generalized in form, addressing only valley width and hillslope constraints.

Rosgen (1985) did not specify at what spatial scale he intends his system to be applied, but several of his stream classes appear to represent a finer level of resolution (and shorter time of persistence), perhaps at the level of stream reaches (sensu Frissell et al. 1986) rather than our valley segments. Confusion about about scale and the conceptual basis of Rosgen’s scheme have caused it to be applied and interpreted
inconsistently and sometimes indiscriminately in research and management. We believe most criticism (largely unpublished) of Rosgen (1985) and other classification systems has stemmed from 1) ambiguity about scale and concepts, leading to misapplication, unrealistic expectations, and inappropriate statistical assumptions, and 2) perfunctory and uncritical extrapolation of classes or information developed for one biogeoclimatic region to another, very different region.

Although fundamental differences exist between regions, there are commonalities as well. For purposes of comparison and translation, Table 5 is our best attempt to summarize correspondences between our valley segment classes and several other stream classifications. Many stream types identified in other studies—glacial outwash valleys, for example—have no apparent counterpart in the Klamath Mountains region. On the other hand, valley segments structurally and functionally similar to those we have described in the Klamath Mountains do appear to occur in many mountainous landscapes, especially in tectonically active coastal zones. We believe that within the Pacific coastal mountain belt, particularly the Klamath Mountains, our classification of valley segments can be more easily applied, more interpretively powerful, and is likely to be more successful in most applications than other valley classification systems we are familiar with. We are currently conducting research elsewhere in Oregon and the Great Basin to determine how these classes can be modified or supplemented to be useful across a wider range of biogeoclimatic conditions.
Table 5. Translation key for valley segment classification in southwest Oregon based on this paper (left column) and most comparable stream segment or reach types from classifications by Cupp (1989), Rosgen (1985), Marion et al. (1987), and Gregory et al. (1991).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial-Fan-Influenced Valley (AFV)</td>
<td>Alluvial/Colluvial Fans (F4)</td>
<td>D1, D2</td>
<td>A3, B5, C4</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>Alluvial Valley (AV)</td>
<td>Alluvial Lowlands (F2); Wide, Alluviated Valley Floor (F3)</td>
<td>C1, C2, C3</td>
<td>B1, C1, C3, C7</td>
<td>Unconstrained</td>
</tr>
<tr>
<td>Terrace-Bound Valley (TBV)</td>
<td>Gently Sloping Plateaus and Terraces (F5)</td>
<td>F1</td>
<td>C2</td>
<td>Unconstrained (terraces)</td>
</tr>
<tr>
<td>Alluviated Canyon (AC)</td>
<td>Alluviated Mountain Valley (V4)</td>
<td>B2, B3, B4</td>
<td>B3, B7, C5</td>
<td>Semi-constrained (hillslopes)</td>
</tr>
<tr>
<td>Colluvial Canyon (CC)</td>
<td>Incised, U-shaped, Moderate or High Gradient Bottom (U2, U3)</td>
<td>A2, A3</td>
<td>B7, C5</td>
<td>Constrained (hillslopes)</td>
</tr>
<tr>
<td>Competent Bedrock Canyon (BRC)</td>
<td>V-shaped, Moderate or Steep Gradient Bottom (V1, V2); Bedrock Canyon (V3)</td>
<td>A1, F2, F3, F4</td>
<td>B7, C5</td>
<td>Constrained (hillslopes)</td>
</tr>
<tr>
<td>Estuary (EST)</td>
<td>Estuarine Delta (F1)</td>
<td>E1, E3, E4</td>
<td>E1, E2, E4</td>
<td>--</td>
</tr>
</tbody>
</table>
6. Potential Applications and Limitations

This classification of valley segments is based on general principles of geomorphic origin and development and landscape function to make it as useful and ecologically meaningful in a variety of applications. Like any general purpose classification it may not be the optimal scheme for any single application (Webster and Oliver 1990). However, we can envision few situations where this kind of classification would not improve study design, analysis, or interpretation. We have used our scheme in research to stratify analysis of stream channel response to the impacts of land use activities (Frissell et al. 1992b). The approach can also be used to identify and map valley segments most likely to be critical for anadromous fish and other species, and to predict the effects of landscape change on those habitats, populations, and biotic communities (Platts 1979, Frissell et al. 1986, Harris 1988, Swanson et al. 1990, Naiman et al. 1992). In policy, planning, and management, the classification could provide a basis for tailoring protective measures, such as forest practice requirements, to particular sites, since different segment classes differ in their sensitivity to on-site and downstream impacts. For example, Budd et al. (1987) classified stream corridors based on geomorphology to delimit buffer widths necessary to protect water quality and fish habitat during urban development. Finally, the classification could facilitate rational selection of representative or most-sensitive sites for monitoring water quality, biota, or habitat quality (Warren 1979, Frissell et al. 1986, MacDonald et al. 1991).

We should stress that any classification of valley segments accounts for variation only within a specific range of temporal and spatial scales. This scale is appropriate for landscape analysis, environmental assessment, and resource planning. Many applications, however, will require at least some information to be stratified at finer levels of resolution— for example, the reach, pool/riffle, and microhabitat scales of
Frissell et al. (1986). Nevertheless, careful accounting for variation in valley segment characteristics can provide a critical geomorphic, ecological, and spatial context for work at finer scales (e.g., Frissell et al. 1992b).

ACKNOWLEDGEMENTS

We thank J. Ebersole, E. Hubbard, and D. Shively for assistance in the field. Discussions with F.J. Swanson improved our concepts immeasurably. We are especially grateful to C.E. Warren and J.A. Lichatowich, the grandfather and godfather, respectively, of this research. The project was funded by the Oregon Department of Fish and Wildlife, under the Wallop-Breaux program for Federal Aid for Sport Fish Restoration, with matching funds provided by Oregon State University.
Chapter 3

Interactive Effects of Valley Geomorphology and Logging on Stream Habitat in South Coastal Oregon

Christopher A. Frissell
William J. Liss
Richard K. Nawa
Joseph L. Ebersole

Oak Creek Laboratory of Biology
Department of Fisheries and Wildlife
104 Nash Hall
Oregon State University
Corvallis, Oregon 97331
We surveyed 17 coastal streams in the Klamath Mountains southwest Oregon in five geomorphically-defined valley segment classes to assess the effects of geomorphology and logging on habitat of anadromous salmonid fishes. Percentage of eroding streambanks increased with logging activity, regardless of valley segment type. Large woody debris was most abundant in alluviated canyon valley segments, which have narrow floodplains and considerable side-slope influence. Abundance of woody debris debris increased with logging in alluviated canyons. Channel-spanning debris jams were common in lightly-logged basins, whereas in heavily-logged basins woody debris was primarily concentrated in lateral accumulations. Pools in hillslope-confined canyon segments were associated with bedrock and boulders, but most pools in low-gradient, floodplain-dominated alluvial valley segments were associated with large wood. Within alluviated canyon segments, pool area and riffle depth declined with logging. Size distribution and embeddedness of bed materials varied among valley segment classes and among pool and riffle types. Within alluviated canyons, surface concentrations of fine sediment were significantly higher in pools and cascades of heavily logged drainage basins. Landslides and erosion associated with logging of steep slopes appeared to be the primary cause of cumulative loss of channel stability, enlargement and destabilization of gravel bars causing loss of pool and riffle habitat, and increased deposition of fine sediments in downstream, low-gradient valley segments. However, many of these effects were detected only after accounting for natural variation imposed by valley geomorphology and drainage basin size.
1. Introduction

Detecting and predicting the effects of land use activity on stream habitat and biota is complicated because responses to disturbance occur across various scales of space and time (Frissell et al. 1986). Particularly in steep, montane watersheds, perturbations in headwater areas are often transmitted downstream, causing off-site, time-lagged impacts that can greatly exceed in magnitude and persistence the short-term, on-site effects of human activity (Leopold 1980, Coats and Miller 1981, Hagans et al. 1986). Furthermore, rarely can a human disturbance in a drainage basin be viewed as an isolated intrusion; more often, the ecosystem's response is an outcome of an interacting series of human and natural perturbations. The long-term, geological and geomorphic structure of the drainage basin however, can be viewed as a fabric or template which structures the complex response of ecosystems (Swanson et al. 1988, Frissell et al. 1986).

Many authors have shown that classification of stream systems can serve to stratify and clarify their complex structure, providing improved understanding of the function and response of streams to human impacts (Platts 1979, Warren 1979, Bravard et al. 1986, Lotspeich and Platts 1987, Mosely 1987, Harris 1988). Stream channels and aquatic habitat in different locations within a stream system differ in morphology and composition, and consequently they may vary in sensitivity to disturbance (Frissell et al. 1986, Swanson et al. 1990, Naiman et al. 1992). However, there have been relatively few attempts to apply the principles of classification in studies of streams of the west coast of North America.
Most research in Pacific Northwest streams has stressed the influence of on-site factors, such as logging of riparian zones, on channel features such as canopy cover (Gregory et al. 1987) and large woody debris (e.g., Bilby and Ward 1991). One widely applied classification scheme is driven solely by stream-adjacent, terrestrial variables (Omernik and Gallant 1986). But such approaches alone may not be sufficient to analyze and predict impacts in landscapes dominated by steep terrain and intense precipitation, where catastrophic processes like landslides and debris flows transmit effects rapidly downstream (Swanson et al. 1982, Tripp and Poulin 1986a and 1986b, Benda 1990). Because of relatively expeditious and often pulsed transfer of sediment and debris, habitat conditions and biota at any point in the stream will bear signatures of both the local channel-adjacent or riparian environment and the dynamic processes originating in upstream segments and up-slope areas.

Severe ecological and cultural consequences could result from research designs which tend to inordinately emphasize the on-site influences of human activities, and neglect both the influences of upstream or up-slope disturbance and the inherent diversity in structure and function of different stream types within a basin. Field studies may be confounded if they focus only on reach or site conditions and do not account for factors in the drainage basin as a whole, resulting in the failure to detect human impacts where they in fact are occurring. In other cases, effects attributed to riparian condition could be at least partly spurious, if in fact they are largely controlled by and contingent on conditions in the watershed as a whole. Unacknowledged geomorphic or ecological factors could render some study sites relatively insensitive to disturbance, while others might be highly vulnerable. If, as we believe, such shortcomings have been prevalent in research, current management policies that provide riparian forest
buffers along major streams, but often fail to protect headwater channels and
slopes, could be completely inadequate to protect stream habitat from long-term
degradation (Chamberlin et al. 1991). Recent acknowledgement that native
populations of anadromous fish are suffering serious declines region-wide (Nehlsen
et al. 1991) strongly implies that science and policy have failed to adequately
identify and control the underlying causes of habitat deterioration (Frissell 1991,

In a previous work (Frissell and Liss 1986, Frissell et al. 1992a), we
described a classification of stream segments based on valley geomorphology that
can be used to assess the origin, routing, and likely downstream effects of
disturbances in a stream network within a large drainage basin. In this paper we
apply this classification of valley segments in a multiple-basin survey and analysis
of logging impacts on freshwater habitat of anadromous fishes in southwest
Oregon, U.S.A.

2. Methods

2.1 Study Area

We conducted field surveys during summer of 1989 in coastal streams
draining the Klamath Mountains of Curry County, southwest Oregon. The terrain is
very steep and erosion prone, as it overlies highly faulted and sheared rock
formations and is subject to intense rainfall during winter months. The rivers have
very high peak flows, and low summer flows relative to other streams in Oregon
(Nawa et al. 1988). They descend rapidly from steep, confined canyons to
sediment-rich, low gradient alluvial flats. Since about 1960 logging activities have moved from comparatively gentle slopes at lower elevation on private lands to very steep, landslide-prone slopes on federally-owned lands in headwater areas. This region harbors one of the most severely endangered faunas of anadromous fish in the Pacific Northwest (Frissell, submitted). The streams provide freshwater habitat for fall-run chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), chum salmon (*O. keta*), steelhead (*O. mykiss*), and sea-run cutthroat trout (*O. clarki*), all of which have suffered severe declines in recent decades and are considered at risk of extinction in most basins in the study area (Nehlsen et al. 1991). More details about the geomorphology and ecology of the study area are provided in Frissell et al., (1992a).

2.2 Study Design

The objective of our field study was to compare geomorphically-defined valley segment types (described in Frissell et al. 1992a) in terms of the kinds of summer habitats they offered for fish and the apparent sensitivity of these habitats to land use activities. The factors whose effects on stream habitat we wished to account for were 1) land use history of the drainage basin; 2) geologic composition of the drainage basin; 3) valley segment type. However, we also collected field data that allowed more detailed comparisons based on correlates such as channel slope and bank material composition among study sites (Frissell et al. 1992a).

We selected 17 streams which covered a range of land use conditions within each of four geologic classes which had distinct, low-gradient valley
segments at their lower ends (Table 6). We focused on low-gradient, alluviated
canyon and alluvial valley segments because other work showed that these
segments were the primary locations of spawning and rearing of anadromous fish
and appeared most sensitive to the impacts of human activity (Frissell et al. 1992a,
1992c). We also surveyed canyon-type valley segments where they intermingled
with alluvial valleys and alluviated canyons. A total of 31 valley segments ranging
in length from about 100m to more than 1 km were surveyed. All of the study
streams had potentially productive, low-gradient (<2% slope) fish habitat, and all
but two were accessible to and used by anadromous fish. The four geologic
classes we considered were 1) basins dominated by Jurassic age, sheared
metasedimentary rocks of the Otter Point Formation; 2) basins dominated by
Cretaceous sedimentary rocks; 3) basins dominated by Dothan Formation, mixed
sedimentary rocks of Jurassic age, concentrated in the southern portion of the
study area; and 4) basins comprised of a mosaic of Colebrook schist Otter Point
Formation, and harder sedimentary rocks. Variation in rock material within these
broadly-defined geologic units was associated with variation in valley segment
morphology (Frissell et al. 1992a).

In order to attain a diversity of sites with respect to geology, valley
morphology, and logging history, our design did not directly control for drainage
basin area and its correlate, stream size, which affects most aspects of physical
habitat. Valley segment classification partly accounts for much of this variation, for
example in valley slope and channel form (Frissell et al. 1992a). However,
because the study basins and streams varied about one order of magnitude in size
(Table 6), it was important in data analysis (see below) to develop appropriate
scaling techniques to account for the effects of stream size on such variables as
wetted habitat area (e.g., Stack 1989).
### Table 6. Study sites in Curry County, southwest Oregon.

<table>
<thead>
<tr>
<th>Stream (River Basin)</th>
<th>Valley Segment Type</th>
<th>Total m Surveyed</th>
<th>Drainage Area (km²)</th>
<th>Basin Geology</th>
<th>Land Use History</th>
<th>Mean Channel Slope(%)</th>
<th>Mean Active Channel Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edson Cr (Sixes R)</td>
<td>AV</td>
<td>1030</td>
<td>26.1</td>
<td>Jop</td>
<td>M/SG</td>
<td>0.5</td>
<td>24.9</td>
</tr>
<tr>
<td></td>
<td>AV</td>
<td>26.9</td>
<td></td>
<td></td>
<td>M/SG</td>
<td>0.6</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>BRC</td>
<td>425</td>
<td>25.0</td>
<td></td>
<td>SG</td>
<td>0.6</td>
<td>18.3</td>
</tr>
<tr>
<td>Big Cr (Sixes R)</td>
<td>CC</td>
<td>114</td>
<td>3.9</td>
<td>Jop</td>
<td>SG/CC/M</td>
<td>10.3</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>244</td>
<td>3.6</td>
<td></td>
<td>OG/SG/M</td>
<td>2.7</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>179</td>
<td>3.6</td>
<td></td>
<td>OG/SG/M</td>
<td>4.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Little Dry Cr (*)</td>
<td>CC</td>
<td>458</td>
<td>3.4</td>
<td>Krh</td>
<td>M/OG/SG</td>
<td>2.3</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>144</td>
<td>4.1</td>
<td></td>
<td>M/OG/SG</td>
<td>1.7</td>
<td>15.2</td>
</tr>
<tr>
<td>Dry Cr (Sixes R)</td>
<td>AV</td>
<td>889</td>
<td>41.7</td>
<td>Krh</td>
<td>M/OG/SG</td>
<td>1.1</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>1994</td>
<td>33.5</td>
<td></td>
<td>OG/SG/M</td>
<td>0.4</td>
<td>22.1</td>
</tr>
<tr>
<td>Rock Cr (Elk R)</td>
<td>AV</td>
<td>104</td>
<td>3.4</td>
<td>Krh</td>
<td>SG/OG/M</td>
<td>0.8</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>237</td>
<td>3.2</td>
<td></td>
<td>SG/OG/M</td>
<td>2.5</td>
<td>8.7</td>
</tr>
<tr>
<td>Avil Cr (Elk R)</td>
<td>AC</td>
<td>357</td>
<td>7.2</td>
<td>Krh</td>
<td>Jc/Krh/OG/SG/M</td>
<td>1.6</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>BRC</td>
<td>103</td>
<td>7.0</td>
<td></td>
<td>Jc/Krh/OG/SG/M</td>
<td>3.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Chismore Fk (Euchre)</td>
<td>AC</td>
<td>771</td>
<td>5.4</td>
<td>Krh</td>
<td>M/OG/SG</td>
<td>2.4</td>
<td>9.7</td>
</tr>
<tr>
<td>Euchre Cr</td>
<td>AV</td>
<td>1420</td>
<td>65.0</td>
<td>Jc/Krh/OG/SG</td>
<td>M/OG/SG</td>
<td>0.5</td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>1000</td>
<td>38.0</td>
<td></td>
<td>Jc/Krh/OG/SG/M</td>
<td>0.8</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>20.7</td>
<td></td>
<td></td>
<td>SG/OG/SG/M</td>
<td>1.3</td>
<td>24.3</td>
</tr>
<tr>
<td>Cedar Cr (Euchre Cr)</td>
<td>AV</td>
<td>1050</td>
<td>23.4</td>
<td>Jop</td>
<td>SG/CC/M</td>
<td>1.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Lobster Cr (Rogue R)</td>
<td>AV</td>
<td>1573</td>
<td>144.8</td>
<td>Jc/Krh/OG/SG</td>
<td>M/OG/SG</td>
<td>0.8</td>
<td>34.9</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>200</td>
<td>125.0</td>
<td></td>
<td>Jc/Krh/OG/SG/M</td>
<td>1.3</td>
<td>37.0</td>
</tr>
<tr>
<td>Quosatana Cr (Rogue R)</td>
<td>AC</td>
<td>1600</td>
<td>65.9</td>
<td>Jc/Krh/OG/SG</td>
<td>M/OG/SG</td>
<td>1.1</td>
<td>38.0</td>
</tr>
<tr>
<td>Deep Cr (Pistol R)</td>
<td>AV</td>
<td>596</td>
<td>9.2</td>
<td>Jop</td>
<td>M/SG/OG/SG/M</td>
<td>1.7</td>
<td>13.7</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>810</td>
<td>8.6</td>
<td></td>
<td>M/SG/OG/SG/M</td>
<td>2.5</td>
<td>17.4</td>
</tr>
<tr>
<td>Jack Cr (Chetco R)</td>
<td>AV</td>
<td>908</td>
<td>22.1</td>
<td>Jd</td>
<td>M/SG/OG/SG/M</td>
<td>1.3</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>AC</td>
<td>337</td>
<td>16.0</td>
<td></td>
<td>M/SG/OG/SG/M</td>
<td>1.5</td>
<td>11.2</td>
</tr>
<tr>
<td>Wheeler Cr (Winchuck R)</td>
<td>AC</td>
<td>340</td>
<td>18.0</td>
<td>Jd</td>
<td>M/SG/OG/SG/M</td>
<td>1.8</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>BRC</td>
<td>260</td>
<td>17.6</td>
<td></td>
<td>M/SG/OG/SG/M</td>
<td>1.2</td>
<td>16.1</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>600</td>
<td>16.2</td>
<td></td>
<td>M/SG/OG/SG/M</td>
<td>2.1</td>
<td>18.2</td>
</tr>
<tr>
<td>E. Fk Winchuck R (*)</td>
<td>AC</td>
<td>1133</td>
<td>58.8</td>
<td>Jd</td>
<td>M/SG/OG/SG/M</td>
<td>1.8</td>
<td>21.5</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>145</td>
<td>50.0</td>
<td></td>
<td>M/SG/OG/SG/M</td>
<td>1.5</td>
<td>24.6</td>
</tr>
</tbody>
</table>

a Codes as follows: AV = alluvial valley; AC = alluviated canyon; CC = coluvial canyon; BRC = competent bedrock canyon. Subscript denotes separate valley segments of the same class in a single stream.

b Codes for dominant basin geology: Jop = Otter Point Formation metasedimentary; Krh = Cretaceous sedimentary rocks, Rocky Peak Formation and Humbug Mountain Conglomerate; Jc = Colebrook schist; Jd = Dothan Formation, sandstones and metasedimentary rocks.

Land use codes: OG = old growth forest (some trees > 200 y old); M = mature forest (most trees 75-200 y old); SG = second-growth forest (logged >15 y previous); CC = clear cuts < 15 y old.
2.3 Field Surveys

We conducted field surveys during late summer of 1989. Field sampling combined compilation of a continuous record of reach-level features, including bank erosion, woody debris, and pool-and-riffle morphology, with more detailed measurements made at selected habitat units. We simultaneously collected data on valley geomorphology and valley segment type, which are presented in Frissell et al. 1992a.

Within each valley segment we tallied the linear extent of actively eroding, unvegetated streambanks along both sides of the channel and recorded it as percent of total streambank length. We recorded the number of pieces of large woody debris (defined as >10 cm diameter and >1 m long) in each accumulation of two or more pieces present within the active channel. Because woody debris occurring as single pieces comprised only a small portion of the total debris population and usually had little effect on the stream channel, single pieces were not counted. Artificial log weirs or deflectors comprised a portion of the large wood in certain streams, and these were identified and excluded in analyses of debris jam abundance and debris loading. We classified each debris accumulation according to whether it spanned the channel perpendicularly or was oriented parallel to the channel along the margin.

At the pool/riffle level, we classified habitats in the low-flow channel following Bisson et al. (1982) and Frissell et al. (1986). For each unit, we classified the associated geomorphic features causing formation of the habitat feature as bedrock outcrop, large boulders (>1 m median diameter), small boulders (<1 m), large woody debris (> 10 cm diameter and >1 m long), small woody debris (<10...
cm diameter or < 1 m long), tree roots, cobble bar, or gravel bar. A single observer visually estimated length and mean width of each unit, and measured maximum depth. Following Hankin and Reeves (1988), for a systematically selected subset of pool/riffle units (e.g., every 10th pool, every 10th riffle) we accurately measured length and width. Later we regressed observed against visually estimated habitat areas to develop a calibration factor. We fit separate calibration factors for different observers and sampling days, and habitat areas so corrected were used in all subsequent analyses. Where fewer than 10-15 units were measured, or where the correlation between estimated and measured areas did not differ from slope = 1.00 and intercept = 0.0 at the significance level of 0.05, we applied no correction factor.

For each pool or riffle unit selected for detailed measurement, we also recorded a suite of microhabitat data. We visually estimated the percent of the bed surface within each habitat unit dominated by each particle size class. Particle size classes were defined as bedrock (massive), large boulders (>1 m median diameter), small boulders (26-100 cm diameter), cobbles (6-25 cm), gravel (0.8-6 cm), fine gravel (2-8 mm), sand (0.06-2 mm, gritty), silt (<0.06 mm, not gritty, easily suspended). We also assessed embeddedness of cobble and gravel patches in pool tailouts, riffles, glides, and side channels by estimating the degree to which these coarse particles, presumably suitable for spawning by anadromous salmonids, were buried within a matrix of sand and finer sediment. Following Platts et al. (1983), we recorded embeddedness as an index, varying from a value of 1 where most coarse particles have >75 percent of their surface covered by finer particles, to 5 where most coarse particles have <5 percent of their surface covered by fines. We measured depth at 9 equally spaced points and averaged these data to estimate mean depth of the unit.
Pieces of large woody debris within each habitat unit selected for intensive sampling were counted and, where possible, were categorized by species of origin based on wood texture, color, hardness, and bark characteristics. To assess habitat complexity and the availability of structural cover for fish, we estimated the percent by area of each habitat unit occupied by each of the following structural elements: bedrock outcrops, boulders, large woody debris, small woody debris, overhanging banks, riparian vegetation projecting immediately above the water's surface, and aquatic vegetation (macrophytes or well-developed blooms of filamentous algae).

2.4 Analysis

Because virtually all alluvial valley and alluvial-fan-influenced valley segments in the study area are affected by riparian logging, deforestation for agricultural uses, and/or extensive logging in upstream areas, we had no control for the analysis of land use effects in these segment types. Among alluviated canyon segments, however, we were able to locate a range of land use states. Because of complex variation in disturbance history, it was difficult to capture all aspects of human activity along a single, continuous, and linear land use gradient. For some analyses, we used cumulative percent of basin logged since 1940 as an index of logging activity. For analysis of variance we divided the basins into two groups: one group had been extensively or completely logged in riparian and upland areas, and consisted of a mosaic of second-growth and clear-cut forest (SG/CC); the second group had experienced little or no logging in riparian areas, limited logging in upland parts of the basin (generally <50% of basin logged), and
therefore included large expanses of native, mature and old-growth forest (OG/M). Two streams (Edson Creek, Little Dry Creek) were anomalous in that they have been heavily logged in headwater areas but retain some mature riparian forest along their lower reaches (Table 1). These were grouped with the SG/CC group for most analyses. Portions of the riparian zones of Big Creek and lower Dry Creek were logged 40 or more years ago, but these streams were aggregated with OG/M basins for most analyses because of the substantial proportion of old-growth forest in their drainage basins.

For variables known to be dependent on stream size, including active channel width, abundance of large woody debris, wetted area of pools or riffles, or mean and maximum depth of pools or riffles, we fitted linear regressions of each variable on drainage basin area, active channel width, or channel slope. In some cases, both axes were log-transformed to normalize the data and stabilize variances. In effect, we sought explanations for the deviation of individual data points from the overall stream size-response variable relationship. Residuals about the fitted regression line were tested against segment type (3-4 classes, with alluvial fan data excluded, and for some analyses where sample sizes were small, colluvial and bedrock canyon segments combined into one category), geology (4 classes), and land use (2 classes) "treatments" using one-way, parametric analysis of variance (ANOVA). When distributions appeared non-normal or variances were strongly unequal between classes and this could not be improved by transformation, we employed the nonparametric Kruskall-Wallis ranks test (Sokal and Rohlf 1981). In the few cases where sample sizes allowed, we tested for interaction effects between segment type, land use, and geology using two-way ANOVA. For variables not directly dependent on stream size, such as substrate particle size distribution and percentage of banks in an eroding state, we
conducted appropriate ANOVA or Kruskall-Wallis tests directly on the data rather than on regression residuals.

In all cases, the null hypothesis tested was that the mean or median of the response variable did not significantly differ between any two classes of the treatment variable. When we detected a statistically significant treatment effect for segment type or geology, we identified differences between treatment groups using, in the case of ANOVA, the Least Significant Differences procedure for paired comparisons (Sokal and Rohlf 1981) or, in the case of Kruskall-Wallis tests, by direct inspection of the data. We used a maximum significance level of 0.10 for most tests; we report maximum P-values to order of magnitude. Our sample size for canyons was small, so again we lumped colluvial canyon and competent bedrock canyons into a single class for some statistical analyses of segment type effects on pool-riffle or microhabitat parameters.

3. Results

3.1 Bank Erosion

Bank erosion was primarily related to the area of the drainage basin impacted by logging (Fig. 14). There was an average 4-6-fold increase in the proportion of banks in an actively eroding state between basins subject to little or no logging and basins subject to extensive logging (Fig. 14, also ANOVA of basins split into two land use classes, SG/CC and OG/M, P<0.0001). Basins less than 30 percent logged all had less than 15 percent of their banks in an eroding state, whereas more than 40 percent of total bank length was actively eroding
Figure 14. Proportion of stream banks that showed evidence of recent or active erosion, plotted against cumulative area of the drainage basin logged since 1940. Open boxes identify basins where logging was concentrated on steep Forest Service lands, causing exceptionally numerous or large landslides above the study site. This figure includes data from four sites not described elsewhere in this paper: Middle Fork Sixes River (alluvial valley), lower Elk River (alluvial valley), Elk River at Sunshine Bar (alluviated canyon), and Red Cedar Creek (tributary to Elk River, alluviated canyon) (Frissell and Nawa, unpublished data).
Figure 14

Eroding Banks (%) vs. Percent of Basin Logged

$p < 0.003$

$r^2 = 0.27$
in several streams draining heavily logged drainage basins.

When we examined the residuals of the regression in Fig. 14, we found a weak but significant difference among valley segment types (ANOVA, P < 0.07). Competent bedrock canyons had relatively less bank erosion, presumably a result of the preponderance of nonerodible bedrock and boulder streambanks. Alluviated canyons had intermediate incidence of bank erosion, and erosion rates in colluvial canyons and alluvial valleys were variable but averaged higher. High incidence of bank erosion in colluvial canyons could be explained by the prevalence of soil creep and failure which cause unstable, stream-adjacent toe slopes to encroach on the channel and subsequently be sheared during floods. The dominance of streambank deposits by highly erodible, silt and sand size fractions can explain the vulnerability of alluvial valleys to bank erosion (Frissell et al. 1992a). In similar analyses basin geology did not account for variation in bank erosion or variation among residuals in the bank erosion/percent logged regression.

As expected, active channel width was highly correlated with drainage area (log-log regression, P < 0.001). However, despite exhaustive analysis of the residuals from the channel width/area relation we could detect no clear trend in channel width in relation to land use, segment type, or basin geology.

3.2 Large Woody Debris

The distribution and abundance of woody debris are summarized in Table 7. Frequency of debris jams within the active channel did not differ significantly among segment types, except that alluvial fan-influenced valleys (mean = 8.8 jams
Table 7. Linear frequency, spatial arrangement, and size of accumulations of large woody debris in the study streams. Data not available for Euchre Creek alluvial valley, and proportion of jams spanning the channel was not recorded for Euchre Creek alluvial-fan-influenced valleys.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Frequency (Jams per 100 m)</th>
<th>Mean Jam Size (No. of Pieces)</th>
<th>Proportion Spanning Channel (%)</th>
<th>Total LWD abundance (Pieces per 100 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edson BRC</td>
<td>0.9</td>
<td>4.0</td>
<td>0</td>
<td>3.6</td>
</tr>
<tr>
<td>Anvil BRC</td>
<td>3.2</td>
<td>6.0</td>
<td>50</td>
<td>19.2</td>
</tr>
<tr>
<td>Wheeler BRC</td>
<td>3.5</td>
<td>10.9</td>
<td>11</td>
<td>38.1</td>
</tr>
<tr>
<td>Big CC₁</td>
<td>4.4</td>
<td>7.8</td>
<td>40</td>
<td>34.3</td>
</tr>
<tr>
<td>Big CC₂</td>
<td>3.6</td>
<td>5.2</td>
<td>40</td>
<td>18.7</td>
</tr>
<tr>
<td>Little Dry CC</td>
<td>3.2</td>
<td>5.4</td>
<td>21</td>
<td>17.3</td>
</tr>
<tr>
<td>Wheeler CC</td>
<td>2.3</td>
<td>10.4</td>
<td>21</td>
<td>23.9</td>
</tr>
<tr>
<td>E. Fk Winchuck CC₁</td>
<td>2.1</td>
<td>6.3</td>
<td>0</td>
<td>13.1</td>
</tr>
<tr>
<td>Big AC</td>
<td>4.9</td>
<td>8.8</td>
<td>77</td>
<td>43.1</td>
</tr>
<tr>
<td>Little Dry AC</td>
<td>3.6</td>
<td>8.6</td>
<td>22</td>
<td>31.0</td>
</tr>
<tr>
<td>Dry AC</td>
<td>1.4</td>
<td>7.4</td>
<td>14</td>
<td>10.4</td>
</tr>
<tr>
<td>Rock AC</td>
<td>5.0</td>
<td>14.1</td>
<td>50</td>
<td>70.5</td>
</tr>
<tr>
<td>Anvil AC₁</td>
<td>2.5</td>
<td>10.4</td>
<td>25</td>
<td>26.0</td>
</tr>
<tr>
<td>Chismore AC</td>
<td>3.6</td>
<td>15.2</td>
<td>32</td>
<td>54.7</td>
</tr>
<tr>
<td>Euchre AC</td>
<td>4.4</td>
<td>29.9</td>
<td>8</td>
<td>131.6</td>
</tr>
<tr>
<td>Quosatana AC₁</td>
<td>1.4</td>
<td>16.5</td>
<td>0</td>
<td>23.1</td>
</tr>
<tr>
<td>Deep AC</td>
<td>6.1</td>
<td>11.2</td>
<td>10</td>
<td>68.3</td>
</tr>
<tr>
<td>Wheeler AC</td>
<td>4.4</td>
<td>6.4</td>
<td>7</td>
<td>28.2</td>
</tr>
<tr>
<td>E. Fk Winchuck AC₁</td>
<td>2.2</td>
<td>6.4</td>
<td>8</td>
<td>14.1</td>
</tr>
<tr>
<td>Edson AV₁</td>
<td>5.2</td>
<td>8.5</td>
<td>13</td>
<td>44.2</td>
</tr>
<tr>
<td>Edson AV₂</td>
<td>2.6</td>
<td>3.9</td>
<td>18</td>
<td>10.1</td>
</tr>
<tr>
<td>Dry AV</td>
<td>1.2</td>
<td>8.0</td>
<td>13</td>
<td>9.6</td>
</tr>
<tr>
<td>Rock AV</td>
<td>2.3</td>
<td>6.4</td>
<td>22</td>
<td>14.7</td>
</tr>
<tr>
<td>Cedar AV</td>
<td>1.9</td>
<td>6.6</td>
<td>14</td>
<td>12.5</td>
</tr>
<tr>
<td>Lobster AV</td>
<td>1.4</td>
<td>10.2</td>
<td>12</td>
<td>14.3</td>
</tr>
<tr>
<td>Deep AV₁</td>
<td>5.3</td>
<td>9.5</td>
<td>16</td>
<td>50.3</td>
</tr>
<tr>
<td>Jack AV₁</td>
<td>1.6</td>
<td>5.8</td>
<td>14</td>
<td>9.3</td>
</tr>
<tr>
<td>Jack AV₂</td>
<td>2.2</td>
<td>6.2</td>
<td>21</td>
<td>13.6</td>
</tr>
<tr>
<td>Euchre AFV₁</td>
<td>5.4</td>
<td>18.5</td>
<td>-</td>
<td>121.8</td>
</tr>
<tr>
<td>Euchre AFV₂</td>
<td>12.2</td>
<td>12.0</td>
<td>-</td>
<td>145.6</td>
</tr>
</tbody>
</table>

* Codes indicate valley segment type: BRC = competent bedrock canyon, CC = colluvial canyon, AC = alluviated canyon, AV = alluvial valley, AFV = alluvial-fan-influenced valley.

b Artificial structures were present, but are excluded from these data.
per 100 m) had a higher frequency than other types (range of means 0.9-3.8) (one-way ANOVA, P<0.10). Similarly, the size of debris jams was not strongly related to land use or channel width, but differed significantly among segment types (one-way ANOVA, P<0.05). The mean number of pieces in jams of alluvial-fan-influenced valleys (mean = 15.3) and alluviated canyons (mean = 12.7) was roughly double that of all other segment types (range in means 5.2-7.2).

Accordingly, the total number of large wood pieces counted (those incorporated in jams) per 100 m of stream also varied by segment type (ANOVA, P<0.001); abundance was significantly higher (P<0.10) in alluvial-fan-influenced valleys (mean = 133) than alluviated canyons (mean = 49), and significantly lower than either of these in all other segment types (range in means 4.4 to 24 pieces per 100 m). Total abundance of wood in accumulations was not correlated with active channel width.

We could discern little effect of land use on large woody debris when data were lumped without regard to segment type. However, when we stratified the analysis by segment type, we found that logging was associated with a doubling of both jam frequency (one-way ANOVA, P<0.04) and overall debris abundance (ANOVA, P<0.03) in alluviated canyons. No trends were detected in other segment types, but this could partly reflect small sample size. The number of pieces of large woody debris per 100 m in our study streams corresponds well to values reported from elsewhere along the Pacific coast (e.g., Sedell et al. 1988, Bilby and Ward 1991), except in some logged basins (e.g., Euchre Creek, Deep Creek) where very large accumulations have formed in alluviated canyons and alluvial fans.

We did not measure size of debris pieces, but it appeared from field observations that, consistent with other studies (e.g., Hartman and Scrivener 1990,
Andrus et al. 1988), piece size was smaller in heavily logged basins, and very large pieces (>50 cm diameter and >10 m long) were more abundant in streams whose riparian areas had not been logged. Debris jams in heavily logged basins, although often formed around key logs of large size that were residual from the pre-logging stand, were usually dominated by small pieces of debris originating from logging slash or second-growth forests. Fragmented, rapidly-decaying, and punky boles of red alder were numerous in these jams.

The spatial configuration and presumably the stability of debris jams differed between heavily logged and lightly impacted basins, but was primarily affected by channel width. As channel width increased, the proportion of debris jams spanning the channel declined (regression, \( R^2 = 0.195, P < 0.02 \)) and the proportion of lateral jams (those confined to channel margins) increased (\( R^2 = 0.423, P < 0.001 \)). When we classified the residuals of the channel width regressions by land use state of the basin, heavily logged basins had a significantly higher proportion of lateral jams (ANOVA, \( P < 0.04 \)) and fewer cross-channel jams (ANOVA, \( P < 0.02 \)). For a given channel width, more of the debris accumulations projected into and across the active channel in lightly-logged basins, whereas in heavily-logged basins more jams were swept laterally along the banks.

We assessed species composition of in-channel woody debris during microhabitat surveys. Coniferous species dominated colluvial canyons and competent bedrock canyons, debris of coniferous and hardwood origin was coequal in alluviated canyons, and red alder dominated in alluvial valleys and alluvial fan-influenced valleys. Port-Orford-cedar, although usually a minor component of the canopy (Frissell et al. 1992a), was represented disproportionately as a structural component in stream channels. We commonly
observed residual debris from this decay-resistant species even in valley segments where mature specimens appeared to have been eliminated decades earlier by logging and disease.

3.3 Pool- and Riffle-Forming Features

Woody debris, boulders, bedrock outcrops, tree-root-defended streambanks, and gravel or cobble bars were the major geomorphic features responsible for creating and shaping pools and riffles. We compared segment types in terms of the relative importance of these different features in creating pools, and found major differences that correlated with valley geomorphology (Table 8). Overall, bedrock and boulders declined in influence with decreasing channel slope, decreasing hillslope interaction, and increasing stream size, and the importance of large wood, tree roots, and gravel bars as pool-forming features increased. This roughly corresponds with a gradient from competent bedrock canyons, which are narrow and steeper, through the wider, gently-sloping alluvial valleys and alluvial-fan-influenced valleys.

Bedrock and boulders were the dominant pool-forming features in competent bedrock canyons, colluvial canyons, and alluviated canyons, but were significantly less common in alluvial valleys and alluvial fan-influenced valleys (ANOVA, P<0.08). The importance of large wood varied with the opposite trend (ANOVA, P<0.03): wood was the primary pool-forming feature in alluvial fan-influenced valleys, alluviated canyons, and alluvial valleys, moderately important in colluvial canyons, and of small influence in bedrock canyons. Since overall abundance of woody debris varied little among the latter four segment types, these
Table 8. Mean percent of pool habitats in each valley segment type associated with each of seven morphogenetic features. Segment codes as in previous tables.

<table>
<thead>
<tr>
<th>Feature</th>
<th>AFV</th>
<th>AV</th>
<th>AC</th>
<th>CC</th>
<th>BRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock</td>
<td>0.0</td>
<td>12.9</td>
<td>23.0</td>
<td>43.0</td>
<td>43.6</td>
</tr>
<tr>
<td>Boulders</td>
<td>0.0</td>
<td>10.4</td>
<td>26.0</td>
<td>48.4</td>
<td>42.7</td>
</tr>
<tr>
<td>Large Wood</td>
<td>81.9</td>
<td>45.0</td>
<td>39.1</td>
<td>22.4</td>
<td>9.5</td>
</tr>
<tr>
<td>Roots</td>
<td>9.3</td>
<td>17.0</td>
<td>6.2</td>
<td>0.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Cutbank</td>
<td>0.0</td>
<td>8.0</td>
<td>3.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Gravel Bar</td>
<td>4.1</td>
<td>3.4</td>
<td>2.6</td>
<td>6.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Beaver dam</td>
<td>0.0</td>
<td>3.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
data suggest that wood present in colluvial and bedrock canyons was substantially less effective at influencing channel morphology than was wood in alluvial valleys. In narrow canyons, where flood flows reach high stage heights, many of the jams of woody debris we counted had been rafted onto rocks along the channel margin or elevated high over the low-flow channel. By contrast, much of the large wood seen in alluvial valleys was embedded in the channel bed and banks.

Other, more transient morphogenetic features were less common overall, but tree roots were significantly more abundant in alluvial valleys and alluvial fan-influenced valleys than other segments (ANOVA, P<0.05), and pools formed at eroding cutbanks were seen more often in alluvial valleys and alluviated canyons than other segments (ANOVA P<0.056). Beaver dams were rare in the surveyed streams, with just two recorded, both in alluvial valleys. Tree roots and cutbanks are widespread features but the percentages reported in Table 3 are low because if large wood, boulders, or bedrock were present we attributed pool formation primarily to these larger flow obstructions (Lisle 1986); we classified only pools where no such "hard" feature was present as formed primarily by cutbanks, tree roots, or gravel bars.

The relationship between logging impacts and pool-forming features is not clear. Although we detected differences between lightly-logged and heavily-logged basins, inspection of the data indicated these differences could mostly be attributed to the disproportionate representation of segment types in the two land use classes (e.g., almost all alluvial valleys were in the heavily-impacted category). When we confined the analysis to alluviated canyons, the only segment type for which we had a good sample size in both land use categories, we detected no significant logging effects on pool-forming features.
We aggregated pool- and riffle-level habitat units into four classes for summary and analysis: pools (including all main channel pool types), riffles (including rapids and cascades), glides (including runs), and off-channel habitats (including backwater pools, secondary channels, and isolated pools) (Table 9). The total wetted area per 100 m of channel of both pools (Fig. 16) and off-channel habitats were positively correlated with drainage basin area ($P < 0.0001$, $R^2 = 0.683$ and 0.414, respectively), but glides were only weakly correlated ($P = 0.068$, $R^2 = 0.114$) and riffles were not correlated at all with basin area.

When we classified by land use the residuals of the regression between pool area and basin area, we found a significant difference between heavily-logged basins and lightly logged basins (1-way ANOVA, $P = 0.022$). Streams in heavily logged basins appeared to have about one-third less area in pools than streams draining basins dominated by mature and old-growth forest. Variation among residuals could not be explained by segment type or basin geology. For glides, residuals could not be explained by land use or segment type, but did differ by geology (ANOVA, $P = 0.031$). By this measure streams draining Otter Point metasedimentary rocks had on average more area in glides per unit channel length than streams draining other rock types. We are unsure what can account for this pattern.

Another way to quantify relative habitat composition is the percent of total wetted area comprised by each habitat class. This analysis produced some discrepancies from the basin-area-corrected analysis. For example, the percent of habitat in pools was not significantly related to land use, but was related to segment type (ANOVA, $P = 0.045$) and geology (ANOVA, $P = 0.004$). However,
Table 9. Pool- and riffle-level composition of habitats in the study segments. Data not available for Euchre AFV. "Pools" includes all main-channel pools; "riffles" includes main-channel riffles, cascades, and rapids; "glides" includes main-channel glides and runs; "off-channel" includes side channels, side channel pools, backwater pools along the main channel, and isolated backwater pools. Data do not include dry reaches, including entire length of Rock Cr alluvial valley.

<table>
<thead>
<tr>
<th>Site</th>
<th>Wetted Area (m² per 100 m)</th>
<th>Percent of Total Wetted Area</th>
<th>Frequency (Number per 100 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pools Riffles Glides Off-Channel</td>
<td>Pools Riffles Glides Off-Channel</td>
<td>Pools Riffles Glides Off-Channel</td>
</tr>
<tr>
<td>Edson BRC</td>
<td>430.9 174.7 170.3 193.2</td>
<td>44.5 18.0 17.6 19.9</td>
<td>2.8 4.1 2.6 3.4</td>
</tr>
<tr>
<td>Anvil BRC</td>
<td>288.1 672.4 0.0 1.0</td>
<td>42.9 57.2 0.0 0.1</td>
<td>6.0 6.0 0.0 1.0</td>
</tr>
<tr>
<td>Wheeler BRC</td>
<td>154.1 543.7 93.6 48.9</td>
<td>18.3 64.7 11.1 5.9</td>
<td>1.6 2.9 1.3 2.7</td>
</tr>
<tr>
<td>Big CC</td>
<td>129.6 205.0 0.0 27.0</td>
<td>35.8 56.7 0.0 7.5</td>
<td>11.4 7.9 0.0 2.6</td>
</tr>
<tr>
<td>Big CC₂</td>
<td>80.6 61.7 91.7 30.8</td>
<td>30.4 23.3 34.6 3.6</td>
<td>7.1 6.4 5.0 3.5</td>
</tr>
<tr>
<td>Little Dry CC</td>
<td>25.3 37.5 16.3 5.3</td>
<td>30.0 44.4 19.3 6.3</td>
<td>3.1 3.8 1.3 3.1</td>
</tr>
<tr>
<td>Wheeler CC</td>
<td>173.5 258.2 84.4 31.9</td>
<td>31.7 47.0 15.5 5.8</td>
<td>2.0 2.4 0.9 1.0</td>
</tr>
<tr>
<td>E. Fk Winchuck CC</td>
<td>572.9 157.7 291.5</td>
<td>44.5 12.2 20.7 22.6</td>
<td>3.3 2.0 3.3 9.3</td>
</tr>
<tr>
<td>Big AC</td>
<td>183.4 94.9 49.0 35.1</td>
<td>50.6 26.2 13.5 9.7</td>
<td>5.2 8.3 3.9 5.2</td>
</tr>
<tr>
<td>Little Dry AC</td>
<td>32.2 101.0 24.1 3.5</td>
<td>20.0 62.8 15.0 2.2</td>
<td>4.2 5.6 2.1 2.1</td>
</tr>
<tr>
<td>Dry AC</td>
<td>406.2 78.0 99.1 39.3</td>
<td>65.3 42.7 15.9 6.3</td>
<td>1.4 1.4 0.5 0.9</td>
</tr>
<tr>
<td>Rock AC</td>
<td>68.2 183.4 46.2 0.0</td>
<td>22.9 61.6 15.5 0.0</td>
<td>4.0 7.0 2.5 0.0</td>
</tr>
<tr>
<td>Anvil AC₂</td>
<td>339.3 175.3 118.2 13.1</td>
<td>52.5 27.2 10.3 2.0</td>
<td>4.1 4.1 1.6 1.1</td>
</tr>
<tr>
<td>Chismore AC</td>
<td>137.6 230.6 54.2 33.6</td>
<td>30.3 50.5 11.9 7.4</td>
<td>4.8 6.0 2.2 2.0</td>
</tr>
<tr>
<td>Euchre AC</td>
<td>333.2 133.6 91.2 61.0</td>
<td>53.8 21.6 14.7 9.9</td>
<td>2.9 2.6 1.1 2.2</td>
</tr>
<tr>
<td>Quosatana AC³</td>
<td>894.6 195.5 188.5 87.1</td>
<td>65.6 14.2 13.8 6.4</td>
<td>0.9 0.8 0.4 1.0</td>
</tr>
<tr>
<td>Deep AC</td>
<td>105.3 201.4 53.7 28.2</td>
<td>27.1 51.8 13.8 7.3</td>
<td>4.7 5.4 1.6 2.2</td>
</tr>
<tr>
<td>Wheeler AC</td>
<td>373.7 580.4 75.7 33.5</td>
<td>35.2 54.7 6.9 3.2</td>
<td>3.8 3.8 1.2 1.6</td>
</tr>
<tr>
<td>E. Fk Winchuck AC³</td>
<td>435.6 171.7 74.4 53.9</td>
<td>59.2 23.7 10.1 7.3</td>
<td>1.9 1.9 0.8 1.0</td>
</tr>
<tr>
<td>Site</td>
<td>Wetted Area (m² per 100 m)</td>
<td>Percent of Total Wetted Area</td>
<td>Frequency (Number per 100 m)</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------</td>
<td>-------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td></td>
<td>Pools</td>
<td>Riffles</td>
<td>Glides</td>
</tr>
<tr>
<td>Edson AV₁</td>
<td>415.7</td>
<td>157.5</td>
<td>75.8</td>
</tr>
<tr>
<td>Edson AV₂</td>
<td>302.4</td>
<td>119.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Dry AV</td>
<td>226.9</td>
<td>217.0</td>
<td>84.8</td>
</tr>
<tr>
<td>Euchre AV₁</td>
<td>384.8</td>
<td>125.2</td>
<td>60.2</td>
</tr>
<tr>
<td>Euchre AV₂</td>
<td>511.6</td>
<td>68.9</td>
<td>55.0</td>
</tr>
<tr>
<td>Cedar AV</td>
<td>289.1</td>
<td>155.8</td>
<td>118.3</td>
</tr>
<tr>
<td>Lobster AV</td>
<td>1040.0</td>
<td>229.6</td>
<td>42.4</td>
</tr>
<tr>
<td>Deep AV₂</td>
<td>215.9</td>
<td>404.5</td>
<td>78.2</td>
</tr>
<tr>
<td>Jack AV₁</td>
<td>221.8</td>
<td>51.1</td>
<td>61.6</td>
</tr>
<tr>
<td>Jack AV₂</td>
<td>212.8</td>
<td>40.3</td>
<td>88.5</td>
</tr>
<tr>
<td>Euchre AFV₁</td>
<td>405.5</td>
<td>178.9</td>
<td>35.6</td>
</tr>
<tr>
<td>Euchre AFV₂</td>
<td>436.8</td>
<td>119.6</td>
<td>6.3</td>
</tr>
</tbody>
</table>

- Codes indicate valley segment type: BRC = competent bedrock canyon, CC = colluvial canyon, AC = alluviated canyon, AV = alluvial valley, AFV = alluvial-fan-influenced valley.
- Artificial structures may have significantly influenced channel morphology, probably by increasing pools or glides at the expense of riffles.
- Artificial structures present, but dispersed and/or ineffective and did not significantly influence channel morphology.
Figure 15. Correlation between drainage basin size and wetted area in pools at low flow. Open boxes are heavily logged basins, solid boxes are lightly logged basins. All valley segment types are combined on this plot.
Figure 15

\[ \ln \text{Pool Area (m}^2/100\text{m}) \]

\[ \ln \text{Basin Area (km}^2) \]

\[ p < 0.0001 \]
\[ r^2 = 0.681 \]
these differences could largely be explained by an inverse correlation of percent pools with channel slope (loge-loge regression, \( P = 0.002, R^2 = 0.296 \)), which is itself highly correlated with geology and segment type (Frissell et al. 1992a). The relative area in riffles increased with channel slope (loge-loge regression, \( P < 0.001, R^2 = 0.346 \)). Off-channel habitats and glides were not clearly associated with any of these factors.

Although we could find no evidence for a relationship between logging and percent area in pools when data from all segment types was lumped, we found a highly significant difference if we analysed alluviated canyons independently (ANOVA, \( P = 0.002 \)), thus partly controlling for slope and other geomorphic effects. Mean percent area in pools among lightly-logged basins (mean = 58.6%) was nearly double that among heavily-logged basins (mean = 31.6%). The relative area in riffles among lightly logged basins (mean = 20.7%) was less than half that among heavily-logged (mean = 50.5%) basins (ANOVA, \( P < 0.003 \)). Percent glides and percent off-channel habitats show little apparent relationship to land use.

Pool and riffle proportions are highly sensitive to channel slope. We examined the possibility that variation in channel slope among different alluviated canyons could explain differences in percent pool area. The correlation between slope and pool area was significant (Fig. 16), but differences among residuals of the relationship confirmed a dramatic difference in pool area between heavily- and lightly-logged basins (ANOVA, \( P = 0.007 \)).

We examined the frequency of habitat units per 100 m of stream as a third measure of habitat condition. Frequencies of pools, riffles, and glides were highly correlated with basin size and channel slope but were insensitive to segment type, geology, and land use. These data indicate that changes in pool area associated
Figure 16. Relationship between channel slope and the proportion of total wetted area comprised by pools, alluviated canyon valley segments only. Open boxes are heavily logged basins (SG/CC), solid boxes are lightly logged basins (OG/M).
Alluviated Canyons

Wetted Area in Pools (%)

Channel Slope (%)

$\text{OG/M}$

$\text{SG/CC}$

$P < 0.03$

$r^2 = 0.423$

Figure 16
with logging resulted primarily from changes in the relative sizes of pools and riffles, rather than changes in their numbers.

3.5 Depth of Pools and Riffles

We expected that if increased sediment load played a significant role in channel morphology (Lisle 1982), the depths of pools and other habitats might decline with logging. However, depths of habitats could also vary between valley types or among basins of different geology, potentially confounding land use effects. Similar to earlier procedures, we regressed the log$_e$-transformed maximum depth or mean depth of habitat units of a given class against the log$_e$-transformed basin area of the segment in which the habitat unit occurred. This accounted for the effects of stream size. Then residuals around the fitted line were tested using ANOVA to detect trends associated with segment type, land use, and basin geology.

For all streams combined, both maximum and mean pool depths relative to drainage area declined with logging (two-way ANOVA on basin area-pool depth residuals, land use $P < 0.10$, geology $P > 0.10$, no interaction effects). When we confined the analysis to alluviated canyons, pool depth did not vary significantly with land use (1-way ANOVA, $P > 0.01$). This suggests that pools in alluviated canyons may be less sensitive to changes in depth than pools in certain other segment types. Although pools in alluviated canyons within heavily logged basins tended to be smaller in surface area, they apparently retain local, deep scour holes (see Lisle 1989). This could be related to the abundance of both boulders and woody debris to act as roughness elements in alluviated canyon valley segments.
Maximum depth of pools in valley types where woody debris was less common may be more sensitive to changes in sediment load. In the field we observed that where woody debris is especially abundant and stable, it functions in two ways: first, it deflects high flows and initiates scour, and second it serves as a structural support to buttress the slip faces of gravel bars, which inhibits their encroachment on scour holes within pools.

Riffles in alluviated canyons of heavily-logged basins were significantly shallower than those in lightly logged-basins (Fig. 17) (one-way ANOVA on mean depth/basin area residuals, $P = 0.021$). Riffle depth did not appear to be strongly affected by segment type or geology. Several reaches of heavily logged streams lacked surface flow entirely, suggesting that shallowing of riffles is a consequence of reduced summer water yield in second-growth basins (Hicks et al. 1991a) and/or reduced surface-to-intragravel flow ratio in aggraded reaches (e.g., McSwain 1987, Hartman and Scrivener 1990).

Depth of glides and off-channel habitats was not correlated with land use. However, relative to basin area, glides were significantly shallower in alluvial valleys than other segment types (ANOVA, $P < 0.01$). This might be associated with the tendency for glides in alluvial valleys to be formed by gently-graded gravel bars, whereas glides in steeper segment types were formed predominantly by larger materials like cobbles and boulders, with a steeper angle of repose and therefore, greater bar relief.
Figure 17. Mean depth of riffles as a function of drainage basin area, alluviated canyons only. Open boxes are heavily logged basins (SG/CC), solid boxes are lightly logged basins (OG/M).
2.5 - 2 - 1.5 -

Alluviated Canyons

p < 0.025
$r^2 = 0.397$

OG/M ■
SG/CC □

Ln Mean Riffle Depth (cm)

Ln Basin Area (km²)

p < 0.025
$r^2 = 0.397$

Figure 17
3.6 Texture of Bed Materials and Instream Cover

Pool and riffle types differ in terms of their particle size distributions (Frissell et al. 1986), but our data indicate that within major classes of pools and riffles, valley segment type further influenced bed material texture. In off-channel habitats, steeper and narrower valley segments tended to be dominated by coarser bed materials and fewer fine sediments. Dominant substrate size in other habitat types was relatively unaffected by valley segment type, except that glides and main-channel pools within bedrock canyons had coarser substrate size than they did in other valley segments. Embeddedness rating (inversely proportional to the preponderance of fine sediments on the bed surface) increased dramatically in pools and off-channel habitats from alluvial fan-influenced and alluvial valleys to narrow, steeper canyons. Due to small sample sizes these data are not amenable to statistical analysis, and they should be interpreted as only an approximate indication of variation in bed texture among valley segment types.

Within alluviated canyons, fine sediment was significantly more abundant in main-channel pools and cascades of heavily-logged drainage basins (Fig. 19). The median abundance of fine sediment approximately doubled with logging in pools and cascades, and also increased in off-channel habitats. Similarly, the index of embeddedness declined significantly with logging as fines increased in these three habitat types (Fig. 19).

Cover types in main channel pools reflected geomorphology of the valley and texture of the channel floor. Bedrock and boulders were the most common cover type in competent bedrock canyons and colluvial canyons, whereas cover in
Figure 18. Effect of valley segment type on bed material size distribution in five classes of low flow habitats. Embeddedness rating is inversely proportional extent of fine sediment on the bed surface. Number above bar indicates sample size within category. Off-channel habitats in bedrock canyons had bimodally-distributed particle sizes, with cobbles and sand nearly co-dominant.
Figure 18
Figure 19. Abundance of fine sediment on the bed surface in habitats located in alluviated canyon valley segments. Fine sediment is measured as relative area of the bed dominated by fine size fractions (left), and as embeddedness rating in gravel and cobble-dominated microhabitat patches considered suitable for spawning by salmonid fishes (right). Shaded columns are habitats in lightly-logged basins, open columns are heavily-logged basins. Vertical bars indicate data range. Stars indicate significance level of differences between lightly-logged and heavily-logged basins, as determined by parametric ANOVA (embeddedness) or nonparametric Kruskall-Wallis tests (percent fines); * = P < .10, ** = P < .01. Sample sizes are indicated below embeddedness bars. Percent fine sediment is determined for two categories: 1) percent less than 1 mm diameter (sand, silt and clay, left); and 2) percent less than 8 mm diameter (previous size classes plus fine gravel). Embeddedness rating is inversely proportional extent of fine sediment on the bed surface.
Figure 19

Old-growth/mature forest basins
Second-growth/clear-cut basins

Main-channel Pools
Glides
Riffles
Cascades
Off-channel Habitats

Percent of Bed Dominated by Fine Sediment (median)

<1 mm <8 mm

Embedding Index (mean)

n=12 n=24

n=7 n=7

n=6 n=6

n=3 n=8

n=11 n=11

Fine Particle Size Range
alluviated canyons and alluvial valleys was dominated by woody debris (Table 10). Overhanging banks and overhanging vegetation were important in alluvial segment types. Cover was proportionally more abundant and diverse in alluvial fan-influenced valleys than in other valley segment types. Although logging did not appear to significantly affect the distribution of cover as we measured it, filling of crevices by fine sediment in heavily-logged basins could reduce the effectiveness or accessibility of cover normally provided by boulders and woody debris (Murphy and Hall 1981). More sensitive measures of cover availability and quality might detect logging-related differences related to fine sediment accumulation.

4. Discussion

Our study indicates that upstream activities causing increased sediment load and loss of channel stability can have adverse effects on stream habitat that override the influence of riparian vegetation, particularly in certain physically sensitive and biologically critical stream segments. Stratification of study design and analysis by a valley segment or similar geomorphic classification can markedly increase the sensitivity of habitat studies. The valley segment classification we used accounts for aspects of channel and valley geomorphology that would otherwise confound detection of land use impacts. For example, a persistent loss of nearly half the pool area from alluviated canyons in logged basins-- despite a doubling in the loading of woody debris-- is a change with potentially severe biological consequences for rearing fishes. It is contrary to a commonly-held belief that woody debris begets pools, and certainly merits further investigation. Yet we would not have detected this phenomenon without carefully controlling for stream...
Table 10. Distribution of cover types in main channel pools of fluvial valley segment types, measured as median percent area of habitat occupied by cover element. In parentheses is proportion of pool units in which cover type is present.

<table>
<thead>
<tr>
<th>Cover Type</th>
<th>Alluvial-fan-influenced Valley</th>
<th>Alluvial Valley</th>
<th>Alluviated Canyon</th>
<th>Colluvial Canyon</th>
<th>Competent Bedrock Canyon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock</td>
<td>0 (0)</td>
<td>0 (.14)</td>
<td>0 (.25)</td>
<td>2 (.17)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Boulders</td>
<td>0 (0)</td>
<td>0 (.43)</td>
<td>2 (.53)</td>
<td>8 (.67)</td>
<td>6 (1.00)</td>
</tr>
<tr>
<td>Large Woody Debris</td>
<td>8.4 (.75)</td>
<td>2 (.67)</td>
<td>2 (.69)</td>
<td>1 (.50)</td>
<td>1 (.50)</td>
</tr>
<tr>
<td>Small Woody Debris</td>
<td>0.8 (1.00)</td>
<td>0 (.48)</td>
<td>0 (.47)</td>
<td>1 (.50)</td>
<td>1 (.50)</td>
</tr>
<tr>
<td>Overhanging Bank</td>
<td>0.2 (1.00)</td>
<td>0 (.48)</td>
<td>0 (.36)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Overhanging Vegetation</td>
<td>2.8 (1.00)</td>
<td>2 (.57)</td>
<td>0 (.36)</td>
<td>0 (0)</td>
<td>4 (.50)</td>
</tr>
<tr>
<td>Aquatic Vegetation</td>
<td>0.2 (.50)</td>
<td>0 (.33)</td>
<td>0 (.03)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>
size and slope and classifying the data by valley segment type, thereby reducing variation imposed by larger-scale geomorphic factors that are not directly affected by human activities.

The results suggest that competent bedrock canyon and colluvial canyon valley segments were insensitive to land use impacts compared to alluviated canyons. However, our failure to detect patterns in the canyon types may result from our small sample size for these valley types. It is possible that narrow canyon-type segments respond to different kinds of disturbance than alluviated canyons, that they respond differently to the same disturbance, or that they recover more rapidly from disturbance. We were unable to assess the vulnerability of alluvial valleys, because virtually all valleys of this type in the study region have suffered a long history of human impact. Most alluvial valleys have been affected by both riparian and upstream sources. Although historical accounts indicate alluvial valleys were once heavily used for spawning by salmon, very few support large spawning populations of anadromous fish today in southwest Oregon (Frissell et al. 1992a). The most critical point is that impacts in alluviated canyons, which support most remaining salmon populations in the study region, can be difficult or impossible to detect if valley types were not discriminated.

We believe the loss of pool area and increased riffle area in alluvial segments of heavily-logged drainage basins is a largely a consequence of increased sediment load, the cumulative effect of which is to expand gravel bars and reduce the effectiveness of large roughness elements in scouring pools (Lisle 1982). Enlarged, unstable gravel bars first encroach on and then overwhelm pools as bedload accumulates in the streambed. Increasing the loading of woody debris and other roughness elements, whether by natural means or human intervention with artificial structures, apparently cannot compensate for the effects of increased
sediment load on channel morphology (Frissell and Nawa 1992). We emphasize that in most of our study basins, extensive logging peaked 20-30 years ago and we are observing the long-term effects of human activity. These effects appear to persist at least several decades following disturbance of the drainage basin. Given a deforestation cycle of about 30-50 years rotation on private lands and 80-100 years on federal lands in the region, there appears to be little opportunity for recovery (Frissell et al. 1992a).

In heavily logged drainage basins, unstable channels with high sediment loads can destabilize woody debris and wash it to the banks, reducing its value as aquatic habitat and its influence on channel morphology. Where floodplains are present, particularly where they have been logged and the root structure afforded by large, streamside conifers weakened (Chamberlin 1991), unstable channels often migrate or avulse laterally, abandoning the hydraulic obstruction that a channel-spanning jam creates. Therefore many of the ecological benefits of large wood in streams can be substantially reduced where natural events or human activities such as logging promulgate channel instability (Trotter 1990, Hartman and Scrivener 1990). This effect is exacerbated by the preponderance of fragile, small wood that originates from second-growth stands (Andrus et al. 1988), making jams more vulnerable to displacement (Bryant 1980, Hartman and Scrivener 1990). Although large, unstable jams can create barriers for fish passage (Bryant 1983), we observed no examples of this problem in the study basins. Channel-spanning jams were heavily used by adult salmon and steelhead for cover. Some large debris jams did divert flood flows against unstable hillslopes, triggering debris slides, particularly in alluviated canyons of heavily-logged basins (Frissell unpublished data).

Both alluviated canyons and alluvial fan-influenced valleys are located
where channel slope tends to abruptly decline and channel and floodplain width increase, encouraging deposition of wood in transport from upstream sources, providing near-channel storage sites for debris accumulations, and allowing room for dissipation of hydraulic forces by lateral deflection of flows around debris obstructions. Furthermore, when destabilized by increased sediment input channels in these segment types erode banks and toeslopes, triggering recruitment of large quantities of debris from the floodplain and, especially in the case of alluviated canyons, adjacent hillslopes. Several factors could account for the smaller quantities of woody debris we observed in alluvial valleys: 1) recruitment of large wood from the riparian zone might be limited by the long-term reduction of large conifers caused by extensive logging of floodplains in alluvial valleys; 2) the recruitment of large wood from hillslopes is limited where the channel is largely buffered from slopes by floodplains and terraces; 3) debris that is recruited from riparian areas is predominantly small, rapidly-decaying red alder (see below); 4) alluviated canyons and alluvial fans might function as traps that "filter out" the largest debris before it can be transported downstream to alluvial valleys; 5) alluvial valleys tend toward large active channel width and larger drainage areas than other segment types, allowing freer export of any large wood that is recruited.

Loss of surface flow in riffles following logging has been observed in other studies of Pacific coastal streams affected by increased sediment load (Tripp and Poulin 1986, Hartman and Scrivener 1990) or changes in vegetation induced by logging (Hicks 1990). Shallowing of riffles could affect productivity by driving juvenile steelhead out of riffles and into pools, where they compete with other species for food and shelter (Hicks 1990, Hicks et al. 1991a). Summer surface flow was completely absent in some of the most obviously aggraded reaches we
visited. In an unpublished file report on Little Dry Creek from 1972, prior to logging of the basin’s steep headwaters, a state biologist documented abundant coho and chinook salmon fry, as well as juvenile steelhead in mid-summer over about a kilometer of stream (Oregon Department of Fish and Wildlife, Elk River Research Lab, Port Orford, Oregon); in 1986-90, this alluviated canyon segment was devoid of surface water and fish between late July and late October. Chinook and coho salmon appear to have been extirpated from this stream due to the effects of landslides originating in logged portions of the headwaters, despite the presence of a well-developed riparian forest (Frissell et al. 1992c).

The extent of actively eroding banks is a good index of channel stability, and our data indicate the primary factor influencing variation in bank erosion among basins is logging. Increased sediment load and increased frequency of sediment pulses from road- and deforestation-related landslides is probably the primary factor responsible for the loss of channel stability, which seriously impairs the survival of eggs and fry of fall- and winter-spawning salmon (Gangmark and Bakkala 1960, Frissell and Nawa unpublished data). Bank erosion along toeslopes adjacent to colluvial canyons and alluviated canyons triggers secondary debris slides that compound the effects of upstream sediment sources (Frissell et al. 1992a). The loss of intragravel flow and crevice cover caused by accumulation of fine sediment damages spawning and rearing habitat of fishes and amphibians (e.g., Murphy and Hall 1981, Scrivener and Brownlee 1989) and high concentrations of fines in the bed or in transport can adversely affect benthic algae, macroinvertebrates, and behavior and feeding efficiency of salmonid fishes (Hicks et al. 1991b).

We were surprised that we failed to find any clear effects of geology or land use on active channel width, since increased sediment load associated with
erosion-prone geologic formations and logging can cause widening of channels having erodible bank materials (Lisle 1982, Richards 1982). However, over several years of observation we noticed that channel width can change relative rapidly with chronic bank erosion, delayed bank collapse, or the encroachment of vegetation onto gravel bars. Channel width measured at any given time, therefore, will reflect the complexities of sediment inputs, timing and magnitude of recent floods, and the rate of vegetation recovery (which is influenced by texture and stability of the deposits, as well as climate and the proximity of sources of propagules).

Furthermore, during analysis of cross-section surveys and estimated flood crests in numerous streams in the study area (Frissell and Nawa 1992, Frissell and Nawa unpublished data) we found some evidence that peak flows for a given storm vary among nearby basins. Relief and orientation of the drainage basin and possible storm tracking effects may underlie this variation, so that hydrologic heterogeneity might account for some of the unexplained variation in active channel width among streams.

When classified following Bisson et al. (1982), pool-and-riffle composition was remarkably similar among valley segment types. Variation within segment types far exceeded variation among segment types. The primary differences between segment types were the presence or absence of habitat types that were relatively rare in the study streams, such as plunge pools and trench pools. Nevertheless, we showed that valley segment types differ markedly in woody debris loading, pool-forming features, microhabitat conditions, and the response of these factors to logging disturbance. Our data from southwest Oregon and other regions (Frissell, unpublished data) suggest that even where human disturbances have serious, long-term effects on channel stability, woody debris loading and stability, water temperature, and bed texture, they sometimes have relatively little
impact on pool-and-riffle morphology of the low-flow channel, as measured by the Bisson et al. (1982) technique. We hypothesize that some channels may respond to loss of large roughness elements such as woody debris by simply adjusting to other available large roughness elements, such as boulders, bedrock outcrops, erosion-resistant banks, or self-formed gravel bars and steps. Changes in pool-and-riffle morphology might be most severe in valley types where such alternative roughness elements are in short supply, such as alluvial valleys, or where humans have acted directly to channelize or dam streams and re-shape floodplains into configurations resistant to fluvial modification during normal peak flows.

For these reasons, we believe that classification and survey of pools and riffles based simply on their gross morphology is likely to be insensitive to all but the most severe changes in stream habitat, and in itself it is a probably a poor technique for monitoring (Platts et al. 1983, MacDonald et al. 1991, Ralph et al. 1991). It also conveys relatively little information about the geomorphic processes shaping habitat and the biotic implications of habitat change. Although pool and riffle classification is extremely useful for improving the accuracy and efficiency of fish population censuses (Hankin and Reeves 1988) and microhabitat characterization (e.g., Fig. 18), we suggest that habitat monitoring programs should be designed to accommodate larger-scale patterns (e.g., valley segments) and to measure selected smaller-scale variables, such as channel stability, water temperature, bed material texture, and habitat depth. Species like anadromous fishes are highly mobile and their life histories are complex. Despite the fact that fishes do exploit pools and riffles assortatively (Bisson et al. 1982), pools and riffles themselves may have far less influence on their population dynamics than do larger-scale features of the watershed and its valley (Warren 1979, Frissell et al. 1986). Examples of such larger-scale phenomena include thermal gradients and
barriers (e.g., Frissell et al. 1992c), the frequency and magnitude of landslide-induced scour events during winter, the distribution of suitable spawning sites, and the availability of quiescent floodplain habitats for winter rearing.

Our study suggests that downstream, cumulative impacts of human activity are pervasive in southwest Oregon, wherever logging has occurred over extensive portions of a drainage basin or has involved operations on steep, unstable slopes. The downstream effects of sedimentation and channel aggradation can severely damage streams even where buffer zones of riparian vegetation have been retained, and such effects persist more than 20-30 years after logging activities have ceased. At present, the downstream effects of logging are perhaps most evident in low-gradient alluviated canyons, where, following historic loss of habitat in alluvial valleys, most of the remnants of productive fish habitat in the region are concentrated (Frissell et al. 1992a). Without classification and stratification of data by valley segment type and stream size or slope, many of these patterns would be confounded by natural variation, and we would not have detected the impacts of human activity. It seems likely that many studies in the literature suffer from the failure to sort large-scale natural variation from the effects of human activities, and the most likely outcome of this is that the frequency, magnitude, and persistence of human impacts on aquatic ecosystems have been widely underestimated.
ACKNOWLEDGEMENTS

This study was completed while the authors were funded by a grant from the Oregon Department of Fish and Wildlife, under the Wallop-Breaux program for Federal Aid in Fish Restoration, with matching funds provided by Oregon State University. Rodney Garlan assisted in data analysis. We thank Mike Hurley of Boise, Idaho, and Steve Ralph, Center for Streamside Studies, University of Washington for encouraging advice.
Chapter 4

Water Temperature and Distribution and Diversity of Salmonid Fishes in Sixes River Basin, Oregon, USA: Changes Since 1965-72

C. A. Frissell
R. K. Nawa
W. J. Liss

Oak Creek Laboratory of Biology
Department of Fisheries and Wildlife
104 Nash Hall
Oregon State University
Corvallis, Oregon 97331
We measured summer water temperature and assessed its relationship to distribution and relative abundance of juvenile fishes in a small coastal river system in the Klamath Mountains of southwest Oregon. To assess changes over time, we compared our results with a similar study in Sixes River in 1965-72. After 20 y, maximum temperature declined 2-3°C at one mainstem site, increased 2-4°C in one tributary affected by grazing, but remained unchanged at four other sites. Interannual climatic and streamflow variation had little detectable effect on maximum water temperature. Rearing distributions of coho and chinook salmon have expanded into headwater tributaries which have afforested and cooled since 1972, but both species were absent from several small tributaries in which they formerly occurred. Juvenile chinook salmon are no longer found during summer in warm, mainstem reaches where they were formerly present. The number of species and age-classes present and density of juvenile salmonids in stream segments were inversely related to maximum summer temperature, with progressive loss of species and age classes indicating ecologically consistent response to thermal stress. Some thermal impacts of land use, such as extirpation of local populations or life history patterns and loss of coolwater refugia in warm mainstem segments, are not readily reversible. Protection and re-establishment of complex channels having cool thermal refugia, created by floodplain spring brooks, stable woody debris accumulations, deep pools, and cool tributary and groundwater sources, is critical to sustaining biodiversity and productivity of warmer rivers of the West Coast. Thermal refugia are probably most important in alluvial valley and alluviated canyon segment types, where wider and less-shaded channels are vulnerable to warming, but where a large hyporrheic reservoir can provide cool inputs to surface waters.
1. Introduction

Water temperature exerts both direct and indirect influences on the distribution, survival, and growth of salmonid fishes (e.g., Stein et al. 1972, Smith and Li 1977, Reeves et al. 1987, Holtby 1988, Holtby et al. 1989). In streams of California, Oregon, and other areas, summer maximum temperatures approach or exceed levels lethal or highly stressful to salmonids. Logging, agriculture, and other land uses cause complex changes in stream systems, including loss of riparian forests, bank erosion, channel widening, and loss or diversion of surface waters, which can further increase water temperature (Beschta et al. 1987). Brown et al (1971) found that clear-cut logging raised maximum water temperature in some Oregon streams by 10°C or more. Recent work on Vancouver Island has shown that temperature increases of as little as a few degrees can significantly disrupt salmonid life histories, indirectly reducing survival (Holtby et al. 1989, Holtby and Scrivener 1989).

Since the mid 1970's numerous agencies have implemented riparian management guidelines, which were intended to reduce warming of streams draining forest lands by requiring buffer strips of vegetation (Beschta et al. 1987). However, many streams were logged prior to these guidelines, and there is evidence that buffer strips are not always sufficient to prevent increases in water temperature (Hewlett and Fortson 1982, Barton et al. 1985, Frissell et al. 1992b). Have new regulations fostered recovery of stream habitats and concomittant recovery of fish populations? Or have we even reduced the rate of loss? Data to answer these questions are few, but answers are important if we are to know whether existing protection measures are sufficient to ensure long-term survival and restoration of depleted populations of salmon and trout (Nehlsen et al. 1991). Global warming could increase the importance of this issue,
especially in southerly and interior portions of the ranges of coldwater species (Meisner et al. 1988, Meisner 1990).

Although water temperature is important in mediating interspecific interactions (e.g., Stein et al. 1972, Reeves et al. 1988), few existing studies relate spatial pattern in water temperature to diversity of fish assemblages. For example, it seems likely that elevated maximum temperature could lead to biotic impoverishment of native assemblages dominated by cold-water-dependent salmonids, particularly near the southern portions of their range. The native fauna of coastal streams of Oregon is heavily dominated by anadromous salmonines, and is unusually sparse in species of cyprinids, catastomids, centrarchids, and other taxa tolerant of warmer conditions (Minckley et al. 1986). Therefore warming of these systems might be expected to cause dramatic declines in fish species richness, diversity, and abundance, rather than simple replacement of intolerant by tolerant species.

Some recent studies have reported cooling trends in West Coast streams resulting from recovery of vegetation removed by logging, but it appears that fish populations have not always responded to these changes. Beschta and Taylor (1988) and Hostetler (In press) reported recent cooling of streams in two Oregon Cascades watersheds, presumably in response to re-growth of vegetation in logged and flood-impacted riparian areas. Dambacher (1991) found that despite cooling and recent construction of artificial habitat structures, summer temperature still strongly limits rearing of juvenile steelhead in Steamboat Creek basin. In the Alsea Watershed Study, Needle Branch warmed by 16°C following clearcut logging in 1966, then recovered nearly to pre-logging temperatures by 1973 (Moring 1975, Hall et al. 1987); however, the cutthroat trout population in Needle Branch still had not recovered to pre-logging levels more than 20 years later (Hall et al. 1987, Schwartz 1991). McSwain (1987) found that the upper Elk River, a southern Oregon coastal stream, had cooled by 4°C since the 1960’s,
corresponding with recovery of riparian forests that had been disturbed by floods and mass failures. There is no evidence that returns of wild salmon to Elk River have increased over this period (Nicholas and Hankin 1988).

In 1972 Stein et al. described the rearing distribution and ecological interactions of juvenile coho and chinook salmon and their relationship to water temperature in Sixes River, a southern Oregon coastal basin just north of Elk River. Stein et al. conducted their work following two decades of intense logging across much of the drainage basin. We had the opportunity to compare recent patterns in water temperature and distribution of juvenile salmonids in Sixes River basin to those of 20 y ago. We expanded the scope of the study to consider other fish taxa, and examined relationships between water temperature, relative abundance of species and age-classes, and the distribution and richness of salmonid assemblages in Sixes River.

2. Methods

2.1 Study Area

Sixes River meets the Pacific Ocean at Cape Blanco, 8 km north of Port Orford, Curry County, Oregon, USA, and drains an area of about 340 km² (Figure 20). A hot and dry period from July through September follows heavy winter and spring rains. The average daily temperature in August at Powers, near the headwaters of Sixes River, is 18°C, whereas milder conditions prevail nearer the coast, where the average daily temperature is 16°C in August at Port Orford. Coastal fog and clouds are common in early morning in the lower 10 km of the basin, but during July and August skies usually clear before 10 AM.
Figure 20. Location of water temperature (open circles) and air temperature (solid circles) stations, 1987-89. Stations are identified in Table 11.
The lower 13 km of the river, a 7 km stretch above the Middle Fork, and lower river tributaries pass through alluvial valleys dominated by pasture, mixed woodlands, and small farms. The remaining 15 km of the river pass through canyons forested with Douglas-fir, Port-Orford-cedar, bigleaf maple, red alder, California bay laurel, and other species. Small placer mining operations have been common since the 1880's, but all have been short-lived and have had only limited, local impacts on streams. The northern two-thirds of the basin, including most of the mainstem riparian area, is second-growth private forest, having been logged between 1930 and 1970. Since about 1988 logging has been renewed in second-growth stands on private lands. The southern part of the basin is extremely steep and erodible terrain mostly inside the Siskiyou National Forest. Much of the Forest Service land has been clearcut since about 1965, but upper Dry Creek and portions of South Fork Sixes River remain in mature and old-growth forest.

Large floods can cause channel widening, damage of riparian vegetation, and consequent elevation of water temperatures (McSwain 1987, Beschta and Taylor 1989). Both the 1968-72 and 1987-89 intervals followed by 3-5 y a high-magnitude (>20-y return interval) flood, so were comparable in this respect.

Sixes River supports an average run of about 2,600 fall chinook salmon (Oncorhynchus tshawytscha) (Nicholas and Hankin 1988); although most spawn in Dry Creek, some spawn in other tributaries and parts of mainstem. Stein et al (1972) reported that the run of coho salmon (O. kisutch) in Sixes River numbered about 250; no recent estimates are available. The winter steelhead (O. mykiss) run averages an estimated 1600 adults (Kenaston 1989). Small numbers of adult sea-run cutthroat trout (O. clarki) begin entering the river as early as July, and there are resident populations of cutthroat and probably rainbow trout in cooler tributaries. Sixes River fresh waters also contain the threespine stickleback (Gasterosteus aculeatus) and the basin is the
southernmost locality of the largescale sucker (*Catostomus macrocheilus*). We counted these species in our surveys. Chum salmon (*O. keta*) are present as adults in winter and fry in spring (Oregon Department of Fish and Wildlife, unpublished data, Elk River Research Laboratory), but are absent in summer. Several benthic species found in streams in the basin, including the Pacific lamprey (*Entosphenus tridentatus*), and three sculpins, *Cottus asper*, *C. aleuticus*, and *C. perplexus* (Reimers and Baxter 1976), were difficult to count with our visual snorkel census technique and are not considered in this paper.

2.2 Historical Data

We obtained information on water temperatures and salmon distribution from Stein et al (1972), Stein (1971), and Reimers (1971), and unpublished records for Sixes River from 1965 through 1972 obtained from the Oregon Department of Fish and Wildlife (Gary Susac, Elk River Research Laboratory, 95159 Elk River Rd., Port Orford, OR). The data consist of daily and weekly water temperature records, and seine sampling and snorkel observations of salmonids (primarily coho chinook salmon). We cross-referenced published data with the original records. In two instances, we located unpublished records in the file which compelled us to make minor additions to the Stein et al. (1972) distribution maps, but otherwise there was good agreement between available field records and published data. We found that the published information relied partly on original data sources we could not locate. In unpublished records we located water temperature data that extended the historical data set beyond that available from published sources.
2.3 Water Temperature

During the summers of 1987-1989, we installed laboratory-calibrated Taylor maximum-minimum thermometers at 14-16 sites in Sixes River and its major tributaries (Figure 20, Table 11). We located six of our stations at approximately the same sites where temperature was recorded during 1965-1972 (Stein et al. 1972, Reimers 1971). Restricted access prevented us from monitoring temperature in upper basin tributaries (North Fork, Crafton Creek, Hayes Creek). Remaining stations were dispersed to capture major tributaries and their influence on the longitudinal thermal profile of the mainstem. We located thermometers in moderately deep, well-mixed water near the margin of the main channel of the river, away from backwaters or other microsites where small-scale thermal gradients are likely.

Maximum, minimum, and present temperature were recorded and thermometers reset at each station at intervals which varied from 1-3 weeks. On each visit we calibrated the maximum-minimum thermometer against a hand-held thermometer of known accuracy, and replaced, or adjusted the maximum-minimum devices as necessary. On some visits we checked nearby locations in the water column with a hand-held thermometer for evidence of thermal stratification and cold or warm pockets. We estimate that nearly all observed temperatures are within about 0.5°C (1.0°F) of true values. Not all stations were monitored during 1987 and 1988, and occasional missing values also resulted from disturbance or loss due to beavers, otters, and humans.

By comparing sampling intervals for maximum temperature data across all years, we identified six periods from May to September within which we could aggregate the raw data to define period-specific maxima and minima for most stations and years (May 5-June 10, June 11-31, July 1-20, July 21-Aug. 10, Aug. 11-31, and Sept. 1-25). For each station where historical data were available, we analyzed trends in maximum
Table 11. Temperature station locations and physical data. Station numbers as plotted on map, Figure 1. Riparian condition codes characterize 100-m reach above station as follows: M = mature and old-growth coniferous and deciduous forest; SG = second growth forest, logged 10-50 years ago; Gr = grazed; Ch = channelized.

<table>
<thead>
<tr>
<th>Number</th>
<th>Location</th>
<th>Stream Order</th>
<th>Riparian Condition</th>
<th>Annual Maximum Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sixes R below Highway 101</td>
<td>7</td>
<td>SG, Gr</td>
<td>22 23.5 23</td>
</tr>
<tr>
<td>2</td>
<td>Lower Crystal Cr</td>
<td>5</td>
<td>SG,Gr,Ch</td>
<td>23.5 24 23</td>
</tr>
<tr>
<td>3</td>
<td>Sixes R below Edson Cr</td>
<td>7</td>
<td>SG</td>
<td>23 23 23</td>
</tr>
<tr>
<td>4</td>
<td>Edson Cr</td>
<td>5</td>
<td>M</td>
<td>19.5 19.5 18</td>
</tr>
<tr>
<td>5</td>
<td>Dry Cr at mouth</td>
<td>6</td>
<td>SG</td>
<td>17.5 -- 19.5</td>
</tr>
<tr>
<td>6</td>
<td>Dry Cr above Westbrook bridge</td>
<td>6</td>
<td>M</td>
<td>-- 20.5 20</td>
</tr>
<tr>
<td>7</td>
<td>Sixes R above Little Dry Cr&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7</td>
<td>SG</td>
<td>25 25.5 24</td>
</tr>
<tr>
<td>8</td>
<td>Sixes R below Elephant Rock Cr</td>
<td>7</td>
<td>M</td>
<td>23 24 22</td>
</tr>
<tr>
<td>9</td>
<td>Elephant Rock Cr</td>
<td>5</td>
<td>SG</td>
<td>23.5 24.5 20.5</td>
</tr>
<tr>
<td>10</td>
<td>South Fork Sixes R</td>
<td>6</td>
<td>M</td>
<td>20 18.5 18.5</td>
</tr>
<tr>
<td>11</td>
<td>Sixes R above S. Fk.</td>
<td>6</td>
<td>M</td>
<td>24 25.5 24.5</td>
</tr>
<tr>
<td>12</td>
<td>Otter Cr</td>
<td>5</td>
<td>SG</td>
<td>17 20.5 17.5</td>
</tr>
<tr>
<td>13</td>
<td>Sixes R below Big Cr</td>
<td>6</td>
<td>SG</td>
<td>-- -- 23</td>
</tr>
<tr>
<td>14</td>
<td>Sixes R at Rusty Butte Cr&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6</td>
<td>SG</td>
<td>24.5 23.5 22</td>
</tr>
<tr>
<td>15</td>
<td>Middle Fork Sixes R</td>
<td>5</td>
<td>SG</td>
<td>21.5 20.5 20.5</td>
</tr>
<tr>
<td>16</td>
<td>Sixes R above Middle Fk.</td>
<td>6</td>
<td>SG,Gr</td>
<td>25 26 24</td>
</tr>
<tr>
<td>17</td>
<td>Air at Rusty Butte Bridge</td>
<td>-</td>
<td>SG</td>
<td>36 33 29</td>
</tr>
<tr>
<td>18</td>
<td>Air above South Fork</td>
<td>-</td>
<td>M</td>
<td>-- -- 28.5</td>
</tr>
<tr>
<td>19</td>
<td>Air at Edson Cr Park</td>
<td>-</td>
<td>M</td>
<td>30 34.5 30.5</td>
</tr>
<tr>
<td>20</td>
<td>Air at Lower Crystal Cr</td>
<td>-</td>
<td>M</td>
<td>-- -- 28</td>
</tr>
</tbody>
</table>

<sup>a</sup> Named Sixes R at Kronenburg Bridge in Reimers (1971) and Stein et al. (1972).

<sup>b</sup> Moved from 20 m below mouth of Rusty Butte Creek in 1987-88 to 100 m above mouth of Rusty Butte Cr in 1989.
and minimum water temperature within each of the six periods separately by comparing the interannual means and variance between the 1968-72 and 1987-89 intervals. The statistical procedure we used was the two-sample t-test, with each year a single observation, p-values >0.05 considered not significant. Sample sizes varied from 2-6.

For each station and each of the six seasonal periods, we compared interannual variance in temperature by calculating the coefficient of variation, corrected for sample size (Sokal and Rohlf 1981, p.59) for the 1968-72 and 1987-89 intervals. Rohlf (1981, p.59).

2.4 Environmental Variation

To assess changes in climatic conditions, we obtained air temperature and precipitation records for NOAA weather stations at Port Orford and Powers (located several km east of the headwaters of Sixes River, see Figure 20). Discharge data for the South Fork Coquille River at Powers, which drains the area immediately east of Sixes River, was used as a surrogate index for Sixes River stream flows. Daily discharge at this station is highly correlated with that of Elk River during summer (McSwain 1987), so we assume it is with the adjacent Sixes River as well. We also established 2-4 air temperature stations each year at stations near selected water temperature stations (Figure 20). Maximum-minimum thermometers were installed at shaded sites on floodplains or adjacent toeslopes about 2 m above the forest floor and 3-10 m from the stream.

To test for differences between early and late years, we compared interannual mean values and variance for the intervals 1968-72 and 1987-89. The values we tested included average daily maximum and mean air temperatures in June and August,
maximum air temperatures during the six periods used for water temperature analysis (see above), days of month with measurable precipitation from June to September (a rough index of cloud cover), and peak annual, mean annual, and July minimum discharge. We also regressed maximum water temperature against these variables to determine whether they consistently influenced interannual variation in water temperature. Finally, we inspected longer time series (1960-89) of each variable to ensure our data years were not outliers relative to longer-term mean conditions.

2.5 Fish Distribution

Our primary objective was to determine late summer species distribution and estimate variation in relative abundance of species among warm and cool segments of the river and its tributaries during the warmest part of the year. We censused fish by visual methods, snorkelling downstream using two divers in mainstem segments and moving upstream with one or two divers in tributaries. We surveyed at various times during the summers of 1987-90, and did some seining in 1987 to help confirm visual identification of species and age classes. From August to early September of 1988 we conducted a comprehensive census of reaches near our thermometer stations. In 1988 and 1989 we made repeated surveys of pools in several stream segments starting as early as April and continuing to early September. Finally in August and September 1990 we snorkeled several tributaries we had not previously visited.

We classified the observations by species and, for cutthroat and rainbow trout, by age class as estimated from relative size (age 0, <10 cm; age 1+, 10-20 cm; age 2+, >20 cm). It was impossible to visually distinguish age 0 cutthroat from age 0
rainbow trout, nor could we distinguish juvenile steelhead from resident rainbow trout. All chinook and coho salmon were thought to be age 0. We sampled from 1 to 15 pools (usually 3-6) per stream segment per visit, and visited many segments 3 or more times. We snorkled only in stream segments accessible to all species of anadromous fish, so our data do not include resident populations above barriers.

Because all species and age classes of salmonids concentrated (estimated 90-99% of individuals) in pools during the low flows of mid-late summer, we use estimates of average density in pools (fish per square meter) during late July-early September as our index of abundance. Based on segments where we sampled both extensively and frequently, density varied by 4-5 orders of magnitude between river segments, but varied less (0-1 order of magnitude) between pools within a single segment, and varied little (<1 order of magnitude) between years within segments and between weeks from late July to early September (see also Hall and Knight 1981, Hankin and Reeves 1988).

Although pool area increased with stream size, and a few age 0 and 1 trout did occur in some riffles, we found that factoring these variables into our analysis had little effect on the distributional pattern and relative abundance estimates, and considerably complicated analytic procedures. Therefore, we determined that order-of magnitude estimates of density captured the vast proportion of between-segment variation in abundance, and proved the most reliable, easily estimated, and parsimonious index for our basin-scale analyses.

As a secondary objective, we expanded our density estimates into crude estimates of basin-wide total abundance. From 8 streams where we had carefully measured field data, we developed a predictive relationship between stream order and average wetted width of pools at low flow. This relationship was used, together with pool length measured using a hip chain during snorkel surveys, to estimate pool area per lineal kilometer of stream for each segment of Sixes River and its tributaries thought
to be accessible to anadromous fish. Total abundance was estimated by multiplying average fish density in pools by estimated pool area in each segment. For analysis of overall distribution of fish through the basin, we aggregated segments into three roughly similar-sized "sections" of the basin (upper, middle, and lower), distinguished by major discontinuities in geology and valley form of the watershed. We acknowledge our abundance estimates are rough (±50%), but because fish distribution varies so dramatically among sections and species, the results are nevertheless meaningful.

The major limitation of our data is that on several tributaries (Crystal Creek, Crafton Creek, North Fork Sixes River) only a few pools were sampled; our expanded estimates of average density for these streams may not be very reliable. We did not visit two small tributaries, Beaver Creek and Hayes Creek. Based on past surveys by Oregon Department of Fish and Wildlife, we assumed anadromous fish do not use South Fork Sixes River above a series of boulder cascades at about km 1.0.

During July 1988 we conducted intensive observations in several pools in Edson Creek and Sixes River near the mouth of Edson Creek. Over two days we made repeated snorkel observations of fish behavior in relation to diel changes and spatial variations in water temperature. Using hand-held thermometers we identified and measured thermal refugia used by fish during the warm part of the day.

3. Results

3.1 Environmental Conditions

Year-to-year fluctuations generally masked any mean differences in environmental variables between the 1968-72 and 1987-89 intervals. With two
exceptions, we found no statistically significant difference between the 1968-72 and 1987-89 intervals in streamflow, air temperature, and precipitation (two-sample t-test with each year as one observation, not significant if p>0.05). Furthermore, interannual variation in climate and streamflow had little detectable relationship to interannual variation in maximum water temperature within the six 2-3 week periods, based on regression analysis of various combinations of environmental variables and water temperature data from stations where we had the longest time series.

Two variables did differ significantly between the year intervals, but in both cases these probably had little effect on maximum water temperature, which occurred in July or August. Minimum annual streamflow was significantly lower (p<0.02) during 1987-89 than 1968-72, but these lowest flows occurred in late September or October, well after late-seasonal cooling of streams had begun. A better comparison of streamflow during the time of warmest water is the July minimum flow, which did not vary significantly between the two intervals. Air temperature was significantly higher in 1987-89 during only the latest period, Sept. 1-25, and then only at Powers (+4.6°C, p<0.02).

Inspection of longer (post-1960) time series of climate and streamflow data confirmed that most years in our data set did not deviate widely from long-term mean conditions. The exceptions were 1) the series of low minimum annual flows during 1987-89 as discussed above, and 2) late summer of 1970 which had the coolest Aug.-Sept. average temperature since 1960 at both Powers and Port Orford. On average the interval 1968-72 appeared slightly cooler and wetter in June-July and slightly cooler in Aug.-Sept. at both stations, compared to the 1987-89 interval. However, these differences were apparently too subtle to be reflected in variation of maximum water temperature on a biweekly scale. Even during cooler years, all months had days-long stretches of hot, dry weather, during which peak water temperatures occurred.
3.2 Water Temperature

Of the six stations where we had data from both the 1968-72 and 1987-89 intervals, we found evidence for warming at one site, cooling at one site, and no change at the remaining sites (Table 12, Fig. 21). Only four of the stations, however, had sufficient data for statistical analysis. Where cooling or warming was observed, only maximum temperature had changed; minimum temperature at all sites during nearly all periods varied little across years. The similarity of minimum temperatures from our stations in 1987-89 to historic minima provides evidence that we located our thermometers accurately near the historic stations.

At the lowermost station on Sixes River below Highway 101 there was some indication of 0.5-1°C warming since 1972 in all six periods (Fig. 2A), but this pattern was not statistically significant in any period (p>0.05). Warming of 3.5-5.5°C was evident at a nearby station on lower Crystal Creek (Fig. 21B), and this was statistically significant in 3 of the 5 periods having sufficient data for analysis. Annual maximum temperature increased by 3°C (p<0.05). Crystal Creek has been affected by both intensive grazing and channelization associated with road construction in recent decades.

If interannual variance in temperature increases, this might indicate that streams are more vulnerable to climatic variation than they formerly were. Of six sites and periods where we detected statistically significant changes in maximum temperature, the coefficient of variation increased in five cases from the 1968-72 interval to the 1987-89 interval. At all three sites where maximum temperature increased significantly, the coefficient of variation increased as well. However, of the three sites where temperature decreased significantly, variation increased at two sites and decreased at one. When we expanded the analysis to include sites and periods where changes in temperature were not statistically significant, coefficient of variation increased from 1968-72 to 1987-89
Table 12. Change in interannual mean water temperature maxima (nearest 0.5 degrees C) between the year intervals 1965-72 and 1987-89. Statistical significance is P-value from two-sample t-test comparing years within daily periods indicated; n.s. means P > 0.05. Temperature change in parentheses is based on sample size of one (one year) within at least one interval; dash indicates no data, or insufficient sample size for statistical analysis.

<table>
<thead>
<tr>
<th>Period</th>
<th>Sixes R. at Hwy. 101</th>
<th>Crystal Creek</th>
<th>Edson Creek</th>
<th>Sixes R. below Little Dry Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp (°C)</td>
<td>Signif.</td>
<td>Temp (°C)</td>
<td>Signif.</td>
</tr>
<tr>
<td>Annual Maximum</td>
<td>+0.5</td>
<td>n.s.</td>
<td>+3.0</td>
<td>0.007</td>
</tr>
<tr>
<td>7 May-10 June</td>
<td>(+1.0)</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>11 June-30 June</td>
<td>(+1.5)</td>
<td>--</td>
<td>(+3.5)</td>
<td>--</td>
</tr>
<tr>
<td>1 July-20 July</td>
<td>+1.0</td>
<td>n.s.</td>
<td>+4.0</td>
<td>0.047</td>
</tr>
<tr>
<td>21 July-10 Aug.</td>
<td>+0.5</td>
<td>n.s.</td>
<td>+2.0</td>
<td>n.s.</td>
</tr>
<tr>
<td>11 Aug.-31 Aug.</td>
<td>+0.5</td>
<td>n.s.</td>
<td>+2.5</td>
<td>0.026</td>
</tr>
<tr>
<td>1 Sep.-25 Sep.</td>
<td>+1.0</td>
<td>n.s.</td>
<td>+2.0</td>
<td>n.s.</td>
</tr>
</tbody>
</table>
Figure 21. Maximum water temperature by seasonal time period beginning May 5 and ending Sept. 25 (see text for dates). Points are interannual means, bars show 95 percent confidence interval around mean.
Figure 21
regardless of whether maximum temperature increased or decreased. The results suggest there is no clear relationship between maximum temperature and interannual variance in temperature.

Another important lower river tributary, Edson Creek, showed no indication of consistent warming or cooling (Fig. 21C). The riparian zone of lower Edson Creek is a mature, mixed-conifer-and deciduous forest protected in a county park. In recent years, however, numerous streamside trees have been fallen by widespread, active bank erosion, which may result from landslides associated with logging in the watershed during the 1970's and early 1980's. Apparently recent change in the watershed of Edson Creek has not yet affected water temperature.

Farther upstream on the mainstem of Sixes River above Little Dry Creek there was strong evidence of cooling (Fig. 21D), perhaps associated with re-growth of riparian trees removed from this part of the basin in the 1950's and 1960's. Cooling varied from 2-3°C depending on the period; the change was statistically significant in 2 of the 4 periods with sufficient data for analysis. Annual peak temperature decreased by 2.5°C.

Data for two other up-river mainstem sites were too limited for statistical comparison, but there was no indication of warming or cooling. Based on the magnitude of interannual variation evident in analyses at the previous stations, it is possible to infer that maximum temperature must change by >2.0°C to be statistically detectable within sample sizes of fewer than 5 years; furthermore, a statistically significant change is usually apparent during two or more consecutive seasonal periods. There were no such indications of temperature change in the few data available for Sixes River above South Fork (Fig. 21E) and Sixes River below Rusty Butte Creek (Fig. 21F).

Although the within-station comparisons indicate only very limited cooling in the mainstem Sixes River and none in two tributaries over recent decades, examination of
data from the complete network of stations affords a higher level of spatial resolution. These data suggest that local cooling has occurred in some tributaries and short reaches of the mainstem. For example, a downstream profile of maximum temperature for the warm period July 20-Aug 10 in 1989 (Figure 22B) suggests that cooling occurs over reaches of perhaps 3-5 km in the mainstem. Chinook salmon and rainbow trout are more abundant in these reaches than in warmer reaches above and below (see below, "Fish Distribution"). Compared to data for the same period in 1970, the year when comparable historic data are available from the greatest number of stations (Fig. 22A), there is some indication of local cooling in 1989 in two segments of upper Sixes River that was not apparent in 1970. It is uncertain whether changes in the downstream temperature profile of the mainstem are driven by increased forest cover along the mainstem, changes in channel morphology, or recovery of riparian vegetation along tributaries logged in the 1960's and early 1970's. The pattern in Figure 22B suggests that cooling of the mainstem occurs below major tributaries.

3.3 Fish Distribution

Distribution and relative abundance of each species and age class of fish we counted are mapped in Figure 23. Although abundance and distribution varied by species and age class, there were some striking common features in the spatial patterns. Several key tributaries supported all species and age classes in good numbers, whereas in some segments of the mainstem most species and age classes were absent (Figure 23A). Coho salmon were absent from all but the uppermost reaches of the mainstem Sixes River during summer. Juvenile coho were most abundant in tributaries in the upper reaches of the basin and in several lower-river
Figure 22. Longitudinal profile of maximum temperature during late July to early August of 1970 (A) and 1989 (B). Circles are mainstem stations, triangles are tributary stations. Horizontal dashed lines indicate biotic thresholds identified at 21 C and 23 C (see text). Typical fish assemblage for the temperature range is summarize as follows: Rb 0,1 means rainbow trout (steelhead) fry and yearlings; Rb 2+ means age 2 and older rainbow trout; Chf means chinook salmon fry; Coho means coho salmon fry; Ctt means cutthroat trout yearlings and older. Shaded areas highlight mainstem segments where maximum temperature is below 23 C.
Figure 22
tributaries (Fig. 23B). Chinook salmon were found in most of the same tributaries, but also occurred in portions of the mainstem Sixes River (Fig. 23C). Substantial numbers of chinook were seen in Dry Creek and in Sixes River from Dry Creek downstream to the estuary. Based on past studies (McGie 1969, Reimers 1971, Reimers 1978, Reimers et al. 1979) and surveys in recent years (G. Susac, unpublished data) by Oregon Department of Fish and Wildlife, large numbers of juvenile chinook spend the summer in Sixes River estuary.

Comparison with data for 1965-72 indicates that local contractions and expansions in distribution have occurred among both coho and chinook salmon (Table 13). The summer rearing range of each species has remained declined in the lower basin, has declined dramatically in the middle portion of the basin, and has expanded in the upper basin.

Range contractions have occurred in tributaries and mainstem segments of the middle portion of Sixes basin. Coho and chinook salmon were absent from two middle-basin tributaries (Elephant Rock Creek, Little Dry Creek) and two lower-river tributaries (Beaver Creek, "Andrews Fork" of Crystal Creek) where they had been observed in 1965-72. Little Dry Creek was reported to support high densities of both coho and chinook juveniles prior to 1972, but from 1986 through 1991 it was entirely dry during summer months in its lower 1 km. A series of landslides followed road construction and clearcutting of portions of this drainage basin in the late 1960's and 1970's, and the channel today is highly aggraded with coarse sediment (Frissell et al. 1992b). Another tributary to upper Sixes River reported to contain summer populations of coho in 1965-72 was nearly dry when we visited it in 1990 and supported only a few trout fry. Finally, chinook are absent today from two warm sections of the mainstem Sixes River where they were apparently present during summer prior to 1972.
Figure 23. Maps of the number of salmonid age classes and species present in Sixes River during late summer in 1987-90 (A) and the distribution and abundance by species and age classes (B-G). Line pattern indicates approximate density (fish per square meter in pools, see key at bottom left). For chinook and coho salmon, dot-dash pattern adjacent to stream indicates distribution in 1969-71 as reported by Stein et al. (1972).
A. NUMBER OF SALMONID SPECIES-AGE CLASSES PRESENT

B. AGE 0 COHO SALMON

C. AGE 0 CHINOOK SALMON

D. AGE 0 TROUT (Rainbow and Cutthroat)

E. AGE 1+ and 2+ RAINBOW TROUT

F. AGE 1-2+ CUTTHROAT TROUT

G. OTHER FISHES

Figure 23
Table 13. Change in summer (July-August) distribution of juvenile coho and chinook salmon in upper, middle, and lower portions of Sixes River basin. Total habitat accessible to anadromous fish estimated from USGS 1:24,000-scale topographic maps, is about 170 lineal km.

<table>
<thead>
<tr>
<th>Species</th>
<th>Section of Basin</th>
<th>1968-72</th>
<th>1987-89</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0+ coho</td>
<td>Upper&lt;sup&gt;a&lt;/sup&gt;</td>
<td>12.2</td>
<td>46.8</td>
<td>+284%</td>
</tr>
<tr>
<td></td>
<td>Middle&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.5</td>
<td>2.7</td>
<td>-58%</td>
</tr>
<tr>
<td></td>
<td>Lower&lt;sup&gt;c&lt;/sup&gt;</td>
<td>43.6</td>
<td>40.9</td>
<td>-6%</td>
</tr>
<tr>
<td></td>
<td>Total, coho</td>
<td>62.3</td>
<td>90.4</td>
<td>+45%</td>
</tr>
<tr>
<td>0+ chinook</td>
<td>Upper</td>
<td>15.3</td>
<td>39.4</td>
<td>+158%</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>42.2</td>
<td>13.7</td>
<td>-68%</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>74.9</td>
<td>77.6</td>
<td>-3%</td>
</tr>
<tr>
<td></td>
<td>Total, chinook</td>
<td>128.2</td>
<td>135.1</td>
<td>-5%</td>
</tr>
</tbody>
</table>

<sup>a</sup> Upper basin = from Rusty Butte Bridge upstream (river km 24-30; 50 lineal km of accessible habitat [29%]).

<sup>b</sup> Middle basin = above Dry Cr upstream to Rusty Butte Cr (river km 12-24; 42 lineal km of habitat [25%]).

<sup>c</sup> Lower basin = Estuary to Dry Cr (river km 0-12; 78 lineal km of habitat [46%]).
Coho salmon have expanded their summer rearing range in the upper basin; populations today are found throughout summer in Middle Fork Sixes River, Upper Sixes River, North Fork Sixes River, and Crafton Creek, none of which were reported to hold coho in summer during 1965-72. According to Stein et al. (1972), many of these streams supported coho in spring months, but these fish either moved from or perished in these habitats as water temperature increased in early summer. The range of summer-resident chinook salmon has likewise increased through headward expansion into upper basin tributaries. The summer-long presence of coho and chinook salmon in Crafton Creek, which formerly exceeded 25°C for much of the summer, suggests that upper-basin streams have cooled substantially in the past 20 y, probably due to vegetation growth in riparian areas that were logged in the 1960’s.

Young-of-the-year trout (probably >90% rainbow, <10% cutthroat) were observed in all streams that had surface flow. The largest concentrations, however, were found in Dry Creek, Edson Creek, and upper basin tributaries (Fig. 23D). Age 1+ rainbow trout occurred in all major tributaries and certain portions of the mainstem; age 2+ rainbows were rare, but were distributed similarly (Figure 23E). Cutthroat trout (age 1 and older) were the rarest group, and appeared to be restricted to cooler tributaries (Fig. 23F). Juvenile cutthroat trout were not observed in the mainstem Sixes River, but we found mature sea-run cutthroat throughout summer holding in large pools, even where water temperature was quite high (Fig. 23F). Pre-1972 seining records did not distinguish between species or age classes of trout sampled in Sixes River, but as today, “trout” in some form were ubiquitous in the basin.

The two other fish species had distribution patterns markedly different from the salmonids (Fig. 23G). Largescale suckers were confined to the mainstem, with adults and fry observed in segments of the upper mainstem and lower mainstem. We never observed more than seven adult suckers in a pool, and observed few or no subadults
(5-20 cm). Only a few mainstem pools held any individuals of this species. Although we did not estimate a population size, the abundance of largescale suckers appeared to be markedly lower than it was in 1979, when Oregon Department of Fish and Wildlife researchers observed large schools, and captured and tagged 88 adults from a single pool (T. W. Downey, unpublished report, Elk River Research Laboratory). Threespine sticklebacks were abundant in the mainstem and tributaries of the lower river as both adults and fry. We commonly observed schools numbering in the hundreds or thousands in backwater pools. While snorkeling we observed juvenile salmonids preying on stickleback fry.

3.4 Basin-Wide Abundance

To assess relative abundance and large-scale patterns in distribution of species, we made crude estimates of total population size (Table 14). Although all three portions of Sixes basin contain roughly equal amounts of available habitat, the populations of all species and age classes are concentrated in upper and lower portions of the basin, with relatively few fish in the central basin. Most cutthroat trout and chinook salmon are found in the lower basin, with most chinook in the mainstem and cutthroat in the tributaries. Assuming that Oregon Department of Fish and Wildlife estimates of average mid-summer peak abundance of chinook salmon in the estuary since 1970 (Reimers and Downey 1980) reflect present-day estuary conditions, we estimate that about one-third of the mid-summer population of juvenile chinook in Sixes River resided in freshwater during 1987-89, with the remainder in the estuary. Based on our observations of tagged fish (unpublished data), we believe that many chinook in the mainstem of Sixes River are migrating downstream during late July and August. Peak migration into the estuary
Table 14. Available habitat and crude estimates of total abundance of juvenile salmonids by species/age class in upper, middle, and lower sections of Sixes River basin in midsummer of 1987-89. Upper, middle, and lower sections defined as in Table 3 except estuary (river km 0-5) broken out from lower basin.

<table>
<thead>
<tr>
<th></th>
<th>Upper Basin</th>
<th>Middle Basin</th>
<th>Lower Basin</th>
<th>Estuary</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0+ coho</strong></td>
<td>8000 (66%)</td>
<td>40 (0.3%)</td>
<td>4100 (34%)</td>
<td>0</td>
<td>12,140</td>
</tr>
<tr>
<td><strong>0+ chinook</strong></td>
<td>5400 (6%)</td>
<td>460 (0.5%)</td>
<td>28,000 (30%)</td>
<td>60,000a (64%)</td>
<td>93,000</td>
</tr>
<tr>
<td><strong>0+ trout</strong></td>
<td>38,000 (29%)</td>
<td>4000 (3%)</td>
<td>88,000 (68%)</td>
<td>60,000a (64%)</td>
<td>93,000</td>
</tr>
<tr>
<td><strong>1+ rainbow</strong></td>
<td>2,500 (50%)</td>
<td>100 (2%)</td>
<td>2,400 (48%)</td>
<td>0</td>
<td>5,000</td>
</tr>
<tr>
<td><strong>1-2+ cutthroat</strong></td>
<td>25 (6%)</td>
<td>5 (1%)</td>
<td>365 (93%)</td>
<td>?b</td>
<td>390?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Upper Basin</th>
<th>Middle Basin</th>
<th>Lower Basin</th>
<th>Estuary</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lineal km of accessible habitat</strong></td>
<td>50 (29%)</td>
<td>42 (25%)</td>
<td>73 (43%)</td>
<td>5 (3%)</td>
<td>170</td>
</tr>
<tr>
<td><strong>Estimated total pool area (X1000m²)</strong></td>
<td>125 (23%)</td>
<td>120 (22%)</td>
<td>195 (35%)</td>
<td>115 (20%)</td>
<td>555</td>
</tr>
</tbody>
</table>

a Based on ODFW estimates.
b ODFW sampling indicates estuary serves as nursery for juvenile cutthroat trout, but numbers are unknown.
c Estimated from US Geological Survey 1:24,000-scale topographic maps.
d Extrapolated from estimate of accessible stream length and field measurements of pool length and wetted width.
during the 1970's occurred in June or early July (Reimers et al. 1979, Reimers and Downey 1980).

3.5 Temperature, Abundance, and Assemblage Diversity

Among stream segments where we had both temperature and biological data for 1987-89, the diversity of the salmonid assemblage, measured by the number of species and age classes observed, declined as maximum water temperature increased (Fig. 24). This pattern reflected a progressive loss of thermally sensitive species with warming. The coolest streams held all four species, including three age classes of rainbow and cutthroat trout. Cutthroat, coho, and chinook dropped out in sequence as maximum temperature increased, with rainbow trout the only species present in waters exceeding 23°C.

Overall abundance of salmonids declined as maximum temperature increased (Fig. 25). However, the response to maximum temperature varied among species and age classes. Several species showed evidence of a threshold response (due to variation in density among cool reaches, simple linear regressions were not significant). Coho salmon were absent or rare in segments exceeding 21°C (Fig. 25B), chinook salmon were absent from two of three segments exceeding 23°C (Fig. 25C), and cutthroat trout were absent where temperature exceeded 21°C (Fig. 25D). The small numbers of chinook and coho salmon in certain warmer segments were in every case found in association with anomalous, small cool pockets in otherwise warm reaches.

Age 0 rainbow trout showed a linear response to temperature, with small numbers present in even the warmest streams (Fig. 25E). The pattern for age 1+ rainbow trout was less clear, with some indication of a threshold response above 22°C.
Figure 24. Salmonid diversity (SD) as measured by the number of species and age classes present, in relation to annual maximum water temperature (MWT). Numbers indicate the number of overlapping observations with identical coordinates.
\[ \text{SD} = -0.588(MWT) + 16.75 \]
\[ p < 0.005 \quad R^2 = 0.481 \]
Figure 25. Abundance of salmonids in relation to maximum water temperature in segments of Sixes River during 1987-90. Data are presented as total combined salmonids (A) and separate species and age classes (B-G). Note log scale on y-axis of total salmonid plot (A). Correlation coefficients, p-values and fitted curves are indicated for statistically significant (p<0.10) linear regressions of log-transformed data (A,B,D,E) (transformation necessary to stabilize variance) or non-transformed data (F).
Figure 25

**TOTAL SALMONID DENSITY**

A. \(\frac{\text{Log}_e}{\text{Log}_2}\), \(p < 0.003\)
\(R^2 = 0.506\)

**AGE 0 COHO SALMON**

B. \(\frac{\text{Log}_e}{\text{Log}_2}\), \(p < 0.015\)
\(R^2 = 0.376\)

**AGE 0 TROUT**

E. \(\frac{\text{Log}_e}{\text{Log}_2}\), \(p < 0.003\)
\(R^2 = 0.505\)

**AGE 0 CHINOOK SALMON**

C.

**I+ RAINBOW TROUT**

F. \(p < 0.08\)
\(R^2 = 0.222\)

**I+ and 2+ CUTTHROAT TROUT**

D. \(\frac{\text{Log}_e}{\text{Log}_2}\), \(p < 0.09\)
\(R^2 = 0.206\)

**2+ RAINBOW TROUT**

G.
Like cutthroat, age 2+ rainbow trout were absent or rare in all streams exceeding 21 C (Fig. 6G). The curve for total salmonid density (Fig. 25A) is strongly influenced by age 0 trout, the most abundant group, but is also shaped by the abrupt declines of coho and chinook salmon and 1+ rainbow trout between 21 and 23°C. We could find no obvious relationship between salmonid diversity or density and stream size, distance from the estuary, or measures of within-reach habitat morphology.

The pattern in diversity might change somewhat with the addition of the largescale sucker and threespine stickleback. Because these two species appeared to be confined to mainstem habitats and lower-basin habitats, respectively, other geographic factors confound the temperature analysis. For the salmonids, all stream segments we included in this analysis were accessible to and appeared to have the morphological capability to support every age class and species; water temperature appeared to be the environmental variate most strongly influencing assemblage structure.

3.6 Juvenile Behavior and Thermal Heterogeneity

During intensive underwater observations we noticed striking patterns in diurnal activity patterns of salmonids that corresponded with temporal and spatial heterogeneity in water temperature. In mainstem Sixes River near Edson Creek, a reach with a maximum temperature of about 22°C, at about 9 AM each morning we observed large numbers of juvenile chinook salmon and rainbow trout emerging from the interstices of boulder clusters along the shoreline. The fish remained active, feeding in the water column, until about 5-6 PM, when they gradually re-entered boulder crevices. These shifts in behavior corresponded approximately with the time of the minimum water temperature in the
morning, and the time of maximum temperature in the evening; fish were active during the period of warming from morning to late afternoon.

At about 6 PM in a neighboring pool, we observed large groups of fish aggregating in a shallow depression along the slip face of a gravel bar. Hundreds of chinook salmon and rainbow trout of all sizes intermingled densely in an area about 1.5 m². The fish lay on or a few mm above the substrate, were not feeding, and showed no evident agonistic behavior. Spot measurements showed the water temperature in the depression within 5 cm of the gravel bed to be 19°C, 2-3°C cooler than the temperature of the water column above. The depression accumulated shallow groundwater which percolates through the gravel bar upstream, creating a small cool lens before mixing with the warmer surface water of the pool. We presume that similar groundwater-fed cold refugia exist within or behind the boulders used by the fish, as these boulders line the bank where the river hugs the toe of a groundwater-rich slump-earthflow landform. The importance of cold refugia may also explain the occurrence of large numbers of fish in a spring-fed backwater pool along the warm mainstem of Sixes River below Dry Creek. We observed fish using other cold pockets formed in accumulations of large woody debris at groundwater inflows, and at depth in thermally stratified, isolated pools in reaches of upper Sixes River and Dry Creek having intermittent surface flow.
4. Discussion

4.1 Temperature and Fish Assemblages

Water temperature appears to be a major factor controlling species distribution and governing the structure of juvenile salmonid assemblages during summer in Sixes River. In warmer rivers whose native fauna are dominated by coldwater species such as salmonids, thermal factors may override or strongly co-determine the effects of habitat morphology, flow, food supply, and behavioral interactions (Smith and Li 1983, Reeves et al. 1987, Dambacher 1991). The relative scarcity of native, warmwater-adapted groups of fishes in many coastal stream systems suggests that in the geologic past, if not the historic past, these rivers were cooler than they are today. In systems open to colonization by warmwater fauna, increased temperature can lead to increased fish diversity, despite the disappearance of salmonid taxa (Barton et al. 1985). Although native salmonids persist in Sixes River, maximum summer temperatures throughout the basin far exceed thermal optima for these species (Beschta et al. 1987), and the ecosystem would likely be highly vulnerable to invasion if exotic, warmwater species of fishes were introduced.

Although all salmonid species in Sixes River appeared to respond negatively to increasing temperature, and species-specific responses generally appeared consistent and predictable, we caution that a simple predictive model of fish assemblage response to stream warming might not be successful. We do not know whether the distribution of fish in relation to temperature reflects mortality or movement; if the primary response to temperature is movement, our data could reflect a change in the distribution of fish with no change in their abundance basin-wide. Thermal refugia, between-basin differences in channel morphology and the spatial arrangement of different kinds of valley segments,
species interactions, food supply, and stock-specific adaptations of life history, behavior, and physiology all complicate biotic response to warming. Survival at egg-to-fry stages may vary dramatically depending on channel stability and flood occurrence (Frissell and Nawa unpublished), and variations in this or other life stages are likely to affect distribution and abundance of juveniles later in their life history. It seems clear, however, that the distribution of juvenile salmonids in Sixes basin is at least partly constrained by summer temperature and that increases in temperature are likely to further stress populations by limiting their movements, possibly capping density or reducing growth in important habitats, and perhaps eliminating key life history options with the imposition of new thermal barriers. Conversely, cooling could remove or relieve such constraints, perhaps result in nonlinear increases in certain habitats and species.

The Siskiyou National Forest (1989) uses a simple linear temperature response model that predicts a 5% decline in salmonid density with each 1°C increase in water temperature, using age 1+ steelhead trout as the indicator species for the assemblage as a whole. Our data indicate that such a linear model may be at least superficially appropriate for age 0 trout, but is not so for other, more thermally sensitive species and life stages. The abrupt loss of thermally sensitive species like coho salmon and cutthroat trout in the range of 21-23°C causes the best fit model for total salmonid density to be a logarithmically declining curve. In other words, there is a more precipitous loss of numbers (and species) between 18-22°C than between 23-27°C. As mentioned earlier, such losses could be a result of migration that does not necessarily lead to mortality. During field work in summer, however, we have frequently observed dead chinook salmon fry and steelhead parr in warmer streams. These individuals rarely showed obvious external evidence of disease, and thermal stress may have caused or contributed their mortality. On the other hand, we also have observed movement of fishes of several kilometers or more during summer (Nawa et al. 1988; Nawa and
Frissell, unpublished data). During repeated seine sampling and snorkel observations of tagged fish we found that some juvenile chinook salmon migrate downstream during summer months. Yearling steelhead (rainbow trout) may leave the mainstem and pack into cooler tributaries during warm periods.

In Sixes River 1+ steelhead (rainbow trout) were apparently less sensitive and less consistent than other fishes in their response to thermal stress, and are therefore a poor indicator of the salmonid community as a whole. A more sensitive indicator species might be cutthroat trout, which appear to decline most rapidly with increasing water temperature. The number of salmonid species present (e.g., in a standard reach of 100 m² sampled for one hour) would make a much more direct, information-rich, and easily measured indicator for monitoring the biotic integrity of native assemblages (sensu Miller et al. 1988) and, by inference, the condition of their habitats. If patterns in Sixes River reflect those in other coastal streams of the Klamath Mountains, species richness should generally be correlated with overall abundance of salmonids. It should be relatively easy to test this prediction with field data, and if it holds, it could considerably facilitate the assessment and monitoring of habitat quality.

4.2 Physical and Biological Recovery

Over time Sixes basin has seen local thermal recovery and some expansion of juvenile chinook and coho salmon into tributaries that were formerly too warm to hold these species through summer. These gains, however, are substantially offset by the disappearance of the same species from tributaries elsewhere in the basin and loss of chinook salmon from portions of the mainstem. The lack of cooling at most mainstem stations, and the fact that despite 3 C cooling since 1972 the mainstem Sixes River
above Little Dry Cr. remains too warm to hold most species, indicate that the lower
mainstem river, the primary fluvial habitat of chinook salmon in summer, has not
markedly improved over time and may rather have deteriorated somewhat. The scarcity
of cutthroat trout in upper and middle Sixes basin is consistent with other studies (Hall
et al. 1987, Schwartz 1991) showing that coastal cutthroat trout populations depressed
by logging have not recovered more than 20 years after the disturbance. Cutthroat trout
in Sixes basin were most abundant in Dry Creek and Edson Creek, two lower-basin
tributaries which have seen relatively limited riparian logging. Despite local habitat
recovery in some tributaries, persistent factors such as thermal barriers in the mainstem
could prevent the re-emergence of mainstem-dependent juvenile life history patterns that
under historical conditions might have sustained much of the productive capacity of
salmon and trout populations.

Because alluvial valleys at low elevations were logged and cleared early in the
century and have experienced extensive disturbance from both upstream and riparian
sources (Frissell et al. 1992a), we are uncertain whether the temperature of lower
mainstems of rivers such as the Sixes has changed in recent decades. Regardless, we
know that along large, wide rivers, especially in alluvial valleys such as lower Sixes River
where bedrock, boulders, and other non-vegetative roughness elements are lacking, the
role of forests in maintaining channel complexity probably greatly outweighs their role in
providing shade. Shade provided by riparian forests has a relatively minor effect on the
temperature of large, wide rivers (Theurer et al. 1985). Floodplain forests provide woody
debris, help stabilize banks, bars, and secondary channels, and they may encourage the
recharge of hyporheic zones, all processes that create complex, thermally
heterogeneous habitats in alluvial streams (Sedell and Swanson 1982, Sedell et al. 1990).

The cumulative, downstream-propagating effects of logging-related erosion in
basins like Sixes River are probably more important for fishes like chinook salmon than
are the direct impacts of human activities in riparian areas and channels (Frissell 1991, Frissell et al. 1992a, 1992b). Lichatowich (1989) suggested that coho salmon may be more vulnerable than chinook salmon to long-term impacts of logging and other activities, because mainstem river habitats are recovering from historic disturbances while tributary streams important for coho continue to be disturbed. However, our study suggests that, due to thermal limitations, in southwest Oregon the capacity for recovery is greatest in tributaries, and least in mainstem segments. Although narrow canyons and alluviated canyon segments in tributaries can be highly vulnerable to heating if riparian areas are logged or destroyed by landslides or debris flows, they recover shade relatively rapidly with riparian revegetation (Frissell et al. 1992a). Whereas coho salmon appear to have responded at least locally to recovery of riparian zones and cooling of headwater tributaries of Sixes River, there is no evidence that the most important summer habitats of fall chinook salmon in the lower mainstem have improved in the past two decades.

Alluvial valleys of mainstem rivers, by contrast, are less affected by loss of riparian shade; their thermal regime can be buffered by contact with a large hyporheic reservoir underlying floodplains and terraces. The cooling evident in the lower kilometers of Sixes River, which Reimers (1971) attributed to cooler climatic conditions along the coastline, may in fact stem from mixing of surface waters with shallow groundwater in the alluvial valley. Dry Creek, a major tributary which contributes no surface water to Sixes River during summer, probably does constitute a major hyporheic plume that cools mainstem Sixes River. It seems likely that long-term depletion of large woody debris, channel aggradation and straightening resulting from the downstream transfer of sediment from landslides and other erosion sources (Kelsey 1980, Lisle 1982, McHugh 1987, Ryan-Burkette 1989, Frissell 1991), and subsequent artificial revetment of unstable reaches to protect roads and farmland, have worsened conditions for chinook
salmon, and possibly steelhead, by reducing the availability of thermal refugia, and perhaps reducing contact between surface and hyporheic waters in the alluvial valley of Sixes River.

4.3 Habitat Refugia and Persistence of Fish Populations

Thermal refugia appear to be critical in shaping the salmonid assemblage of Sixes basin at two different spatio-temporal scales (Sedell et al. 1990). On the scale of the stream system as a whole, we hypothesize that one important factor was the persistence of unlogged, debris-rich, cool river segments in the Dement Ranch in upper Sixes River, a portion of the basin that otherwise was heavily logged and extensively warmed during the 1960's-1970's (Stein et al. 1972, Reimers 1971). The Dement Ranch segments may have provided refuge several kilometers long from which salmon colonized other upper-basin tributaries as logged streams revegetated and cooled. This refuge may have sustained coho salmon and the upper-basin runs of chinook salmon and cutthroat trout. The absence of any productive, cool refuge in the middle portion of Sixes basin could help explain the apparent extripation of salmon populations from that portion of Sixes basin.

At a finer scale, thermal micro-refugia are critical to sustain salmonids in otherwise warm surface waters within alluvial valley segments. Protected cold pockets were heavily used by juvenile salmonids during the warmest hours of the day, and these refugia allowed persistence of thermally sensitive species in some warmer segments of Sixes River. Similar phenomena have been observed in other studies (Gibson 1966, Kaya et al. 1977, Bilby 1989, Ozaki 1987), but the overall significance of thermal
microrefugia for fish production and species diversity has not been adequately investigated. Thermal refugia in Sixes River were associated with large woody debris accumulations, boulder banks along the toe of large slump-earthflow slopes, deep pools, and spring-fed side channels or backwaters.

As in Redwood Creek, a highly aggraded stream in the Klamath Mountains of northern California (Ozaki 1987), thermal refugia in lower Sixes River are associated with interannually transient geomorphic features that are easily disrupted by moderate-sized floods. In damaged watersheds, floods inhibit the recovery of riparian forests along aggraded channels by eroding streambanks and toppling or burying floodplain trees (Lisle 1981, Frissell et al. 1992b). During sediment-charged floods, secondary channels and backwater pools are rapidly filled with bedload deposits, making them dry in summer (Frissell, personal observation). Significant improvement of habitat in the alluvial valley segments of Sixes River and other southwest Oregon streams will probably not occur without stabilization of the watershed and consequent reduction of sediment load from upstream sources, together with restoration of fully-functioning floodplain forests (Lisle 1981, Frissell and Nawa 1992).

We suggest that long-term persistence of coho salmon, chinook salmon, and other salmonids in the Klamath Mountains region, where most stocks are currently seriously depressed (Nehlsen et al. 1991), will require special protection of areas that serve as refugia and sustain both downstream and riparian ecological functions (Moyle and Williams 1990, Frissell 1991, Johnson et al. 1991). Such forested refugia appear to be critical for survival of sensitive amphibians in coastal basins (Corn and Bury 1989, Welsh 1990) and there is increasing evidence that this is true for native fishes as well (Frissell 1991). To sustain the full complement of native aquatic species, effective refugia must protect both watersheds and corridors of lower-elevation, alluviated canyon or alluvial valley segments having forested floodplains.
ACKNOWLEDGEMENTS

Kelly Redmond and George Taylor of the Office of the State Climatologist at Oregon State University provided weather data. We thank Mr. Basil Andrews for sharing his daily weather data for Sixes, Oregon. We thank Joe Ebersole, Earl Hubbard, and Dan Schively for assisting in the field. Joe Ebersole and Shaun Robertson helped with data analysis. Gary Susac and Ken Fliszar of ODFW kindly provided access to historic records. We gratefully acknowledge Georgia-Pacific for allowing access to their lands for research purposes. This study was supported by the Oregon Department of Fish and Wildlife through the Wallop-Breaux program for Federal Aid for Sport Fisheries Restoration, with matching funds provided by Oregon State University.
Chapter 5

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

Christopher A. Frissell
Richard K. Nawa

Oak Creek Laboratory of Biology
Department of Fisheries and Wildlife
Nash Hall 104
Oregon State University
Corvallis, Oregon 97331
ABSTRACT

In recent years an increasing share of fishery management resources has been committed to alteration of fish habitat using 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 between 2-10-y recurrence interval. The incidence of functional impairment and outright failure varied widely among streams, with a median failure rate of 18.5% and median damage rate (impairment plus failure) of 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 showing signs of recent watershed disturbance, high sediment loads, and unstable channels. Comparison of estimated 5-10-year damage rates from 46 projects from throughout western Oregon and southwest Washington, showed high but variable rates (median 14%, range 0-100%) in regions where 10-y recurrence interval unit peak discharge of streams exceeds 1.0 m$^3$ sec$^{-1}$ km$^{-2}$ (92 cfs mi$^{-2}$). Results suggest that commonly prescribed structural modifications are often inappropriate and counterproductive in stream systems with high or elevated sediment loads, high peak flows, or highly erodible bank materials. Restoration of 4th-order and larger alluvial valley streams, where most potential fish production exists in the Pacific Northwest, will require re-establishment of natural watershed and riparian processes over the long term.
1. Introduction

During the past decade, popular demand and financial support for restoration of fish habitat in North American streams have increased dramatically. Restoration or "enhancement" activity in the west has been concentrated on direct modification of streams by installing artificial structures, such as log weirs and gabions. Despite numerous pleas for careful scientific evaluation (e.g., Reeves and Roelofs 1982; Hall and Baker 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 1980's, habitat management programs of federal agencies became increasingly dominated by artificial structure programs. For example, according to the 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 $5 million annually on stream structures and related projects in Idaho, Oregon, and Washington in attempts to mitigate for 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 the Pacific Northwest Region, and the budget for this program far
exceeded funds available to protect, monitor, and rehabilitate soil and watershed resources (U.S.D.A. Forest Service, unpublished data).

An illustration of the new reliance that resource managers are placing on artificial fish habitat technology is the Siskiyou National Forest Management Plan (U.S.D.A. 1989), which prescribes fish habitat structure projects costing more than 1.7 million dollars over three years. In the computer model used by the Siskiyou National Forest to assess the economic effects of its activities planners assumed, without supporting evidence, a net gain of three to four pounds 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 was assumed to have no significant adverse effect on fishery values (U.S.D.A. 1989). The Forest Service assumed that any adverse effects on fish habitat and water quality would be more than compensated by fish habitat created from new artificial structures.

On-going 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) suggests that studies which showed 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 sometimes damaging. For example, Hamilton (1989) observed reduced trout abundance in a northern California stream reach with artificial boulder structures, compared to 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, Petrosky and Holubetz (Idaho Department of Fish and Game, unpublished data) found little evidence that in-stream structures increased the abundance of juvenile chinook salmon and steelhead trout, and in one project more than 20 percent 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 after a flood just two years after construction. Several of the remaining structures apparently created migration barriers for fishes, a problem also observed in Oregon (C. Frissell, Oregon State University, 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). In order to achieve specific biological and economic objectives, most structure designs employed to date (e.g., wire gabions or log weirs) must remain intact at the intended site for the projected life span. Yet in the Northwest few projects have been in place long enough to assess the durability of artificial structures across a range of stream flows. In this paper we evaluate the incidence and causes of physical damage to several stream structure projects in Washington and Oregon. The occurrence of a flood event of 2-10-year recurrence
interval within the first few years after construction provided an excellent 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
discuss the implications for fish habitat management in the Pacific Northwest.

2. Methods

2.1 Study Sites

In the summer of 1986 we evaluated the incidence of physical impairment or
failure in artificial structure projects on 8 streams in southwest Oregon and 7 streams in
southwest Washington (Fig. 26, Table 15). The sample included 161 structures built by
the state of Oregon's Salmon and Trout Enhancement Program and the U.S. Forest

South coastal Oregon has intense winter precipitation, flashy streamflow, and
very high sediment yields, particularly from heavily logged watersheds. In southwest
Oregon, projects were intended to increase spawning habitat for fall chinook salmon
Oncorhynchus tshawytscha by stabilizing gravel and providing cover for adults, and to
improve rearing habitat for juvenile chinook salmon, steelhead O. mykiss, and cutthroat
tROUT O. clarki, by increasing area, depth, and complexity of pools (Johnson 1984;
Structures in southwest Oregon included lateral log deflectors, cross-stream log weirs,
multiple-log structures, and cabled natural debris jams. Benefit-cost projections were
Figure 26. Location of stream structure projects evaluated in southwest Oregon and southwest Washington during 1986. 1) Bear Cr; 2) Silver Cr; 3) Shasta Costa Cr; 4) Foster Cr; 5) Euchre Cr; 6) Crooked Bridge Cr; 7) Outcrop Cr; 8) Boulder Cr; 9) Lower Trout Cr; 10) Layout Cr; 11) Upper Trout Cr; 12) Wind R; 13) Trapper Cr; 14) Falls Cr; 15) Rush Cr.
Table 15. Physical characteristics of study sites. Valley segment types are large-scale geomorphic units, following Frissell et al. (1992a) 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; slash between two codes means both valley types occurred within project area.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Elev. (m)</th>
<th>Drainage Area (km²)</th>
<th>Mean Channel Slope (%)</th>
<th>Mean Active Channel Width (m)</th>
<th>Mean Active Channel Depth (m)</th>
<th>Valley Segment Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bear Cr</td>
<td>50</td>
<td>22.9</td>
<td>2.0</td>
<td>10.9</td>
<td>0.7</td>
<td>AC</td>
</tr>
<tr>
<td>Foster Cr</td>
<td>60</td>
<td>30.6</td>
<td>1.5</td>
<td>9.6</td>
<td>0.8</td>
<td>TBV</td>
</tr>
<tr>
<td>Silver Cr</td>
<td>20</td>
<td>25.1</td>
<td>1.0</td>
<td>8.9</td>
<td>0.4</td>
<td>AFV</td>
</tr>
<tr>
<td>Shasta Costa Cr</td>
<td>50</td>
<td>46.0</td>
<td>1.0</td>
<td>18.2</td>
<td>0.9</td>
<td>TBV</td>
</tr>
<tr>
<td>Euchre Cr</td>
<td>25</td>
<td>51.4</td>
<td>1.0</td>
<td>30.0</td>
<td>1.0</td>
<td>AV/AFV</td>
</tr>
<tr>
<td>Crooked Bridge Cr</td>
<td>25</td>
<td>2.7</td>
<td>2.5</td>
<td>6.0</td>
<td>0.7</td>
<td>AV</td>
</tr>
<tr>
<td>&quot;Outcrop&quot; Cr</td>
<td>25</td>
<td>1.2</td>
<td>4.0</td>
<td>5.5</td>
<td>0.5</td>
<td>AFV</td>
</tr>
<tr>
<td>Boulder Cr</td>
<td>25</td>
<td>5.9</td>
<td>2.0</td>
<td>12.0</td>
<td>0.7</td>
<td>AFV/AV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southwest Oregon:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rush Cr</td>
<td>945</td>
<td>17.8</td>
<td>2.0</td>
<td>10.4</td>
<td>0.7</td>
<td>AV</td>
</tr>
<tr>
<td>Falls Cr</td>
<td>830</td>
<td>24.8</td>
<td>6.0</td>
<td>8.1</td>
<td>0.6</td>
<td>IUH</td>
</tr>
<tr>
<td>Layout Cr</td>
<td>540</td>
<td>14.8</td>
<td>1.0</td>
<td>15.6</td>
<td>0.7</td>
<td>AV</td>
</tr>
<tr>
<td>Upper Trout Cr</td>
<td>565</td>
<td>10.8</td>
<td>2.0</td>
<td>9.3</td>
<td>0.6</td>
<td>AV</td>
</tr>
<tr>
<td>Lower Trout Cr</td>
<td>535</td>
<td>62.7</td>
<td>1.0</td>
<td>20.0</td>
<td>1.0</td>
<td>AV</td>
</tr>
<tr>
<td>Wind R</td>
<td>335</td>
<td>632.0</td>
<td>1.0</td>
<td>31.2</td>
<td>1.0</td>
<td>AV</td>
</tr>
<tr>
<td>Trapper Cr</td>
<td>340</td>
<td>28.8</td>
<td>1.5</td>
<td>25.6</td>
<td>0.8</td>
<td>AV</td>
</tr>
</tbody>
</table>
In southwest Washington, a region of moderately high sediment yield and high peak flows from winter rain-on-snow events, projects were intended to increase pool area for rearing of juvenile salmonids (U.S.D.A. 1987). Steelhead trout, brook trout *Salvelinus fontinalis*, and spring chinook salmon occurred in project streams. The projects included log weirs, diagonal log deflectors, multiple-log structures, cabled natural woody debris jams, and single and clustered boulders.

2.2 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. Gauged streams in southwest Oregon experienced an instantaneous peak flow of about 2 year recurrence interval (Geological Survey Water Resources Data for Washington and Oregon, Water Year 1986; Friday and Miller 1984). However, this flood was unusual in its duration, with high flow for several consecutive days. After adjusting for duration the estimated recurrence interval is 5-7 years, based 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 (Thorne and Zevenbergen 1982; Richards 1982) 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.)
183

1979; Campbell et al. 1982; and 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 km² drainage area, where only the Andrus et al. (1989) method appeared to provide reasonable estimates. Because peak discharge estimates often err by as much as 30 percent (Thorne and Zevenbergen 1982), and additional error exists in recurrence interval predictions, 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.

2.3 Definitions

We classified structures into three different categories, depending on their physical condition and function. A structure that had been washed downstream, severely fragmented, or grossly dislocated such that it had 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. Where the structure remained in its original location, but due to alteration of the structure or changes in the stream channel, no longer functioned in the intended mode or appeared to be at least temporarily ineffective, it was classified as impaired. Structures which had been buried under bedload deposits were considered impaired. Structures not visibly damaged or debilitated were categorized as “functioning roughly as intended,” or successful.

We define damage rate as the proportion of structures of a project in either the failed or impaired performance categories, i.e., the proportion of structures which were not successfully meeting physical objectives. Failure rate is defined as the proportion of structures of a project in the failure category only, i.e., structures that were lost or completely dysfunctional. Based on the time since installation and the estimated
recurrence interval of the February 1986 flood, we assume these rates reflect the incidence of damage and failure to be expected over a 5-10-year time span.

Some subjectivity is obviously involved in judgments about impairment, and to a lesser extent failure, particularly where the intent of the designer is 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, whereas a log weir would be expected to produce a plunge pool, a single boulder was probably intended only to create a small scour hole; a cabled natural debris jam would be expected to stay in place and maintain pre-existing 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.

2.4 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 or events contributing to impairment or failure of the structure, and in some cases drew a small sketch map. Our previous knowledge of structure design and placement at many of the projects helped us reconstruct failure processes, although 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 stream bank materials and riparian landform in the field, and compared these data with topographic maps to classify stream segments following Frissell et al. (1992a) and Cupp (1989). We calculated failure and impairment rates for each structure type and each stream, and compared them with stream-specific data on flood flow magnitude, mean channel width, slope, drainage area, and stream segment type (Table 15).

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

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 stream flow statistics for gauged streams in each region (Friday and Miller 1984) and used these to characterize regional peak flow magnitudes.
3. Results

3.1 Damage Rates in Relation to Stream Characteristics

The incidence of structure failure and damage varied widely among streams (Table 16). Overall, failure rates were higher in southwest Oregon streams (median 40%, mean 48%, range 7-100%) than 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 southwest Washington (median 42%, mean 46%, range 0-89%).

Rates of damage were higher in larger and wider streams (Fig. 27a). Projects in streams with active channel widths wider than 15 m had a median damage rate of 79% (range 50-100, 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 (Fig. 27b). In southwest Washington, failure rate was not apparently correlated with stream width, although impairment and therefore damage rate was 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).
Table 16. Flood magnitude estimates and rates of total damage and failure for fish habitat structure projects surveyed in 1986. Flood peak is estimated peak discharge in m$^3$ per second, and estimated recurrence interval in parentheses. Dash indicates discharge data not available; recurrence interval at these sites estimated from nearby streams or regional analyses by US Geological Survey.

<table>
<thead>
<tr>
<th>Stream</th>
<th>1985-86 Flood Peak</th>
<th>Number of Structures</th>
<th>Damage Rate (%)</th>
<th>Failure Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Southwest Oregon:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bear Cr.</td>
<td>28 (2 y)</td>
<td>19</td>
<td>79</td>
<td>32</td>
</tr>
<tr>
<td>Foster Cr.</td>
<td>30 (2 y)</td>
<td>15</td>
<td>27</td>
<td>7</td>
</tr>
<tr>
<td>Silver Cr.</td>
<td>17 (2 y)</td>
<td>6</td>
<td>50</td>
<td>17</td>
</tr>
<tr>
<td>Shasta Costa Cr.</td>
<td>45 (&lt;2 y)</td>
<td>18</td>
<td>83</td>
<td>55</td>
</tr>
<tr>
<td>Euchre Cr.</td>
<td>92 (5 y)</td>
<td>19</td>
<td>100</td>
<td>95</td>
</tr>
<tr>
<td>Crooked Bridge Cr.</td>
<td>12 (10 y)</td>
<td>6</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>&quot;Outcrop&quot; Cr.</td>
<td>7 (5 y)</td>
<td>5</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Boulder Cr.</td>
<td>- (5 y)</td>
<td>5</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td><strong>Southwest Washington:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rush Cr.</td>
<td>- (&lt;2 y)</td>
<td>9</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Falls Cr.</td>
<td>- (&lt;2 y)</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Layout Cr.</td>
<td>- (3-5 y)</td>
<td>9</td>
<td>89</td>
<td>11</td>
</tr>
<tr>
<td>Upper Trout Cr.</td>
<td>- (3-5 y)</td>
<td>19</td>
<td>42</td>
<td>0</td>
</tr>
<tr>
<td>Lower Trout Cr.</td>
<td>- (3-5 y)</td>
<td>5</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Wind R.</td>
<td>- (3-5 y)</td>
<td>10</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Trapper Cr.</td>
<td>- (3-5 y)</td>
<td>10</td>
<td>60</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 27. Failure (A) and damage (B) rates of projects in southwest Oregon (open circles) and southwest Washington (solid squares) in relation to active channel width. Stream numeric codes are same as Figure 1. Damage rate includes both failed and impaired structures (see text).
Figure 27
Although Hamilton (1989) concluded that projects located 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 fact, in southwest Washington the incidence of damage increased as slope decreased (regression analysis, $P < 0.04$, $r = -0.79$), due largely to burial of structures 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 located 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 using 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 projects experienced during 1986. There was little difference in median or range of failure rates between one group of projects that had peak flows of 2-year recurrence interval and another group that had 5-10-year peak flows. Falls Creek was the only project where no incidence of 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 relationships among these variables and drainage area, discharge, and bed and bank texture, make simple, univariate explanations of patterns in damage 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 parameters (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 fan areas, which are susceptible to bedload 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.

3.2 Mode of Damage

Processes that damaged structures included design- or material-related phenomena, such as failure of cables and anchoring devices, but also included a wide variety of processes producing changes in the immediate environment of structures, such as bank erosion and bedload deposition (Table 17). 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]). However, in most instances, the channel changes that damaged structures appeared to be primarily driven by watershed-scale phenomena, such as active landslides or road failures upstream causing massive bedload deposition in the project area. Many structures exhibited evidence of multiple, 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 bedload transport and deposition. In comparison, 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
Table 17. Percent 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 add to 100. Modes of damage are arranged from high-energy, scour-related processes at left to low-energy, deposition-related processes at right.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Log Breakage</th>
<th>Anchor Bolt Failure</th>
<th>Cable Failure</th>
<th>Logs Stranded Out of Channel</th>
<th>Bed scour Undermining Structure</th>
<th>Bank Erosion</th>
<th>Anchor Tree Washout</th>
<th>Bar or Channel Shift</th>
<th>Burial by Bedload</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bear Cr.</td>
<td>0</td>
<td>21</td>
<td>21</td>
<td>0</td>
<td>16</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Silver Cr.</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>33</td>
<td>0</td>
</tr>
<tr>
<td>Snasta Costa Cr.</td>
<td>6</td>
<td>11</td>
<td>17</td>
<td>22</td>
<td>0</td>
<td>11</td>
<td>17</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Foster Cr.</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Euchre Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>89</td>
</tr>
<tr>
<td>Crooked Bridge Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Outcrop Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Boulder Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Total S. W. OR</td>
<td>1</td>
<td>6</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>13</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>27</td>
</tr>
</tbody>
</table>
Table 17. Continued

<table>
<thead>
<tr>
<th>Stream</th>
<th>Log Breakage</th>
<th>Anchor Bolt Failure</th>
<th>Cable Failure</th>
<th>Logs Stranded Out of Channel</th>
<th>Bed Scour Undermining Structure</th>
<th>Bank Erosion</th>
<th>Anchor Tree Washout</th>
<th>Bar or Channel Shift</th>
<th>Burial by Bedload</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layout Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>6</td>
<td>0</td>
<td>11</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Upper Trout Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Lower Trout Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Wind R.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>Trapper Cr.</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Falls Cr.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Rush Cr.</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total S.W. WA</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>13</td>
<td>7</td>
<td>0</td>
<td>10</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>Total All Projects</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>3</td>
<td>9</td>
<td>11</td>
<td>2</td>
<td>7</td>
<td>12</td>
<td>17</td>
</tr>
</tbody>
</table>
Wind River, expected to scour pools within a long riffle, instead triggered deposition of a large mid-channel gravel bar, isolating the structures from the low-flow channel.

We noted numerous sites where structures caused inadvertant 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 pre-existing natural pools, and 6) concentrated flood pulses of bedload and debris triggered by collapse of structures during the flood. Eggs and fry of fish which 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 1988). Frayed cables and sheets of ripped-out geotextile or chain-link anchoring material at damaged structures created obvious aesthetic impacts. Furthermore, repairs may have exacerbated initial damage. Rip-rap, which was used extensively in attempts to suppress 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).

Modes of damage differed by valley segment type. In canyon-type segments, scour-related damage processes, such as cable breakage and loss of anchor trees, were common. In alluvial valleys, bank erosion, channel switching, and bedload aggradation were the primary proximal causes of damage and failure. These differences are partly related to different hydraulic and sedimentological forces and constraints
between valley segment types, but are also related to differences in structure design (e.g., anchoring systems) between valley types.

3.3 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 failed in more than half the cases (Fig. 28). 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 reported low failure rates for boulder structures in streams of less than two percent gradient, but higher failure rates in steeper streams (Hamilton 1989). Although many boulders had been almost completely buried in place by bedload deposits, we classified these as impairments rather than failures, since they could someday be re-excavated by the stream.

To some extent, failure and impairment rates presented in Fig. 28 are biased by the fact that 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.
Figure 28. Failure and impairment rates of structures classified by design. Structure type codes are: 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 MOG = multiple log structure; BLD = individually placed boulders; BCLUS = clustered boulders. Number at top of bar indicates number of structures in sample.
Figure 28
3.4 Inter-regional Patterns

When we compared our results with data from other regions in western Oregon (Table 18), we found that the projects we studied had higher than average rates of impairment and failure. However, the projects we evaluated were located in regions with intense winter precipitation and substantially higher peak discharge than most other regions (Figure 29, Table 19). There was a positive relationship between impairment and failure rates and peak flows. Streams in regions characterized by 10-year-recurrence-interval peak flows exceeding 1.0 m$^3$s$^{-1}$km$^{-2}$ had high but variable rates of damage (range 0-100%, median 46%) and failure (range 0-100%, median 14%) (Figure 30).

The regions with highest peak flows include the North Coast Range and South Coast/Klamath Mountains in Oregon, very steep and mountainous areas within 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 that is subject to severe and frequent winter storms funneling through the Columbia Gorge from both coastal and interior areas. The South Coast/Klamath Mountains region, which had the highest incidence of damage to structures, has mean 10-year peak flows in excess of 2.0 m$^3$s$^{-1}$km$^{-2}$ (180 cfs/mi$^2$). Projects in other parts of western Oregon experience 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 30).

We had limited data for North Coast Oregon streams. We expect that when more projects are evaluated, many will suffer high failure and impairment rates because of the region's high peak flows and high frequency of long-runout debris flows (C. Frissell and R. Nawa, Oregon State University, unpublished data). However, the abundance of clays and lower proportion of fine sands and silt in soils of this region
Table 18. Rates of physical failure and damage reported for projects in western Oregon surveyed by other agencies. \( n \) = number of structures in project. Data sources indicated in parentheses as follows: \( a \) = B. Higgins and H. Forsgren, Mt. Hood National Forest, unpublished data; \( b \) = D. Hohler, Mt. Hood National Forest, unpublished data; \( c \) = House et al. (1989).

<table>
<thead>
<tr>
<th>Region</th>
<th>Project</th>
<th>( n )</th>
<th>Failure Rate (%)</th>
<th>Damage Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Lake Br. (a)</td>
<td>24</td>
<td>12.5</td>
<td>25</td>
</tr>
<tr>
<td>Cascades</td>
<td>Rock Cr. (a)</td>
<td>83</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Buck Cr. (a)</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Clear Br. (a)</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Robinhood Cr. (a)</td>
<td>12</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Western</td>
<td>Fish Cr. (b)</td>
<td>252</td>
<td>4</td>
<td>31</td>
</tr>
<tr>
<td>Cascades</td>
<td>Pansy Cr. (a)</td>
<td>11</td>
<td>13</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Cooper Cr. (a)</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Oak Grove Cr. (a)</td>
<td>79</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Pinhead Cr. (a)</td>
<td>17</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Fall Cr. (a)</td>
<td>12</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Central</td>
<td>E.F. Lobster Cr. (1981) (c)</td>
<td>45</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Coast Range</td>
<td>Tobe Cr. (1982) (c)</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>U. Lobster Cr. (1982) (c)</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>S.Fk. Lobster Cr. (1982) (c)</td>
<td>65</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Little Lobster Cr. (1986) (c)</td>
<td>142</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>J Line Cr. (1987) (c)</td>
<td>30</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Lobster Cr. (1987) (c)</td>
<td>37</td>
<td>7</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>U. Lobster Cr. (1987) (c)</td>
<td>14</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>E.F. Lobster Cr. (1987) (c)</td>
<td>11</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>North</td>
<td>E. Beaver Cr. (1983) (c)</td>
<td>32</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Coast Range</td>
<td>U. Nestucca R. (1984) (c)</td>
<td>148</td>
<td>3</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>L. Elk Cr. (1986) (c)</td>
<td>92</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Mid. Nestucca R. (1987) (c)</td>
<td>42</td>
<td>19</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>U. Elk Cr. (1987) (c)</td>
<td>77</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Columbia</td>
<td>S.Fk. Salmon R. (a)</td>
<td>34</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>Cascades</td>
<td>Kool Cr. (a)</td>
<td>6</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Clear Cr. (a)</td>
<td>16</td>
<td>56</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Clear Fk. Sandy R. (a)</td>
<td>10</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Still Cr. (a)</td>
<td>264</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Ramsey Cr. (a)</td>
<td>7</td>
<td>0</td>
<td>57</td>
</tr>
</tbody>
</table>
Table 19. Unit discharge \( (m^3 \cdot sec^{-1} \cdot km^2) \) of ten-year recurrence interval peak flow \( (Q_{10}) \) of selected Oregon streams having greater than 20 years of record, drainage area exceeding 100 \( km^2 \) but less than 2500 \( km^2 \), and no significant influence of reservoir regulation. Data from Friday and Miller (1984). Some stations with records starting about 1957 or later were excluded due to bias of large floods in 1960’s and 1970’s. For stations with present flow regulation, data are for pre-dam period only. HC = High Cascades, WC = Western Cascades, CCR = Central Coast Range, NCR = North Coast Range, CCA = Columbia Cascades, SCK = South Coast/Klamath Mountains.

<table>
<thead>
<tr>
<th>Region</th>
<th>Station</th>
<th>Elev.(m)</th>
<th>Unit ( Q_{10} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>Salmon R. near Government Camp</td>
<td>1050</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Salmon R. below Linnery Cr.</td>
<td>760</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Clackamas R. at Big Bottom</td>
<td>620</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Squaw Cr. near Sisters</td>
<td>1060</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Red Blanket Cr. near Prospect</td>
<td>845</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>Middle Fk. Rogue R. nr. Prospect</td>
<td>800</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Rogue R. above Bybee Cr.</td>
<td>1055</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>High Cascades median</strong> = 0.38</td>
</tr>
<tr>
<td>WC</td>
<td>Clackamas R. above Three Lynx Cr.</td>
<td>335</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>Breitenbush R. above Canyon Cr.</td>
<td>480</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td>K. Santiam R. below Boulder Cr.</td>
<td>485</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>S. Santiam below Cascadia</td>
<td>230</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>Calapooia R. at Holley</td>
<td>160</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>Mohawk R. near Springfield</td>
<td>135</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>S. Fk. McKenzie R. above Cougar L.</td>
<td>520</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Salmon Cr. near Oakridge</td>
<td>445</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>N. Fk. Mid. Fk. Willamette R. near Oakridge</td>
<td>315</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>Hils Cr. above Hils Cr. Lake</td>
<td>500</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Mid. Fk. Willamette R. ab. Salt Cr.</td>
<td>370</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Elk Cr. near Trail</td>
<td>445</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Western Cascades median</strong> = 0.77</td>
</tr>
<tr>
<td>CCR</td>
<td>Taquina R. near Chitwood</td>
<td>15</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Alsea R. near Tidewater</td>
<td>15</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>Sluwap R. near Mapleton</td>
<td>10</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>K. Fk. Sluwap R. near Minerva</td>
<td>10</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Central Coast Range median</strong> = 0.86</td>
</tr>
<tr>
<td>CCA</td>
<td>W.Fk. Hood R. near Dee</td>
<td>245</td>
<td>1.38</td>
</tr>
<tr>
<td></td>
<td>Little Sandy R. near Bull Run</td>
<td>220</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>Sandy R. near Harriet</td>
<td>220</td>
<td>1.14</td>
</tr>
<tr>
<td></td>
<td>Salmon River at Welches</td>
<td>410</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Columbia Cascades median</strong> = 1.27</td>
</tr>
<tr>
<td>NCR</td>
<td>Wilson R. near Tillamook</td>
<td>20</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>Trask R. near Tillamook</td>
<td>20</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>Westucca R. near Beaver</td>
<td>15</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>Siletz R. at Siletz</td>
<td>30</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>North Coast Range median</strong> = 1.46</td>
</tr>
<tr>
<td>SCK</td>
<td>S.Fk. Coquille R. at Powers</td>
<td>60</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>E. Fk. Illinois R. near Taklma</td>
<td>540</td>
<td>2.01</td>
</tr>
<tr>
<td></td>
<td>W. Fk. Illinois R. below Rock Cr.</td>
<td>460</td>
<td>2.39</td>
</tr>
<tr>
<td></td>
<td>Sucker Creek near Holland</td>
<td>540</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>Chetco R. at Brookings</td>
<td>15</td>
<td>2.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>South Coast/Klamath Mountains median</strong> = 2.01</td>
</tr>
</tbody>
</table>
Figure 29. Box plots of 10-y peak flow standardized by drainage area for streams in six regions of western Oregon. Horizontal bar is median, box is interquartile range, and vertical line is data range. Number is sample size. HC = High Cascades, WC = Western Cascades, CCR = Central Coast Range, CCA = Columbia Cascades, NCR = North Coast Range, SCK = South Coast/Klamath Mountains.
Figure 29
Figure 30. Relation between rates of failure (A) and overall damage (B) of projects and regional median 10-y-recurrence-interval peak flow standardized by drainage area. Each point represents one or more projects (full data in Appendix 1). Horizontal bars indicate regional median. Curves are second-order regressions fitted to indicate trend, are not necessarily statistically significant. Southwest Washington projects from Table 2 are classified as Columbia Cascades region, except Rush Cr. and Falls Cr. in High Cascades. Southwest Oregon projects from Table 2 comprise the sample for South Coast/Klamath Mountains region.
Figure 30
may render stream banks more resistant to erosion than those of South Coast Oregon, moderating failure rates somewhat.

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/Klamath mountains region of Oregon are likely representative of conditions in much of northwest California as well.

4. Discussion

Artificial stream structures suffered widespread damage in most of the streams we surveyed in southwest Oregon and southwest Washington. Rather unpredictable damage rates and the wide range of causes of failure indicate that complex, multi-scale 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 experience intense flood flows, high bedload 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, apparently unanticipated by project designers. These changes were often related to dynamic conditions in the watershed or riparian zone, particularly as they
affected sediment load, streambank stability, and hydrology. Internal structure or material failure, 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 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 occurring in recent clear cuts in the basin. We did not survey Deep Creek and several other projects in detail because repairs were already well underway before we were able to inspect the sites.

Few simple rules about design of artificial structures emerge from our study, but we can offer some general guidelines for stream restoration projects. Structure designs that least often failed were those that minimally modified the pre-existing 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 on the locations 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. These 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, and in fact the opposite result may be as likely.
Within the study areas, the stream habitats that are 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 the streams draining watersheds most severely damaged by roads, logging, and landslides. Projects with highest failure rates in southwest Washington were located in an alluvial depositional 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 bedload 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 and coho salmon, and steelhead trout (Reimers 1971; Stein et al. 1972; Leider et al. 1986; Lichatowich 1989; and Nawa and Frissell, Oregon State University, 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 due to loss of shade (e.g., Lisle 1982; Hagans et al. 1986; Everest et al. 1987). The dominance of sand and gravel in streambanks in alluvial valley and alluvial fan segments 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 bedload accumulation (Lisle 1981; Madej 1984; Hagans et al. 1986). Such a recovery process 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, streamside landslides in second-growth forests, increased logging on steep, highly erodible lands under federal ownership (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). Re-establishment of mature riparian forests to stabilize streambanks and floodplain surfaces is also needed for recovery of channel morphology (Lisle 1981).

4.1 Implications for Economic Analyses

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

Larger floods might have more severe effects. The probability of at least one 20-y flood occurring within any 20-y period is 0.64, and the probability of a flood of 50-y or greater recurrence interval within 20 y 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 the average half-life (the time elapsed
when 50% of the structures are destroyed) of projects in southwest Oregon is less than 10 years, and that of southwest Washington is 15 years or less.

It is unlikely that most stream structure projects in Southwest Oregon and southwest Washington projects 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 in the field 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 realized or potential net damage, rather than benefit to fish and water quality; such risks should be explicitly addressed in project plans and disclosed in environmental analyses.

4.2 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, prescriptive or "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 mechanistic assumption that the problem is simply 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 northwest streams is symptomatic of a complex of ecological problems, driven by changes in riparian forests, channelization, and basin-scale erosion and sedimentation processes (Bisson et al. 1987; Elmore and Beschta 1987; Hicks et al. In press). Events such as sediment-laden floods and debris flows often re-shape channel morphology and fish habitat many kilometers downstream from their site of origin (Benda 1990).

Restoration programs in the regions we studied should follow a hierarchical strategy, emphasizing 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). Direct structural modifications of channels are unlikely to succeed unless these larger-scale concerns are dealt with first.

Our results point to the general need to consider physical (as well as biological) phenomena in regional and watershed-scale contexts when planning stream restoration projects. In the long run, evaluation and planning of stream modification projects could greatly benefit from application of a hierarchical classification system, such as 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 can provide a conceptual framework to order, analyze, and predict complex aspects of system behavior across different scales of space and time, by setting local, site-specific concerns in the context of large-scale dynamics of the watershed and 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 could undoubtedly 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.

ACKNOWLEDGEMENTS

This research was conducted while the authors were funded by a grant from the Wallop-Breaux Federal Aid to Fish Restoration program, contracted through the Oregon Department of Fish and Wildlife, with additional support from Oregon State University. Preliminary results of this study were presented at a workshop held October 21-23, 1986 in Portland, Oregon. Bruce Sims, now of the Santa Fe National Forest, encouraged this investigation and assisted in locating projects. George Westfall of Oregon Department of Fish and Wildlife, Don King of the Siskiyou National Forest, Dave Heller of U.S. Forest Service Region 6, and Bob House of Salem District B.L.M., provided helpful information and constructive criticism. We thank Eric Leitzinger for assisting in data analysis, and J. Dambacher, J.D. Hall, W.J. Liss, R.J. White, W.S. Platts, and R.W. Wiley for constructive reviews of the manuscript.
BIBLIOGRAPHY


Dambacher, J. 1991. Distribution, abundance, and emigration of juvenile steelhead (Oncorhynchus mykiss), and an analysis of stream habitat in the Steamboat Creek basin, Oregon. M.S. Thesis, Oregon State University, Corvallis, OR, USA.


Fontaine, B.L. 1988. An anchoring system for fish habitat structures: field techniques, evaluation, and applications. USDA Forest Service Research Note PNW-RN-481.


Frissell, C.A., and W.J. Liss. 1986. Classification of stream habitat and watershed systems in south coastal Oregon, and an assessment of land use impacts. Progress Report prepared for Oregon Department of Fish and Wildlife. Oak Creek Laboratory of Biology, Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon.


Frissell, C.A. 1991. Water quality, fisheries, and aquatic biodiversity under two alternative
forest management scenarios for the west-side federal lands of Washington, Oregon, and northern California. Report prepared for The Wilderness Society, Washington, D.C.


Chapter and Western Division, American Fisheries Society, and California Cooperative Fishery Unit, Humboldt State University.


Hicks, B.J. 1990. The influence of geology and timber harvest on channel morphology and salmonid populations in Oregon Coast Range streams. Doctoral Dissertation, Oregon State University, Corvallis, Oregon.


Kelsey, H.M. 1990. Late Quaternary deformation of marine terraces on the Cascadia subduction zone near Cape Blanco, Oregon. Tectonics 9:983-1014.


Nawa, R.K., C.A. Frissell, and W.J. Liss. 1988. Life history and persistence of anadromous salmonid stocks in relation to stream habitats and watershed classification. Annual progress report prepared for Oregon Department of Fish and Wildlife, Portland, Oregon. Oak Creek Laboratory of Biology, Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon.


Scrivener, J.C., and M.C. Brownlee. 1989. Effects of forest harvesting on spawning gravel and incubation survival of chum (Oncorhynchus keta) and coho salmon (O. kisutch) in Carnation Creek, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46:681-696.


